Augmentation of in-tube condensation of R-113

Minh Luu

Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/rtd

Recommended Citation

https://lib.dr.iastate.edu/rtd/7341

This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.
INFORMATION TO USERS

This was produced from a copy of a document sent to us for microfilming. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help you understand markings or notations which may appear on this reproduction.

1. The sign or “target” for pages apparently lacking from the document photographed is “Missing Page(s)”. If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure you of complete continuity.

2. When an image on the film is obliterated with a round black mark it is an indication that the film inspector noticed either blurred copy because of movement during exposure, or duplicate copy. Unless we meant to delete copyrighted materials that should not have been filmed, you will find a good image of the page in the adjacent frame.

3. When a map, drawing or chart, etc., is part of the material being photographed the photographer has followed a definite method in “sectioning” the material. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.

4. For any illustrations that cannot be reproduced satisfactorily by xerography, photographic prints can be purchased at additional cost and tipped into your xerographic copy. Requests can be made to our Dissertations Customer Services Department.

5. Some pages in any document may have indistinct print. In all cases we have filmed the best available copy.

University
Microfilms
International

300 N. ZEEB ROAD, ANN ARBOR, MI 48106
18 BEDFORD ROW, LONDON WC1R 4EJ, ENGLAND
LUU, MINH

AUGMENTATION OF IN-TUBE CONDENSATION OF R-113

Iowa State University

University Microfilms International

300 N. Zeeb Road, Ann Arbor, MI 48106

18 Bedford Row, London WC1R 4EJ, England
Augmentation of in-tube condensation
of R-113

by

Minh Luu

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of The
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
Major: Mechanical Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1980
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>TABLE OF CONTENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOMENCLATURE</td>
<td>xix</td>
</tr>
<tr>
<td>CHAPTER I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>CHAPTER II. GENERAL REVIEW OF HORIZONTAL IN-TUBE CONDENSATION AND AUGMENTATION TECHNIQUES</td>
<td>4</td>
</tr>
<tr>
<td><strong>Flow Regime Studies</strong></td>
<td>4</td>
</tr>
<tr>
<td>Introduction</td>
<td>4</td>
</tr>
<tr>
<td>Literature review</td>
<td>5</td>
</tr>
<tr>
<td>Selection of flow regime formats</td>
<td>9</td>
</tr>
<tr>
<td><strong>Pressure Drop Studies</strong></td>
<td>12</td>
</tr>
<tr>
<td>Introduction</td>
<td>12</td>
</tr>
<tr>
<td>Literature review</td>
<td>13</td>
</tr>
<tr>
<td>Two-phase flow pressure drop studies</td>
<td>13</td>
</tr>
<tr>
<td>Two-phase pressure drop correlations</td>
<td>15</td>
</tr>
<tr>
<td>Selection of pressure drop correlations</td>
<td>25</td>
</tr>
<tr>
<td><strong>Heat Transfer Studies</strong></td>
<td>31</td>
</tr>
<tr>
<td>Introduction</td>
<td>31</td>
</tr>
<tr>
<td>Literature review</td>
<td>33</td>
</tr>
<tr>
<td>Vertical film condensation</td>
<td>33</td>
</tr>
<tr>
<td>In-tube condensation</td>
<td>38</td>
</tr>
<tr>
<td>Effect of superheat</td>
<td>42</td>
</tr>
<tr>
<td>Effect of heat flux</td>
<td>45</td>
</tr>
<tr>
<td>Effect of tube inclination</td>
<td>46</td>
</tr>
<tr>
<td>Effect of pressure level</td>
<td>48</td>
</tr>
<tr>
<td>Effect of D/L</td>
<td>48</td>
</tr>
<tr>
<td>Effect of fluid properties and subcooling</td>
<td>49</td>
</tr>
<tr>
<td>Selection of heat transfer correlations</td>
<td>50</td>
</tr>
<tr>
<td><strong>Augmentation Technique Studies</strong></td>
<td>60</td>
</tr>
<tr>
<td>Twisted-tape inserts</td>
<td>61</td>
</tr>
</tbody>
</table>
iii

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literature review</td>
<td>61</td>
</tr>
<tr>
<td>Conclusion</td>
<td>64</td>
</tr>
<tr>
<td>Internally finned tubes</td>
<td>65</td>
</tr>
<tr>
<td>Single-phase studies</td>
<td>66</td>
</tr>
<tr>
<td>Condensation studies</td>
<td>70</td>
</tr>
<tr>
<td>Conclusion</td>
<td>74</td>
</tr>
<tr>
<td>Rough tubes</td>
<td>75</td>
</tr>
<tr>
<td>Single-phase studies</td>
<td>77</td>
</tr>
<tr>
<td>Condensation studies</td>
<td>83</td>
</tr>
<tr>
<td>Conclusion</td>
<td>85</td>
</tr>
<tr>
<td>CHAPTER III. EXPERIMENTAL PROGRAM</td>
<td>87</td>
</tr>
<tr>
<td>Experimental Facility Description</td>
<td>87</td>
</tr>
<tr>
<td>Refrigerant flow loop</td>
<td>87</td>
</tr>
<tr>
<td>Coolant loop</td>
<td>90</td>
</tr>
<tr>
<td>Test condenser tubes</td>
<td>92</td>
</tr>
<tr>
<td>General operating procedure</td>
<td>94</td>
</tr>
<tr>
<td>Data Acquisition and Reduction</td>
<td>95</td>
</tr>
<tr>
<td>CHAPTER IV. SMOOTH TUBE</td>
<td>98</td>
</tr>
<tr>
<td>General Considerations</td>
<td>98</td>
</tr>
<tr>
<td>Flow regimes</td>
<td>98</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>100</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>103</td>
</tr>
<tr>
<td>Results and Discussions</td>
<td>107</td>
</tr>
<tr>
<td>Experimental results</td>
<td>107</td>
</tr>
<tr>
<td>Flow regime results</td>
<td>114</td>
</tr>
<tr>
<td>Comparison of correlations</td>
<td>124</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>124</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>136</td>
</tr>
<tr>
<td>Effect of superheat</td>
<td>154</td>
</tr>
<tr>
<td>Complete condensation</td>
<td>154</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Incomplete condensation</td>
<td>159</td>
</tr>
<tr>
<td>Conclusion</td>
<td>166</td>
</tr>
<tr>
<td>Effect of heat flux</td>
<td>166</td>
</tr>
<tr>
<td>Conclusion</td>
<td>173</td>
</tr>
<tr>
<td><strong>CHAPTER V. SMOOTH TUBES WITH TWISTED-TAPE INSERTS</strong></td>
<td>177</td>
</tr>
<tr>
<td>General Considerations</td>
<td>177</td>
</tr>
<tr>
<td>Results and Discussion</td>
<td>177</td>
</tr>
<tr>
<td>Correlation of Experimental Results</td>
<td>183</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>183</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>184</td>
</tr>
<tr>
<td>Tangential velocity effect</td>
<td>186</td>
</tr>
<tr>
<td>Fin effect</td>
<td>187</td>
</tr>
<tr>
<td>Wall shear effect</td>
<td>188</td>
</tr>
<tr>
<td>Effect of superheat</td>
<td>196</td>
</tr>
<tr>
<td>Effect of heat flux</td>
<td>198</td>
</tr>
<tr>
<td><strong>CHAPTER VI. THE FINNED TUBES</strong></td>
<td>203</td>
</tr>
<tr>
<td>General Considerations</td>
<td>203</td>
</tr>
<tr>
<td>Results and Discussion</td>
<td>204</td>
</tr>
<tr>
<td>Correlations of Experimental Results</td>
<td>215</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>215</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>218</td>
</tr>
<tr>
<td>Discussion of difference between R-113 and steam correlations for heat transfer coefficient</td>
<td>223</td>
</tr>
<tr>
<td>Comparison of correlations</td>
<td>227</td>
</tr>
<tr>
<td>Effect of superheat</td>
<td>234</td>
</tr>
<tr>
<td>Effect of heat flux</td>
<td>238</td>
</tr>
<tr>
<td><strong>CHAPTER VII. THE ROUGH TUBES</strong></td>
<td>245</td>
</tr>
<tr>
<td>Test Fluid</td>
<td>Page</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>325</td>
</tr>
<tr>
<td>Data acquisition system</td>
<td>325</td>
</tr>
<tr>
<td>Temperature</td>
<td>325</td>
</tr>
<tr>
<td>Pressure</td>
<td>326</td>
</tr>
<tr>
<td>Flow rate</td>
<td>328</td>
</tr>
<tr>
<td>Boiler power</td>
<td>331</td>
</tr>
</tbody>
</table>

**APPENDIX B: EXPERIMENTAL PROCEDURE**

| Initial Testing                     | 333  |
| Removal of Noncondensable Gases     | 333  |
| Details of the Experimental Procedure | 336  |
| Procedure                           | 336  |
| Acceptance criteria                 | 338  |

**APPENDIX C: THERMODYNAMIC AND THERMOPHYSICAL PROPERTIES OF R-113**

| Thermodynamic Properties            | 344  |
| Enthalpy of saturated liquid        | 344  |
| Enthalpy of vapor                   | 344  |
| Enthalpy of vaporization            | 345  |
| Density of saturated liquid         | 345  |
| Density of vapor                    | 345  |
| Saturation temperature              | 346  |
| Saturation pressure                 | 347  |

<p>| Thermophysical Properties           | 347  |
| Liquid thermal conductivity         | 347  |
| Liquid specific heat at constant pressure | 347  |
| Vapor specific heat at constant volume | 348  |
| Liquid viscosity                    | 348  |
| Vapor viscosity                     | 349  |
| Surface tension                     | 349  |</p>
<table>
<thead>
<tr>
<th>Appendix</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Temperature Distribution Along a Single Fin</td>
<td>350</td>
</tr>
<tr>
<td>E</td>
<td>Sample Calculation of Experimental Data</td>
<td>355</td>
</tr>
<tr>
<td>F</td>
<td>Estimation of Experimental Uncertainties</td>
<td>367</td>
</tr>
<tr>
<td></td>
<td>Introduction</td>
<td>367</td>
</tr>
<tr>
<td></td>
<td>Propagation of Error</td>
<td>368</td>
</tr>
<tr>
<td></td>
<td>Estimate of $w_q$</td>
<td>370</td>
</tr>
<tr>
<td></td>
<td>Estimate of $w_A$</td>
<td>374</td>
</tr>
<tr>
<td></td>
<td>Estimate of $w_{TS}$</td>
<td>375</td>
</tr>
<tr>
<td></td>
<td>Estimate of $w_{TW_{wi}}$</td>
<td>377</td>
</tr>
<tr>
<td>G</td>
<td>Selected Tables</td>
<td>380</td>
</tr>
<tr>
<td>H</td>
<td>Data Reduction Computer Program Listing</td>
<td>395</td>
</tr>
<tr>
<td>I</td>
<td>Tabulation of Experimental Data</td>
<td>403</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure Number</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flow regimes in a horizontal tube.</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Layout of experimental facility.</td>
<td>88</td>
</tr>
<tr>
<td>3</td>
<td>Photograph of experimental facility.</td>
<td>89</td>
</tr>
<tr>
<td>4</td>
<td>Photograph of test condenser tubes, top to bottom: Tube 2, 3, 4, 5, 6, 7, 8, and 8.</td>
<td>93</td>
</tr>
<tr>
<td>5</td>
<td>Typical plots of experimental parameters.</td>
<td>108</td>
</tr>
<tr>
<td>6</td>
<td>Experimental overall pressure drops versus mass flux, Tube 1, all inlet pressures.</td>
<td>113</td>
</tr>
<tr>
<td>7</td>
<td>Experimental overall average heat transfer coefficients versus mass flux, Tube 1, all inlet pressures.</td>
<td>115</td>
</tr>
<tr>
<td>8</td>
<td>Modified Baker flow regime map.</td>
<td>117</td>
</tr>
<tr>
<td>9</td>
<td>Taitel and Dukler flow regime map.</td>
<td>119</td>
</tr>
<tr>
<td>10</td>
<td>Comparison of overall pressure drops with predictions of homogeneous model, Eq. (2.16a), Tube 1.</td>
<td>125</td>
</tr>
<tr>
<td>11</td>
<td>Comparison of overall pressure drops with predictions of homogeneous model, Eq. (2.16b), Tube 1.</td>
<td>126</td>
</tr>
<tr>
<td>12</td>
<td>Comparison of overall pressure drops with predictions of homogeneous model, Eq. (2.16c), Tube 1.</td>
<td>127</td>
</tr>
<tr>
<td>13</td>
<td>Comparison of overall pressure drops with predictions of homogeneous model, Eq. (2.16d), Tube 1.</td>
<td>128</td>
</tr>
<tr>
<td>14</td>
<td>Comparison of overall pressure drops with predictions of Miropol'skii et al. correlation [31], Tube 1.</td>
<td>129</td>
</tr>
<tr>
<td>15</td>
<td>Comparison of overall pressure drops with predictions of Lockhart and Martínelli correlation [35], Tube 1.</td>
<td>130</td>
</tr>
<tr>
<td>Figure Number</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>16</td>
<td>Comparison of overall pressure drops with predictions of Chisholm correlation [39], Tube 1.</td>
<td>131</td>
</tr>
<tr>
<td>17</td>
<td>Comparison of overall pressure drops with predictions of Dukler II correlation [29], Tube 1.</td>
<td>132</td>
</tr>
<tr>
<td>18</td>
<td>Comparison of overall pressure drops with predictions of Lockhart and Martinelli correlation [35] modified according to Eq. (2.11a), Tube 1.</td>
<td>134</td>
</tr>
<tr>
<td>19</td>
<td>Comparison of overall pressure drops with predictions of Dukler II correlation modified according to Eq. (2.11a), Tube 1.</td>
<td>135</td>
</tr>
<tr>
<td>20</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Carpenter and Colburn correlation [64], Tube 1.</td>
<td>137</td>
</tr>
<tr>
<td>21</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Akers et al. correlation [90], Tube 1.</td>
<td>138</td>
</tr>
<tr>
<td>22</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Rosson and Myers correlation [101], Tube 1.</td>
<td>139</td>
</tr>
<tr>
<td>23</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Boyko and Kruzhilin correlation [92], Tube 1.</td>
<td>140</td>
</tr>
<tr>
<td>24</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Soliman et al. correlation [53], Tube 1.</td>
<td>141</td>
</tr>
<tr>
<td>25</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Traviss et al. correlation [7], Tube 1.</td>
<td>142</td>
</tr>
<tr>
<td>26</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Azer et al. correlation [80,81], Tube 1.</td>
<td>143</td>
</tr>
<tr>
<td>27</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Cavallini and Zecchin correlation [95], Tube 1.</td>
<td>144</td>
</tr>
<tr>
<td>Figure Number</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>28</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Shah correlation [97], Tube 1.</td>
<td>145</td>
</tr>
<tr>
<td>29</td>
<td>Comparison of overall pressure drops with predictions of modified Dukler II in superheat effect study, Tube 1.</td>
<td>156</td>
</tr>
<tr>
<td>30</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Traviss et al. [7] in superheat effect study, Tube 1.</td>
<td>157</td>
</tr>
<tr>
<td>31</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Boyko and Kruzhilin [92] in superheat effect study, Tube 1.</td>
<td>158</td>
</tr>
<tr>
<td>32</td>
<td>Distributions of sectional heat fluxes and sectional heat transfer coefficients in superheat effect study.</td>
<td>161</td>
</tr>
<tr>
<td>33</td>
<td>Distributions of saturation temperatures, coolant and wall temperatures, and heat transfer coefficients for extended desuperheating zone, Tube 1.</td>
<td>164</td>
</tr>
<tr>
<td>34</td>
<td>Comparison of sectional heat transfer coefficients with predictions of Traviss et al. [7] in heat flux study with incomplete condensation, Tube 1.</td>
<td>168</td>
</tr>
<tr>
<td>35</td>
<td>Comparison of sectional heat transfer coefficients with predictions of Boyko and Kruzhilin [92] in heat flux study with incomplete condensation, Tube 1.</td>
<td>169</td>
</tr>
<tr>
<td>36</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Traviss et al. [7] in heat flux study with wet inlet vapor, Tube 1.</td>
<td>171</td>
</tr>
<tr>
<td>37</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Boyko and Kruzhilin [92] in heat flux study with wet inlet vapor, Tube 1.</td>
<td>172</td>
</tr>
<tr>
<td>Figure Number</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>38</td>
<td>Distribution of sectional heat transfer coefficients in heat flux study with wet inlet vapor, Tube 1.</td>
<td>174</td>
</tr>
<tr>
<td>39</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of Rosson and Myers [101] in heat flux study with wet inlet vapor, Tube 1.</td>
<td>175</td>
</tr>
<tr>
<td>40</td>
<td>Comparison of overall pressure drops with predictions of modified Dukler II in heat flux study with wet inlet vapor, Tube 1.</td>
<td>176</td>
</tr>
<tr>
<td>41</td>
<td>Typical temperature distributions along test condenser, Tube 2.</td>
<td>180</td>
</tr>
<tr>
<td>42</td>
<td>Experimental overall pressure drops versus mass flux, Tubes 2 and 3.</td>
<td>181</td>
</tr>
<tr>
<td>43</td>
<td>Experimental overall heat transfer coefficients versus mass flux, Tubes 2 and 3.</td>
<td>182</td>
</tr>
<tr>
<td>44</td>
<td>Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void, Tubes 2 and 3.</td>
<td>185</td>
</tr>
<tr>
<td>45</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (5.7), Tube 2.</td>
<td>191</td>
</tr>
<tr>
<td>46</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (5.7), Tube 3.</td>
<td>192</td>
</tr>
<tr>
<td>47</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Traviss et al., Tube 2.</td>
<td>194</td>
</tr>
<tr>
<td>48</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Traviss et al., Tube 3.</td>
<td>195</td>
</tr>
<tr>
<td>49</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin, Eq. (5.7), in superheat effect study, Tube 3.</td>
<td>197</td>
</tr>
<tr>
<td>Figure Number</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>50</td>
<td>Comparison of sectional heat transfer coefficients with predictions of modified Boyko and Kruzhilin, Eq. (5.7), in heat flux study with incomplete condensation, Tube 3.</td>
<td>199</td>
</tr>
<tr>
<td>51</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin, Eq. (5.7), in heat flux with wet inlet vapor, Tube 3.</td>
<td>200</td>
</tr>
<tr>
<td>52</td>
<td>Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void in heat flux study with wet inlet vapor, Tube 3.</td>
<td>202</td>
</tr>
<tr>
<td>53</td>
<td>Typical temperature distributions along test condenser, Tube 4.</td>
<td>206</td>
</tr>
<tr>
<td>54</td>
<td>Typical temperature distributions along test condenser, Tube 5.</td>
<td>207</td>
</tr>
<tr>
<td>55</td>
<td>Typical temperature distributions along test condenser, Tube 6.</td>
<td>208</td>
</tr>
<tr>
<td>56</td>
<td>Experimental overall pressure drops versus mass flux, Tube 4, all inlet pressures.</td>
<td>209</td>
</tr>
<tr>
<td>57</td>
<td>Experimental overall pressure drops versus mass flux, Tube 5, all inlet pressures.</td>
<td>210</td>
</tr>
<tr>
<td>58</td>
<td>Experimental overall pressure drops versus mass flux, Tube 6, all inlet pressures.</td>
<td>211</td>
</tr>
<tr>
<td>59</td>
<td>Experimental overall heat transfer coefficients versus mass flux, Tube 4, all inlet pressures.</td>
<td>212</td>
</tr>
<tr>
<td>60</td>
<td>Experimental overall heat transfer coefficients versus mass flux, Tube 5, all inlet pressures.</td>
<td>213</td>
</tr>
<tr>
<td>61</td>
<td>Experimental overall heat transfer coefficients versus mass flux, Tube 6, all inlet pressures.</td>
<td>214</td>
</tr>
<tr>
<td>62</td>
<td>Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void, Tubes 4, 5, and 6.</td>
<td>217</td>
</tr>
<tr>
<td>Figure Number</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>63</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), Tube 4.</td>
<td>220</td>
</tr>
<tr>
<td>64</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), Tube 5.</td>
<td>221</td>
</tr>
<tr>
<td>65</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), Tube 6.</td>
<td>222</td>
</tr>
<tr>
<td>66</td>
<td>Condenser reduction index versus mass flux for R-113 and steam, $P_{in} = 6.55$ bar and $P_{in} = 4.9$ bar, respectively.</td>
<td>224</td>
</tr>
<tr>
<td>67</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Vrable et al. correlation [116], Tube 4.</td>
<td>230</td>
</tr>
<tr>
<td>68</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Vrable et al. correlation [116], Tube 5.</td>
<td>231</td>
</tr>
<tr>
<td>69</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Vrable et al. correlation [116], Tube 6.</td>
<td>232</td>
</tr>
<tr>
<td>70</td>
<td>Comparison of data of Vrable [115] with predictions of Eq. (6.1).</td>
<td>233</td>
</tr>
<tr>
<td>71</td>
<td>Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void in superheat effect study, Tubes 5 and 6.</td>
<td>235</td>
</tr>
<tr>
<td>72</td>
<td>Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in superheat effect study, Tube 5.</td>
<td>236</td>
</tr>
<tr>
<td>73</td>
<td>Comparison of sectional overall and heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in superheat effect study, Tube 6.</td>
<td>237</td>
</tr>
</tbody>
</table>
Comparison of sectional heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in heat flux study with incomplete condensation, Tube 5.

Comparison of sectional heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in heat flux study with incomplete condensation, Tube 6.

Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void in heat flux study with wet inlet vapor, Tubes 5 and 6.

Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in heat flux study with wet inlet vapor, Tube 5.

Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation. Eq. (6.1), in heat flux study with wet inlet vapor, Tube 6.

Typical temperature distributions along test condenser, Tube 7.

Typical temperature distributions along test condenser, Tube 8.

Experimental overall pressure drops versus mass flux, Tube 7, all inlet pressures.

Experimental overall pressure drops versus mass flux, Tube 8, all inlet pressures.

Experimental overall heat transfer coefficients versus mass flux, Tube 7, all inlet pressures.

Experimental overall heat transfer coefficients versus mass flux, Tube 8, all inlet pressures.

Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void, Tube 7.
<table>
<thead>
<tr>
<th>Figure Number</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>86</td>
<td>Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void, Tube 8.</td>
<td>258</td>
</tr>
<tr>
<td>87</td>
<td>Comparison of overall and sectional heat transfer coefficients with predictions of modified Webb correlation [143], Tube 7.</td>
<td>261</td>
</tr>
<tr>
<td>88</td>
<td>Comparison of overall and sectional heat transfer coefficients with predictions of modified Webb correlation [143], Tube 8.</td>
<td>262</td>
</tr>
<tr>
<td>89</td>
<td>Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void in superheat effect study, Tube 7.</td>
<td>264</td>
</tr>
<tr>
<td>90</td>
<td>Comparison of overall and sectional heat transfer coefficients with predictions of modified Webb correlation [143] in superheat effect study, Tube 7.</td>
<td>265</td>
</tr>
<tr>
<td>91</td>
<td>Comparison of sectional heat transfer coefficients with predictions of modified Webb correlation [143] in heat flux study with incomplete condensation, Tube 7.</td>
<td>267</td>
</tr>
<tr>
<td>92</td>
<td>Comparison of overall and sectional heat transfer coefficients with predictions of modified Webb correlation [143] in heat flux study with wet inlet vapor, Tube 7.</td>
<td>268</td>
</tr>
<tr>
<td>93</td>
<td>Comparison of overall sectional and heat transfer coefficients with predictions of modified Webb correlation [143] in heat flux study with wet inlet vapor, Tube 8.</td>
<td>269</td>
</tr>
<tr>
<td>94</td>
<td>Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void in heat flux study with wet inlet vapor, Tubes 7 and 8.</td>
<td>270</td>
</tr>
<tr>
<td>95</td>
<td>Experimental overall pressure drops versus mass flux, all tubes, $P_{in} = 3.45$ bar.</td>
<td>272</td>
</tr>
<tr>
<td>Figure Number</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>96</td>
<td>Experimental overall pressure drops versus mass flux, all tubes, $P_{\text{in}} = 4.48$ bar.</td>
<td>273</td>
</tr>
<tr>
<td>97</td>
<td>Experimental overall pressure drops versus mass flux, all tubes, $P_{\text{in}} = 5.52$ bar.</td>
<td>274</td>
</tr>
<tr>
<td>98</td>
<td>Experimental overall pressure drops versus mass flux, all tubes, $P_{\text{in}} = 6.55$ bar.</td>
<td>275</td>
</tr>
<tr>
<td>99</td>
<td>Experimental overall heat transfer coefficients versus mass flux, all tubes, $P_{\text{in}} = 2.41$ bar.</td>
<td>276</td>
</tr>
<tr>
<td>100</td>
<td>Experimental overall heat transfer coefficients versus mass flux, all tubes, $P_{\text{in}} = 3.45$ bar.</td>
<td>277</td>
</tr>
<tr>
<td>101</td>
<td>Experimental overall heat transfer coefficients versus mass flux, all tubes, $P_{\text{in}} = 4.48$ bar.</td>
<td>278</td>
</tr>
<tr>
<td>102</td>
<td>Experimental overall heat transfer coefficients versus mass flux, all tubes, $P_{\text{in}} = 5.52$ bar.</td>
<td>279</td>
</tr>
<tr>
<td>103</td>
<td>Experimental overall heat transfer coefficients versus mass flux, all tubes, $P_{\text{in}} = 6.55$ bar.</td>
<td>280</td>
</tr>
<tr>
<td>104</td>
<td>Condenser reduction index versus mass flux, $P_{\text{in}} = 6.55$ bar.</td>
<td>285</td>
</tr>
<tr>
<td>105</td>
<td>Pressure drop index versus mass flux, $P_{\text{in}} = 6.55$ bar.</td>
<td>287</td>
</tr>
<tr>
<td>106</td>
<td>Spacer, pressure tap and thermocouple mounting detail.</td>
<td>300</td>
</tr>
<tr>
<td>107</td>
<td>Ratio of overall heat transfer coefficients, $h_{\text{exp}}/h_{\text{cal}}$, versus $(T_s-T_{\text{wi}})/(T_{\text{wo}}-T_c)$.</td>
<td>341</td>
</tr>
<tr>
<td>108</td>
<td>Sketch illustrating one-dimensional conduction and convection through a trapezoidal fin.</td>
<td>350</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table Number</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.</td>
<td>Values of exponents $m$, $n$ and constants $C_1$, $C_2$ for the Lockhart-Martinelli parameter in various flow types</td>
<td>19</td>
</tr>
<tr>
<td>2.2.</td>
<td>Values of constant and exponents suggested by the various correlations and models in Eq. (2.24)</td>
<td>30</td>
</tr>
<tr>
<td>2.3.</td>
<td>Details of the selected in-tube condensation correlations</td>
<td>52</td>
</tr>
<tr>
<td>3.1.</td>
<td>Experimental facility operative parameter ranges</td>
<td>94</td>
</tr>
<tr>
<td>4.1.</td>
<td>Results of flow regime study according to Mandhane et al. [9]</td>
<td>118</td>
</tr>
<tr>
<td>4.2.</td>
<td>Results of flow regime study according to Jaster and Kosky [14]</td>
<td>121</td>
</tr>
<tr>
<td>4.3.</td>
<td>Liquid entrainment prediction</td>
<td>123</td>
</tr>
<tr>
<td>4.4.</td>
<td>Ranking of the selected smooth tube correlations as predictors of the experimental results</td>
<td>153</td>
</tr>
<tr>
<td>6.1.</td>
<td>Values of some geometrical factors for the finned tubes</td>
<td>219</td>
</tr>
<tr>
<td>D.1.</td>
<td>Typical values of fin efficiency for the three finned tubes</td>
<td>354</td>
</tr>
<tr>
<td>G.1.</td>
<td>Selected geometrical parameters of the experimental tubes</td>
<td>381</td>
</tr>
<tr>
<td>G.2.</td>
<td>Tabulation of statistical information for curve fits to experimental overall pressure drops</td>
<td>383</td>
</tr>
<tr>
<td>G.3a.</td>
<td>Tabulation of statistical information for curve fits to experimental overall heat transfer coefficients (Tubes 1-6)</td>
<td>385</td>
</tr>
<tr>
<td>G.3b.</td>
<td>Tabulation of statistical information for curve fits to experimental overall heat transfer coefficients (Tubes 7-8)</td>
<td>387</td>
</tr>
<tr>
<td>Table Number</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>G.4.</td>
<td>Statistical parameters for pressure drop calculations</td>
<td>389</td>
</tr>
<tr>
<td>G.5.</td>
<td>Statistical parameters for comparison of the smooth-tube correlations</td>
<td>390</td>
</tr>
<tr>
<td>G.6.</td>
<td>Statistical parameters for comparison of the modified correlations for smooth tube with twisted tape</td>
<td>393</td>
</tr>
<tr>
<td>I.1.</td>
<td>Reduced data - heat transfer coefficients and static pressures</td>
<td>404</td>
</tr>
<tr>
<td>I.2.</td>
<td>Reduced data - saturation temperatures, inside wall temperatures and flow regime observations</td>
<td>418</td>
</tr>
<tr>
<td>I.3.</td>
<td>Reduced data - heat fluxes and energy transfers</td>
<td>432</td>
</tr>
<tr>
<td>I.4.</td>
<td>Reduced data - coolant flow rate and temperatures at test condenser and qualities</td>
<td>446</td>
</tr>
</tbody>
</table>
### Latin Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>constant or constant variable</td>
</tr>
<tr>
<td>A</td>
<td>surface area</td>
</tr>
<tr>
<td>A_1</td>
<td>constant</td>
</tr>
<tr>
<td>A_x</td>
<td>cross sectional area</td>
</tr>
<tr>
<td>B</td>
<td>dimensionless quantity or fin width</td>
</tr>
<tr>
<td>c_p</td>
<td>specific heat at constant pressure</td>
</tr>
<tr>
<td>C, C̄, C'</td>
<td>constant, constant variable, or correction factor</td>
</tr>
<tr>
<td>D</td>
<td>diameter</td>
</tr>
<tr>
<td>e</td>
<td>roughness height</td>
</tr>
<tr>
<td>e⁺</td>
<td>roughness Reynolds number</td>
</tr>
<tr>
<td>f</td>
<td>friction factor</td>
</tr>
<tr>
<td>F, F_1</td>
<td>factor or dimensionless quantity</td>
</tr>
<tr>
<td>g</td>
<td>gravitational acceleration</td>
</tr>
<tr>
<td>g⁺</td>
<td>heat transfer function, Eq. (2.64)</td>
</tr>
<tr>
<td>G</td>
<td>mass flux</td>
</tr>
<tr>
<td>h</td>
<td>heat transfer coefficient</td>
</tr>
<tr>
<td>H</td>
<td>height</td>
</tr>
<tr>
<td>i</td>
<td>enthalpy or integer variable</td>
</tr>
<tr>
<td>j</td>
<td>superficial velocity</td>
</tr>
<tr>
<td>k</td>
<td>thermal conductivity</td>
</tr>
<tr>
<td>K, K_1, K₂</td>
<td>dimensionless quantity</td>
</tr>
<tr>
<td>Symbol</td>
<td>Meaning</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>L</td>
<td>length</td>
</tr>
<tr>
<td>m</td>
<td>variable, dimensionless quantity or exponent</td>
</tr>
<tr>
<td>(\dot{m})</td>
<td>mass flow rate</td>
</tr>
<tr>
<td>M</td>
<td>flow meter scale reading</td>
</tr>
<tr>
<td>n</td>
<td>exponent or number of thermocouple junctions</td>
</tr>
<tr>
<td>n'</td>
<td>exponent</td>
</tr>
<tr>
<td>N</td>
<td>number of fins</td>
</tr>
<tr>
<td>p</td>
<td>pitch</td>
</tr>
<tr>
<td>p₁</td>
<td>exponent</td>
</tr>
<tr>
<td>P</td>
<td>pressure</td>
</tr>
<tr>
<td>(\tilde{P})</td>
<td>reduced pressure</td>
</tr>
<tr>
<td>q</td>
<td>heat transfer rate</td>
</tr>
<tr>
<td>q₁</td>
<td>exponent</td>
</tr>
<tr>
<td>(\dot{q})</td>
<td>heat flux</td>
</tr>
<tr>
<td>r</td>
<td>radial coordinate</td>
</tr>
<tr>
<td>r₁</td>
<td>exponent</td>
</tr>
<tr>
<td>R</td>
<td>radius or performance index</td>
</tr>
<tr>
<td>(R^+)</td>
<td>roughness function, Eq. (2.60)</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
</tr>
<tr>
<td>T₁</td>
<td>dimensionless quantity</td>
</tr>
<tr>
<td>u</td>
<td>velocity</td>
</tr>
<tr>
<td>U</td>
<td>frictional velocity</td>
</tr>
</tbody>
</table>
v  specific volume
V  voltage
w  uncertainty
W  weight or width of interfin channel
x  quality
y  half-pitch-to-diameter ratio
Y  coordinate perpendicular to axial direction
Z  axial coordinate or dimensionless quantity

Greek Symbols

α  void fraction
β  correction factor, Eq. (2.37)
δ  thickness
θ  temperature excess relative to T_s or half the fin spacing angle
μ  dynamic viscosity
ν  kinematic viscosity
π  3.1415...
ρ  density
σ  surface tension
τ  shear stress
η  fin efficiency or density ratio
§  dimensionless quantity, Eq. (2.11b)
λ  \([\left(\frac{\rho_V}{\rho_A}\right)\left(\frac{\rho_I}{\rho_W}\right)]^{1/2}\)
Γ  flow rate per unit width
\[ \psi = \left( \frac{\sigma_w}{\sigma} \right) \left( \frac{u_1}{u_w} \right)^2 \left( \frac{\rho_w}{\rho_1} \right)^2 \right)^{1/3} \]

\( \phi \) two-phase friction multiplier

\( \chi \) Lockhart-Martinelli parameter

**Dimensionless Group**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fr</td>
<td>Froude number</td>
<td>( \frac{u^2}{gD} )</td>
</tr>
<tr>
<td>Ga</td>
<td>Galileo number</td>
<td>( \frac{D^3 \rho_1 (\rho_1 - \rho_g) g}{\mu_1^2} )</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number</td>
<td>( \frac{kD}{k} )</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
<td>( \frac{c_p \mu}{k} )</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
<td>( \frac{CD}{\mu} )</td>
</tr>
<tr>
<td>St</td>
<td>Stanton number</td>
<td>( \frac{h}{c_p G} )</td>
</tr>
</tbody>
</table>

**Subscripts**

- aug: augmented
- A: air
- c: coolant
- cal: calculated value
- cr: critical
- ch: interfin channel
- e: equivalent or edge
- exp: experimental value
- f: related to friction or fin
- g: vapor or gas phase
- i: interface
- in: inlet
- l: liquid phase or assuming liquid phase to be total flow
assuming total flow to be liquid
related to momentum change
no slip
based or outside
outlet
saturation or side
standard
tangential direction
two-phase flow quantity
twisted tape or liquid phase turbulent/vapor phase turbulent
liquid phase turbulent/vapor phase viscous
liquid phase viscous/vapor phase turbulent
liquid phase viscous/vapor phase turbulent
wall
inside wall
outside wall
water
mean quantity
condensation
dimensionless quantity
CHAPTER I. INTRODUCTION

In-tube condensation is often involved in the air-conditioning and refrigeration, petro-chemical, and process industries. The condensate usually forms as a film on the cold tube wall. The film flow is acted upon by gravitational, interfacial shear, and pressure forces. The thickening film can thus be redistributed to form different flow patterns which, in turn, affect momentum and heat transfer. Stratification, interfacial waves, entrained liquid droplets, bubbles, and vapor slugs all can be present.

Usually, in-tube condensation is a heat transfer process with rather high heat transfer coefficients. However, there are circumstances where the condensing process provides the controlling heat transfer resistance. This occurs with many industrially important organic liquids as well as the common fluorocarbon refrigerants. Hence, there is motivation for improved in-tube condenser design by modification or augmentation of the condensing process.

Improvements in condenser design could result in smaller devices which would require less material. Alternatively, for improved condensers of the same size as the original unit, the heat duty may increase. Another possibility is that the temperature difference may decrease, thereby permitting more effective utilization of thermodynamics availability. These potential improvements with accessible technologies have motivated advanced condenser design for
the many existing applications. The application of advanced condenser design not only improves existing devices but also extends to new applications. The Rankine-cycle automotive power plant and large-scale horizontal tube evaporator distillation facilities are such applications.

Active or passive augmentation techniques can be used to modify real film condensation process as described in [1] and [2]. In view of their greater practical interest, research work pertaining to investigation of in-tube condensation has mostly dwelt on passive techniques. A brief review of available literature suggests that three passive techniques have the most promise for practical application to in-tube condensation: internally finned tubes, surface roughness, and twisted-tape inserts.

The present program was undertaken to extend Royal's study [2] to in-tube condensation of refrigerants. Direct experimentation with refrigerants is necessary since some physical properties, notably surface tension and density ratio, are greatly different for water and refrigerants. However, in addition to the testing of twisted-tape inserts and internally finned tubes as done in [2], the present program also included testing of rough surfaces and studies of the effect of both superheat and heat flux on the condensing process.

For this study, a conventional research program was chosen. Literature on the in-tube condensation process and on augmentation techniques was comprehensively surveyed to acquire a state-of-the-art
understanding of the process and transport mechanisms involved.

This survey was then followed by a program of experiments. A test loop was established by modifying the existing facility used in [2]. The experimental program consisted of testing of a smooth tube, two twisted-tape inserts, three internally finned tubes, and two tubes with repeated-rib roughness.

The smooth tube results were to provide the reference standard with which the augmentation schemes were to be compared. These results also proved valuable as a means of evaluating the existing models or correlations for in-tube condensation. Understandably, the best model or correlation would provide the basis upon which the correlation methods for the augmentation schemes were developed. The correlation methods were then compared with the present experimental results of the augmented tubes and, where available, with the experimental results of the other investigators. Finally, the performance of the augmentation schemes was evaluated using several performance indices.
CHAPTER II. GENERAL REVIEW OF HORIZONTAL IN-TUBE CONDENSATION AND AUGMENTATION TECHNIQUES

Flow Regime Studies

Introduction

When vapor, flowing inside a horizontal tube, is in contact with the tube wall having a temperature lower than the vapor saturation temperature, the vapor starts condensing. The condensate may form either as liquid drops or as a film, depending on the physical properties of the condensing medium and the surface chemistry of the tube wall. In the former case, the condensing mechanism is termed dropwise condensation, and in the latter case, filmwise condensation.

In most cases, especially for a condensing medium with low surface tension, in-tube condensation is filmwise condensation. The wall becomes covered with an annular layer of condensate which is acted on by gravitational, pressure, and interfacial shear forces. The latent heat released by the condensing vapor has to pass through this layer of liquid before it reaches the wall. The condensate film provides a major resistance to heat flow.

Depending on the relative magnitudes of interfacial shear and gravitational forces, the condensate may form an axisymmetrical film or become stratified. When the vapor flow rate increases, ripples or waves will appear at the interface. Further increases in vapor velocity will induce liquid droplet entrainment at the tips of these waves. Downstream of the tube inlet where appreciable condensation has occurred and there is high liquid loading, the
waves may bridge the lower and upper parts of the thickening film and create liquid slugs which divide the vapor core into large bubbles. Further downstream these bubbles will shrink in size and drift toward the upper part of the tube. In the case of low liquid loading, completely stratified flow occurs.

The above-mentioned geometrical configurations observed during condensing flow are called flow regimes or flow patterns. From the physics of a condensing flow, the geometry of the flow regime is intuitively seen to affect strongly the heat transfer and pressure drop characteristics of a condensing flow. This has been confirmed in the study by Bell et al. [3]. Hence, a flow regime study is a prerequisite to better understanding of the condensing flow.

Since the flow regimes are more a subjective judgement than an objective measurement, their terminology has not been standardized. In the present study, the generally accepted flow regimes, as given by Alves [4], were used with some modifications and are shown diagrammatically in Fig. 1. The characteristics of each flow pattern are briefly stated along with each flow pattern.

Literature review

Because of complexities of two-phase flow, there has been limited success in developing mathematical formulations for two-phase flow regimes. Most studies are empirical with adiabatic flow of air-water mixtures or with heat addition to steam-water mixtures, in either horizontal or vertical flow. Many studies were reviewed by Hosler [5].

The first major effort to develop a generalized flow regime map
ANNULAR MIST FLOW  
(SYMMETRIC ANNULUS  
UNIFORMLY CLOUDY)

ANNULAR FLOW  
(SYMMETRIC ANNULUS  
LIQUID ENTRAINMENT)

SEMIANNULAR FLOW  
(ASYMMETRIC ANNULUS  
CLEAR PHASES)

SLUG FLOW  
(WAVY INTERFACE  
FROTHY SLUG)

PLUG FLOW  
(LARGE BUBBLES  
CLEAR PHASES)

BUBBLY FLOW  
(SMALL BUBBLES  
CLEAR PHASES)

STRATIFIED FLOW  
(SMOOTHER INTERFACE  
CLEAR PHASES)

WAVY FLOW  
(WAVY INTERFACE  
CLEAR PHASES)

Fig. 1. Flow regimes in a horizontal tube.
for horizontal flow in conduits was made by Baker [6] using published data for adiabatic flow of low pressure gas-liquid mixtures. This map was purely empirical and was created by noting the flow regime of a set of experimental conditions characterized by a dimensional group \((G_\lambda/\lambda)\) and a dimensionless group \((G_\Pi/\lambda)\). This flow regime map has been generally considered to be also applicable to diabatic horizontal two-phase flow, as indicated by the good agreement with the Traviss et al. study of in-tube condensation of R-12 [7]. As outlined in [8], this map has been modified by transposing its coordinates such that the superficial mass velocities of each phase only appear in one coordinate.

Following a similar approach, other authors have proposed various flow regime maps using different dimensionless or dimensional groups. Among these is the one devised by Mandhane et al. [9] with \(U_1\) and \(U_g\) as coordinates. This map was constructed from a large data base and is suitable for incorporation in a computer program.

Soliman and Azer [10,11] were the first to study flow patterns of condensing flow. They found a large displacement of the wavy regime relative to the Baker map and proposed their own flow map in terms of superficial liquid velocity and void fraction.

All of the above-mentioned flow maps involve a strictly empirical boundary selection and are characterized by two generalized groups or parameters. The choice of the two groups or parameters may not be adequate to represent all transitions between regions in general, because different transitions are governed by different balances of
forces. This is indicated by the discrepancies between flow map predictions for the same set of data.

A more realistic approach was initiated by Quandt [12] in his analysis of gas-liquid flow patterns in vertical flow. He suggested that all flow patterns could be identified by balances of several forces. In his study, he considered three forces: pressure gradient, gravity, and surface tension. Taitel and Dukler [13] presented a means for analytical prediction of the transition between flow regimes and proposed a flow map based on four dimensionless groups for horizontal gas-liquid flow. Their flow regime boundaries were compared with the Mandhane et al. [9] map through analysis of a data set. A general agreement was found.

In condensing flow, Jaster and Kosky [14] established a dimensionless group to identify annular and stratified flows. This group is the ratio of axial shear force to gravitational body force. Recently, Palen et al. [15] used a similar ratio, but with a different expression, to predict two kinds of flow: vapor-shear-controlled flow and gravity-controlled flow. As stated by the authors, this ratio is similar to the Wallis $j_g$ parameter [16]; however, the actual expression is not given in their paper.

These two approaches to flow regime prediction were well-summarized in a recent study by Dunn et al. [17] for condensation of refrigerants inside horizontal tubes. Although the authors realized that the approach using force balances seems to offer a real insight into the flow regime mechanism and a promise of greater accuracy, they tried to
extend the other approach, using a digital computer, to map the flow patterns into three, four, or higher dimensional space as necessary. This method allows the influence of a greater number of variables to be taken into account. However, a conclusive result has not been reached yet.

Selection of flow regime formats

As described later, the present experiments were run with a water-jacketed condenser tube divided into four sections. Visual observation of the flow regime was possible only at the outlet of the last section.

Four flow regime prediction schemes were chosen to predict the flow pattern or kind of flow prevailing at the outlet of each test section. These are: the modified Baker flow map, the Taitel and Dukler flow map, the Mandhane et al. flow map, and the Jaster and Kosky parameter. Since no single scheme has been proven to be the best predictor of condensing flow regimes, this approach avoids bias which might be introduced by using only one scheme to estimate the flow pattern. It also indicates how the predictions of these schemes vary for the same set of data.

The modified Baker flow map [8] was used because it has been widely employed to study condensing flow. Hence, a comparison can be made on the same map for the present study with respect to other condensation studies. This modified map is plotted as $G_g/\lambda$ against $G_1^\psi$. 
The Mandhane et al. [9] flow map was selected because it has a broader data base and is available in a computer code. Plug and bubble flows were grouped into elongated bubble flow in this map.

The Taitel and Dukler [13] flow map was chosen since it is theoretically sound. Slug, plug, and bubble flows were not identified individually but were collectively termed intermittent flow. Four dimensionless groups were used with the Lockhart and Martinelli parameter, $\chi$, as the abscissa and the others as the ordinate. For horizontal flow, these groups were defined as follows:

\begin{align*}
\chi & = \left[ \frac{\frac{dP}{dz}}{\frac{dP}{dz}}_1 / \left( \frac{dP}{dz} \right)_g \right]^{1/2} \quad (2.1a) \\
F_1 & = \frac{ug}{(Dg)^{1/2}} \left( \frac{\rho_g}{\rho_1 - \rho_g} \right)^{1/2} \quad (2.1b) \\
K & = \left[ \frac{\rho_g u_g^2 u_1}{(\rho_1 - \rho_g)g\nu_1} \right] \quad (2.1c) \\
T_1 & = \left[ \frac{\frac{dP}{dz}}{\frac{dP}{dz}}_1 / \left( g(\rho_1 - \rho_g) \right) \right]^{1/2} \quad (2.1d)
\end{align*}

The particular transitions are controlled by the following groups:

- $\chi, F_1$ stratified to annular, stratified to intermittent
- $\chi, T_1$ intermittent to dispersed bubble
- $\chi, K$ stratified smooth to stratified wavy

The parameter of Jaster and Kosky [14] was selected because it was developed from condensing flow considerations. This parameter is
defined as

\[ F_2 = \frac{\tau_w}{\rho_1 g \delta} = \frac{(1 + \frac{2}{M})^{3M/2} \rho_1 x G^3 f^{3/2}}{2^{3/2} (\rho g \rho_1)^{3/2} \nu_1 \delta^+ g} \]  

(2.2)

where

\[ M = 5.13 \]

\[ \delta^+ = \left( \frac{\text{Re}_1}{2} \right)^{1/2} \quad \text{if} \quad \text{Re}_1 \leq 1250 \]

\[ \delta^+ = 0.0504 \text{Re}_1^{0.875} \quad \text{if} \quad \text{Re}_1 > 1250 \]

If \( F_2 > 29 \) annular

5 \( \leq F_2 \leq 29 \) transition

\( F_2 < 5 \) stratified
Pressure Drop Studies

Introduction

The pressure gradient in a horizontal two-phase flow system is usually divided into two parts, friction and momentum:

\[
\frac{dP}{dZ} = \left( \frac{dP}{dZ} \right)_f + \left( \frac{dP}{dZ} \right)_m \tag{2.3}
\]

In forced convection condensation inside a tube, the friction part arises from transverse momentum transfer from the vapor flow at the center of the tube to the condensate flow near the wall. The most important contributions to the frictional pressure drop probably come from the viscous dissipation in the liquid film, the pressure drop associated with gas flow over the wavy interface, and losses involved with the formation of droplets from the waves and their subsequent deposition. The magnitude of the interfacial shear stress at the vapor-condensate interface is expected to be influenced by the geometry of the condensate. This, in turn, will result in a variety of frictional pressure drops being observed during condensing experiments.

The momentum part of the pressure drop comes from the deposition of faster moving vapor onto the slower condensate flow. Usually, the resulting pressure recovery is small compared with the pressure loss due to the frictional pressure drop. Hence, the momentum pressure drop has received less attention than the frictional pressure drop. The following literature review considers only the frictional pressure drop.
Literature review

While pressure drop in condensing flow is usually studied simultaneously with, but subordinate to, the study of the heat transfer characteristics, pressure drop in adiabatic two-phase flow has received considerable attention because of its vital role in the petroleum industry.

Two-phase flow pressure drop studies  

Two-phase flow pressure drop studies Physical understanding and studies of the effects of some flow variables on pressure drop have been attempted. In early investigations of pressure drop in both horizontal and vertical condensing flows, Bergelin et al. [18,19] found somewhat different pressure drop characteristics for each flow regime in horizontal flow. In bubble flow, an unsteady and highly fluctuating pressure drop was observed. Slug flow had occasional violent fluctuations. Similar characteristics were observed in wavy flow, except that the fluctuation was periodic. In stratified flow, the pressure drop was steady with respect to time but not with distance. The pressure drop was steady with respect to both time and distance in annular flow. Bergelin and co-workers also concluded from the gas-phase friction factor plot that the liquid layer acted in a manner similar to a rough pipe wall.

This idea of wave roughness was adopted in several analytical studies of pressure drop in two-phase flow [20,21]. Agreement with experimental data was found only in a limited range of conditions.

Magiros and Dukler [22] investigated the influence of liquid properties on pressure drop and entrainment in co-current gas-liquid
flow. They found that the degree to which viscosity affected the pressure gradient depended upon the liquid flow rate. The pressure drop was only weakly dependent on surface tension. The authors concluded that the observed effects of fluid property variation suggested that it is not correct to treat a wavy interface as being equivalent to a rough solid surface.

Levy [23] derived expressions for two-phase density, velocity distribution, and pressure drop by treating the two-phase system as a continuous medium. He used a model similar to the single-phase turbulent mixing-length, and assumed equal mixing-lengths for momentum and density. However, the agreement with experimental results was not significantly improved over other correlations.

Many subsequent studies of two-phase pressure drop were conducted to investigate the relationship of the waviness of the gas-liquid interface to the pressure drop. It was generally agreed that wavy motion enhances the interface momentum, heat, and mass transfer. In his study of the effect of disturbance waves on the overall pressure drop in annular flow, Jameson [24] abandoned the wave-roughness model and used a linearized theory to calculate the pressure drop for gas flowing in an assumed wavy-walled tube. This method for calculating pressure drop was then applied to the two-phase annular flow problem using data for disturbance waves from the corresponding literature. The author found that, although the disturbance waves were typically long and of small height, their contribution to the total pressure drop was important,
especially at high gas velocities. Nevertheless, the application of the theoretical result requires the input of wave length and amplitude.

Wood and Subrahmaniyam [25] applied Prandtl's mixing length and von Karman similarity theory to their study of pressure drop in annular condensation. The proposed model assumed annular flow with a turbulent vapor core and a finite shear stress at the presumably smooth vapor-liquid interface. No substantial comparison with other experimental results was included.

Pimsner and Toma [26] were able to develop a new function statistically characterizing the wavy aspect of the two- and three-dimensional wavy flow based on the classical law-of-the-wall equation. The new function was found to correlate the pressure drop results from their experimental study.

The above literature review of theoretical studies of two-phase pressure drop is not exhaustive. The review does note various factors contributing to the frictional pressure drop and the existing theoretical tools to predict this pressure drop. Because of the oversimplified assumptions and the limited number of factors considered, these theoretical analyses or models are of limited utility in predicting experimental results. Most predictions are still made using two-phase pressure drop correlations.

Two-phase pressure drop correlations Basically, two models have been utilized to develop correlations to calculate pressure drop in two-phase flow. These are the homogeneous model and the separated
flow model.

For the homogeneous model, the basic assumptions involved are:

a) equal vapor and liquid linear velocities,

b) the attainment of thermodynamic equilibrium between the phases,

c) the use of a suitably defined single-phase friction factor for two-phase flow.

Under these assumptions, the frictional pressure drop can be expressed as

\[- \frac{dP}{dz} f = \frac{2f_{\text{tp}} G^2 v_1}{D} \left[ 1 + x\left(\frac{v_{lg}}{v_1}\right) \right] \quad (2.4a)\]

The two-phase friction factor is sometimes replaced by \(f_{10}\) which involves the liquid viscosity. Then, Eq. (2.4a) can be written as

\[- \frac{dP}{dz} f = -\left(\frac{dP}{dz}\right)_{f,10} \phi_{10}^2 \quad (2.4b)\]

where \(\phi_{10}^2\) is known as the two-phase frictional multiplier.

Several forms of the mean viscosity in \(f_{\text{tp}}\) have been proposed such that Eq. (2.4a) reduces to the formulation of single-phase pressure drop of liquid and vapor at \(x = 0\) and \(1\), respectively. These forms of the relationship are

1. \(\frac{1}{\bar{\mu}} = \frac{x}{\mu_\text{g}} + \frac{(1-x)}{\mu_1}\) (recommended by McAdams et al. [27]) \(\quad (2.5a)\)

2. \(\bar{\mu} = \frac{x\mu_\text{g} + (1-x)\mu_1}{\mu_1}\) (suggested by Cicchitti et al. [28]) \(\quad (2.5b)\)
3. \[ \overline{\mu} = \rho \left[ x v g v_g + (1-x) v l v_l \right] \] (proposed by Dukler et al. [29]) (2.5c)

When the expressions of \( \overline{\mu} \) are substituted in Eq. (2.4a), this equation can be reduced to the form of Eq. (2.4b) with the grouping of \( 1 + x(v g / v l) \) and the residual term of \( \overline{\mu} \) in the two-phase friction multiplier, \( \phi_{10}^2 \).

This model is simple to apply and should correlate well the pressure drop results at very low quality or very high quality where the assumptions concur with the actual flow pattern. It had been widely used in earlier studies of two-phase flow before the separated flow model was proposed. Nevertheless, as presented in [30], this model has not lost its ground completely, and, in fact, is quite popular in the Russian literature, e.g., [31,32].

For the separated flow model, the first and third assumptions of the homogeneous model are discarded. Instead, unequal vapor and liquid velocities are allowed, and the two-phase friction multiplier and the void fraction are related to the independent flow variables by the use of empirical correlations or simplified concepts. Because of the assumption of different phase velocities, the frictional pressure drop can be written separately in terms of the single-phase pressure gradient for the total flow considered as liquid, for the liquid phase considered to flow alone, and for the gas phase considered to flow alone:
Martinelli and Nelson [33] were among the first to use this approach to predict pressure drop during forced convection boiling of water. They considered that both phases were in turbulent flow and found that $\phi_{ltt}$ and $\phi_{gtt}$ could be correlated by means of a dimensionless parameter, $\chi_{tt}$, where

$$\chi_{tt} = \left( \frac{v_1}{v_g} \right)^{0.571} \left( \frac{\mu_1}{\mu_g} \right)^{0.143} \left( \frac{1}{x} - 1 \right)$$  \hspace{1cm} (2.9)$$

The correlation, in graphical form with $\phi_{ltt}$ and $\phi_{gtt}$ plotted against $\sqrt{\chi_{tt}}$, was based on the isothermal pressure drop data from [34]. This graph provides the values of $\phi_{ltt}$ at any $x$ such that Eq. (2.7) can be integrated to attain total pressure loss once the variation of $x$ along the tube is known.

Lockhart and Martinelli [35] later developed a more generalized parameter $\chi$ which is defined as
$x^2 = \left( \frac{dP}{dz} \right)_1 / \left( \frac{dP}{dz} \right)_g = \frac{Re^m_g}{Re^n_1} \frac{C_1}{C_g} \left( \frac{U_1}{U_g} \right) \frac{\rho_g}{\rho_1}$

(2.10)

where $n$, $C_1$ and $m$, $C_g$ are the appropriate exponent and constant in the friction factor expression of the liquid and vapor phases, respectively. Their values depend on the types of the flow encountered in each phase, and are listed in Table 2.1.

<table>
<thead>
<tr>
<th>Flow types</th>
<th>tt</th>
<th>vt</th>
<th>tv</th>
<th>vv</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re_1$</td>
<td>&gt;2000</td>
<td>&lt;1000</td>
<td>&gt;2000</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>$Re_g$</td>
<td>&gt;2000</td>
<td>&gt;2000</td>
<td>&lt;1000</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>$n$</td>
<td>0.2</td>
<td>1.0</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>$m$</td>
<td>0.2</td>
<td>0.2</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$C_1$</td>
<td>0.046</td>
<td>16</td>
<td>0.046</td>
<td>16</td>
</tr>
<tr>
<td>$C_g$</td>
<td>0.046</td>
<td>0.046</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

Using the data for the simultaneous flow of air and liquids, which included benzene, kerosene, water and various oils, in pipes with diameters varying from 0.0586 in. to 1.017 in. at near atmospheric pressure, the authors graphically correlated the two-phase friction multipliers as functions of $x$. 
A similar approach was adopted in several subsequent studies of two-phase pressure drop, but with different parameters and/or different experimental bases. Some of these studies, including the Lockhart and Martinelli results, were compared in a review study by Dukler et al. [36]. In their study, they found the Lockhart and Martinelli correlation showed the best agreement with a set of carefully culled experimental data on pressure drop. Notwithstanding their finding, the authors looked to a more physically reasonable approach to obtain an improved correlation.

In parallel to single-phase pressure drop studies, Dukler et al. [29] used a similarity analysis to investigate two-phase pressure drop. The basic idea derives from the dynamic similarity of two flow systems. Relevant forces encountered in two-phase flow form ratios to establish dimensionless groups. Once the relationship between these dimensionless groups is found from experimental data for one system, the same relationship should apply to all similar systems. The authors considered inertial, viscous, and pressure forces and ended up with two dimensionless groups analogous to the Reynolds number and Euler number (twice the Darcy friction factor) of a single-phase flow. Two out of four special cases considered were of practical interest. Case I was identical to the homogeneous model with the viscosity given by Eq. (2.5c). Case II was similar to the separated flow model. However, Dukler and his co-workers used their own correlation between the liquid volume fraction
and the two-phase friction factor normalized with the single-phase friction factor which was calculated from the mixture Reynolds number. The correlation was derived from 800 selected data points and is valid for Re from 2000 to 120,000. Using Hughmark's void fraction correlation [37], the authors found that their correlation gave better agreement with the data than did the Lockhart and Martinelli correlation.

Several subsequent studies of two-phase flow pressure drop involved modification of the Lockhart and Martinelli correlation by introducing mass velocity into the two-phase multipliers. Among these are the studies done by Baroczy [38] and by Chisholm [39].

Recently, Mandhane et al. [40] did a critical evaluation of sixteen friction pressure drop prediction methods for gas-liquid flow in horizontal pipes, including two proposed by the authors. For about 10,500 data points, the investigators grouped the data by predicted flow pattern using the Mandhane et al. [9] flow pattern map as a basis, and then tested each correlation against all the data points within each flow pattern grouping. They found the correlations were sensitive to flow patterns. Nevertheless, for all flow patterns considered, the Dukler et al. correlation was found to agree best with all the data.

The frictional pressure drop in condensing flow differs from that in adiabatic flow. In condensing flow, a net mass transfer exists at the interface and thus modifies the interfacial shear stress.
However, the extent to which the adiabatic flow pressure drop correlation is affected is not yet well-established. The momentum pressure drop is also required to get the total pressure drop in horizontal in-tube condensation. In a condensing pressure drop study by Robson and Hilding [41], with steam flow rates from 40 to 500 lbm/hr in 1/4 and 1/2 in. diameter tubes, the Lockhart and Martinelli approach was used. They established a series of curves representing the two-phase multiplier, $\phi$, as a function of the parameter $\chi$. The homogeneous model was used to estimate the momentum pressure drop. Some of the experiments demonstrated the possibility of a local rise in static pressure because of momentum pressure gain. No comparison was made with other experimental results.

Supported by the experimental results of Wallis [42], who performed a simulated study of condensation pressure drop by extracting air through a porous tube wall, Silver and Wallis [43] proposed a simple model to account for the effect of condensation on interfacial shear stress by using the concept of Reynolds flux. They showed that

\[
\frac{f_i^*}{f_i} = e^{\frac{g}{2f_i} - \frac{g}{f_i}} \tag{2.11a}
\]

where

\[
g = \frac{2}{\rho g \mu} \frac{d\Gamma}{dZ} \tag{2.11b}
\]

\[
\Gamma' = \frac{m_x}{\pi D} \tag{2.11c}
\]
Linehan et al. [44] confirmed this result in a subsequent study of the interfacial shear stress in annular flow condensation. However, they modified the expression in Eq. (2.11a) as follows:

\[
\frac{f_i^*}{f_i} = 1 - \frac{g}{f_i}
\]  

(2.12)

Boiko [45] realized the influence of the radially directed flow of the vapor mass condensing on the tube wall in his experimental study of pressure drop with steam condensation in a horizontal tube. He followed the homogeneous model and set up the following friction factor ratios:

\[
\frac{f_i^*}{f_i} = C_1 \text{Re}^{0.35} \left(\frac{\rho_l}{\rho_g}\right)^{0.1} \left(\frac{L}{D}\right)^{0.15} 
\]

\[+ \frac{2(x_1 - x_2)}{L/D} \quad \text{for } \text{Re} \leq 70,000 \]  

(2.13a)

\[
\frac{f_i^*}{f_i} = C_2 \left(\frac{\rho_l}{\rho_g}\right)^{0.1} \left(\frac{L}{D}\right)^{0.15} 
\]

\[+ \frac{2(x_1 - x_2)}{L/D} \quad \text{for } \text{Re} > 70,000 \]  

(2.13b)

where Re is the Reynolds number based on all flow as liquid, and

\[
C_1 = 0.0091, \quad C_2 = 0.45 \quad \text{for } x_1 = 1
\]

\[
C_1 = 0.45, \quad C_2 = 0.60 \quad \text{for } 0.26 < x_1 < 0.86
\]
The experiments covered Reynolds numbers from $6 \cdot 10^3$ to $4 \cdot 10^5$, inlet pressures from 12.3 to 88 bar, inside tube diameters from 11.5 mm to 18.5 mm, and test section lengths from 2.5 m to 11.95 m.

Besides their study on condensation heat transfer, Miropol'skii et al. [31] found that the pressure drop with condensation did not agree with the pressure drop of adiabatic flow. Their ratio is given by

$$\frac{\Delta P^*_f}{\Delta P_f} = 1 + 2.5K_{\perp}^{0.25} \quad (2.14a)$$

where

$$K_{\perp} = \frac{q/A}{i_{lg} \rho_u} \quad (2.14b)$$

Cavallini and Zecchin [46] used the modified adiabatic friction factors suggested by Wallis [16] and Linehan et al. [44] to evaluate their experimental pressure drop results. They found that the latter proposal, Eq. (2.12), gave better agreement with the data. However, Traviss et al. [7] found their frictional pressure drop results were reasonably predicted by the Lockhart and Martinelli correlation. In several studies of pressure drop of refrigerant-oil mixtures in horizontal pipes, Scheideman et al. [47-49] also reported good agreement between the experimental results and the Lockhart and Martinelli prediction.

In a recent study of augmented in-tube condensation, Royal and Bergles [50] compared their smooth tube pressure drop results with the
correlations of the homogeneous model, Lockhart and Martinelli, Hughmark [51,52], Dukler I (Case I), and Dukler II (Case II). They found the correlation of Dukler II and the Hughmark void fraction [37] for the momentum pressure drop gave the best prediction of the smooth tube results.

**Selection of pressure drop correlations**

The above literature review indicates that there are numerous correlations for pressure drop; however, mixed results have been obtained when these correlations are compared with the experimental data. One of the main tasks here is to establish a correlation to describe accurately the present experimental smooth tube pressure drops, thus establishing a basis for correlation of pressure drops in enhanced in-tube condensation. In order to accomplish this, several correlations, out of many available, have to be selected for comparison with the smooth tube pressure drop results.

The choice of these correlations is based on several factors: some degree of success of the correlation appears in former studies, the range of the important physical quantities of the experiments on which the correlation was derived is comparable to that of the present experiments, and the correlation has a physically sound basis. With these considerations, the correlations of the homogeneous model [8], Lockhart-Martinelli [35], Chisholm [39], Dukler II [29], and Miropol'skii et al. [31] were chosen. All of these
correlations, except the correlation of Miropol'skii et al., are for adiabatic flows. Modification to these correlations due to condensation as described in Eqs. (2.11-2.12) will be considered after a preliminary comparison of these correlations with the experimental results.

Unless otherwise stated in a specific correlation, the Blasius form of the friction factor was adopted, i.e.,

$$f = \frac{0.079}{\text{Re}^{0.25}}$$  \hspace{1cm} (2.15)

In addition, all correlations are formulated in the form of Eqs. (2.6-2.8) so that only the expressions of these two-phase multipliers are needed when presenting these correlations. For the homogeneous model, four possible forms of $\phi_{10}^2$ corresponding to the liquid viscosity and Eqs. (2.5) were considered.

Correlation of homogeneous model [8]:

$$\phi_{10}^2 = 1 + x \left( \frac{v_{lg}}{v_{1}} \right)$$ \hspace{1cm} (2.16a)

$$\phi_{10}^2 = \left[ 1 + x \left( \frac{v_{lg}}{v_{1}} \right) \right] \left[ 1 + x \left( \frac{\mu_{l}}{\mu_{g}} - 1 \right) \right]^{-0.25}$$ \hspace{1cm} (2.16b)

$$\phi_{10}^2 = \left[ 1 + x \left( \frac{v_{lg}}{v_{1}} \right) \right] \left[ 1 + x \left( \frac{\mu_{l}}{\mu_{g}} - 1 \right) \right]^{0.25}$$ \hspace{1cm} (2.16c)

$$\phi_{10}^2 = \left[ 1 + x \left( \frac{v_{lg}}{v_{1}} \right) \right] \left( \frac{\frac{x v}{g} \left( \frac{\mu_{g}}{\mu_{l}} \right) + (1 - x) v_{1}}{x v + (1-x) v_{1}} \right)^{0.25}$$ \hspace{1cm} (2.16d)
Correlation of Miropol'skii et al. [31]:

\[ \phi_{10}^2 = \frac{f^*}{f} \frac{\bar{v}}{v_1} (1 + 2.5K^{0.25}) \]  \hspace{1cm} (2.17)

where \( f^* \) is determined from Eq. (2.15) with

\[ Re = \frac{GD}{\mu_1 (1-x) + \mu_g x} \]

and \( \bar{v} = v_1 (1-x) + v_g x \)

Correlation of Lockhart-Martinelli [35]:

\[ \phi_g = 1 + 2.85X^{0.523} \]  \hspace{1cm} from [53] \hspace{1cm} (2.18)

and \[ f_g = \frac{0.045}{(G D/\mu_g)^0.2} \] \hspace{1cm} (2.19)

Correlation of Chisholm [39]:

\[ \phi_{11}^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad \text{for } G \leq 1.47 \times 10^6 \text{lbm/hr-ft}^2 \] \hspace{1cm} (2.20a)

\[ C = \left[ \lambda_1 + (C_2 - \lambda_1) \left( \frac{v_1}{v_g} \right)^{0.5} \right] \left[ \left( \frac{v_g}{v_1} \right)^{0.5} + \left( \frac{v_1}{v_g} \right)^{0.5} \right] \] \hspace{1cm} (2.20b)

\[ \lambda_1 = 0.75 \quad C_2 = 1.47 \times 10^6 / G \]
for $G > 1.47 \cdot 10^6 \text{lbm/hr-ft}^2$

\[
\phi_1^2 = \left[ 1 + \frac{C}{X} + \frac{1}{X^2} \right] \psi_1 \quad (2.21a)
\]

\[
\psi_1 = \left[ 1 + \frac{C}{X_{tt}} + \frac{1}{X_{tt}^2} \right] / \left[ 1 + \frac{C}{X_{tt}} + \frac{1}{X_{tt}^2} \right] \quad (2.21b)
\]

\[
\bar{C} = \left( \frac{v_g}{v_{1}} \right)^{0.5} + \left( \frac{v_{1}}{v_g} \right)^{0.5} \quad (2.21c)
\]

$C$ is evaluated as in Eq. (2.20a)

Correlation of Dukler et al. [29]:

\[
\phi_{10}^2 = \frac{f_{tp}}{f} \frac{\rho_{1}}{\rho_{NS}} \left[ \frac{\rho_{1}}{\rho_{NS}} \frac{\lambda^2}{(1-\alpha)} + \frac{\rho_{g}}{\rho_{NS}} \frac{(1-\lambda)^2}{\alpha} \right] \quad (2.22a)
\]

\[
\frac{f_{tp}}{f} = 1 - \ln \lambda / [1.281 - 0.478(-\ln \lambda) + 0.444(-\ln \lambda)^2 \\
- 0.094(\ln \lambda)^3 + 0.00843(-\ln \lambda)^4] \quad (2.22b)
\]

\[
f = 0.0014 + \frac{0.125}{(Re)^{0.32}} \quad (2.22c)
\]

\[
\rho_{NS} = \rho_{1}\lambda + \rho_{g}(1 - \lambda) \quad (2.22d)
\]
\[ \lambda = 1 - \alpha_{NS} \]

\( \alpha_{NS} \) is identical to the homogeneous void

The momentum pressure drop was estimated as outlined in [8]. This pressure gradient can be expressed for the homogeneous flow model as

\[ -(\frac{dP}{dZ})_m = G^2 \left[ v_1 g \frac{dx}{dZ} + x \frac{dv_g}{dP} (\frac{dP}{dZ}) \right] \]  \hspace{1cm} (2.23)

Or, in the separated flow model

\[ -(\frac{dP}{dZ})_m = G^2 \frac{d}{dZ} \left[ \frac{x^2 v_g}{\alpha} + \frac{(1-x)^2 v_1}{(1-\alpha)} \right] \]  \hspace{1cm} (2.24)

To use Eq. (2.24), a knowledge of void-fraction, \( \alpha \), is needed. The void fraction correlations of the homogeneous model, Lockhart-Martinelli [35], Baroczy [54], Zivi [55], Thom [56], Turner and Wallis [57], and Hughmark [37] were chosen. The first six correlations were reduced by Butterworth [58] to the following condensed form:

\[ \alpha = \frac{1}{1 + A_1 \left( \frac{1-x}{x} \right)^{p_1} \left( \frac{\rho_g}{\rho_1} \right)^{q_1} \left( \frac{\mu_1}{\mu_g} \right)^{r_1}} \]  \hspace{1cm} (2.25)

with the entries of \( A_1, p_1, q_1, \) and \( r_1 \) corresponding to a specific correlation listed in Table 2.2.
Table 2.2. Values of constant and exponents suggested by the various correlations and models in Eq. (2.24)

<table>
<thead>
<tr>
<th>Correlation or Model</th>
<th>A</th>
<th>p₁</th>
<th>q₁</th>
<th>r₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous [8]</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0</td>
</tr>
<tr>
<td>Zivi [55]</td>
<td>1.00</td>
<td>1.00</td>
<td>0.67</td>
<td>0</td>
</tr>
<tr>
<td>Turner &amp; Wallis [57]</td>
<td>1.00</td>
<td>0.72</td>
<td>0.40</td>
<td>0.08</td>
</tr>
<tr>
<td>Lockhart &amp; Martinelli [35]</td>
<td>0.28</td>
<td>0.64</td>
<td>0.36</td>
<td>0.07</td>
</tr>
<tr>
<td>Thom [56]</td>
<td>1.00</td>
<td>1.00</td>
<td>0.89</td>
<td>0.18</td>
</tr>
<tr>
<td>Baroczy [54]</td>
<td>1.00</td>
<td>0.74</td>
<td>0.65</td>
<td>0.13</td>
</tr>
</tbody>
</table>

The Hughmark correlation is based on the following equation:

\[
\frac{1}{x} = 1 - \frac{p_1}{\rho g} (1 - \frac{K_2}{\alpha})
\]

where \(K_2\) is a function of the parameter \(Z_1\) which is defined as follows:

\[
Z_1 = \frac{(Re)^{1/6} (Fr)^{1/8}}{1 - \alpha_{NS}}
\]

\[
Re = \frac{DG}{(1-\alpha)\mu_1 + \alpha\mu_\theta}
\]

\[
Fr = \frac{\mu^2}{gD}
\]

Tabulated values of \(K_2(Z)\) are given in [52].
Introduction

Heat transfer in a condensing flow of pure vapor occurs in two steps: condensation at the liquid-vapor interface, and transfer of the latent heat released by the condensing fluid through the condensate by conduction and convection. Subcooling of the condensate is also a possibility. Thus, an interfacial thermal resistance and a resistance in the condensate are encountered in this process. If noncondensable gases and impurities at the solid surface are present, additional interfacial resistances at the vapor-liquid and the liquid-solid interfaces have to be considered.

The necessary existence of the interfacial resistance for pure vapor condensing arises simply from the fact that the pressure of the molecules escaping from the liquid surface must be less than the incident pressure of molecules on the liquid surface. Thus, the vapor pressure at the liquid surface must be less than the pressure of the ambient vapor, which means that the temperature of the liquid surface must be below the saturation temperature of the ambient vapor. Using the simple, modified kinetic theory proposed by Schrage [59] and some reasonable assumptions, Rohsenow [60] found that this interfacial resistance was negligible for nonmetals, except at very low pressures.

The heat transfer in the condensate has been the subject of much discussion in the condensation literature. It is expected that
the type of flow in the condensate film, the interface geometry, and the circumferential film distribution in horizontal in-tube condensation have significant effects on the rate of condensation.

Condensation of vapor in the presence of noncondensable gases brings about a more significant resistance at the vapor-liquid interface. As condensing vapor moves toward a cool surface, it will tend to drag with it any noncondensable gases contained within the vapor. Since these gases do not condense at the vapor-liquid interface, their concentration tends to build up there until a balance is reached between the rate at which noncondensables are transported to the interface and the rate at which they diffuse away from the interface. The condensing vapor must diffuse through this blanketing gas; hence, there is a decrease in the vapor pressure near the interface. This will, in turn, lower the interface saturation temperature below the vapor-gas mixture temperature. Thus, a significant decrease in heat transfer coefficient can result from the presence of noncondensable gases. A more detailed description of the effect of noncondensable gases can be found in [60].

The additional resistance at the liquid-solid interface due to trapped impurities is important only when it is comparable to the resistance provided by the condensate. Usually, in a clean and chemical-reaction-free condensing flow of a single component, this resistance can be neglected.

In conclusion, the major thermal resistance during condensation
without the presence of noncondensable gases occurs in the condensate. The following review will examine the open literature pertaining to the study of the effects of those quantities which affect film condensation.

**Literature review**

**Vertical film condensation**  
Nusselt [61] formulated the first simple model to study condensation. In his analysis of condensation over a vertical plate, he made the following assumptions:

1. The vapor is saturated and does not exert any frictional drag on the film. The film is drained by gravity only.

2. The condensate film is in laminar flow.

3. Heat is transferred through the condensate film by conduction only. Thus, the temperature profile is linear.

4. The heat transfer surface is smooth and clean and at a constant temperature. The interface curvature is neglected.

The derived equation for the mean heat transfer coefficient on a vertical plate is

\[
\overline{h} = \frac{4}{3} \left[ \frac{(\rho_1 (\rho_1 - \rho_g) g \gamma \kappa L)}{(4\mu L (T - T_\infty))} \right]^{0.25} \tag{2.27}
\]

The physical properties were suggested to be evaluated at the mean temperature of the film. A similar analysis was applied to condensation on a vertical tube and on a horizontal smooth tube.

This model predicts a decrease in the heat transfer coefficient with an increase in temperature difference which is, in turn,
directly related to heat flux. This result is to be expected since a greater heat flux results in a thicker condensate film which produces a larger resistance to heat transfer.

The first major amendments to this simple model were based on the realizations that the condensate film flow would eventually become turbulent with sufficiently long plates and that, usually, the vapor velocity is not zero. Colburn [62], among other early investigators, modified Eq. (2.27) by assuming turbulent flow in the condensate film. Usually, the transition Reynolds number based on the condensate flow is set at 2000; i.e., \( \text{Re} = \frac{4 \Gamma_1}{\mu_1} = 2000 \).

Tepe and Mueller [63] studied condensation of benzene and methanol vapors inside vertical tubes and found the Nusselt equation, modified according to [62], underestimated the experimental results. They attributed this discrepancy to the neglect of vapor velocity in the analysis.

The Nusselt analysis is readily modified to include the effect of interfacial shear, \( \tau_i \), on laminar film condensation. The mean heat transfer coefficient can be shown in dimensionless form as

\[
\bar{h}' = \frac{h}{k} \left( \frac{\nu}{g} \right)^{1/3} = \frac{4}{3} \frac{\left( \delta_L' \right)^3}{Z_L'} \pm 2 \tau_i \frac{\left( \delta_L' \right)^2}{Z_L'}
\]

(2.28)

where

\[
\delta_L' = \delta_L \left( \frac{g}{\nu^2} \right)^{1/3}
\]

\[
Z_L' = \frac{4L(T_s - T_w)}{Pr} \frac{c_p}{\frac{1}{\text{l}_g} \left( \frac{g}{\nu^2} \right)^{1/3}} \frac{1}{1 - \frac{\rho_g}{\rho_i}}
\]
\[ \tau_i' = \frac{\tau_i}{g(\rho_1 - \rho_g)^2/3} \]

and

\[ Z_L' = (\delta_L')^4 \pm \frac{4}{3} \tau_L' (\delta_L')^3 \]

\[ \delta_L \left( \text{condensate film thickness at the bottom of the plate} \right) = \frac{4k\mu(T_s - T_w)L}{g\rho_1(\rho_1 - \rho_g) \nu_{lg}} \]

The plus sign is for downward flow of vapor and the minus sign is for upward flow of vapor. This equation indicates a potentially large effect of interfacial shear on heat transfer.

Carpenter and Colburn [64,65] undertook the first investigation of turbulent film condensation which included the effects of interfacial shear forces. They observed that, in the presence of vapor flow, ripples always appeared at the interface, even in the laminar flow region. In spite of these ripples, they found that the average film thickness seemed to check the calculated thickness for true laminar flow. However, heat transfer coefficients in general ran somewhat higher than those predictions by the Nusselt equation, and it seemed very likely that one of the major reasons was that the true average thickness for resistance to heat transfer was less because of these ripples.

At higher vapor flow rates, Carpenter and Colburn observed that the condensate layer apparently became turbulent at much lower values
of Reynolds number than were found when vapor friction was negligible. The authors reasoned that when the major force acting on the condensate layer was vapor friction rather than gravity, the velocity distribution might follow that found for a pipe filled with liquid, in which case the thickness of the laminar sublayer could be estimated by relations applying to this case. As a first approximation, they assumed that the entire thermal resistance was provided by the laminar sublayer, and established both local and average correlations to take this into account as well as the momentum change of the condensing vapor and the gravity, if applicable. They found reasonable agreement between the correlation and the experimental results.

Seban [66] subsequently performed an analysis of turbulent condensate films assuming the existence of the "universal velocity distribution" in the condensate film flow, but excluding vapor velocity. Rohsenow et al. [67] extended this work by including vapor velocity and using the Martinelli analogy to obtain the local heat transfer coefficients. The authors pointed out that although the assumed velocity distribution was quite likely to be in error in the highly turbulent region near the liquid-vapor interface, it seemed that this velocity formulation should predict actual conditions quite closely in the remainder of the condensate film. Realizing that the region of expected error was also a region of very small resistance to heat flow as compared to that of
the buffer layer and the laminar sublayer, the investigators felt that deviations in this area would have but little effect on the predicted values of heat transfer coefficient for the entire film.

These studies were all essentially based on the concept that the condensate film flow could be modeled as a boundary layer flow. This concept was further developed in several subsequent studies performed about 1960 dealing with laminar as well as turbulent film condensation.

Sparrow and Gregg [68], Koh et al. [69], and Koh [70] pioneered the application of the mathematical techniques of laminar boundary layer theory, i.e., boundary layer approximations and similarity transformations, to the condensation process on a flat plate. Their numerical results showed that, in laminar film condensation, the inertia forces could be neglected for Pr \( \geq 10 \). The inertial forces had little effect, even for Pr = 1. Also, the authors found that the effects of the interfacial shear, induced by the condensate drained under gravity alone, on heat transfer were negligible for Pr \( \geq 10 \) and were small at Pr = 1. These results confirmed the broad validity of the Nusselt model.

Dukler considered both laminar and turbulent film condensations in his important paper published in 1960 [71]. For the turbulent part, he used the expression proposed by Deissler for the eddy viscosity and eddy thermal conductivity near the solid wall while he retained the expression proposed by von Karman for the eddy
viscosity and thermal conductivity away from the solid wall.

Subsequent adoption of the notion that the condensate film flow could be treated as a boundary layer flow soon gave rise to as many condensation models as there were boundary layer models and analogies between momentum and heat transfer. While sophisticated boundary layer techniques are methodologically rigorous, they usually require cumbersome explicit or iterative correlations and are difficult to use without digital computation facilities.

In-tube condensation

In-tube condensation differs from vertical film condensation in a sense that different flow regimes occur during the course of condensing because of the confined space. In vertical in-tube condensation, gravity and interfacial shear are parallel. In horizontal in-tube condensation, they are perpendicular and the condensate flow is thus complicated.

Application of boundary layer techniques to the horizontal in-tube condensation process requires the explicit assumption of a flow pattern. For simplicity, the choice is usually an axisymmetric, smooth-film annular flow; this implies high mass flow rate of the condensing vapor. The effects of pressure level, heat flux, and fluid properties are implicitly incorporated into the analyses as long as the expressions of the physical quantities and assumptions used during developing the models already account for pressure level and heat flux effects. This type of study is represented by the analyses done by Altman et al. [72], Kutateladze [73],
Bae et al. [74-77], Traviss et al. [7,78], Kosky and Staub [79], Azer et al. [80,81], Ueda et al. [82], Shekirladze and Mestvirishvili [83,84], Davis et al. [85], Ueda and Inoue [86], and Razavi and Damile [87]. Some of these studies are for vertical tubes. For high mass flow rates with prevalence of axisymmetrical annular flow, analyses for vertical tubes are also applicable to horizontal tubes.

Following a line of development analogous to that used in single-phase turbulent flow, many investigators adopted the technique of dimensional analysis to attain correlations for their experimental results for in-tube condensation. This technique constitutes another major group of studies of condensation. Usually, either a direct application of dimensional analysis to a condensing system or modeling through a single-phase similarity is used.

Dimensionless groups are formed from the physical quantities describing a condensing system. Some of the dimensionless groups are eliminated due to their insignificant contribution or by some pre-determined conditions, i.e., flow patterns, type of condensate flow, etc. The remaining groups are correlated using experimental results. Generally, the application of resulting correlation is restricted by the imposed pre-determined conditions and the range of operation conditions. This approach was employed by Kutateladze [73], Akers and Rosson [88], and Yusufova and Neikdukht [89] in their studies of horizontal in-tube condensation at low and moderate mass flow rates.
The application of a single-phase similarity is based on the fact that the condensate provides the controlling thermal resistance. Mechanisms involved in single-phase heat transfer are seemingly responsible for heat transfer through the condensed liquid. Thus, a single-phase turbulent heat transfer correlation can be modified to reflect the co-current flow of liquid and vapor and the resulting vapor shear. As with the previous approach, the resulting correlation has a limited range of applicability and sometimes includes some experimentally determined constants. Nevertheless, this approach requires no explicit assumption of a flow pattern, though annular flow is sometimes implied, thus making the resultant correlation more general than an approach which assumes a flow pattern. Also, with this and the previous approach, the effects of the major physical quantities can be established by a well-planned experiment. This approach was used in the studies by Akers et al. [90], Ananiev et al. [91], Boyko and Kruzhilin [92], Miropol'skii and Charyev [93], Murthy and Sarma [94], Cavallini and Zecchin [95], Izumi et al. [96], and Shah [97].

Another model is the so-called "lumped" type where the phases are averaged over the flow cross-section and are each represented by a mean velocity. Appropriate relations between some of these mean quantities and other physical parameters can be found from other existing analyses or experimental results. Extending the work of Carpenter and Colburn [64], Soliman and his co-workers [53] adopted this technique in their effort to derive a general heat transfer
correlation for annular flow condensation.

All of the above-described techniques or models are more or less concerned with annular flow condensation which exists only at high mass flow rates. In horizontal in-tube condensation, gravity, acting perpendicular to the flow direction, tends to pull the condensate towards the bottom of a tube at moderate and low flow rates. In this case, the condensate flow is stratified or wavy, with the flow being either laminar or turbulent. The analysis is more difficult because of asymmetry of the condensate plus additional condensate flow draining down from top to bottom of the tube.

A combination of the above-mentioned techniques or models is usually used to study this complicated flow situation. In some studies, Nusselt's original methodology was empirically corrected to account for stratification. In others, the analysis took the form of dividing the wetted perimeter into a zone where the Nusselt model was valid and a stratified zone where either heat transfer was neglected or some sort of turbulent flow analogy was applied to model the heat transfer. In this category are the analyses done by Chaddock [98], Myers and Rosson [99], Chato [100], Rosson and Myers [101], Rufer and Kezios [102], Roetzel [103], Connel et al. [104], and Butterworth [105].

The resultant correlations or equations from most of the studies published before 1974, along with the classification of techniques, are listed in the survey of condensation heat transfer
literature by Royal [2]. In his study of in-tube condensation of steam at low pressure level, Royal found that the correlations of Akers et al. [90] and of Soliman et al. [53] best correlated the experimental results. So far, no single correlation can be used comfortably over the whole range of physical quantities and properties of practical interest. Nevertheless, with pre-determined test fluid and selected range of the physical quantities, some correlations may appear to be better predictors than others.

All the models described above assume the condensing vapor to be saturated. However, in practicality, there are cases where the condensing vapor is superheated. The superheating would somehow modify the transport mechanism occurring in condensing saturated vapor. Other possible effects which were not considered in the previous models or in some of the models are those of heat flux, tube inclination, pressure level, variation of fluid properties, and subcooling. The following paragraphs are devoted to the literature pertaining to the study of these effects.

**Effect of superheat**  The effect of superheat on condensation was first discussed in Nusselt's original work [61] where he suggested that $i_{lg}$ should reflect the total heat removed in condensing the superheated vapors. The difference in the condensation of superheated vapors from the process for saturated vapors lies in the removal of the superheat from the vapor in an extremely short distance from the condensate surface and in the effect that
this process has on the temperature of the liquid at the vapor-liquid interface.

In their study of heat transfer from superheated vapors to a horizontal tube, Balekjian and Katz [106] were able to correlate the experimental condensing load with the degree of superheat using the Schrage analysis and equations [59] for relating mass and heat transfer at the interface. They found that the effect of superheat was to lower the heat flux and condensing load; there was a depression of the interface temperature below that of the saturated vapor.

Using the boundary layer approach, Sparrow and Eckert [107] incorporated the superheat in the equations describing laminar film condensation on a vertical plate. They found that, for a given temperature difference between $T_w$ and $T_i$, superheat increased the heat transfer coefficient. They suggested, for a very thin film, the Nusselt equation could be applied to predict the condensing coefficient in this situation if the quantity $i_{lg}$ in Eq. (2.27) was replaced by $i_{lg} + c_{p,g} (T_v - T_i)$. Similar conclusions were reached by Spencer and Ibele [108] in their investigation of laminar film condensation of superheated vapor on a vertical surface.

Condensing R-22 inside a horizontal tube, Altman and his co-workers [72] found that some of their experiments with moderate superheat (up to 42 F) at the inlet could not be predicted by the correlation derived for saturated vapor condensation. Based on
the experimental results, they proposed an adjustment factor, $\beta$, as follows

$$\beta = 0.29 (T_s - T_w)^{0.52}$$  \hspace{1cm} (2.29)

to account for the effect of superheat on in-tube condensation.

Several recent publications deal with condensation of superheated vapor inside a tube in either vertical [109,110] or horizontal [111,112] positions. Of practical interest and importance is the study of Fujii and his co-workers [112]. They condensed superheated R-11 and R-113 in a horizontal tube of 0.84 in. inside diameter and 13.12 ft length at low pressure (10-27 psia). For most of the experiments, stratified flow occurred because of the large tube inside diameter and low flow rates. They observed that, in general, superheat increased local heat transfer coefficient, pressure drop, and heat flux, but suppressed condensing load at the inlet of the test section. This last observation was in agreement with that of Balekjian and Katz [106]. To correlate the pressure drop results, Fujii and his co-workers used the Lockhart-Martinelli parameter, $\chi_{tt}$, which was experimentally related to $\phi_g$ by the following expression:

$$\phi_g = 1 + a \chi_{tt}^{0.2}$$  \hspace{1cm} (2.30)

where $a = 1.24 \left( \frac{G}{\sqrt{\rho_1 \rho_g}} \right)^{0.7}$ for $\frac{G}{\sqrt{\rho_1 \rho_g}} \leq 1.5 \text{m/s}$

$a = 1.65$ for $\frac{G}{\sqrt{\rho_1 \rho_g}} > 1.5 \text{m/s}$
For the heat transfer coefficients, they derived two semi-empirical correlations for stratified flow in either laminar or turbulent situations.

**Effect of heat flux** As mentioned before, Nusselt's model predicts a decrease in heat transfer coefficient with increase in temperature drop, which is directly related to heat flux. In their study of condensation inside a horizontal tube within the stratified and laminar annular flow regimes, Akers and Rosson [88] found a decrease in the condensing coefficient with an increase in heat flux, as predicted by the Nusselt model. They suggested

\[
\frac{\text{Nu}}{\text{Re}^0.2} = 13.8 \frac{\text{Pr}^{1/3} \left( \frac{T_g - T_w}{c_p} \right)^{1/6}}{\text{Re}^{2/3} \text{g}}
\]

for \( 1,000 < \text{Re}_g < 20,000 \)  

\[
\frac{\text{Nu}}{\text{Re}^{2/3} \text{g}} = 0.1 \frac{\text{Pr}^{1/3} \left( \frac{T_g - T_w}{c_p} \right)^{1/6}}{\text{Re}^{0.2} \text{g}}
\]

for \( 20,000 < \text{Re}_g < 100,000 \)

where

\[
\text{Re}_g = \frac{D G_g}{\mu_l} \left( \frac{\rho_l}{\rho_g} \right)^{0.5}
\]
In the region of turbulent condensate film flow, the authors found that the condensing coefficient increases with increased liquid loadings and is independent of the temperature difference. This suggests that the increase in interfacial shear due to increasing mass velocities will upset the possibly higher thermal resistance provided by the thickening film.

Using the smooth tube correlation of Boyko and Kruzhilin and the homogeneous model, Miropol'skii and Khasanev [32] investigated the effect of heat flux on heat transfer coefficient and pressure drop. When assuming a linear heat flux distribution along a pipe,

$$\dot{q}_Z = \dot{q}_{in} (1 + m\overline{Z})$$  \hspace{1cm} (2.32)

where $\overline{Z} = Z/L$, they found that, over a wide range of pressure levels, the overall heat transfer coefficient and pressure drop are significantly affected only when $-1 < m < 10$. Thus, the authors suggested that the use of a linear approximation for the quality in calculating $\overline{h}$ and $\Delta P$ without allowing for the effect of the distribution of $\dot{q}$ along the pipe on these quantities can result in significant errors.

**Effect of tube inclination**

Inclined condensers are sometimes unavoidable and, in other cases, are intended for a possible augmentation effect. Inclining a tube in the direction of flow would introduce a significant component of gravitational force in the flow direction which might help condensate drainage. On the
other hand, inclining a tube in the opposite direction would increase the relative velocities between phases by introducing a gravitational force component in the direction opposite to the condensing flow.

In the early study by Tepe and Mueller [63], their experimental results for in-tube condensation at an inclination of $15^\circ$ from the horizontal in the direction of flow showed little effect on heat transfer coefficients. The recent investigation by Royal [2] also indicated that, at inclinations of $\pm10^\circ$, the augmentation effects was no greater than approximately 10 percent.

For stratified flow, inclination in the direction of flow would promote the effective drainage of condensate. However, for annular film flow at higher mass velocities, as in the above two experiments, the effect of promoting the condensate drainage is probably small and is compensated by the adverse effect of reducing the relative interfacial velocities.

In his study of laminar film condensation inside inclined tubes, Kröger [113] found that the smooth tube experimental results showed an increase in heat transfer rate with an inclination in the direction of flow. For the range of inclination tested, a maximum heat transfer rate was attained between $5^\circ$ and $10^\circ$.

In contemporary with the Kröger study, Izumi et al. [114] undertook a systematic investigation of laminar film condensation in an inclined tube for both upward and downward flows. The inclination ranged from $0^\circ$ (horizontal) to $90^\circ$ (vertical). In upward flow, heat transfer coefficients increased with inclination up to $70^\circ$ and decreased with
larger angles. In downward flow, although the data were scattered, the trend showed that heat transfer coefficients increased with inclination up to $10^\circ$ and were little affected until the inclination reached $60^\circ$. The coefficients decreased with larger angles. A correlation for the experimental results was provided.

**Effect of pressure level**  
Along with testing of the augmented tubes, Royal [2] conducted condensation experiments in a smooth tube. His smooth tube data demonstrated the marked parametric effect of pressure, showing that the lower the pressure the higher the heat transfer coefficient at a given mass velocity. Similar results were obtained in the smooth tube study of Vrable and his co-workers [115, 116]. This effect of pressure level is expected since the condensing coefficient should increase as the vapor velocity increases. For a given quality, the vapor velocity varies directly as the vapor density; consequently, the heat transfer coefficient would be expected to be higher at a lower pressure, other things being equal. This effect is readily accounted for in those models which consider interfacial shear forces.

**Effect of D/L**  
It can be shown that the dimensionless group

$$\frac{D}{L} = 4 \frac{A_x}{A} = 4 \tilde{q} / \left( \frac{\dot{m}_{lg}}{A_x} \right)$$

(2.33)

Hence, this ratio is indicative of relative magnitude of heat flux involved in the experiment. This dimensionless group appears in the
correlations which were derived from dimensional analysis by Kutateladze [73], Yusufova and Neikdukh [89], Murthy and Sarma [94], and Izumi et al. [96]. It is noted that the mass velocities involved in these studies fall into the range in which stratified or laminar flow exists in some or whole part of the condensate film flow. Thus, as in the effect of heat flux, this effect seems to be important at lower flow rates only.

**Effect of fluid properties and subcooling**

Most analyses for condensation assume that the fluid properties are constant across the film and that they can be evaluated at the corresponding saturation temperature. However, since the wall temperature is lower than the saturation temperature, a portion of the condensate is subcooled. This temperature distribution gives rise to fluid property variations across the film.

As with single-phase flow, these fluid property variations, notably \( \mu \), are expected to have some effect on laminar film condensation. With the Nusselt equation, Drew, as described in [65], recommended that the fluid properties be evaluated at

\[
T_{ref} = T_w + 0.31 (T_s - T_w)
\]  

(2.34)

Bromley [117] modified the Nusselt equation by the factor

\[
\sqrt{1 + 0.4 \frac{c_p(T_s - T_w)}{\mu_{lg}}}
\]

to account for the effect of subcooling on
laminar condensation.

The boundary layer model for laminar film condensation can readily take into account the property variations across the film, as demonstrated by Minkowycz and Sparrow [118], Poots and Miles [119], Lott and Parker [120], and Roetzel [121]. In general, a few percent deviation was found between calculated heat transfer coefficients using constant and variable fluid properties. Reference temperatures were suggested at which the fluid properties of the condensate should be evaluated.

The above review of literature is by no means complete; however, it does cover most aspects of the in-tube condensation process. This background is necessary to provide a basis for choice of augmentation techniques. In addition, the models and correlations suggest useful ways for predicting and correlating the performance of the augmented tubes.

Selection of heat transfer correlations

Because of the vast number of existing correlations and limited resources, only several correlations were selected for comparison with the present smooth tube results. The best correlation(s) would serve as predictor(s) of the smooth tube data. It was expected that appropriate modifications could then be made to the correlations to suitably predict the performance of augmented tubes.

Nine smooth tube correlations were selected. These correlations, which encompass the several different techniques or models described
in the literature review, are chronologically listed in Table 2.3
along with the information pertinent to the development of the
correlations.

The correlation of Carpenter and Colburn [64] was selected
because it was the simplest model with consideration of interfacial
shear and, above all, it was considered by Dunn and his co-workers
[122] to be the best predictor of in-tube condensation of
refrigerants. The correlation is

\[ h = 0.045 \frac{k}{\mu} \frac{P_r^{0.5}}{(\rho \cdot F)^{0.5}} \]  \hspace{1cm} (2.35)

where \( F = F_f + F_m \)

\[ F_f = \frac{f G^2}{2 \rho g} \]  \hspace{1cm} \text{where } f \text{ is given in graphical form in [18]}

\[ F_m = \frac{G^2}{\rho g} \left( \frac{d \Gamma}{dZ} \right) \]

All properties are evaluated at the saturation temperature.

The correlation of Akers, Deans, and Crosser [90] was considered
because it was found to be an accurate single-phase similarity
correlation by Royal and other investigators. As suggested by the
authors, this correlation can be used either as an average or as a
local expression. This correlation is
Table 2.3. Details of the selected in-tube condensation correlations

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Type</th>
<th>Model</th>
<th>$G$ kg/hr-m$^2$</th>
<th>$\rho_1/\rho_v$</th>
<th>Inlet quality %</th>
<th>$\bar{p}$</th>
<th>$\bar{q}$ W/m$^2$</th>
<th>Fluids (Pr$^1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carpenter &amp; Colburn</td>
<td>Local</td>
<td>Lumped type laminar sublayer resistance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$&gt;1577.3$ H$_2$O, C$_2$H$_6$O</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CH$_4$, C$_2$HCl$_3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C$_7$H$_8$</td>
</tr>
<tr>
<td>Akers et al. [90]</td>
<td>Average</td>
<td>Single-phase similarity</td>
<td>1.63-438.07</td>
<td>1.5-12.0</td>
<td>~ 100</td>
<td>0.42-0.99</td>
<td>1.5-438.07</td>
<td>R-12, C$_3$H$_8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(2.3-3.9)</td>
</tr>
<tr>
<td>Rosson &amp; Myers [101]</td>
<td>Local</td>
<td>Laminar upper tube Von Karman analogy lower tube</td>
<td>90-100</td>
<td></td>
<td>90-100</td>
<td>0.011-0.018</td>
<td>441.6-19873.82</td>
<td>CH$_4$, C$_3$H$_6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boyko &amp; Kruzhilin [92]</td>
<td>Average</td>
<td>Single-phase similarity</td>
<td>36.62-1763.13</td>
<td>14.5-138.5</td>
<td>20-100</td>
<td>0.06-0.41</td>
<td>151419.6</td>
<td>$H_2O$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.9-1.1)</td>
</tr>
<tr>
<td>Soliman et al. [53]</td>
<td>Local</td>
<td>Laminar sublayer resistance</td>
<td>3-99</td>
<td></td>
<td></td>
<td>0.0047-0.44</td>
<td>1577287.1</td>
<td>$H_2O$, C$_2$H$_6$O</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CH$_4$, C$_2$HCl$_3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C$_7$H$_8$, R-22,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R-113</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1-10)</td>
</tr>
<tr>
<td>Correlation</td>
<td>Type</td>
<td>Model</td>
<td>( \frac{G}{\text{kg/hr-m}^2} )</td>
<td>( \frac{\rho_1}{\rho_v} )</td>
<td>Inlet quality %</td>
<td>( \bar{\rho} )</td>
<td>( \bar{q} )</td>
<td>Fluids(Pr)</td>
</tr>
<tr>
<td>----------------------</td>
<td>----------</td>
<td>------------------</td>
<td>-------------------------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>----------------</td>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>Traviss et al. [7]</td>
<td>Local</td>
<td>von Karman</td>
<td>162.75-623.88</td>
<td>8.5-33.0</td>
<td>2-100</td>
<td>0.17-0.50</td>
<td>3470.0-85173.5</td>
<td>R-12 (3.0-3.3)</td>
</tr>
<tr>
<td>Azer et al. [80,81]</td>
<td>Local</td>
<td>135.63-447.56</td>
<td>14.7-27.1</td>
<td>100</td>
<td>0.20-0.34</td>
<td>R-12 (3.0-3.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavallini &amp; Zecchin [95]</td>
<td>Average</td>
<td>Single-phase</td>
<td></td>
<td></td>
<td></td>
<td>R-11, R-21</td>
<td>R-14</td>
<td></td>
</tr>
<tr>
<td>Shah [97]</td>
<td>Local</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Present Experiment</td>
<td></td>
<td>86-760</td>
<td>29.0-85.0</td>
<td>100</td>
<td>0.07-0.19</td>
<td>3486-27,887</td>
<td>R-113 (5.0-6.0)</td>
<td></td>
</tr>
</tbody>
</table>
\[ \bar{h} = C \frac{k_1}{D} \frac{1}{\text{Re}_e^\frac{n}{3}} \]  
(2.36a)

where

\[ \text{Re}_e = \frac{DG}{\mu_e} \]

\[ \text{Ge} = \left[G \left(1 - \frac{x}{X}\right) + \frac{x}{X} \sqrt{\frac{1}{\rho_1}} \right] \]  
(2.36b)

\[ C = 0.0265 \quad n = 0.8 \quad \text{for} \ \text{Re}_e > 5 \times 10^4 \]

\[ C = 5.03 \quad n = 1/3 \quad \text{for} \ \text{Re}_e \leq 5 \times 10^4 \]

All properties are evaluated at the average film temperature; i.e.,

\[ T_{\text{ref}} = \frac{T_w + T_s}{2}. \]

The correlation of Rosson and Myers [101] was selected because it includes considerations of stratification which may appear in some part of the test section at low and medium flow rates. The correlation is

\[ h = \frac{h_\pi + (h_\pi - h_o) B}{\pi} \]  
(2.37)

where

\[ h_o = 0.131 \text{Re}^{0.12} \sqrt{\frac{k_1 l_{1g} \rho_1 (\rho_1 - \rho_v)g}{D_\mu_1 (T_{\text{sat}} - T_w)}} \]

\[ h_\pi = \frac{\sqrt{\frac{c}{2}} \phi_1 \text{Re}_1^{1-0.5n}}{5 + \frac{5}{\text{Pr}_1} (\ln 5 \text{Pr}_1 + 1)} \]
\[ \beta = 0.27 \pi \frac{Re^{0.1}}{g} \quad \text{if} \quad \frac{0.6 Re_1}{g} \leq 6.4 \times 10^{-5} \]

\[ \beta = \frac{1.74 \times 10^{-5} \pi G}{(Re_g)^{0.5}} \quad \text{if} \quad \frac{0.6 Re_1}{g} > 6.4 \times 10^{-5} \]

\[ C = 16 \quad n = 1 \quad \text{if} \quad Re_1 \leq 2100 \]

\[ C = 0.079 \quad n = 0.25 \quad \text{if} \quad Re_1 > 2100 \]

\[ \phi_1 \] evaluated as in Table 2.1

All properties are evaluated at the saturation temperature.

The correlation of Boyko and Kruzhilin [92] was chosen because it is the widely applied correlation in Russian studies of in-tube condensation. It is a single-phase similarity correlation and is simple in form. The correlation is

\[ \overline{h} = 0.024 \frac{Re}{D} \frac{Re^{0.8}}{10} \frac{Pr}{Re^{0.43}} \left( \frac{\rho}{\rho_m} \right)^{0.5} + \left( \frac{\rho}{\rho_m} \right)^{0.5} \]

(2.38)

where

\[ \frac{\rho}{\rho_m} = 1 + \left( \frac{\rho_1 - \rho_g}{\rho_g} \right) x \]

All properties are evaluated at the saturation temperature.

The correlation of Soliman et al. [53] was included because it is the refined form of the correlation of Carpenter and Colburn [64]. The correlation is
\[ h = 0.036 \frac{k_1}{\mu_g} Pr^{0.65} \sqrt{F_{p_1}} \] (2.39a)

where

\[ F = F_f + F_m \]

\[
\frac{F_f}{8m^2/\pi^2 \rho_g D^4} = 0.045 \left( \frac{1}{\mu_g} \right)^{0.0523} (1-x)^{0.47} \left( \frac{\rho_g}{\rho_1} \right)^{0.261}
\]

\[ + 5.70 \left( \frac{1}{\mu_g} \right)^{0.0523} (1-x)^{0.47} \left( \frac{\rho_g}{\rho_1} \right)^{0.261} \]

\[ + 8.11 \left( \frac{1}{\mu_g} \right)^{0.105} (1-x)^{0.94} \left( \frac{\rho_g}{\rho_1} \right)^{0.522} \]

(2.39b)

\[
\frac{F_m}{8m^2/\pi^2 \rho_g D^4} = 0.50D \frac{dx}{dZ} \left[ 2(1-x) \left( \frac{\rho_g}{\rho_1} \right)^{2/3} + \frac{1}{x} - 3 + 2x \right] \left( \frac{\rho_g}{\rho_1} \right)^{4/3}
\]

\[ + (2x - 1 - \beta x) \left( \frac{\rho_g}{\rho_1} \right)^{1/3} + (2\beta - \frac{\beta}{x} - \beta x) \left( \frac{\rho_g}{\rho_1} \right)^{5/3} \]

\[ + 2(1-x-\beta+\beta x) \left( \frac{\rho_g}{\rho_1} \right) \]

(2.39c)

\[ \beta = 1.25 \quad \text{for turbulent film} \]

\[ \beta = 2.0 \quad \text{for laminar film} \]

All properties are evaluated at the saturation temperature.
The correlation of Traviss et al. [7] was selected because it has been a reasonably good predictor of data for several in-tube condensation studies with refrigerants. It is based on annular flow with the von Karman velocity distribution through the film. The correlation is

\[ h = \frac{k_1}{D} \frac{\Pr \Re^{0.9}}{F^2} \quad \text{(2.40a)} \]

where

\[ F = 0.15 \frac{1}{\chi_{tt}} + 2.85x^{-0.476} \quad \text{(2.40b)} \]

\[ F_2 = 0.707 \Pr \Re^{0.5} \quad \text{for } \Re \leq 50 \quad \text{(2.40c)} \]

\[ F_2 = 5\Pr_1 + 5\ln(1 + \Pr_1)(0.09636\Re^{0.585} - 1) \]
\[ \text{for } 50 < \Re \leq 1125 \quad \text{(2.40d)} \]

\[ F_2 = 5\Pr_1 + 5\ln(1 + 5\Pr_1) + 2.51\ln(0.00313\Re^{0.812}) \]
\[ \text{for } \Re > 1125 \quad \text{(2.40e)} \]

\[ \chi_{tt} = \left(\frac{\mu}{\mu_g}\right)^{0.1} \left(\frac{\rho_g}{\rho_1}\right)^{(1-x)} \left(\frac{1-x}{x}\right)^{0.9} \]

All properties are evaluated at the saturation temperature.
The correlation of Azer et al. [80,81] was considered because it represents another version of annular flow analysis using the von Karman velocity distribution in the condensate film. The correlation is

$$h = 0.153 \frac{k}{D} Pr_l Re_0^{0.9} \frac{\mu_l}{\mu_g} \left(\frac{1}{\rho_l} \frac{1}{\rho_g}\right)^{0.5} x^{0.9} \frac{g}{t_+^*}$$

(2.41a)

where

$$\phi_g = 1 + 1.0986 \chi_{tt}^{0.039}$$

(2.41b)

$$t_+^* = 3.88 Pr_l^{0.663} (4.67 - x) \text{ for } x > 0.18$$

(2.41c)

All properties are evaluated at the saturation temperature.

The correlation of Cavallini and Zecchin [95] was selected because it is simple in form but, as stated by the authors, it well-represents the results of an accompanying analysis by the authors which is similar to that of Bae et al. [77]. Furthermore, its
dimensionless form was attained based on the results of horizontal in-tube condensation of refrigerants. The correlation is

\[ h = 0.05 \frac{k_1}{D} \text{Re}^{0.8} \text{Pr}^{0.33} \]  

(2.42)

where

\[ \text{Re}_e = \frac{\mu_1}{\rho_1} \left( \frac{1}{\mu_1} \right)^{0.5} \text{Re}_g \]

All properties are evaluated at the saturation temperature.

The correlation of Shah [97] was chosen because it was the most recent effort to correlate condensation heat transfer coefficients on a broad base. The correlation is

\[ h = 0.023 \frac{k_1}{D} \text{Re}^{0.8} \text{Pr}^{0.4} \left[ (1-x)^{0.8} + \frac{3.8x^{0.76}(1-x)^{0.04}}{p^{0.38}} \right] \]  

(2.43)

All properties are evaluated at the saturation temperature.
Augmentation Technique Studies

Augmentation techniques are usually applied to a heat transfer process having a relatively large thermal resistance. These techniques are classified into two groups: passive and active. Passive techniques do not require external power for operation while active ones do.

Passive techniques consist of treated surfaces, rough surfaces, extended surfaces, displaced enhancement devices, swirl flow devices, coiled tubes, surface tension devices, and additives. Active techniques include mechanical aids, surface vibration, fluid vibration, electrostatic fields, injection, and suction. Previous literature reviews [1,2] describe how techniques of both types have been used to improve condensation process for both vapor-space and in-tube situations. The reviews indicate that in-tube condensation has received relatively little attention.

The selection of augmentation techniques to enhance filmwise condensation is primarily based upon the mechanisms governing the rate of condensation. From the fundamental understanding of in-tube condensation, it can be inferred that any technique to increase the condensate turbulence would improve the heat transfer, as would any technique to reduce the condensate film thickness. Therefore, it is expected that techniques of treated surfaces, rough surfaces, extended surfaces, swirl flow devices, mechanical
aids, surface vibration, electrostatic fields, and suction would
increase, to some extent, heat transferred through the condensate.

In the present study, three kinds of passive techniques were
considered. These are: twisted-tape inserts, internally finned
tubes and rough tubes. These augmented schemes were selected
because of their practical feasibility on one hand. On the other
hand, part of the present study was undertaken with the intent to
Direct experimentation with refrigerants is necessary since important
physical properties, notably the density ratio and the surface
tension, are greatly different for water and refrigerants.

Twisted-tape inserts

Literature review  There have been a number of studies of
the effects of twisted tapes on heat transfer in single-phase as
well as two-phase flow. Besides the 16 experimental investigations
listed in the work of Lopina and Bergles [123], several studies
have been added in recent years including the experimental study
of Royal and Bergles [2,124] for in-tube condensation augmentation.
Readers can find this literature in a recent bibliographic report
[125]. The present review concentrates only on the understanding
of the effects of twisted tapes on fluid flow and heat transfer.

Gambill and his co-workers [126,127] first formulated the
effects of twisted tapes in a systematic way in their investigation
with full-length twisted tapes in both single-phase and boiling
flows. In single-phase flow, they singled out the effects of radial acceleration and enhanced buoyancy forces due to the twisted tape as prime factors in increasing heat transfer coefficients. They derived a correlation to predict heat transfer coefficients and friction factors by modifying a smooth tube Reynolds-analogy-type equation to include these effects. In boiling flow, they found that the twisted tape increased the critical heat flux up to 400 percent over straight-flow critical heat flux, other things being equal. This is understandable since the generated rotating flow tends to keep the heavier part of the fluid, the liquid phase in this case, at the wall.

Smithberg and Landis [128,129] initiated the analytical study of single-phase flow in tubes with twisted tapes. The authors considered the flow field around a twisted tape and concluded the velocity field was helicoidal and corresponded to a forced vortex in the core superposed on an essentially uniform axial flow. They argued that this velocity field gave rise to a better mixing of fluid near the tube wall with that of the core, thus improving heat transfer. Predictive methods for friction factors and heat transfer coefficients were provided based on the analysis.

In their investigation of effects of twisted tapes on both single-phase and subcooled nucleate boiling flow, Lopina and Bergles [123,130] identified several independent mechanisms which enhanced heat transfer. These are: a) the increased flow path created by
the tape (induced tangential velocity), b) buoyancy effect set up by the large centrifugal force present, and c) tape fin effects. A single-phase heat transfer correlation was developed accordingly. Fully developed nucleate boiling was found to be unaffected by the swirl flow.

Narasimhamurty and Vara Prasad [131] investigated flow regime and pressure drop for adiabatic air-water flow in a tube with a twisted-tape insert. They could predict pressure drop reasonably well using the Lockhart and Martinelli parameters with a slightly modified expression of the friction factor proposed by Smithberg and Landis. From flow regime observations, they concluded that the turbulence promoter tended to accentuate annular flow, especially at high gas velocities.

Royal and Bergles [2,124] presented the first study of twisted tapes in in-tube condensation. They studied heat transfer and pressure drop for condensing steam flow with two twisted-tape inserts, and reported increases in heat transfer coefficients of as much as 30 percent. Modifications of the smooth tube correlations of Akers et al. [90] and Soliman et al. [53] were suggested to account for the tangential velocity effect $F_t$, fin effect $F_{tt}$, and wall shear effect $F_f$. The Akers et al. smooth tube correlation was modified as follows:

$$
\bar{h} = 0.0265 \frac{k_1}{D_e} \left( \frac{F_t G e D_e}{\nu_1} \right)^{0.8} \text{Pr}^{0.4} F_{tt}
$$

(2.44)
where

\[ F_t = \frac{1}{2y} \left( \pi^2 + 4y^2 \right)^{0.5} \]

\[ F_{tt} = 1 + \frac{2}{\pi} \frac{\xi(4y^2 + \pi^2)}{2y} - \frac{\delta_{tt}}{D_i} \]

\[ D_e = \frac{\pi D_i^2}{[\pi D_i + 2(D_i - \delta_{tt})]} \]

\[ \xi = \frac{2 \tanh \left( \frac{m D_i}{2} \right)}{m D_i} \]

\[ m = \frac{2h}{k_{tt} \delta_{tt}} \]

\[ 0.5 \]

The Soliman et al. correlation was modified by incorporating, in addition to \( F_t \) and \( F_{tt} \), a friction factor, \( F_f \), where

\[ F_f = \frac{f_{tt}}{f} = 2.75y^{-0.406} \]  \hspace{1cm} (2.45)

according to [123], into the friction shear stress term in the correlation. The pressure drop results were reasonably predicted using the Dukler II correlation with the Hughmark void and the friction factor \( F_f \), as well as replacing \( D_i \) by \( D_e \).

**Conclusion** The studies of two-phase flows suggest that, in condensing flow, the increase in heat transfer is caused by the
tangential velocity and the fin effects, as in a single-phase system. However, while the presence of centrifugal force in a single-phase system enhances mixing between the fluid near the wall and the fluid in the core, it stabilizes the annular separated flow in condensing flow. The entrained liquid droplets are centrifuged out of the vapor core and contribute to the liquid layer on the wall - a feature not desirable in condensing flow. In addition, the increased wetted perimeter due to twisted tapes also increases the frictional pressure drop, especially in the vapor core. Despite these shortcomings, the advantages of twisted tapes, together with their easy handling and ready application to modify existing devices, still make them one of the attractive schemes considered in augmentation of in-tube condensation.

**Internally finned tubes**

In recent years, new manufacturing techniques have been developed to produce a wide variety of tubing with internal, longitudinal fins. These tubes have been used to improve heat transfer performance in both single-phase and two-phase flows. Increases in single-phase heat transfer coefficients up to 200 percent have been reported. As in the case of twisted-tape inserts, the present review presents only the literature relevant to the understanding of the fluid flow and heat transfer inside finned tubes. The remaining literature can be found in [125].
Single-phase studies. Hilding and Coogan [132] were among the first to experiment with internally finned tubes with air as the heat transfer medium. The tubes were custom-fabricated by brazing fins inside smooth tubes. They concluded that the best performing tube, the one with multiple interruptions of fins, increased the relative heat transfer-flow performance index up to 100 percent in the laminar and transition regions but was less effective in turbulent flow. This relative heat transfer-flow performance index was given as \( \frac{\overline{h}u}{\Delta P_{c}} \left( \frac{L}{D} \right) \).

Vasil'chenko and Barbaritskaya [133,134] tested five finned tubes in single-phase flow. They proposed separate correlations for laminar flow and turbulent flow by modifying the corresponding smooth tube correlation using the equivalent diameter and a geometrical factor, \( H/(2\theta D_e) \). For single-phase laminar flow

\[
Nu = C_3 \ Re^{0.19} \ Gr^{0.43} \ Pr^{0.43} \left( \frac{Pr}{Pr_w} \right)^{0.25}
\]

(2.46)

where \( C_3 \) and \( s \) were plotted against \( H/(2\theta D_e) \) in [133]. For single-phase turbulent flow

\[
Nu = C_4 \ Re^{0.8} \ Pr^{0.43} \left( \frac{Pr}{Pr_w} \right)^{0.25}
\]

(2.47)

where \( C_4 \), a function of \( Pr \) and \( H/2\theta D_e \), was given in graphical form in [133].

In their effort to broaden the base for correlating finned-tube
experimental results, Ornatskii and his co-workers [135,136] pioneered in the experimental study of the velocity distribution and heat transfer in the interfin channel. The motion of the medium in tubes with rectangular and longitudinal fins was considered as co-current flows of a main flow in the core and a number of "rivulet" flows in the interfin channels. Based on the velocity distribution measurements, the investigators derived an expression for the mean velocity in a channel in terms of the mean velocity of the flow and some geometrical factors as follows:

\[
\frac{1}{u_{ch}} = 1.22 \frac{1}{u} \left( \frac{W}{D_{e,m}} \right)^{0.25} \left[ 1 - \exp \left( -\frac{3.8D_{e,f}}{H} \right) \right]
\]  

(2.48)

In these expressions

\[ D_{e,m} = \text{equivalent diameter of main flow channel} \]
\[ D_{e,f} = \text{equivalent diameter of interfin channel}, \quad \frac{2WH}{W+H} \]

For their heat transfer study, they found for small values of \( W/H \), i.e., \( W/H < 1 \), the lowest and highest average heat transfer coefficients occurred at the fin base and the fin tip, respectively. For large values of \( W/H \), heat transfer coefficients at the wall between the fins and the sides of the fin approach those at the fin tip. They then proposed a way to calculate the average heat transfer coefficient over the fin surface using three semi-empirical correlations for the heat transfer coefficients at the tube wall between fins, the side of the fin, and the fin tip:
The heat transfer at the fin wall is

\[
\frac{h_{W/2}}{2} = 0.0144 \frac{k}{D_{e,f}} \frac{W^{0.63}}{H} \text{Re}_{ch}^{0.8} \text{Pr}^{0.43} (2.50)
\]

The heat transfer coefficient at the side of the fin is

\[
h_{H} = 0.0158 \frac{k}{D_{e,f}} \text{Re}_{ch}^{0.8} \text{Pr}^{0.43} (2.51)
\]

The heat transfer at the fin tip is

\[
h_{\delta_f/2} = 0.021 \frac{k}{D_{e,m}} \text{Re}_{m}^{0.8} \text{Pr}^{0.43} (2.52)
\]

In these expressions

\[
\text{Re}_{ch} = \frac{\overline{u}_{ch} D_{e,f}}{\nu} \quad \text{Re}_{m} = \frac{\overline{u} D_{e,m}}{\nu}
\]

In contemporary with the Ornatskii et al. study, Bergles et al. [137,138] tested seven different finned tubes, some of which had spiralled fins. Based on their experimental results, they suggested qualitatively that within the interfin channel the fluid velocity would average much less than it would in the free stream. Thus,
the laminar sublayer thickness would be very large at the bottom of the channel and would steadily decrease as it went up the sides of the fin to a relatively small thickness over the fin tip. A similar pattern of heat transfer coefficient distribution as that in the previous study [136] would then result. For spirally finned tubes, they speculated that the low velocity region was compounded by flow stagnation behind the fins even though the fins would be expected to act as turbulence promoters. The flow stagnation is less likely to occur for short fins. Therefore, the experimental results showed that any rifling of the short fins raised heat transfer coefficients above the straight fin values while more severe rifling of moderately high fins was necessary to elevate the coefficients. The authors concluded that even the short fins were to be shaped and spaced to avoid stagnation and low velocity regions between fins.

Watkinson and his co-workers [139] tested seventeen finned tubes with some similar to those tested by Bergles et al. They found, for tubes with long straight fins, the Nusselt number based on effective area and equivalent diameter was larger for tubes with fewer fins. The authors also observed the best spiral fin tubes tested had a low pitch-to-diameter ratio or fewer fins at a given pitch-to-equivalent-diameter ratio. They then correlated the heat transfer results by modifying the Dittus-Boelter type correlation using the geometrical factor $W/D_e$. For the five
straight finned tubes, the proposed correlation was

\[ h = 0.212 \frac{k}{D_e} \text{Re}_{e}^{0.6} \left( \frac{W}{D_e} \right)^{0.34} \text{Pr}^{1/3} \left( \frac{\mu}{\mu_w} \right)^{0.14} \]  \hspace{1cm} (2.53a)

For the spirally finned tubes, the correlation for the heat transfer coefficients was

\[ h = 0.369 \frac{k}{D_e} \text{Re}_{e}^{0.63} \left( \frac{W}{D_e} \right)^{-0.27} \text{Pr}^{3} \left( \frac{\mu}{\mu_w} \right)^{0.14} \]  \hspace{1cm} (2.53b)

Condensation studies The application of internally finned tubes to condensation flow has been received considerable attention in the 1970's. Reisbig [140] studied condensation of R-12 inside horizontal tubes with internal longitudinal fins. He found that the finned tubes performed best in the two-phase flow region and that these tubes were not advantageous at extremes of quality. However, the condensing medium was oil-contaminated. No attempt to predict enhanced heat transfer performance was presented.

Vrable and his co-workers [115,116] condensed R-12 in two longitudinally finned tubes. They reported that, due to the significant increase in heat transfer area, the finned tube can fulfill the same heat duty with approximately 60 percent of the smooth tube length. The authors also proposed a correlation based on the smooth tube correlation of Cavallini and Zecchin [95]. A new constant, a characteristic length equal to twice the equivalent
diameter, and a new term incorporating the pressure effects were used in the correlation:

\[
h = 0.02 \frac{k_1}{2D_e} \left( \frac{2D_e G_e}{\mu_1} \right)^{0.8} Pr_1^{0.33} \left( \frac{\rho_p}{\rho_{cr}} \right)^{-0.65}
\]

(2.54)

where

\[
G_e = G \left[ \left( \frac{\rho_l}{\rho_g} \right)^{0.5} x + (1-x) \right]
\]

The calculated coefficients agreed with the heat transfer results within ±30 percent. It should be noted that the authors already included the fin effect in reducing the experimental results.

For pressure drop predictions, they used the separated flow model, the homogeneous model, and the model proposed by Wallis in the annular, dispersed, and slug flow regimes, respectively. Either the equivalent diameter or twice the equivalent diameter was used as the characteristic length, as appropriate, in those models. An agreement of the data with all of these correlations to within approximately ±40 percent was found.

Royal and Bergles [2,124] investigated horizontal in-tube condensation of steam in tubes with spiral or straight fins. Three spiral and one straight finned tubes were tested. They found that the rifling of fins improved finned tube performance; however, the geometry effects were very complex. They speculated on the importance of interfin channel flooding considerations and on the possibility of interfacial shear increase and liquid entrainment
promotion. The best performing finned tube increased heat transfer coefficients up to 150 percent over the smooth tube values.

For correlating the experimental heat transfer results, the authors modified the smooth tube correlation of the Akers et al. [90], as follows:

\[ h = 0.0265 \frac{k_1}{D_e} \left( \frac{G D e}{v_1} \right)^{0.8} \frac{Pr_1^{0.33}}{160 \left( \frac{H}{WD_1} \right)^{1.91} + 1} \]  \hspace{1cm} (2.55)

The calculated heat transfer coefficients correspond to the condensing coefficients based on the inside diameters of the augmented tubes. The investigators also correlated with reasonable success the pressure drop results using the homogeneous void and the Dukler II correlation, which was modified only by replacement of the inside diameter by the equivalent diameter.

Kröger [113] studied laminar condensation heat transfer inside tubes with and without longitudinal fins in both horizontal and inclined positions using R-12. He noted that, in the horizontal position, the heat transfer rate for the larger diameter tube having twelve fins was almost the same as that for the smaller tube having nine fins, other things being equal. The author suggested that the existence of a constant heat transfer rate under these circumstances might in part be ascribed to the fact that the condensation process was to a large extent controlled by droplet formation on the edges of the fins in the upper half of the tube.
The heat transfer rate at an inclination of ten degrees was found to be up to 200 percent larger than that in an equivalent smooth horizontal tube. No correlation was provided.

Using both R-12 and R-22, Kikkawa and his co-workers [141] investigated laminar condensation heat transfer inside tubes with internal circumferential fins. They presented the heat transfer results, but they did not attempt any enhanced heat transfer performance prediction. The heat transfer results were correlated using the Nusselt type correlation for condensation on horizontal tubes with modification of the coefficient.

Rifert and Zadiraka [142] condensed steam inside a smooth tube and in a tube having internal longitudinal grooves with a curvature radius of 0.5 mm. According to their experimental results, the augmented tube outperformed the smooth tube only at high mass velocities, due to reduction of the section of the tube where the fins were submerged in condensate. At low mass velocities, visual observations showed that over the greater part of the tube the fins in the lower portion of the tube were completely submerged in condensate. The authors suggested that this stratification and flooding caused lower heat transfer coefficients in the finned tube than those in the smooth tube. Also, dependence of heat transfer coefficients on heat flux was found in both the smooth and augmented tubes at low mass velocities.

To correlate their augmented tube experimental results at high
mass velocities, the investigators suggested an expression similar to the smooth tube correlation of Boyko and Kruzhilin [92]:

\[
\bar{h} = 0.042 \frac{k_1}{D} Re_1^{0.8} Pr_1 \left[ \left( \frac{\rho}{\rho_m} \right)_{in}^{0.5} + \left( \frac{\rho}{\rho_m} \right)_{out}^{0.5} \right]
\]  \hspace{1cm} (2.56)

**Conclusion**

Despite complex geometrical effects occurring in internally finned tubes, it is generally agreed that the internal fins primarily increase heat transfer area and act as turbulence promoters, especially for the case of spiral fins in both single-phase and condensing flows. Additionally, in condensing flow, the fins are expected to increase interfacial shear and promote liquid entrainment.

Nevertheless, the finned tubes seemingly have disadvantages. In single-phase flow, low velocity regions in interfin channels and flow stagnation behind the spiral fins are encountered. These phenomena are also expected to affect the condensate film in condensing flow. Furthermore, the circumferential distribution of the condensate, particularly flooding and submergence of the fins, is expected to degrade the augmentation effect of the finned tubes.
Rough tubes

Rough tubes encompass tubes with a great variety of roughness geometries. In this review, only two basic geometries, two-dimensional rib-type and three-dimensional sand-grain-type, are considered. Literature on other types of rough tube can be found in [125].

Rough tubes have received considerable attention because of the interest in the increase of heat transfer and friction associated with practical roughness configurations and the development of large heat exchangers, such as those associated with gas-cooled nuclear reactors. General agreement on the mechanism of augmentation in single-phase flow has been established.

For a wall covered by two-dimensional rib-type roughness which is characterized by roughness height, e, and pitch, p, the flow over the rough surface differs depending on p/e. Two basic flow patterns are observed. Boundary layer separation and subsequent reattachment occurs when p/e > 8, with the reattachment point about seven rib heights downstream of a rib. When p/e < 5, a skimming flow exists for which boundary reattachment does not occur. Standing vortices are found between the ribs which are fed with energy from the turbulent main flow. When p/e lies between 5 and 8, a transitional flow between boundary reattachment and skimming flow is observed. In this case, the wake zone behind rib overlaps with the wake zone of the next element. A more detailed description of the flow field can be found in [143].
The friction factor is strongly dependent on the flow field. For the boundary reattachment case, the friction factor is affected by the form drag on the roughness elements plus the friction drag on the wall surface between ribs. For skimming flow, the friction factor is influenced by a pseudo-wall formed by the roughness crests and the standing vortices in the interstices.

For a wall covered by three-dimensional sand-grain roughness, Dipprey [144] speculated that "the rough wall can be imagined to consist of a series of small cavities of depth \( e \) and that the time-mean flow in and about these cavities consists of a pattern of one or more standing vortices."

Heat transfer increases on rough surfaces are brought about by better mixing in the laminar sublayer due to generated vortices in and around roughness elements. However, transport of heat and momentum is different on rough surfaces. The rate of heat transfer in the immediate neighborhood of the surface is restricted by a purely molecular transport of the fluid despite the turbulence near the wall caused by roughness elements. This explains some experimental results which show that rough surfaces become more efficient than smooth ones in the transition region for high Prandtl number fluids.

Although several analytical studies [145-147] have advanced understanding of the flow field and heat transfer of rough surfaces, these studies are not sufficiently developed for friction factor
and heat transfer prediction. All prediction schemes still rely on semi-empirical correlations.

**Single-phase studies**

The first important work on rough surfaces was published by Nikuradse in 1933 [148]. He investigated velocity distribution of turbulent flow in rough pipes with sand-grain roughness and found that the dimensionless velocity distribution normal to the wall is given by

\[
\frac{u^+}{V} = 2.5 \ln \left( \frac{h}{e^+} \right) + R(e^+) \tag{2.57}
\]

or

\[
\frac{u^+}{V} = 2.5 \ln \frac{Y^+}{e^+} - 2.5 \ln e^+ + R(e^+)
\]

where

\[
Y^+ = \frac{Yu^*}{V}
\]

\[
e^+ = \frac{eu^*}{V} = \frac{e}{D} \frac{Re}{\sqrt{f/2}}
\]

\[
u^* = \sqrt{\frac{\tau_w}{\rho}}
\]

After comparing this velocity profile with the one established in his earlier work in turbulent flow in smooth tubes,

\[
\frac{u^+}{V} = 2.5 \ln y^+ + 5.5 \quad \text{for} \quad y^+ \geq 70 \tag{2.58}
\]
Nikuradse showed that the fluid velocity in the presence of rough walls differs from the velocity in presence of smooth walls only by an additive factor. This factor becomes more important near the wall and is characteristic of the microscopic geometry of the roughness. The author showed that

a) \( e^+ \leq 5 \), hydraulically smooth regime for which roughness elements are submerged in the laminar sublayer,

\[
R(e^+) - 2.5 \ln e^+ = 5.5
\]  

Eq. (2.57) reduces to Eq. (2.58), thus indicating that roughness does not affect the velocity distribution.

b) \( e^+ > 70 \), fully rough regime for which roughness elements protrude out of the laminar sublayer,

\[
R(e^+) = 8.5
\]  

The velocity distribution is independent of Reynolds number.

c) \( 5 < e^+ < 70 \), transition regime for which \( R(e^+) \) varies with \( e^+ \).

The friction factor corresponding to the velocity distribution in Eq. (2.57) can be calculated:

\[
\left( \frac{2}{f} \right)^{1/2} = 2.5 \ln \frac{D}{2e} + R(e^+) - 3.75
\]  

The roughness elements affect the friction factor in the same way as in the velocity distribution. In laminar flow, the resistance is
practically the same for both smooth and rough pipes.

Heat transfer in rough pipes was first studied by Cope [149]. The internal surfaces were artificially roughened by a special knurling process to produce roughness of pyramid shape. The author found that, when fully turbulent conditions were established, the roughness had very little effect on the heat transfer coefficient, but in the transition region, the roughness might increase the coefficient to considerably more than its value for a smooth pipe. In general, the author concluded that for a given pressure drop more heat would be transmitted if the pipes was smooth than if it was rough.

Based on his experimental results of rough tubes with two-dimensional roughness, Nunner [150] proposed a model to explain and correlate the heat transfer results. The investigator argued that the thickness of laminar sublayer was same in both rough and smooth tubes and the roughness contributed to increased heat transfer by increasing the level of turbulence in the turbulent core. In other words, Nunner suggested that roughening the surface had the effect of reducing the thermal resistance of the turbulent core, the thermal resistance of the laminar sublayer remaining unaltered. By using the momentum-heat analogy, the author obtained the following relationship:

\[
\text{Nu} = \frac{f_{\text{aug}}}{8} \frac{\text{Re} \\text{Pr}}{(u_{\delta^*}/u)(\text{Pr} (f_{\text{aug}}/f)-1)}
\] (2.61)
where

\[
\frac{u_{\delta_1}}{\bar{u}} = 1.5 \text{ Re}^{-1/8} \text{ Pr}^{-1/6}
\]

Rough surfaces have since become an object of much study. A comprehensive review of the literature before 1964 was presented by Bhattacharyya [151] in his survey of heat transfer and pressure drop with rough surfaces. A more detailed listing of literature on rough surfaces through 1978 can be found in [125]. Some investigations [152-155] concentrated on studying the flow field near rough surfaces, others [156-160] stressed on understanding of the heat transfer mechanism, and others [143,144,161-172] were concerned with correlation of the heat transfer results using some appropriate model. Among these models, the one suggested by Dipprey and Sabersky [161] has been widely used and is thus described in detail here.

Dipprey and Sabersky investigated momentum and heat transfer in three rough tubes which contained a close-packed, granular type of surface. They observed that, at any given Reynolds and Prandtl number, Stanton number increases with progressively higher roughness heights. This follows the friction behavior. At a given Prandtl number, the general tendency indicates that Stanton number increases with Reynolds number in the transition region. A maximum is reached in this region near the start of the fully rough region. In the fully rough region, the Stanton number decreases monotonically with Reynolds number.
To correlate the heat transfer results in the fully rough region, the authors used the same method suggested by Nikuradse to correlate friction data, i.e., the friction similarity law. The basic similarity assumptions are the principle of Reynolds number similarity and the "law of the wall similarity". For turbulent pipe flow, the first assumption implies that there is a region which is away from the immediate vicinity of the wall and where the direct effect of viscosity on the mean flow is negligible. The second postulates that, at a region close to wall, the velocity distribution depends exclusively on the local conditions: $Y$, $\overline{T_w}$, $\rho$, $\nu$, and $e$. Accordingly, the Stanton number for rough surfaces can be written as

$$\frac{1}{St} = \frac{\rho \overline{cp} \overline{u}}{\overline{q_w}} (T_w - T') + \frac{\rho \overline{cp} \overline{u}}{\overline{q_w}} + (T' - \overline{T}) \tag{2.62}$$

where $T'$ is the temperature at the distance $Y'$, which is arbitrarily set to be far enough from the wall that viscous shear stresses are negligible. It can be shown that the second term on the right hand side of Eq. (2.62) is

$$\frac{\rho \overline{cp} \overline{u}}{\overline{q_w}} (T' - \overline{T}) = \frac{2}{f} - \frac{u'/u^*}{\sqrt{f/2}} \tag{2.63a}$$

where

$$\frac{u'^*}{u^*} = f_1 (Y'^*, e^+) \tag{2.63b}$$
By using dimensional analysis with the velocity distribution characteristic at the wall, the first term can be expressed as

\[ \frac{\rho c_p}{q_w} \bar{u} \left( T_w - T' \right) = \frac{1}{\sqrt{f/2}} - f_2 \left( Y'^+, e^+, \text{Pr} \right) \] (2.63c)

After substituting Eqs. (2.63) into Eq. (2.62), and reorganizing and dropping \( Y'^+ \) since it is an arbitrary constant, the latter equation gives

\[ \frac{f}{2S^+} - 1 \frac{1}{\sqrt{f/2}} + R(e^+) = g(e^+, \text{Pr}) \] (2.64)

The function \( g \) is then determined from the experimental results to be

\[ g(e^+, \text{Pr}) = 5.19(e^+)^{0.2} \text{Pr}^{0.44} \] (2.65)

Using a slightly different approach, Webb [143] applied the above model to a two-dimensional rib roughness and obtained

for \( e^+ > 35 \) and \( 10 < p/e < 40 \)

\[ R(e^+, p/e) = 0.95(p/e)^{0.53} \] (2.66)

\[ g(e^+, \text{Pr}) = 4.5(e^+)^{0.28} \text{Pr}^{0.57} \] (2.67)
The other major part of literature [173-183] in single-phase studies comprises mainly experiments inside annuli with the outside surface of the inner tube roughened in different ways. This follows from the development of gas-cooled reactors where the fuel elements are formed in clusters of rods. Another advantage of performing experiments in annuli is to avoid difficulties involved in machining roughness elements inside a long pipe. Several transformation schemes [184-190] have been devised to reduce these experimental results to a form in which they are directly comparable with the experimental results of rough tubes with internal flow. These schemes are described rather clearly in [190].

Condensation studies The above literature review indicates that heat transfer on rough surfaces for single-phase flow has been receiving much attention. Comparatively, only a few studies exist pertaining to study of the flow field and heat transfer on rough surfaces for condensing or two-phase flows.

Medwell and Nicol [191,192] were among the first to study the effects of surface roughness on condensate films. They condensed steam on the outside of one smooth and three artificially roughened pipes with pyramid shape roughness. The tubes were oriented vertically and the condensate was drained under gravity alone. The mean heat transfer coefficients were found to increase significantly with roughness height, the values of the roughest tube being almost double those of the smooth tube. The investigators suggested that,
close to the top of the tube, the roughness acted as extended surface and the flow was subsequently in wavy flow, fully rough, transition, and hydraulically smooth regions as the condensate grew thicker. High heat transfer was expected to occur in the first three regions.

The investigators also made a preliminary analysis of a falling film with zero interface shear using the Prandtl mixing length concept. Different formulations for the mixing length were used to match the assumptions and boundary conditions in the three regions considered, i.e., hydraulically smooth, transition, and fully rough regions. Because of the dependence of some physical quantities on the roughness height in the transition region, the authors could only predict the mean heat transfer coefficients in the hydraulically smooth and fully rough regions. All the heat transfer results were found to fall in between the theoretical values of these two regions.

Nishikawa et al. [193] examined the effects of tube roughness on mean liquid film thickness, mean velocity and frequency of disturbance waves, entrainment flow rate, and pressure drop of vertically upward air-water annular flow. Their results showed that the behaviors of ripples and disturbance waves in the grooved tubes were considerably different from those in smooth tube. The pressure drop, as would be expected, increased with roughness. However, at some lower flow rates of both air and water, the pressure drop of the grooved tube became less than that of the
smooth tube. Nishikawa and his co-workers also found the boundaries of flow regimes were shifted only slightly owing to the difference in wall roughness. This observation was later confirmed by Taitel [194], except for the intermittent - dispersed bubble transition where the boundary extended further into the intermittent regime. Taitel also demonstrated that the flow regime map by Taitel and Dukler is directly applicable provided that the friction factor for rough pipes are used in evaluating those pressure drop terms.

Cox et al. [195] used several kinds of augmented tubes to improve performance of horizontal-tubes multiple-effect process for saline water conversion. Two of the augmented tube considered were with circumferential V-shaped grooves. The best performing grooved tube showed an increase of heat transfer up to 60 percent over the smooth tube.

Sheynkman [196] used the physical model developed by Millionshchikov [197] for single-phase flow on rough surfaces to analyze turbulent film condensation of vapor on a vertical rough surface. No comparison was made between the theoretical studies and experimental results.

**Conclusion**  Rough surfaces have been studied extensively for single-phase flow. At some operating ranges, roughness heights and physical properties of the working fluid, namely the transition region and fluids with high Prandtl numbers, the performance of rough tubes are superior than that of smooth tubes. In
condensing flow, however, little investigation has been done on rough surfaces, especially for in-tube condensation.

Rough surfaces should improve heat transfer in condensing flows. The roughness elements are expected to increase mixing in the condensate where the major thermal resistance lies. The roughness can also promote wavy flow when its height is comparable to the condensate thickness. However, improved heat transfer is likely to be accompanied by an increase in pressure drop. With horizontal in-tube condensation, the accumulated condensate at the bottom of the tube may degrade the roughness quality.

In conclusion, this chapter presented a state-of-the-art understanding of the in-tube condensation process and the augmentation techniques selected for this study. This understanding is essential for supporting this research effort to extend and/or better the previous works [2,115] on augmentation of in-tube condensation and to explore the prospective application of rough tubes to in-tube condensation augmentation. This effort also includes the study of the effects of superheat and heat flux on the in-tube condensation process. A comprehensive experimental program was devised for these purposes and is detailed in the next chapter.
CHAPTER III. EXPERIMENTAL PROGRAM

Because of the lack of understanding of the effects of augmentation on in-tube condensation, the major effort in this study was devoted to the experimental program. This program consisted of testing of a smooth tube and tubes with three potentially useful passive augmentation techniques. These techniques are: twisted-tape inserts, internally finned tubes, and rough tubes.

A general description of the experimental facility and the data reduction process are presented here. Details of the experimental procedure can be found in Appendix B.

Experimental Facility Description

The apparatus used in the present study is a closed refrigerant flow loop in parallel with an open coolant loop. This apparatus was established through extensive modification of the facility developed by Royal [2] in his study of in-tube condensation of steam. A schematic of the experimental facility and a photograph are shown in Figs. 2 and 3, respectively.

Refrigerant flow loop

The refrigerant loop consisted of a boiler, a superheater, a test condenser, an after-condenser, a drier and filter, a pump, and a degassing tank. Detailed descriptions of these components are provided in Appendix A. R-113 was employed as the test fluid.
Fig. 2. Layout of experimental facility.
Fig. 3. Photograph of experimental facility.
The test fluid was degassed in the degassing tank and directed to pass through the drier and filter during the initial starting of the test loop. The drier and filter were bypassed during normal operation, and the fluid was supplied directly to the boiler via the pump. Electrical heating was used in the boiler. A demister placed at the top of the boiler removed most of the larger liquid droplets in the wet vapor which was generated. The vapor entered the condensing-steam-heated superheater where it could attain 0°-22.2°C (40°F) superheat before entering the test condenser. The condensate or condensate-vapor mixture coming out of the test condenser passed through an adiabatic sight glass section where the exit flow regime could be observed. The condensate or condensate-vapor mixture then flowed to the after-condenser for complete condensation and/or subcooling. The subcooled condensate was metered in the condensate flow meter before it went through the system pressure regulating valve to the pump.

The degassing tank was bypassed during operation; however, the tank served as a receiver to accommodate expansion or contraction of the loop fluid.

The void trap, initially intended to measure the void fraction, was not used in the present study because of its poor performance in the previous study [2].

**Coolant Loop**

The coolant, delivered at 70 psig from a 2 in. water main from
University water well, entered the test condenser through a flow control valve and a flow meter. The test condenser was a counterflow, concentric tube heat exchanger with R-113 flowing through the inner tube and the coolant flowing in the annulus. The test condenser was divided into four equal test sections. The coolant was directed, at the end of each section, to a measuring station where it was thoroughly mixed before proceeding to the next section. After leaving the condenser the coolant was discharged through a coolant exit valve to a floor drain. The coolant main also supplied water to the after-condenser, to the condenser in the degassing tank, and for other auxiliary purposes.

During the trial runs after the completion of the facility, it was found that pressure fluctuations in the water main had a significant effect on the system stability. This was due to the larger coolant-side thermal resistance at the test condenser. A solution to this problem was to maintain a constant coolant flow through the test condenser during a test run. The most practical solution was to reduce the thermal resistance at the coolant side to such a level that a small fluctuation of the coolant thermal resistance would not significantly alter the conditions in the test condenser. This was accomplished by raising the coolant inlet temperature and increasing the coolant flow rate. These changes increased the coolant side heat transfer coefficient and thus reduced the coolant side resistance. The heating was accomplished
by a steam-heated preheater installed upstream of the flow meter. The coolant exit valve was used together with the flow control valve to pressurize the coolant side of the test condenser to suppress possible subcooled boiling of the coolant.

**Test condenser tubes**

The test condenser tubes consisted of a smooth tube, the smooth tube with two different pitch twisted-tape inserts, three internally finned tubes, and two tubes with repeated-rib roughness. All tubes had approximately the same outside diameter except one of the finned tubes. These tubes are shown in Fig. 4 and their dimensions are listed in Table G.1. The general terminology ascribed to these test condenser tubes can be found in Fig. 106 in Appendix A.

The two twisted tapes were provided by Bas-Tex Corporation. The tapes were installed in the smooth tube by pulling them into the tube after taking apart the test condenser end fittings. To enable the tape to be installed in the tube, a small clearance up to 0.12 mm (0.047 in.) was allowed. Since the tape was not straight, an intermittent contact between the tape and the tube wall was expected.

The finned and the rough tubes were manufactured by the Forge-Fin Division of Noranda Metal Industries, Inc. The finned tubes were standard production seamless tubes with integral, longitudinal spiral fins. The rough tubes were seamless tubes with internal ribs; these tubes were custom-fabricated for this study.
Fig. 4. Photograph of test condenser tubes, top to bottom: Tubes 2, 3, 4, 5, 6, 7, and 8.
### General operating procedure

The tubes were tested in the order shown in Table G.1. For each tube, data were taken over a range of inlet pressures and condensing fluid mass velocities. Usually, the test fluid mass velocity was varied for a specific inlet pressure. The operating ranges for some of the important parameters are tabulated in Table 3.1.

#### Table 3.1. Experimental facility operative parameter ranges

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flux</td>
<td>$86(63,700)-760(560,000)$, $\frac{kg}{s-m^2}$</td>
</tr>
<tr>
<td></td>
<td>$\frac{1b}{hr-ft^2}$</td>
</tr>
<tr>
<td>Heat Flux</td>
<td>$11,000(3486)-88,000(27,887)$, $\frac{W}{m^2}$</td>
</tr>
<tr>
<td></td>
<td>$\frac{(Btu)}{hr-ft^2}$</td>
</tr>
<tr>
<td>Overall Condensing Heat Transfer Coefficient</td>
<td>$1056(186)-7382(1,300)$, $\frac{W}{m^2}$</td>
</tr>
<tr>
<td></td>
<td>$\frac{(Btu)}{hr-ft^2-^oF}$</td>
</tr>
<tr>
<td>Overall Heat Transfer Rate</td>
<td>$1550(5288)-14,000(47,765)$, $W\frac{(Btu)}{hr}$</td>
</tr>
<tr>
<td>Inlet Coolant Temperature</td>
<td>$10(50)-104(219)$, $^oC\ (^oF)$</td>
</tr>
<tr>
<td>Test Fluid Inlet Pressure</td>
<td>$2.41(35.0)-6.55(95)$, bar(psia)</td>
</tr>
<tr>
<td>Test Fluid Inlet Superheat</td>
<td>$0(0)-22.2(40)$, $^oC\ (^oF)$</td>
</tr>
<tr>
<td>Outlet</td>
<td>$-0.052\ (subcooled) - 0.06$</td>
</tr>
</tbody>
</table>
Usually, single-phase vapor flow at the test condenser inlet was maintained. This meant that the reading from the thermocouple, installed at the test condenser inlet, should indicate the saturation temperature corresponding to the inlet pressure. However, to insure single phase of vapor entering the test condenser, 0-5°C (9°F) superheat was usually established.

Besides complete condensation, part of the experimental program was also devoted to study the effects of superheat and heat flux on condensation. The inlet superheat was established by the superheater. For the heat flux effect study, a mixture of vapor and liquid of the test fluid generated in the boiler was allowed to enter the test condenser directly. In this case, the test fluid bypassed the superheater. There was another case, namely $P_{in} = 35$ psia, that the test fluid had to bypass the superheater, because the pressure drop across the superheater made it difficult to attain this inlet condition with an inlet superheat of only a few degrees. The liquid level at the boiler was maintained several inches below the top of the electric heater during the course of an experiment so that the test fluid inlet conditions were as close to saturation as possible.

Data Acquisition and Reduction

Data monitoring, acquisition, and reduction were performed by the Heat Transfer Laboratory Data Acquisition System. Instrumentation
and installation for measurements of all experimental quantities are described in Appendix B.

For each test run, four sectional condensation heat transfer coefficients and an overall heat transfer coefficient were calculated from

\[ \bar{h} = \frac{q}{\pi D_i} \frac{\Delta Z}{\Delta Z} (T_s - T_{wi}) \]

\[ = \left[ \frac{\pi D_i}{q} \frac{\Delta Z (T_s - T_{wo})}{\Delta Z} - \frac{D_i}{2k_w} \ln \left( \frac{D_o}{D_i} \right) \right]^{-1} \]  (3.1)

The energy transfer, \( q \), was obtained from the coolant flow rate and coolant temperature rise through each respective section. The average wall temperature, \( T_{wo} \), for the respective section was calculated by first averaging the circumferential temperatures at each station using Simpson's rule and then averaging linearly the circumferential average temperatures for the section. The average saturation temperature, \( T_s \), for each respective section was the saturation temperature corresponding to the linear average of the static pressures of the condensing medium at the section entrance and exit. A sample data reduction calculation of an experiment is presented in Appendix E. An error analysis for
Eq. (3.1) is given in Appendix F. Generally, a 10 percent error is expected for the experimental heat transfer coefficients.

In general, the experimental results for each condenser tube were internally consistent. At low flow rates, the pressure drop data were somewhat scattered due to low pressure drop and low resolution of the mercury manometer. Nevertheless, neither the heat transfer data nor the pressure drop data were erratic in nature and all expected trends were observed.
CHAPTER IV. SMOOTH TUBE

The smooth tube was included in the present study for two main reasons: to provide verification of the experimental facility and to serve as a reference for comparisons among the other augmented tubes considered here. The smooth tube data were also necessary to check smooth tube condensation models and predictive correlations; successful models can serve as a basis for correlations of the augmented condenser tubes.

General Considerations

Flow regimes

From the literature review, it is understood that flow regimes strongly affect the heat transfer and pressure drop characteristics of a condensing flow. The experimental facility was equipped with a sight glass to enable flow regime observation at the test condenser exit. At the outlet of other test condenser sections, flow pattern determination relies on predictive flow regime formats. These formats were discussed in Chapter 2, and four such formats were selected.

The four chosen flow regime formats are: the modified Baker flow map [Collier, 8], the Taitel and Dukler flow map [13], the Mandhane et al. flow format [9], and the Jaster and Kosky parameter [14]. A computer code was developed for each format to determine the flow pattern at each section outlet for each run using the local experimental
conditions. These codes produced the results of the calculations in graphical or tabular form, as appropriate. The predictions from these formats at the test condenser exit can be compared with the visual observations at the sight glass.

An attempt was also made to determine the possibility of liquid entrainment in each test section by referring to the local conditions at the test-section inlet and outlet. The procedure used here to determine entrainment follows closely the suggestion outlined in [8]. It was also written in a computer code.

Entrainment from a liquid film is associated with the onset of disturbance waves at the interface and in general depends on both the vapor and liquid flow rates. For liquid film Reynolds numbers below 200, i.e., \( \text{Re}_L = \frac{G(1-x)D}{\mu_L} \leq 200 \), little or no entrainment will take place even at very high vapor velocities. This region was designated Region 1 in the computer code. For \( 200 < \text{Re}_L \leq 3000 \), designated as Region 2, with the onset of turbulence in the film, the amount of entrainment is a function of both vapor and liquid flow rates. In fully turbulent film flow, \( \text{Re}_L > 3000 \), the conditions for possible entrainment are largely independent of the liquid film flow rate and depend primarily upon the vapor velocity. The critical vapor velocity for the onset of entrainment from the film was given in [8] as

\[
\dot{j}_{g,\text{crit}} = 1.5 \times 10^{-4} \frac{\rho_L}{\rho_g} \frac{a}{\mu_g} \quad (4.1)
\]
The region was called Region 3a for \( j_g \geq j_{g,\text{crit}} \), and Region 3b for \( j_g < j_{g,\text{crit}} \). At high liquid flow rates in the wispy annular flow region, the concept of a critical vapor velocity for the start of liquid entrainment does not hold, and considerable entrainment occurs at all values of vapor velocity. This occurs for \( Re_l > 20,000 \) and was designated Region 4.

The results from the above investigation for possible liquid entrainment are subject to some uncertainty due to insufficient experimental information and the lack of a comprehensive theory. Further work is required to refine the scheme.

**Pressure drop**

The present experimental pressure drop results for the smooth tube were compared with predicted values from five of the many existing correlations in the literature presented in Chapter 2. These are the correlations of the homogeneous model [8], Miropol'skii et al. [31], Lockhart and Martinelli [35], Chisholm [39], and Dukler II [29]. These correlations were used along with the seven void fraction correlations listed in Chapter 2 to calculate the pressure drop for the smooth tube experiments.

After preliminary calculations of the pressure drop correlations with the void fraction correlations for some smooth tube experiments, it was noted that the calculated momentum pressure drop was insensitive to predicted values of void fraction. On the other hand, the calculated momentum pressure drops were found to amount
to only 7 to 20 percent of the frictional pressure drop and were thus too small to permit an accurate assessment of the most suitable void fraction correlation. Hence, for simplicity, the homogeneous momentum equation was chosen for estimation of the momentum pressure drop.

Void fraction also appears in the frictional pressure drop correlation of Dukler II. The preliminary calculations also showed that the use of the homogeneous void gave the best agreement with the experimental results; thus, the homogeneous void was used in the Dukler II correlation.

Because of practical interest in overall pressure drop, the correlations were integrated along the test condenser to obtain the overall pressure drop using Simpson's rule. The test condenser was divided into a number of small increments (80) of constant length. Owing to the relatively small pressure drop across each test condenser section, fluid properties could be assumed constant over each section. The properties were determined by the mean value of inlet and outlet pressures. Intermediate values of quality within each section were acquired by a piece-wise cubic interpolation polynomial.

In order to compare these correlations with the measured pressure drop results, a statistical inference scheme was established. Within this scheme, four error parameters were calculated or estimated as follows:
\begin{equation}
\bar{e} = \frac{1}{N} \sum_{i} e_i \tag{4.2}
\end{equation}

\begin{equation}
s = \left[ \sum_{i} (e_i - \bar{e})^2 / (N - 1) \right]^{0.5} \tag{4.3}
\end{equation}

\begin{equation}
s_1 = \frac{100}{N} \left[ \sum_{i} \left| \frac{e}{\Delta P_{\exp i}} \right| \right] \tag{4.4}
\end{equation}

\begin{equation}
s_2 = \frac{100}{N} \left[ \sum_{i} \left( \frac{e}{\Delta P_{\exp i}} \right)^2 \right] \tag{4.5}
\end{equation}

where

\[ e_i = (\Delta P)_{i,\text{cal}} - (\Delta P)_{i,\text{exp}} \]

\( N \) : number of data points

The first parameter, error mean, roughly indicates the agreement between the calculated and experimental values. The smaller the value of \( \bar{e} \), the better the correlation. The second parameter, standard deviation, is an indicator of the scatter of the data around the error mean. The third parameter, given as a percentage, indicates the average absolute error of the experimental results relative to the calculated values. The fourth parameter, also a percentage, measures the average deviation of the experimental results from the calculated values in a relative sense.
Heat transfer coefficient

The experimental smooth tube results from the present study were compared with calculated values from nine of the many correlations available in the literature. As presented and discussed in Chapter 2, these are the correlations of Carpenter and Colburn [64], Akers et al. [90], Rosson and Myers [101], Boyko and Kruzhilin [92], Soliman et al. [53], Traviss et al. [7], Azer et al. [80,81], Cavallini and Zecchin [95], and Shah [97].

As indicated in Table 2.3, some of these correlations are local expressions and others are average expressions. In order to evaluate these correlations, they must be calculated at the corresponding experimental conditions. These conditions include pressure and quality at inlet and outlet of each section and average saturation temperature, wall temperatures, and heat flux.

For the average correlations, only the end conditions and the arithmetic mean of quality are involved; thus, these correlations are readily used to predict heat transfer coefficients at the experimental conditions. For the local correlations with expressions written in term of local quality and properties, difficulty arises because the experimental conditions are not sufficient to evaluate these correlations. Hence, some additional suppositions or assumptions have to be made.

In [2], Royal suggested two schemes to overcome this difficulty. The first scheme was to divide the tube into a number of increments
of constant change in quality. Then the calculation proceeded by applying the correlations to the conditions at each increment to predict the heat transfer coefficient there. Properties and wall temperatures were obtained from the experimental data and assumed to be constant over each of the four sections of the experimental condenser. The second scheme was to treat each section as approximating an infinitesimal element. Average sectional internal conditions, estimated from experimental results, were used as appropriate approximations to the local conditions. Royal claimed that the calculated sectional heat transfer coefficients were valid predictors of experimental results because of the way at which the experimental sectional coefficients were calculated. However, the use of the arithmetic mean of quality at each section inlet and outlet to approximate the "local" quality of the section has still to be justified. It can be shown that the approximation is valid if the local heat transfer coefficient variation at each section versus quality for a local correlation does not depart from linearity.

The first scheme assumes implicitly constant temperature difference \((T_s - T_{w1})\) over each section as shown here:

\[
\frac{dq}{\Delta t} = \frac{\pi Di g \Delta \Gamma}{h Z} \Delta T \pi D dZ
\]

(4.6)

or over a section
\[ q = \pi D i_{lg} \Gamma_1 = \bar{h} \Delta T \pi D \Delta Z \] (4.7)

where

\[ \Gamma_1 = \frac{\dot{m}(1-x)}{\pi D} = \frac{h}{4} \text{Re}_1 \]

Equation (4.6) can also be written as

\[
\int_{\Gamma_{1,1}}^{\Gamma_{1,2}} \frac{d\Gamma_1}{hZ} = \int_{Z_1}^{Z_2} \frac{\Delta T}{i_{lg}} \frac{dZ}{\bar{h}} = \frac{\Delta T}{i_{lg}} \frac{Z}{\bar{h}} = \frac{\Delta \Gamma}{\bar{h}} \] (4.8)

which can be shown to be

\[
\frac{1}{\bar{h}} = \frac{1}{x_1 - x_2} \int_{x_2}^{x_1} \frac{dx}{hZ} \] (4.9)

The assumption of constant temperature difference comes in Eq. (4.7) and during integration of Eq. (4.8). Thus, for this scheme, either a constant temperature difference exists in the experimental results or an appropriate mean has to be used in both Eqs. (4.7) and (4.8). For the present experiment, the former situation is very unlikely. However, since pressure drop and wall temperature variations across each test condenser section were small in the present study, it is plausible to replace \( \Delta T \) in both Eqs. (4.7) and (4.8) by the difference between the sectional average wall temperature and the saturation temperature corresponding to the average internal pressure, i.e., the same temperature difference.
used in the data reduction. In this case, the local correlations, except the correlations of Carpenter and Colburn [64] and Soliman et al. [53], will be valid predictors for the experimental sectional heat transfer coefficients.

For the correlations of Carpenter and Colburn [64] and Soliman et al. [53], the quality gradient $\frac{dx}{dZ}$ is involved in the expressions. Thus, an additional assumption has to be made about the distribution of $x$ in each section. The piece-wise cubic interpolation method used in the pressure drop calculation could be applied here. However, after some trial calculations, it was found that the results from using either cubic or linear interpolation were almost the same. Linear interpolation was thus used to save computer time.

The overall heat transfer coefficient can be calculated in the same way as the sectional heat transfer coefficients although larger pressure drop and wall temperature variations are expected. Alternatively, the overall heat transfer coefficient can be obtained by integrating the local correlations using the experimentally acquired sectional linear quality distribution along the test condenser. Both schemes were used in this study.

For all local correlations, the local properties were estimated by linearly interpolating the sectional saturation pressures from which the corresponding saturation temperature was determined. As in the pressure drop calculation, the same statistical parameters were
used to compare the calculated and experimental values.

Results and Discussions

Experimental results

The smooth tube experiments yielded 62 valid runs at five inlet pressures: 2.41 bar (35 psia), 3.45 (50), 4.48 (65), 5.52 (80), and 6.55 (95). Among these experiments, 15 runs were for the superheat effect study and 5 runs were for the heat flux effect study. All subsequent runs for studying both effects were performed at about the same mass velocity (321.4 kg/s-m²) and at an inlet pressure of 6.55 bar. The experimental conditions and experimental results are tabulated in Appendix I.

Computer-generated plots of the distribution of heat flux, quality, test fluid static pressure, sectional heat transfer coefficients, wall temperatures, coolant temperatures, and test fluid saturation temperatures along the test condenser, were prepared for each run. A sample of these plots is shown in Fig. 5.

The change of quality, Δx, across each section is evaluated from the heat transfer rate; hence, it is associated with the average heat flux in that section. The sectional heat flux distribution is affected by coolant inlet temperature. Usually, with elevated coolant inlet temperature, the sectional heat flux variation is small, as shown in Fig. 5a. Accordingly, the variation of x, based on the calculated quality at the end of each section, is approximately linear, as shown in Fig. 5b. This distribution of the sectional qualities suggests that the
Fig. 5. Typical plots of experimental parameters.
C. TEST FLUID STATIC PRESSURE

D. SECTIONAL HEAT TRANSFER COEFFICIENTS

Fig. 5. Continued.
Fig. 5. Concluded.
actual quality change in a test condenser section would not be far from linear. Hence, the use of a linear sectional quality change approximation to evaluate some of the local correlations is justified. On the other hand, without elevating the coolant inlet temperature as in those runs in lower pressure levels, sectional heat flux increased with decreasing quality. Thus, sectional quality change is not constant with the largest drop occurring at Section 1. In this case, the use of a linear sectional quality change approximation might introduce slightly larger uncertainty in the calculated results. The drawn line in Fig. 5b is for visual aid only.

Test fluid pressure generally decreased along the test condenser, as shown in Fig. 5c. However, in some experiments at low flow rates, there were some observable increases in pressure at Station 4 due to momentum recovery and laminar condensate flow. Usually, a larger pressure drop was found in Sections 2 and 3 at high flow rates. This was convincingly caused by turbulent film flow, wavy interface, and/or liquid entrainment. Fluctuations were observed during some pressure measurements. Further discussion on this behavior is given in Appendices A and B.

The sectional heat transfer coefficient variation is presented in Fig. 5d. As calculated in the study by Boyko and Kruzhilin [92], the local heat transfer coefficient during in-tube condensation should decrease with decreasing quality. This trend was observed in all of the present experiments with the exception of a few tests
which displayed coefficients at the fourth section (condenser inlet) which were lower than those of the next section. A similar observation was noted in Royal's study [2]. This might be due to the combined effects of film instability and liquid entrainment causing an increased coefficient in the third section.

As shown in Fig. 5e, the average wall temperature increased monotonically with increasing quality. However, this was not always the case for the wall temperatures at a circumferential position along the test condenser. Variations of circumferential temperatures at several stations were observed. This variation was especially pronounced at the station near the exit of the test condenser for the high pressure runs. Because of accumulated condensate at the bottom and the residual vapor phase at the top of the tube near the exit, this observation appears to be phenomenologically sound. The distributions of the coolant temperatures and test fluid saturation temperatures were closely related to those of the heat fluxes and test fluid pressures, respectively.

Overall pressure drops were plotted versus mass velocity for different inlet pressures in Fig. 6. The data for $P_{in} = 2.41$ bar display much larger scatter. It was believed the pressure drops in those runs were affected by fluctuating quantities, notably the inlet pressure. A more detailed discussion of this behavior can be found in the section on system stability in Appendix B. In general, higher pressure drops were associated with lower pressures. However, this trend was not so clear at high mass velocities.
Fig. 6. Experimental overall pressure drops versus mass flux, Tube 1, all inlet pressures.
Figure 7 presents for the smooth tube the overall heat transfer coefficient versus mass velocity, with inlet pressure as a parameter. Generally, the pressure effect is obvious at high mass velocities, i.e., higher heat transfer coefficients accompany lower inlet pressures. From the figure it can be observed that a change in pressure from 2.41 bar to 6.55 bar raises the overall heat transfer coefficients up to 30 percent.

Along with the data points shown in Figs. 6 and 7, straight lines were drawn through these data points for illustrative purposes. These straight lines were fitted to the data with a least-square technique based on the following functional form:

\[
P = CG^n \\
h = C'G^{n'}
\]

The values of the constants C, C', the exponents n, n', and the correlation coefficient, as well as the standard deviation of the pressure drop and heat transfer data from the expressions in Eqs. (4.10) are tabulated in Tables G.2 and G.3, respectively. The fitted curves also served as the standards to which the performance of the augmented tubes were compared.

**Flow regime results**

The observed test fluid flow regimes at the test condenser exit for the smooth tube are tabulated in Table I.2. The observations indicated that the exit flow regime of most test runs was transitional.
Fig. 7. Experimental overall average heat transfer coefficients versus mass flux, Tube 1, all inlet pressures.
between semi-annular and slug flow, with intermittent bursts of wavy and plug flow.

Flow regimes at the end of all four sections were predicted using the four previously mentioned schemes with local experimental conditions. Figure 8 presents the flow regime predictions for the smooth tube on the modified Baker flow map. An examination of these data points on Fig. 8 indicates that while the predicted exit flow regimes were mostly in the slug flow regime, predicted flow regimes at the ends of the other sections were dominated by the annular flow regime. Thus, the predicted exit flow regimes are mostly in accordance with experimental observations. When compared the present results on the Baker map with the previous in-tube condensation observations of Traviss et al. [7] and Royal [2], it was found that the present smooth tube experiments had roughly the same flow pattern variations as the above two studies.

The flow regime predictions by the Mandhane et al. flow map [9] are tabulated in Table 4.1. This scheme predicts that the elongated bubble flow pattern prevailed at the exit station and the stratified or wavy flow pattern predominated at other stations. In other words, the scheme predicts that gravity had a considerable effect on the present smooth tube experiments.

Figure 9 presents the flow regime predictions on the Taitel and Dukler flow map [13]. The predicted flow regimes at Station 1 were largely in the intermittent region. The predicted flow regimes at
Fig. 8. Modified Baker flow regime map.
Table 4.1. Results of flow regime study according to Mandhane et al. [9]

<table>
<thead>
<tr>
<th>Station</th>
<th>Run No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.012</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.013</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.014</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.015</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.018</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.019</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.020</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.021</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.022</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.023</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.024</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.025</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.026</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.027</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.028</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.033</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.034</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.035</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.036</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.037</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.038</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.039</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.040</td>
<td>elongated bubble</td>
<td>slug</td>
<td>wavy</td>
<td>wavy</td>
</tr>
<tr>
<td></td>
<td>1.041</td>
<td>elongated bubble</td>
<td>slug</td>
<td>wavy</td>
<td>wavy</td>
</tr>
<tr>
<td></td>
<td>1.042</td>
<td>elongated bubble</td>
<td>slug</td>
<td>wavy</td>
<td>wavy</td>
</tr>
<tr>
<td></td>
<td>1.043</td>
<td>elongated bubble</td>
<td>slug</td>
<td>wavy</td>
<td>wavy</td>
</tr>
<tr>
<td></td>
<td>1.044</td>
<td>elongated bubble</td>
<td>slug</td>
<td>wavy</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.045</td>
<td>elongated bubble</td>
<td>slug</td>
<td>wavy</td>
<td>wavy</td>
</tr>
<tr>
<td></td>
<td>1.046</td>
<td>elongated bubble</td>
<td>slug</td>
<td>wavy</td>
<td>wavy</td>
</tr>
<tr>
<td></td>
<td>1.047</td>
<td>elongated bubble</td>
<td>slug</td>
<td>wavy</td>
<td>wavy</td>
</tr>
<tr>
<td></td>
<td>1.048</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.049</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.050</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.051</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.052</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.053</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.054</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.055</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.056</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.057</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.058</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
<tr>
<td></td>
<td>1.059</td>
<td>elongated bubble</td>
<td>stratified</td>
<td>stratified</td>
<td>stratified</td>
</tr>
</tbody>
</table>
Fig. 9. Taitel and Dukler flow regime map.
other stations were found to be mostly in the annular-dispersed region. However, bearing in mind the approximation of the flow regime boundaries, those data points near the boundary between the annular-dispersed and the stratified-wavy regions might exhibit a transitional characteristic. In general, these predictions are in agreement with those of the modified Baker flow map.

Those data points of Station 1 which are located in the stratified-wavy region deserve some further comment. These data points, when first located by the dimensionless group $F_1$, were in the intermittent region and then shifted to the stratified-wavy region when their ordinates were changed to the dimensionless group $T_1$. Since it is the first time that this flow map is used for in-tube condensation study, no such observation has been reported.

The Jaster and Kosky scheme [14] does not give the specific predicted flow regime. The parameter used in this scheme indicates only whether the flow is controlled by shear, by gravity, or by a combination of these two forces (transition). The results predicted by this scheme are tabulated in Table 4.2. An examination of the results indicates that the condensing flow at Station 1 was mainly in the gravity-controlled flow region while the flow at Station 4 was mainly in the shear-controlled flow region. Thus, the flow at some intermediate station had to be in the transition flow region.

There are some variations in the predictions of the flow regime for the present smooth tube experiments by these four flow
Table 4.2. Results of flow regime study according to Jaster and Kosky [14]

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Station 1</th>
<th>Station 2</th>
<th>Station 3</th>
<th>Station 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.012</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.013</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.014</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.015</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.018</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.019</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.020</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.021</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.022</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.023</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.024</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.025</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.026</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.027</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.028</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.033</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
</tr>
<tr>
<td>1.034</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
</tr>
<tr>
<td>1.035</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
</tr>
<tr>
<td>1.036</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
</tr>
<tr>
<td>1.037</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
</tr>
<tr>
<td>1.038</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
</tr>
<tr>
<td>1.039</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.040</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.041</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>shear</td>
</tr>
<tr>
<td>1.042</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
<td>shear</td>
</tr>
<tr>
<td>1.043</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
<td>shear</td>
</tr>
<tr>
<td>1.044</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.045</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
<td>shear</td>
</tr>
<tr>
<td>1.046</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
<td>shear</td>
</tr>
<tr>
<td>1.047</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.048</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.049</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.050</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.051</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
<td>shear</td>
</tr>
<tr>
<td>1.052</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.053</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.054</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
<tr>
<td>1.055</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.056</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.057</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.058</td>
<td>gravity</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
</tr>
<tr>
<td>1.059</td>
<td>gravity</td>
<td>gravity</td>
<td>transition</td>
<td>transition</td>
</tr>
</tbody>
</table>
regime predicting schemes. However, a consensus was reached that the section nearest the test condenser inlet exhibited shear-controlled behavior, while the section nearest the test condenser outlet exhibited gravity-controlled behavior. These observations are important when comparing the present smooth tube results with the selected heat transfer correlations.

The results of the liquid entrainment calculations for the smooth tube experiments are tabulated in Table 4.3. At lower flow rates, the possibility of liquid entrainment at Stations 3 and 4 depends on the vapor and liquid velocities (Region 2). At the other two stations, the liquid film is thickening but the vapor velocities are lower than the critical velocity for the onset of liquid entrainment (Region 3b). At higher flow rates, the liquid film is thicker and the vapor velocities well exceed the critical velocity for the start of entrainment from the film at Stations 3 and 4 (Region 3a); thus entrained liquid occurred in Sections 2, 3, and 4. Liquid entrainment at Stations 1 and 2, as indicated in Table 4.3, is possible when the liquid film is so thick that $Re_l > 20,000$ (Region 4). In this case, considerable entrainment occurs regardless of the values of vapor velocity. The result is not in complete agreement with the predictions of the four flow regime predicting schemes, but it indicates a high probability of liquid entrainment at the upstream sections of the test condenser at high mass velocities.
Table 4.3. Liquid entrainment prediction

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Station</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.012</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.013</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.014</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.015</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.018</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.019</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.020</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.021</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.022</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.023</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.024</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.025</td>
<td>Region 2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1.026</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.027</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.028</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.033</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.034</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.035</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.036</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.037</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.038</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.039</td>
<td>Region 3b</td>
<td>3b</td>
<td>3a</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.040</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.041</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.042</td>
<td>Region 3b</td>
<td>3b</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.043</td>
<td>Region 3b</td>
<td>3b</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.044</td>
<td>Region 3b</td>
<td>3b</td>
<td>3a</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1.045</td>
<td>Region 3b</td>
<td>3b</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.046</td>
<td>Region 3b</td>
<td>3b</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.047</td>
<td>Region 3b</td>
<td>3b</td>
<td>3b</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1.048</td>
<td>Region 3b</td>
<td>3b</td>
<td>3a</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1.049</td>
<td>Region 3b</td>
<td>3b</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.050</td>
<td>Region 3b</td>
<td>3a</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.051</td>
<td>Region 3b</td>
<td>3a</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.052</td>
<td>Region 3b</td>
<td>3a</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.053</td>
<td>Region 3b</td>
<td>3a</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.054</td>
<td>Region 3b</td>
<td>3a</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.055</td>
<td>Region 3b</td>
<td>3a</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.056</td>
<td>Region 3b</td>
<td>3a</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.057</td>
<td>Region 3b</td>
<td>3a</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.058</td>
<td>Region 3b</td>
<td>3a</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
<tr>
<td>1.059</td>
<td>Region 3b</td>
<td>3a</td>
<td>3a</td>
<td>3a</td>
<td></td>
</tr>
</tbody>
</table>
Comparison of correlations

Pressure drop Calculations of all selected pressure drop correlations as outlined in this chapter and Chapter 2 were performed for each smooth tube test. Figures 10-17 present the plots of calculated pressure drop versus the experimental pressure drop for the correlations. The estimated statistical parameters are tabulated in Table G.4. It should be noted that data points shown in Figs. 10-17 are overall pressure drops Comparisons for sectional pressure drops were not made because they were beyond the scope of this study.

As shown in these figures and by the parameter $s_2$ in Table G.4, all correlations except the Chisholm correlation under-predicted the experimental results. However, as indicated by the parameter $s$ in Table G.4 as well as in Fig. 16, the calculated values from the Chisholm correlation exhibited the largest scattering around the error mean. In addition, this correlation had the largest average absolute error among the tested correlations.

For the four viscosity expressions used in the homogeneous model, the expression suggested by Cicchitti et al. [28] gives the closest agreement with the experimental results (Fig. 12). Yet, there is still an average absolute error of about 52 percent. This finding is quite contrary to that in the study by Idsinga et al. [30] where the homogeneous-Cicchitti was appraised as one of the best pressure drop correlations for steam-water systems.
Fig. 10. Comparison of overall pressure drops with predictions of homogeneous model, Eq. (2.16a), Tube 1.
Fig. 11. Comparison of overall pressure drops with predictions of homogeneous model, Eq. (2.16b), Tube 1.
Fig. 12. Comparison of overall pressure drops with predictions of homogeneous model, Eq. (2.16c), Tube 1.
Fig. 13. Comparison of overall pressure drops with predictions of homogeneous model, Eq. (2.16d), Tube 1.
Fig. 14. Comparison of overall pressure drops with predictions of Miropol'skii et al. correlation [31], Tube 1.
Fig. 15. Comparison of overall pressure drops with predictions of Lockhart and Martinelli correlation [35], Tube 1.
Fig. 16. Comparison of overall pressure drops with predictions of Chisholm correlation [39], Tube 1.
Fig. 17. Comparison of overall pressure drops with predictions of Dukler II correlation [29], Tube 1.
The Miropol'skii correlation is the only one which was obtained from correlating pressure drops in condensing flow. However, as shown in Fig. 14 and Table G.4, the correlation exhibits no improvement over the best homogeneous model. Because of the empirical nature of the correlation, the disagreement is possibly attributable to different experimental conditions as well as different working fluids.

The separated flow models of Lockhart-Martinelli and Dukler II do not produce better results than the homogeneous models do. This suggests that the effect of condensation on interfacial shear stress has to be accounted for in the present study.

The Lockhart-Martinelli and the Dukler II correlations can be readily modified by assuming that the increase of the two-phase friction multipliers with condensation, relative to corresponding ones without condensation, is the same as $f_1^*/f_1$ in Eq. (2.11a). This assumption is reasonable as $\tau_w = \tau_1$, i.e., the contribution of the pressure force and momentum recovery to the liquid film shear is comparatively small as compared with $\tau_1$.

The calculated values from the modified Lockhart-Martinelli and the modified Dukler II correlations are plotted against the experimental results in Figs. 18 and 19, respectively. The estimated statistical parameters are listed along with others in Table G.4. Although the scattering of the data is about the same as in the case without modification, figures 18 and 19 display
Fig. 18. Comparison of overall pressure drops with predictions of Lockhart and Martinelli correlation [35] modified according to Eq. (2.11a), Tube 1.
Fig. 19. Comparison of overall pressure drops with predictions of Dukler II correlation modified according to Eq. (2.11a), Tube 1.
a better agreement between the calculated and the experimental values. Seventy-five percent of the data points lie within ±40 percent as compared with 50 percent of the data originally. The relatively large deviations of the data points, especially at low flow rates, are due to the low resolution of the differential mercury manometer and other factors discussed in Appendix A.

According to the statistical analysis, the modified Lockhart-Martinelli is slightly better than the modified Dukler II correlation because of smaller value of \( s_2 \). However, the former correlation exhibits larger average absolute error (\( s_1 \)) and more scattering (\( s \)). It was thus concluded that these two correlations are the best predictors of the present experimental pressure drop results.

**Heat transfer coefficient** As shown in Figs. 20 - 28, the experimental smooth tube heat transfer results were compared with the nine selected correlations described in Chapter 2. Calculations for each valid smooth tube experiment were performed as outlined in this chapter. Results of calculations of those statistical parameters are presented in Table G.5.

It was found for the local correlations that calculations of the overall heat transfer coefficients based on overall linear quality distribution or sectional linear quality distribution had little effect on the values of the overall heat transfer coefficient. Since in most cases less than 5 percent difference was noted, the results
Fig. 20. Comparison of sectional and overall heat transfer coefficients with predictions of Carpenter and Colburn correlation [64], Tube 1.
Fig. 21. Comparison of sectional and overall heat transfer coefficients with predictions of Akers et al. correlation [90], Tube 1.
Fig. 22. Comparison of sectional and overall heat transfer coefficients with predictions of Rosson and Myers correlation [101], Tube 1.
Fig. 23. Comparison of sectional and overall heat transfer coefficients with predictions of Boyko and Kruzhilin correlation [92], Tube 1.
Fig. 24. Comparison of sectional and overall heat transfer coefficients with predictions of Soliman et al. correlation [53], Tube 1.
Fig. 25. Comparison of sectional and overall heat transfer coefficients with predictions of Traviss et al. correlation [7], Tube 1.
Fig. 26. Comparison of sectional and overall heat transfer coefficients with predictions of Azer et al. correlation [80, 81], Tube 1.
Fig. 27. Comparison of sectional and overall heat transfer coefficients with predictions of Cavallini and Zecchin correlation [95], Tube 1.
Fig. 28. Comparison of sectional and overall heat transfer coefficients with predictions of Shah correlation [97], Tube 1.
of the latter scheme to calculate overall heat transfer coefficients are not presented.

Only those data points with mass velocities up to 258 Kg/s-m² (190,000 lbm/hr-ft²) were compared with the local correlation of Carpenter and Colburn [64] because the graph for friction factors given in [18] does not cover the whole range of experimental conditions. As shown in Fig. 20, this correlation predicted slightly higher values for Sections 2 and 3 and lower values for Section 1, Section 4, and the overall average. At high pressure level, the data points started deviating from the -30 percent margin. Since the data from which the correlation was developed are not available, a comparison between the experimental conditions could not be made.

The calculations for the average correlation of Akers et al. [90] are presented in Fig. 21. Satisfactory agreement was found between the experimental and calculated values for Section 1 in general and for Section 2, Section 3, and the overall average at low mass velocities. However, for other data points, the correlation consistently under-predicted the experimental data. The equivalent Reynolds number for these data points was above the break point \( Re_e = 50,000 \) in the correlation which, as suggested by Akers et al., indicates a change from a laminar mechanism to a turbulent shear mechanism in the flow. The general trend of lower predicted values from the correlation in other studies was mentioned by Shah [97] as
well as in a recent study of steam condensation by Sernas et al. [198].

Calculations were also performed for the experiments by treating the correlation as a local one as suggested by Akers et al. for large quality variation along the test condenser. There was only a small difference (<5%) for the two calculations and, thus, the result is not presented. As far as the experimental conditions were concerned, part of the mass velocity ranges for the correlation and the experiment overlapped, but data for much higher reduced pressures were used in the correlation.

The Rosson and Myers correlation [101] was a reasonable predictor of the experimental results, as shown in Fig. 22. The figure shows wide variations of the experimental results as compared with the correlation, but most of these variations are within ±30 percent. There was also stratification of sectional heat transfer coefficients with respect to heat transfer coefficient values. It should be noted this is the only correlation, among those selected, to account for flow stratification. The present experiments were carried out at higher reduced pressures and only experiments at low mass velocities had a heat flux level comparable to that of the correlation.

The Boyko and Kruzhilin [92] correlation generally was a good predictor of the experimental results; however, it tended to over-predict the experimental values at Sections 2 and 3, as shown in Fig. 23. This average correlation predicted the experimental
values within ±30 percent for about 94 percent of the data. The ranges of experimental conditions upon which this correlation was based were similar to those of the present study, except that the heat fluxes were much lower in the present study.

The local correlation of Soliman et al. [53] predicted reasonably well the experimental values at Section 4, as shown in Fig. 24. At this section, the flow was presumably annular, which is one of assumptions of the correlation. However, the correlation was a poor predictor for other sectional values except at lower mass velocities and higher pressure levels. A similar trend was observed in [53] in which Soliman et al. compared their correlation with the experimental study of R-113 condensation by Goodykoontz and Brown [199]. It is noted that this correlation is semi-empirical in nature, i.e., the constant and exponent of Pr in Eq. (2.39) were attained by curve fitting a large and varied data base. Thus, it covered a wide range of experimental conditions of which some were comparable with the present ones.

The local correlation of Traviss et al. [7], as expressed in Eq. (2.40a), proved to be one of the best predictors of local correlations, as shown in Fig. 25. Nevertheless, the correlation tended to overpredict the experimental values at Sections 2 and 3. When the correlation was used with the function F in Eq. (2.40b) raised to 1.15 power, as suggested in [7] to account for possible liquid entrainment, there was consistent over-prediction of the
experimental values for Sections 2-4 and for the overall average. The present experimental conditions were comparable with those in [7], except that the latter study attained higher reduced pressures.

The local correlation of Azer et al. [80,81] was a poor predictor of the experimental results, except at Section 2, as shown in Fig. 26. It under-predicted substantially the experimental values for Section 1 and for the overall average, and over-predicted the values for Sections 3 and 4. An examination of the original work by Azer et al. [80,81] indicates a similar trend prevailed in most of the plots comparing their experimental results with the correlation. However, the data were less scattered than in the present case. The substantial under-prediction at Section 1 is possibly attributable to the empirical nature of $t^+_0$ in Eq. (2.41c), which was obtained by fitting the investigators' experimental results for $x > 0.18$. The experimental conditions in both studies were approximately similar except for the higher reduced pressure in the Azer et al. study.

The average correlation of Cavallini and Zecchin [95] predicted the experimental results with relative success, as shown in Fig. 27. About 87 percent of data points were within ±30 percent. However, the correlation consistently over-predicted the experimental values at high mass velocities. Although details of the experimental conditions upon which this correlation was based are not given in [95], the correlation was compared with the experimental results of
Goodykoontz and Brown [199] and was found to always over-predict the data. The experiments by Goodykoontz and Brown have much higher mass velocities than the present experiments, but the pressure levels in both studies are comparable. Thus, it is possible that the disagreement is due to variation of fluid properties and/or different reduced pressure range.

The local correlation of Shah [97] proved more satisfactory, as shown in Fig. 28. Nevertheless, it tended to under-predict some experimental results at Section 1 and slightly over-predict others at Sections 2 and 3. This correlation was developed from the Shah correlation for saturated boiling heat transfer [200] by noting the similarity between the mechanisms of heat transfer during film condensation and boiling. The final form of the correlation was attained by adjusting the constant(s) and exponent(s) involved, based on analysis of an extensive data base.

The results of these comparisons indicate that, because of different experimental conditions and uncertainties as well as theoretical assumptions and other effects which have not been fully studied, none of the selected correlations is a really excellent predictor of the experimental results. Most of the average correlations were only involved with a curve fitting of several dimensionless groups based on experimental results and would thus be expected to apply only over the same range of experimental conditions. The local correlations, except for the
Shah correlation, were developed based on the assumptions that the condensate flow is annular and that the liquid film is uniformly distributed around the tube wall. The flow is thus one-dimensional at a given cross-section. The good agreement at Section 4 between the experimental and calculated values with most of the selected local correlations reflected this valid assumption. However, there was a consistent tendency that the experimental values at Sections 2 and 3 were over-predicted. It is plausible that this was caused by the competing contributions from possible liquid entrainment, interfacial waves, and liquid film stratification.

Interfacial waves, liquid entrainment, and liquid film stratification were not taken into account in the local correlations. The former two flow mechanisms were found to increase the heat transfer through the condensate film. On the other hand, the results of the previous flow regime studies demonstrated that gravity may have considerable effect at the downstream end of the test condenser. Gravitational force tends to pull the liquid film down to the bottom of the tube; thus, the film is thicker at the bottom than at the rest of the tube and the flow is then two-dimensional. The stratification is expected to decrease heat transfer. The local correlation of Rosson and Meyers attempted to take the gravitational effect into account. However, a semi-empirical correlation was involved in developing the correlation, and its application is thus limited.
According to the tabulated statistical results in Table G.5, Table 4.4 was constructed such that the selected correlations were listed in accordance to decreasing performance for each section. This table indicates that the correlations of Shah [97] and Traviss et al. [7] are the best predictors of the experimental results. In order, there follow the Boyko and Kruzhilin [92], Rosson and Myers [101], Cavallini and Zecchin [95], Azer et al. [80,81], Akers et al. [90], and Soliman et al. [53] correlations. The Carpenter and Colburn correlation was not included because only part of the experimental results could be compared. The leading five correlations were considered acceptable predictors of the experimental results.

The satisfactory agreement between the experimental results and the five reasonably successful correlations mentioned above indicated that the experimental apparatus was capable of producing experimental results consistent with those of other investigators. These experimental results could then serve as a reference in comparisons between the augmented tubes. Further, the leading local and average correlations in the five acceptable predictors, where appropriate, could provide a basis from which to develop an effective predictor of sectional and overall average heat transfer coefficients for augmented in-tube condensation. Therefore, the local correlation of Traviss et al. [7] and the average correlation of Boyko and Kruzhilin [92] were used for this purpose. The Shah correlation was not selected because its model is less physically sound.
Table 4.4. Ranking of the selected smooth tube correlations as predictors of the experimental results

<table>
<thead>
<tr>
<th></th>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akers et al.</td>
<td>Shah</td>
<td>Shah</td>
<td>Shah</td>
<td>Shah</td>
<td>Shah</td>
</tr>
<tr>
<td>[90]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traviss et al.</td>
<td>Shah</td>
<td>Traviss et al.</td>
<td>Traviss et al.</td>
<td>Traviss et al. a</td>
<td></td>
</tr>
<tr>
<td>[7]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boyko &amp; Kruzhilin</td>
<td>Traviss et al. a</td>
<td>Boyko &amp; Kruzhilin a</td>
<td>Boyko &amp; Kruzhilin a</td>
<td>Boyko &amp; Kruzhilin a</td>
<td></td>
</tr>
<tr>
<td>[92]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavallini &amp; Zecchin</td>
<td>Cavallini &amp; Zecchin a</td>
<td>Rosson &amp; Myers a</td>
<td>Soliman et al.</td>
<td>Rosson &amp; Myers</td>
<td></td>
</tr>
<tr>
<td>[95]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rosson &amp; Myers a [101]</td>
<td>Rosson &amp; Myers a</td>
<td>Azers et al. a</td>
<td>Cavallini &amp; Zecchin a</td>
<td>Cavallini &amp; Zecchin</td>
<td></td>
</tr>
<tr>
<td>Azer et al. [80,81]</td>
<td>Soliman et al.</td>
<td>Soliman et al.</td>
<td>Akers et al.</td>
<td>Soliman et al.</td>
<td></td>
</tr>
</tbody>
</table>

aIndicating approximately same performance for this section.
Effect of superheat

According to the literature review in Chapter 2, the influence of superheat on condensation heat transfer ranges from small to moderate depending on experimental conditions. For the present study, a low level of superheat was allowed for most of the experimental runs at the test condenser inlet to ensure single-phase vapor flow there. Thus, an attempt is made here to determine the effect of superheat on condensing flow under the present experimental conditions.

Two test series (Runs 1.075-1.079, Runs 1.060-1.069) were devised to investigate the effect of superheat on the smooth tube heat transfer coefficients and pressure drops. Because it was expected that the superheat effect was insensitive to varied mass velocities and pressure levels, both series were held at an approximately constant mass velocity (322.0 kg/s-m²) and pressure level (6.55 bar).

Complete condensation The series of Runs 1.075 - 1.079 was performed for complete condensation, but with varied inlet superheat (2.8(5) - 16.7°C(30°F)). For these runs, the desuperheating zone was confined to a very small region near the entrance. This was indicated by the wall temperatures at this section which were lower than the saturation temperature corresponding to the inlet pressure. This saturation temperature was used to calculate the heat transfer coefficient at Section 4 as well as the overall average coefficient.

A comparison could be made between this series and a similar
experimental run (Run 1.056) from the complete condensation study. Generally, the distributions of heat flux, quality, static pressure, temperatures, and sectional heat transfer coefficients varied slightly with inlet superheat as compared with those of Run 1.056. The increase in heat flux was proportionally higher at Sections 1 and 2, while the quality was higher at Sections 2, 3, and 4. The increase in overall pressure drop with inlet superheat was small and not definite due to the low resolution of the mercury manometer. The overall heat transfer coefficient fluctuated while the variation of the sectional heat transfer coefficients at Section 4 suggested a small increase of the coefficient with inlet superheat. These observations were in agreement with those in [112].

The experimental pressure drop results are compared with the predicted values of the modified Dukler II correlation in Fig. 29. The result from Run 1.056 was also included. The inlet quality was set equal to unity for the calculation. As seen in Fig. 29, the departure of these calculated values from the experimental ones is approximately the same for the series and Run 1.056.

The calculated heat transfer coefficients from the Traviss et al. [7] and the Boyko and Kruzhilin [92] correlation versus the experimental values are plotted in Figs. 30 and 31, respectively. As in the pressure drop calculations, the inlet quality was set equal to unity and the result from Run 1.056 was included. An examination of these figures indicates that these two correlations predict
Fig. 29. Comparison of overall pressure drops with predictions of modified Dukler II in superheat effect study, Tube 1.
Fig. 30. Comparison of sectional and overall heat transfer coefficients with predictions of Traviss et al. [7] in superheat effect study, Tube 1.
Fig. 31. Comparison of sectional and overall heat transfer coefficients with predictions of Boyko and Kruzhilin [92] in superheat effect study, Tube 1.
reasonably well the experimental results.

The above comparisons suggest that, with inlet superheat up to 16.7°C (30°F) and at this mass velocity level or higher, inlet superheat has no or little effect on pressure drops and overall heat transfer coefficients when the desuperheating zone is small. However, further experiments are needed at low mass velocities as it was reported in [112] that the superheat had modest effect on stratified condensing flow.

Incomplete condensation The series of Run 1,060 - 1,069 was performed with two levels of superheated vapor at the test-section inlet (13.9°C (25°F), 21.7°C (39°F)) and at increasing outlet quality (0.075 - 0.939) such that different heat flux levels could be attained. The lower heat flux levels would allow the study of heat flux effect at those sections with quality at the section inlet less than unity. This will be further discussed in the subsequent section.

Once again, the effect of superheat on condensing flow could be observed by comparing Runs 1.060 and 1.065 because they had about the same exit quality (x = 0.075) but different inlet superheat (13.9°C and 21.7°C). As seen in the tabulated data in Table I.3 for those two runs, the heat flux was found generally higher at each section for the run with higher inlet superheat, but heat transfer coefficients were approximately the same except at Sections 2 and 3. However, the difference had a maximum of 4.4 percent which was well within the experimental uncertainty and was thus considered to be
insignificant. Also, the small difference between the overall pressure drops of the two runs did not justify any effect of superheat on pressure drop.

By increasing exit quality at the test condenser outlet the desuperheating zone extends further downstream of the test condenser. Simultaneously, the wall temperatures are elevated. At some location where a superheated vapor core exists, the wall temperatures can exceed the saturation temperature. Along a section, if the recorded wall temperatures are higher than the saturation temperature corresponding to the test fluid static pressure, the wall is dry and the conventional single-phase correlations can be expected to apply to predict heat transfer and pressure drop. Therefore, no attempt was made to study this region.

If only some wall temperatures at a section exceed the saturation temperature such that the sectional average wall temperature is a few degrees lower or higher than the saturation temperature, the wall is most likely partly wetted. This region is of more interest and prevails in this study in the upstream sections of the test condenser in those experimental runs with high quality at the test condenser outlet.

Figure 32a presents the distributions of heat flux for Runs 1.060 - 1.064 along the test condenser. It is observable that the sectional heat flux distributions vary as the wall temperatures near the test condenser inlet approach the saturation temperature. At
Fig. 32. Distributions of sectional heat fluxes and sectional heat transfer coefficients in superheat effect study.
B. HEAT TRANSFER COEFFICIENT.

Fig. 32. Concluded.
some point, the lowest heat flux occurs at Section 3, which opposes the general trend of the heat flux distributions in the complete condensation study. In this case, the flow is probably in the "rivulet" flow region and is developing; thus the heat flux is higher in Section 4. The corresponding sectional heat transfer coefficient distributions are plotted in Fig. 32b. The saturation temperature corresponding to the average static pressure at the sections was used to calculate the sectional coefficients. The big jump in the heat transfer coefficient at Section 4 at Runs 1.063 and 1.064 reflects the combined effect of small temperature difference \((T_s - T_w)\) and the entrance effect. Similar behaviors were observed in Runs 1.065 - 1.069 which were carried out at a higher inlet superheat level.

Runs 1.064 and 1.068 with different inlet superheat were further examined to enlighten these observations. Plotted in Fig. 33 are the distributions of the vapor temperatures, the saturation temperatures, the average wall temperatures at the thermocouple stations, the coolant temperatures, and the sectional heat transfer coefficients. The calculated values of the single-phase (Dittus-Boelter) and the condensing (Boyko and Kruzhilin) heat transfer coefficients based on the experimental conditions were also included for comparison. As seen in this figure, the desuperheating zone covers Sections 3 and 4 and extends into Section 2 in both runs. The average wall temperatures are generally lower than the saturation temperatures except at the first two thermocouple stations of Section
Fig. 33. Distributions of saturation temperatures, coolant and wall temperatures, and heat transfer coefficients for extended desuperheating zone, Tube 1.
4 in Run 1.068. In this case, the major portion of the section is probably dry and the sectional average wall temperature is also higher than the average sectional saturation temperature. Thus, the sectional heat transfer coefficient at this section is not shown.

The distribution of sectional heat transfer coefficients differs in these two runs. This is probably caused by the random process of coalescence and collapse of an existing unstable film on the tube wall at the upstream sections of the test condenser. In any case, the heat transfer coefficient at Sections 1, 2, and 3 lies between the calculated values from the single-phase correlation and the Boyko and Kruzhilin correlation. The heat transfer coefficient at Section 4 in Run 1.064 increases abruptly while the corresponding one in Run 1.068 is negative. This suggests that the driving temperature difference to be used to calculate the coefficient is not identifiable in this case since the vapor core is superheated and it is unlikely that a stable annular film exists at this section in both runs. However, limited data preclude further inference on this behavior.

The average heat transfer coefficient of Run 1.068 is higher than that of Run 1.064. The higher value in the former run probably comes partly from the higher wall temperatures as previously described; however, it would certainly be associated with the higher sectional heat transfers. The analytical study of Minkowycz and Sparrow [111] on the effect of superheating on condensation heat
transfer suggested that the effect is significant only in the range of relatively small differences between the saturation temperature and the wall temperature. Altman et al. [72] had a similar finding in their superheat runs without complete condensation and with 
\[ T_s - T_w = 0.7(1.3) - 4.1^\circ C(7.4^\circ F) \] as compared with 2.5°C(4.5°F) in the present study. They introduced \( \beta \), given in Eq. (2.29), to account for this effect. Hence, the tendency based on these studies indicates that, with low temperature difference or considerably extended desuperheating zone, superheat may affect condensation heat transfer. Further study is needed to establish a more general correlation or formulation for this effect on heat transfer as well as pressure drop.

**Conclusion**  
Inlet superheat up to 16.7°C(30°F) was found to have little or no effect on pressure drop and heat transfer for complete condensation with moderate and high mass velocities. When condensing at small temperature difference, the data are sensitive to superheat level.

**Effect of heat flux**

The previous literature review demonstrated that the temperature difference, which is proportional to heat flux, affects the condensation heat transfer coefficient over some range of mass velocity. Since the actual overall temperature differences are smaller in practical equipment, an attempt was made here to investigate the effect of heat flux under the present experimental conditions.
Along with the series of Runs 1.060 - 1.069 in the study of the superheat effect, an additional series (Runs 1.070 - 1.074) was taken to study the heat flux effect. In the former series, heat flux level decreases with increasing outlet quality. Thus, at those sections with inlet quality less than unity, the experimental results can be used to detect any heat flux effect. The latter series was performed with wet R-113 ($0.4 < x_{in} < 0.78$) at the test condenser inlet for varied inlet and outlet qualities.

The appropriate way to study the heat flux effect is to compare runs with comparable mass velocity, pressure level, and approximately equal quality change at unequal condensing length. However, it was found that during these experiments the above conditions could hardly be attained. Thus, an alternate approach was adopted. Since no heat flux parameter is incorporated in the two smooth tube (Traviss et al. and the Boyko and Kruzhilin) correlations, a comparison between the experimental sectional heat transfer coefficients from the above two series and the calculated values from these correlations could demonstrate any possible heat flux effect.

Except for Runs 1.064, 1.068, and 1.069, the experimental heat transfer coefficients derived from the series of Runs 1.060 - 1.069, as described above, were compared with the predicted values of the Traviss et al. and the Boyko and Kruzhilin correlations in Figs. 34 and 35, respectively. These figures indicate that the heat flux effect is not significant in the quality range ($0.3 < x < 0.9$).
Fig. 34. Comparison of sectional heat transfer coefficients with predictions of Traviss et al. [7] in heat flux study with incomplete condensation, Tube 1.
Fig. 35. Comparison of sectional heat transfer coefficients with predictions of Boyko and Kruzhilin [92] in heat flux study with incomplete condensation, Tube 1.
While the Traviss et al. correlation predicted slightly higher values, the Boyko and Kruzhilin correlation had good agreement with the experimental results. For the three above-mentioned runs, Section 1 was the only section that had inlet quality less than unity and the corresponding condensate Reynolds number was about or below 1000. Both correlations predicted higher values; thus the condensate flow is probably laminar. The correlation introduced by Akers and Rosson [88] in Eq. (2.31) to account for laminar annular flow with the heat flux effect predicted these three sectional experimental coefficients within 15 percent.

For the series of Runs 1.070 - 1.074, the experimental results are compared with the calculated values of the Traviss et al. and the Boyko and Kruzhilin correlations in Figs. 36 and 37, respectively. Both correlations gave higher predicted values, except at Section 4. This appeared to contradict the finding with the first series. It was believed that this was caused the uncertainty involved in the data reduction and other factors peculiar to this series.

R-113 entering the boiler was in the subcooled condition. Since the enthalpy at the subcooled condition was not available, the enthalpy of the saturated liquid at the corresponding inlet temperature was used. This ended up with higher calculated inlet quality at the test condenser inlet; thus, the quality at subsequent stations was thus higher than it should be and the heat balance was usually high. The higher quality led to higher calculated heat
Fig. 36. Comparison of sectional and overall heat transfer coefficients with predictions of Traviss et al. [7] in heat flux study with wet inlet vapor, Tube 1.
Fig. 37. Comparison of sectional and overall heat transfer coefficients with predictions of Boyko and Kruzhilin [92] in heat flux study with wet inlet vapor, Tube 1.
transfer coefficients. On the other hand, an examination of the
distribution of sectional heat transfer coefficients, as shown in
Fig. 38 demonstrates a possible entrance effect because the heat
transfer coefficient at Sections 3 and/or 2 becomes smaller than the
others. Installation of a precondenser should eliminate this problem.

Another comparison was made for the results of the second series
with the Rosson and Myers correlation in Fig. 39. Better agreement
was found between the calculated and experimental results. This
suggests that the condensate redistributes itself and exhibits a
greater gravity effect in a relatively long test section for a
small quality change.

As presented in Fig. 40, the pressure drop measurements were
insensitive to the different factors described above.

Conclusion Based on the series of Runs 1.060 - 1.069, the
heat flux effect on condensation heat transfer is insignificant as
long as the condensate flow is turbulent. The several factors
accompanying the series of Runs 1.070 - 1.074 preclude a definite
conclusion from this series.
Fig. 38. Distribution of sectional heat transfer coefficients in heat flux study with wet inlet vapor, Tube 1.
Fig. 39. Comparison of sectional and overall heat transfer coefficients with predictions of Rosson and Myers [101] in heat flux study with wet inlet vapor, Tube 1.
Fig. 40. Comparison of overall pressure drops with predictions of modified Dukler II in heat flux study with wet inlet vapor, Tube 1.
CHAPTER V. SMOOTH TUBES WITH TWISTED-TAPE INSERTS

The objectives of the twisted-tape test program were to determine the extent of heat transfer augmentation and pressure drop penalty with R-113 and to predict the experimental results with the correlations suggested by Royal and Bergles [124].

General Considerations

The twisted tape inserts undoubtedly modify the flow regime during condensation. The generated centrifugal force tends to promote annular flow and to suppress liquid entrainment at higher qualities with higher flow rates, as observed in [131]. Thus, the usual flow regime and liquid entrainment prediction schemes are not appropriate.

The data were reduced on the basis of the smooth tube inside diameter so that results could be compared directly with smooth tube data. Similar schemes were used as in the smooth tube experiments for calculations of overall pressure drop, sectional heat transfer coefficients, and overall heat transfer coefficient.

Results and Discussion

The experimental study of Tube 2 produced 51 valid runs at five inlet pressures: 2.41, 3.45, 4.48, 5.52, and 6.55 bar. The study of Tube 3 produced 39 runs at two inlet pressures: 5.52 and 6.55 bar. Among these 39 runs, 19 runs (Run 3.017 - 3.040) were for the study
of the superheat effect and 4 runs (Run 3.036 - 3.039) for the study of the heat flux effect. These 24 experimental runs were performed at essentially the same mass velocity and inlet pressure as in the corresponding studies in the smooth tube. The experimental results along with the experimental conditions are detailed in Appendix I.

Since both tapes were extended through the exit sight glass, observations could be made to study the effect of the twisted-tape inserts on flow regime (or flow field) at low quality. Because the tape did not fit tightly either the tube or the sight glass, vapor tended to stratify in the upper part of the tube, and pass through the tube-tape gap there. Thus, the tapes had little effect on the flow regime at low flow rates. However, at much higher flow rates, there was observable swirling flow at the exit sight glass. Plug and slug flows were frequently observed at low flow rates while semiannular and slug flows prevailed at high flow rates. The flow regime observations are also given in Appendix I.

Similar patterns to those in the smooth tube experiment were found for the heat flux and quality variations with coolant inlet temperature. An examination of the sectional pressure drop results indicates that pressure drop at Sections 2, 3, and 4 was larger than at Section 1. This is clearly caused by the increased wetted perimeter exposed to the high velocity vapor in the upstream portion of the tube. No pressure rise was detected and, generally, higher pressure drop occurred at Sections 2 and 3 than at Section 4.
The sectional heat transfer coefficients decreased as the quality decreased along the tube. Generally, the wall temperature distributions for the smooth tube with the twisted-tape were similar to those for the smooth tube as shown in Fig. 41. However, for approximately the same inlet pressure, mass velocity, and heat transfer rate as in Fig. 5e, the overall temperature is lower with the tape insert as is the wall-minus-saturation temperature difference. The heat transfer coefficients are thus generally increased.

Overall pressure drop and overall heat transfer coefficient were plotted against mass velocity with inlet pressure as a parameter in Figs. 42 and 43, respectively. As with the smooth tube, there was a stratification of data points with inlet pressure. The constant C, C' and exponent n, n' of the parametric expression of ΔP and $\overline{h}$ in Eqs. (4.10) and given in Tables G.2 and G.3, respectively.

Figure 43 indicates that the two twisted tapes with small difference in pitch had small effect on heat transfer performance. However, a larger effect on pressure drop is found in Fig. 42. The larger difference in pressure drop at $P_{in} = 6.55$ bar between the two tapes might probably be due to the different degree of tightness of the tapes with the tube wall, the fluctuating measured differential pressures, or the low resolution of the mercury manometer. The fluctuations were large at Sections 3 and 4 and at high flow rates.

The heat transfer performance of the twisted-tape inserts with R-113 is comparable to that observed previously with condensing
Fig. 41. Typical temperature distributions along test condenser, Tube 2.
Fig. 42. Experimental overall pressure drops versus mass flux, Tubes 2 and 3.
Fig. 43. Experimental overall heat transfer coefficients versus mass flux, Tubes 2 and 3.
Correlations of Experimental Results

Correlations were developed by appropriately modifying the smooth tube correlations such that they could predict successfully the anticipated pressure drop increase and heat transfer augmentation. The correlations were also used to study the effects of superheat and heat flux.

Pressure drop

The success of using the equivalent diameter together with the single-phase friction factor, Eq. (2.45) to correlate the overall pressure drop results in steam condensation with twisted-tape inserts [50] prompted the use of a similar methodology here. The single-phase adiabatic friction factor was first modified according to Eq. (2.11) and was then corrected according to Eq. (2.45) which is repeated here for convenience:

\[ \frac{F_f}{f} = \frac{f_t}{f} = 2.75y^{-0.406} \quad (2.45) \]

This corrected friction factor was used along with the replacement of the nominal diameter by the equivalent diameter in the Lockhart-Martinelli and the Dukler II correlations to calculate the frictional
pressure drop. For the momentum pressure drop, the separated momentum equation combined with different formulations of the void fraction described in Chapter 2 was utilized.

A preliminary calculation demonstrated that the experimental results were satisfactorily predicted by either frictional pressure drop correlation when combined with the homogeneous void; i.e., the homogeneous momentum equation. Further scrutiny of the two pairs based on the statistical analysis described in Chapter 3 indicated that the modified Dukler II was a better predictor of the experimental results. Figure 44 presents the calculated pressure drops from the Dukler II correlation versus the experimental pressure drops for both twisted tapes. It shows that the data agree with the correlation to within ±40 percent. The same correlation, with the Hughmark void fraction and without the interphase shear correction, was chosen for condensation of steam in tubes with twisted-tape inserts [50]. However, the calculated values presented in [50] were consistently lower than the experimental results (~15 percent). It is noted that no special constant was incorporated in either correlation.

**Heat transfer coefficient**

Three important twisted-tape effects which were formulated in [124] for condensing steam are: tangential velocity effect, fin
Fig. 44. Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void, Tubes 2 and 3.
effect, and wall shear effect. Similar effects are expected to be important for condensing R-113. However, these formulations had to be modified to make them more compatible with the Traviss et al. and the Boyko and Kruzhilin correlations selected for the smooth tube in the present study.

Tangential velocity effect The twisted tape induces a tangential component of fluid velocity \( u_t = u_z \frac{r}{2yR} \) which, when added vectorially to the axial velocity \( u_z \), yields the increased velocity due to the tape:

\[
u = u_z \left[ \frac{\pi^2}{4y^2} \left( \frac{r}{R} \right)^2 + 1 \right]^{0.5} \tag{5.1}\]

Use of this velocity accounts for the longer spiral flow path created by the tape. This velocity varies across the cross section. Since a single-phase average velocity is used to calculate the Reynolds number in both the Traviss et al. and the Boyko and Kruzhilin correlation, this suggests that a similar average velocity should be used.

By assuming a uniform axial velocity across each half of the tube separated by the tape, the velocity \( \bar{u} \) in Eq. (5.1) can be averaged as

\[
\bar{u} = \frac{2}{\pi R^2} \int_0^R u_z \left[ \frac{\pi^2}{4y^2} \left( \frac{r}{R} \right)^2 + 1 \right] (\pi r) dr
\]
In in-tube condensation, as existence of large void and turbulent vapor core would validate this assumption. In any case, this factor tends to be over-predicted slightly. This factor is applied to the Reynolds number of a correlation of interest.

**Fin effect** The fin effect is modeled using the optimistic assumptions that the tape insert is in good contact with the tube wall and that the wall temperature is not affected by the fin. As outlined in [124], the tape can be modeled as two rectangular fins attached to the wall with insulated tips at the middle of the tape. Thus, the heat transferred in a segment of the test condenser with fin effect included is the heat transferred at the unfinned wall plus the heat transferred through the two fins:

\[ h \pi D_t L (\overline{T_s} - \overline{T_w}) = h^* L (\pi D_t - 2 \delta_t) (\overline{T_s} - \overline{T_w}) \]

\[ + 4 \eta_f L_t R_h^* (\overline{T_s} - \overline{T_w}) \]  

or

\[ F_{tt} = \frac{h}{h^*} = 1 + \frac{2}{\pi} \left( \eta_f \frac{L_t}{L} - \frac{\delta_t}{D_t} \right) \]
where

\[
\frac{L_t}{L} = \frac{(4y^2 + \pi^2)}{2y}
\]

The equation for fin efficiency is

\[
\eta_f = \frac{2 \tanh \left( \frac{m D_i}{2} \right)}{m D_i}
\]

(5.5a)

where

\[
m = \left[ \frac{2h^* (L_t + \delta_t)}{k_t L_t \delta_t} \right]^{1/2} = \left( \frac{2h^*}{k_t \delta_t} \right)^{0.5}
\]

(5.5b)

The heat transfer coefficient, \(h^*\), is evaluated from the selected smooth tube correlations including the tangential velocity effect and the wall shear effect, which is described in next section.

Wall shear effect. The twisted-tape inserts in a tube contribute to a large increase of wetted surface, but the reduction of the cross-sectional flow area by the thin tapes is small. This additional wetted surface causes a large jump in the total wall shear, and, thus, the pressure drop because the tape is embedded in the fast moving vapor core. For single-phase flow, Lopina and Bergles [123] proposed the friction factor \(F_f\), given in Eq. (2.45), to account for the effect. This friction factor was used in the present study and in the Royal and Bergles study [50] for pressure drop, and good agreement with
experimental results was found. However, this equation, when
incorporated in the Soliman et al. heat transfer correlation [53] by
Royal and Bergles [124], produced rather high predicted values.

The above-mentioned effects in the modified form can be readily
applied to the Boyko and Kruzhilin correlation. Since this
correlation does not include a friction factor, increased wall shear
is accounted for by using the equivalent diameter

\[ D_e = \frac{2}{\pi D_i - 4\delta_{tt} D_i} \]  \( (5.6) \)

instead of the nominal diameter in the calculation. As modified, the
correlation becomes

\[ \frac{1}{h} = 0.024 \frac{k_i}{D_e} F_{tt} \left( \frac{F_{G D_e}}{\mu_1} \right)^{0.8} Pr_1^{0.43} \left[ \left( \frac{\rho_m}{\rho_m} \right)^{0.5} \left( \frac{\rho_m}{\rho_m} \right)^{0.5} \right] \]

\[ \frac{1}{2} \]  \( (5.7) \)

For the present tests, the correlation factors varied as follows:

\[ F_t = 1.03 - 1.08 \]

\[ F_{tt} = 1.06 - 1.24 \]
\[ F_f = 1.48 - 1.81 \]

It is noted that the twisted tapes were not in perfect contact with the tube wall. The condensate with lower thermal conductivity that filled the narrow gap will degrade the fin effect. Thus, the values of \( F_{tt} \) should be lower than those listed above which were obtained by assuming perfect contact. Since the portion of the twisted tapes in contact with the tube wall was not known actually, an assumption of 50 percent equivalent perfect contact would seem to be appropriate. Therefore, the values of \( F_{tt} \) were reduced to \( 1 + (F_{tt} - 1)/2 \) when this effect was incorporated into the two selected smooth-tube predictors.

The calculated heat transfer coefficients are compared with the experimental coefficients in Figs. 45 and 46. The statistical parameters are tabulated in Table G.6 for comparison. The modified correlation of Boyko and Kruzhilin predicted the experimental results of both tubes to within \( \pm 30 \) percent for nearly the entire set of data. The accuracy was comparable to that obtained when the same correlation (unmodified) was compared to the smooth tube data (Fig. 23).

For the local correlation of Traviss et al., the extent of the above-mentioned effects on the vapor core and the condensate may be different. For the condensate, the boundary layer effects are important. The tangential velocity effect is smaller because the condensate is thin for most of the tube during condensing, and,
Fig. 45. Comparison of sectional and overall heat drop transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (5.7), Tube 2.
Fig. 46. Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (5.7), Tube 3.
further, the condensate could "leak" through the tape clearance with the tube. Thus, the Reynolds numbers in Eqs. (2.40b, c, d) were not corrected with $F_t$. The tangential velocity effect was thus only accounted for in the vapor flow which is related to the Reynolds number in Eq. (2.40). The wall shear effect was also considered to be important in the vapor core only and was taken into account by using the single-phase friction factor in Eq. (2.45). The fin effect was incorporated into the correlation as describe before.

The modified Traviss et al. correlation performed reasonably well as a predictor of the experimental data (Figs. 47 and 48) although it tended to over-predict slightly as compared with Fig. 25 for the smooth tube results. Nevertheless, most data were predicted with errors of less than thirty percent. Table 5.1 demonstrates that the modified Boyko and Kruzhilin correlation better correlated the experimental results.

The reasonable success of the modified correlations to predict the experimental results demonstrates that those discrete effects as suggested by Royal and as modified above, are the specific factors to be considered for in-tube condensation inside tubes containing twisted-tape inserts. This success also suggests that the same correlations should be used in the study of superheat and heat flux effects. Only the Boyko and Kruzhilin correlation is used, however, since it is simpler to apply.
Fig. 47. Comparison of sectional and overall heat transfer coefficients with predictions of modified Traviss et al., Tube 2.
Fig. 48. Comparison of sectional and overall heat transfer coefficients with predictions of modified Traviss et al., Tube 3.
Effect of superheat

The investigation of the effect of superheat was performed at different levels of inlet superheat and outlet quality (Run 3.017 - 3.035). Among these experimental runs, only two were for complete condensation (Runs 3.017, 3.022) and at two different inlet superheat levels (13.9, 21.9°C). For these two runs, the desuperheating zone was small. The heat transfer results as compared with the calculated values from the modified Boyko and Kruzhilin correlation are presented in Fig. 49. No superheat effect is observable.

The effect of superheat can be observed with Runs 3.018, 3.023, and 3.028 since they have approximately same exit quality (x = 0.34) but different inlet superheat. At this heat flux level, the effect is still insignificant, although the trend indicates a slight increase in heat transfer coefficient at Section 4 and in the overall average coefficient with higher inlet superheat.

As exit quality increases and the desuperheating zone extends into Section 2 (Runs 3.021 and 3.025), the superheat effect is considerable. The heat flux variation follows the same pattern observed in the corresponding smooth-tube case. However, single-phase vapor flow exists at Section 4 in both runs since the wall temperatures are higher than the section saturation temperatures. The overall average heat transfer coefficient for the first three sections (Sections 1, 2, and 3) of Run 3.025 is higher than that of Run 3.021,
Fig. 49. Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin, Eq. (5.7), in superheat effect study, Tube 3.
with the former run having higher inlet superheat.

It is noted that the presence of the twisted tape seems not to change significantly the condensing process in the desuperheating zone. The percentage increase in the overall average coefficient is comparable to that in the complete condensation study.

In conclusion, the heat transfer results exhibited no or little effect from the inlet superheat up to 22°C for complete condensation. At a small temperature difference or low heat flux, the superheat effect is modest. More experiments are required to determine how the presence of the twisted tapes modifies the flow field during desuperheating.

**Effect of heat flux**

Besides the previous series for superheat effect study, the heat flux study comprised four additional runs with wet vapor entering the test condenser. From the previous series, the heat transfer coefficients for the section with inlet quality less than unity are compared with the calculated results from the modified Boyko and Kruzhilin correlation, as shown in Fig. 50. Quality ranges from 0.33 to 0.98. Good agreement is found for the experimental and calculated values. Laminar annular condensation observed at Section 1 in the corresponding smooth tube experiments does not exist in this case (Runs 3.021, 3.025). This indicates the existence of turbulent flow in the condensate because of higher velocity from the tangential velocity effect.

Figure 51 presents the heat transfer results from other series
Fig. 50. Comparison of sectional heat transfer coefficients with predictions of modified Boyko and Kruzhilin, Eq. (5.7), in heat flux study with incomplete condensation, Tube 3.
Fig. 51. Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin, Eq. (5.7), in heat flux study with wet inlet vapor, Tube 3.
(0.35 < x_{in} < 0.99) and the calculated values from the modified Boyko and Kruzhilin correlation. The results from one of the two experimental runs (Run 3.036) with high inlet quality agree with the predicted values. However, the results from the other are over-predicted. It is noted that the latter run has a much smaller quality change; thus, the laminar condensate flow region near the entrance extended further downstream of the test condenser. This caused the experimental values to be over-predicted.

The other two experimental runs with lower inlet quality produced lower experimental values than the calculated values from the modified correlation. However, the extent of over-prediction is less than the corresponding smooth tube experiments. In addition, the entrance effect observed in the smooth tube case is relatively small in this series. Figure 52 indicates that overall pressure drops from this series are not affected significantly by heat flux.

In conclusion, as with the smooth tube case, no heat flux effect is observed when the condensate flow is turbulent.
Fig. 52. Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void in heat flux study with wet inlet vapor, Tube 3.
CHAPTER VI. THE FINNED TUBES

The objectives of the finned tube test program were to investigate the heat transfer augmentation and pressure drop increase, to compare the data with existing correlations, and, if necessary, to develop new correlations.

General Considerations

The presence of internal fins inside tubes greatly alters the flow mechanism in in-tube condensation. The condensate flows in channels provided by the spacings between fins at the initial stage of condensing and gradually submerges the fins. In addition to interfacial shear, friction, gravity, and momentum forces, surface tension created by curvature of the fins will affect to some extent the condensate flow. It is also probable that the fin tips will disturb the condensate film and promote a wavy interface and/or liquid entrainment. Macroscopically, of course, the fins provide larger heat transfer area which, in turn, increases the nominal heat transfer coefficient, provided that the fin efficiency is high.

Similar procedures were used as in the twisted-tape experiment to acquire the calculated values of the experimental results. The equivalent smooth tube inside diameter was again used for data reduction.
Results and Discussion

Forty experimental runs were completed for Tube 4, 63 for Tube 5, and 55 for Tube 6, each at five inlet pressures: 2.41, 3.45, 4.48, 5.52, and 6.55 bar. Among the 63 runs for Tube 5 were 14 runs (Runs 5.045 - 5.058) for the superheat effect study and 5 runs (Runs 5.059 - 5.063) for the heat flux effect study. The smaller diameter of Tube 6 warranted a separate study of these effects. Thus, among the 55 runs for Tube 6, 7 (Runs 6.46 - 6.52) and 3 experimental runs (Runs 6.053 - 6.055) were devised to study the effect of superheat and heat flux, respectively. Details of the experimental results and the experimental conditions are given in Appendix I.

From the observation at the exit sight glass, no traceable swirling was found in the flow, as might have been expected from the spiral fins. Admittedly, there was no extension of fins into the sight glass. In addition, the thickening condensate film with high wettability tends to flow over the spiral fins rather than in the interfin channels.

Heat flux and quality distributions varied with coolant inlet temperature. Distributions of the test fluid static pressure demonstrate that the major pressure drop occurs at Sections 4, 3, and 2 for all three finned tubes at high flow rates. The dramatic reduction in pressure drop at Section 1 is attributable to the thickening condensate film. The flow at Section 1 is somewhat similar to the flow field on a rough surface because the spiral fins, to some
extent, act like roughness elements.

The distributions of sectional heat transfer coefficient generally followed the same pattern as in the twisted tape experiments, i.e., decreasing coefficient with decreasing quality. Only at low flow rates, slightly higher heat transfer coefficients were found at Section 2 than at Section 3 for both Tubes 4 and 6. This experience with the inner-fin tubes is somewhat contrary to that observed when condensing steam in the same tubing [2]. Royal found the general trend for the sectional heat transfer coefficient distributions was increasing heat transfer coefficient with decreasing quality to a point, followed by decreasing heat transfer coefficient with decreasing quality. These differences are attributable to different flow mechanisms encountered in these two experiments as will be further discussed later in this chapter.

Typical temperature distributions are shown in Figs. 53-55 for the finned tubes. The figures demonstrate much smaller differences between the average wall temperatures and the saturation temperatures than in the case of the smooth tube without or with the twisted tapes. The circumferential wall temperature variation is also smaller for the finned tubes.

Overall pressure drops and heat transfer coefficients are generally larger at lower pressure levels, Figs. 56-61. As shown in these figures, the overall pressure drop is highest in Tube 4. Tube 5, with the shortest fins and highest number of fins, exhibited the largest increase in heat transfer coefficient at low flow rates. At
Fig. 53. Typical temperature distributions along test condenser, Tube 4.
Fig. 54. Typical temperature distributions along test condenser, Tube 5.
Fig. 55. Typical temperature distributions along test condenser, Tube 6.
Fig. 56. Experimental overall pressure drops versus mass flux, Tube 4, all inlet pressures.
Fig. 57. Experimental overall pressure drops versus mass flux, Tube 5, all inlet pressures.
Fig. 58. Experimental overall pressure drops versus mass flux, Tube 6, all inlet pressures.
Fig. 59. Experimental overall heat transfer coefficients versus mass flux, Tube 4, all inlet pressures.
Fig. 60. Experimental overall heat transfer coefficients versus mass flux, Tube 5, all inlet pressures.
Fig. 61. Experimental overall heat transfer coefficients versus mass flux, Tube 6, all inlet pressures.
high flow rates, the heat transfer coefficients of all the finned tubes were comparable. Tables G.2 and G.3 include the constants $C$, $C'$ and exponents $n$, $n'$ of the parametric expression of $\Delta P$ and $\bar{h}$.

For condensing steam in the same tubing, Royal [2] found that Tubes 4 and 6 had clearly better heat transfer performance than Tube 5 over the same range of mass velocity. Once again, this appears to be related to different condensing mechanisms in these two experiments, due to the different physical properties of the two fluids. Among these are surface tension and density ratio ($\rho_1/\rho_g$). Thus, an optimum design of inner-fin tube geometry for condensing service has to take the fluid properties into consideration.

Correlations of Experimental Results

An attempt was made to correlate the experimental results of the finned tubes for in-tube condensation. The objective was to provide appropriate modifications to smooth in-tube condensation correlations to enable the modified correlations to successfully predict the pressure drop increases and the anticipated improved heat transfer coefficients. The derived correlation(s) could then be used to interpret the effects of superheat and heat flux.

Pressure drop

As with the twisted tapes, the Lockhart-Martinelli and the
Dukler II correlations, with the modification of interfacial shear and the use of equivalent diameter, were used along with the separated momentum equation for a preliminary calculation of pressure drop. Different formulations of the void fraction, described in Chapter 2, were included in the evaluation. The calculation indicated the results were not very sensitive to different formulations of the void fraction. Thus, the separated momentum equation with the homogeneous void, i.e., homogeneous momentum equation, was chosen for simplicity.

Based on the statistical analysis, the modified Dukler II correlation, with homogeneous voids along with the equivalent diameter of the finned tubes, was found most suitable to correlate the experimental pressure drops. The same correlation without modification and with homogeneous void was selected for steam condensation in [50].

Figure 62 presents the calculated pressure drops versus the experimental pressure drops. Good agreement between the calculated and the experimental values is found at large pressure drops. Eighty one percent of the data points agree with the correlation to within ±40 percent. The scatter of the data at lower pressure drops was attributable to several factors described before.

As found in [50] and [115], the equivalent-diameter approach was clearly the best for finned tubes. Use of the friction factor, derived in [139] for single-phase flow in internally finned tubes, as an alternate to the equivalent-diameter approach, resulted in poor correlation [50].
Fig. 62. Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void, Tubes 4, 5 and 6.
Heat transfer coefficient

Because of complex geometry effects and other interrelated factors, modeling of finned tube performance has scarcely been attempted. In his study of in-tube condensation of steam for the internally finned tubes, Royal [2] tried to identify several discrete effects due to the fins and to incorporate them into smooth tube correlations. The effects considered were fin effect, tangential velocity effects, and geometry effects of increased surface area and reduced flow area. He found that the modified correlations greatly over-predicted the experimental data.

Usually, one or two geometrical factor(s) are used to account for the effects of the internal fins. This is also the methodology adopted for the present study, and the Boyko and Kruzhilin correlation was readily modified for the purpose. Several geometrical factors have been proposed in single-phase flow as well as in two-phase flow. The values of these geometrical factors for the three finned tube tested here are tabulated in Table 6.1. For these geometrical factors, only the values of the factor $H^2/WD$ suggested by Royal [2] appears to comply with the relative performance of the finned tubes in the present study. However, besides these geometrical factors, the geometrical factor used by Watkinson et al. [139] to account for the effects of fin rifling might also be involved.

After a number of trials, it appeared that the geometrical factor proposed by Royal was the best one to be used with the smooth tube
Table 6.1. Values of some geometrical factors for the finned tubes

<table>
<thead>
<tr>
<th>Geometrical Factor</th>
<th>Tube 4</th>
<th>Tube 5</th>
<th>Tube 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{W}/H$</td>
<td>1.1426</td>
<td>1.6835</td>
<td>2.4226</td>
</tr>
<tr>
<td>$H^2/WD$</td>
<td>0.0909</td>
<td>0.0242</td>
<td>0.0606</td>
</tr>
<tr>
<td>$H/2\theta D_e$</td>
<td>0.4525</td>
<td>0.3094</td>
<td>0.1921</td>
</tr>
<tr>
<td>$H/D_e$</td>
<td>0.2145</td>
<td>0.0726</td>
<td>0.2275</td>
</tr>
<tr>
<td>$\bar{W}/D_e$</td>
<td>0.2451</td>
<td>0.1222</td>
<td>0.5511</td>
</tr>
</tbody>
</table>

correlation. The combination of $p/D$ with any of the factors did not improve the prediction. The final modified Boyko and Kruzhilin correlation is

$$h_e = 0.024 \frac{k_1}{D_e} \left( \frac{C_D}{\nu_1} \right)^{0.8} Pr_1^{0.43} \left( \frac{H}{WD_i} \right)^{-0.22} \left[ \left( \frac{\rho}{\rho_m} \right)_{in} + \left( \frac{\rho}{\rho_m} \right)_{out} \right]^{0.5}$$

(6.1)

As seen in Figs. 63-65, Eq. (6.1) correlates the sectional and overall heat transfer coefficients for Tubes 4, 5, and Tube 6 within 30 percent, for 86 percent (Tubes 4 and 5) and 96 percent (Tube 6) of the data. For all three tubes, the much higher experimental heat transfer coefficients (exceeding -30 percent) at Section 4 were caused by a combination of particularly high heat transfer rates and uncertainty in measurement of wall temperatures. In these
Fig. 63. Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), Tube 4.
Fig. 64. Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), Tube 5.
Fig. 65. Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), Tube 6.
experiments, the tube-side resistance was so small that the average wall temperature was within 2°C of the saturation temperature. A measuring error of 0.5°C would result in a 25 percent error in heat transfer coefficient. On the other hand, the scatter of the heat transfer coefficients suggests that a single factor is not adequate to describe the complicated flow phenomena during condensation inside the finned tubes. Due to the empirical nature of Eq. (6.1), caution should be exercised in utilizing the equation far beyond conditions upon which it was based.

Discussion of difference between R-113 and steam correlations for heat transfer coefficient

It is noted that the exponent of the geometrical factor in Eq. (6.1) has a negative value, in contrast to the positive value of the corresponding term in Eq. (2.54). Thus, in the present study, Tube 5 with the smallest value of the geometrical factor has the largest increases in heat transfer coefficients, with Tubes 6 and 4 following in order. The relative performance of these finned tubes is in reverse order to that observed in the Royal and Bergles study.

Plotted in Fig. 66 are the condenser size reduction index, $R_h$ (see Chapter 8), versus mass velocity for Tubes 4 and 5 from both studies. Tube 6 was not shown because of different inside diameter. This index is the ratio of the overall heat transfer coefficients of the smooth tube to those of the augmented tubes; the lower the index value, the better the corresponding finned tube performance. Thus,
Fig. 66. Condenser reduction index versus mass flux for R-113 and steam, $P_{in} = 6.55$ bar and $P_{in} = 4.9$ bar, respectively.
this graph serves to indicate the relative improvement on heat transfer of the finned tubes for condensing R-113 and steam.

As seen in Fig. 66, Tube 5 had the best performance for condensing R-113 at low flow rates while Tube 4 was the best for condensing steam at high flow rates. For R-113 condensation, the percentage increase in heat transfer coefficients for Tube 5 ranged from 140 to 90 at low and high flow rates, respectively; an increase of 73 percent was found for Tube 4. For steam condensation, Tube 5 was found to increase coefficients by about 50 percent while Tube 4 increased coefficients from 67 percent to 212 percent at low and high flow rates, respectively. Further, the index for Tube 5 increased with mass velocity while the index for Tube 4 decreased with mass velocity in both studies. As described before, this behavior appears to be due to differences in the condensing medium properties. R-113 has much smaller surface tension and density ratio than water does. These property differences, compounded by fin geometry and varying condensate distribution during condensing flow, would certainly modify the heat transfer mechanism in each case.

At low flow rates, with a low surface tension fluid like R-113, the condensate spreads out over much of the finned surface and is not held up in the axial direction by surface tension in interfin channels. Thus, the augmentation is partly due to area increase in the finned tubes. On the other hand, the spiral fins could have a roughness effect since the condensate flows across the finned surface. In addition, the fins tend to promote a wavy interface and/or liquid
entrainment. Tube 5 is better than other tubes because its area and short fins are more effective in this regard. Contrarily, with a relatively high surface tension fluid such as water, the condensate is held up by surface tension in interfin channels. Only the exposed fin tips represent effective heat transfer area. For Tube 5, the fins are so closely spaced that the condensate drains poorly in the axial direction and the short fins are easily submerged, i.e., the interfin channels are easily flooded. Thus, Tube 5 performed poorly for condensing steam. Tubes 4 and 6 are better in this regard.

At high flow rates, interfacial shear is dominating and would help to drain the condensate in the axial direction. It is speculated that this action has a much larger effect in the water case than in the R-113 case because the higher interfacial shear tends to improve axial drainage of the condensate and, meanwhile, the fin tips are still partly exposed to the vapor core. On the other hand, the accompanying higher liquid loading (higher condensate flow at the same quality as compared with that at low flow rates) would certainly degrade the roughness effect of the short fins of Tube 5 but upgrade the effect of the medium long fins of Tube 4 for condensing R-113. These explain the slow increase and decrease in performance relative to increasing mass velocity for Tubes 4 and 5, respectively. For steam condensation, the even poorer performance of Tube 5 at high flow rates is probably caused by earlier flooding of interfin channels owing to higher liquid loading. The large increase in performance of Tube 4 likely comes
from the combined effects of partly exposed fin tips, wavy interface, and/or liquid entrainment.

While the provided explanation of the heat transfer mechanism in R-113 and steam condensation is plausible, further experimental evidence or analysis is needed to substantiate its reliability.

Comparison of correlations In addition to the Royal and Bergles correlation [124] for in-tube condensation with internally finned tubes, there are other two correlations in the open literature which could be applied to the present experimental results. One was suggested by Rifert and Zadiraka [142] for steam condensation and is in the form similar to the Boyko and Kruzhilin correlation, Eq. (2.55). Since the experiment upon which the correlation was based involved only one fin geometry, the derived correlation was attained by adjusting the constant in the Boyko and Kruzhilin correlation. The increased value in the constant reflects a relative increase of 250 percent. Due to lack of a geometrical correlation, it was not possible to compare the correlation with the experimental results.

The other correlation was developed by Vrable et al. [115,116] based on R-12 condensation in internally finned tube. This correlation is of more interest because of its inclusion of the fin effect. In order to compare the present experimental results with the correlation, the data were reduced again to account for the fin effect. In this case, the total heat transfer is equated to the heat transferred through the fins plus the heat through the unfinned wall:
\[ q = \frac{Nq_o + h_c L(T_s - T_w)}{\pi D_i - NWL_f/L} \] (6.2)

where \( L_f/L \) accounts for the fin rifling. \( q \) is the heat transfer over \( L \) determined experimentally. \( q_o \) is heat transferred at the base of each fin and was presented in Appendix D:

\[ q_o = kB_o \left( \frac{\omega}{\beta H + B_e} \right)^{0.5} \left( T_s - T_w \right) \frac{h_g}{k \theta_o} \left( \frac{B}{\omega} \right) \left[ K_0(Y_o)I_1(Y_o) \right. \]

\[ + K_1(Y_o)I_0(Y_o)] + K_1(Y_e)I_1(Y_o) - I_1(Y_e)K_1(Y_o) \right\] (6.3)

\[ \left[ I_o(Y_o)K_1(Y_e) + I_1(Y_e)K_o(Y_o) \right] \]

where

\[ \omega = \frac{2h_c}{k \cos \phi} \]

\[ \beta = \frac{B_o - B_e}{H} \]

\[ Y^2 = 4K^2 \left[ y + \frac{B_e}{\beta} \right] \]

\[ K_1, I_1, K_o, I_o \] are Bessel functions

After substituting Eq. (6.3) into Eq. (6.2), iteration has to be used to determine the heat transfer coefficient \( h_c \). The computed sectional
and overall heat transfer coefficients can then be compared with the Vrable et al. correlation in Eq. (2.53). The pressure ratio was excluded in the calculations because experience with the Cavallini and Zecchin correlation in the smooth tube experiment indicated that inclusion of the pressure ratio as suggested by Vrable [115] over-predicted the present experimental smooth tube results at lower pressure.

The results of the calculation and the experimental values are presented in Figs. 67-69 for Tubes 4, 5, and 6, respectively. In general, the Vrable et al. correlation proved to be a good predictor for Tube 4 at low flow rates, for Tube 5 at high flow rates, and for Tube 6 at Section 1 and the overall average. At other flows the correlation tended to over-predict the experimental results for Tube 4 and to under-predict the results for Tubes 5 and 6.

An attempt was made to predict Vrable's data with Eq. (6.1). This effort met with mixed success, as shown in Fig. 70 for the Vrable's 150 percent tube (The 275 percent tube was not included because the data were not presented clearly for evaluation). Equation (6.1) tended to over-predict the data at higher flow rates. Similar behavior was observed when comparing Eq. (6.1) with Tubes 4 and 6 (see Figs. 63 and 65). It is noted that the value of the geometrical factor, $H/WD$, for Vrable's 150 percent tube approaches that of Tube 4. Also, only tubes with straight fins were used in Vrable study.

In conclusion, the results from the correlating and comparison
Fig. 67. Comparison of sectional and overall heat transfer coefficients with predictions of modified Vrable et al. correlation [116], Tube 4.
Fig. 68. Comparison of sectional and overall heat transfer coefficients with predictions of modified Vrable et al. correlation [116], Tube 5.
Fig. 69. Comparison of sectional and overall heat transfer coefficients with predictions of modified Vrable et al. correlation [116], Tube 6.
Fig. 70. Comparison of data of Vrable [115] with predictions of Eq. (6.1).
studies indicates that the increase in heat transfer performance of
the finned tubes, at some experimental conditions, can be directly
attributable to area increase. However, with different condensing
media, there are some other considerable effects provided by the
fin geometry at some operating conditions, i.e., roughness, wavy
interface, interfin stagnation, etc. The modified Boyko and Kruzhilin
correlation with the inclusion of the geometrical factor, Eq. (6.1), is
shown to account with reasonable success for all these effects for
the three finned tubes, tested under the present experimental conditions.

Effect of superheat

Experiments were performed with varied inlet superheat and with
complete condensation for Tubes 5 and 6. The pressure drop results
as compared with the modified Dukler II correlation are presented in
Fig. 71 for both tubes. The experimental heat transfer results versus
the calculated values from the modified Boyko and Kruzhilin correlation,
Eq. (6.1), are shown in Figs. 72 and 73 for Tubes 5 and 6, respectively.
As expected, there are no observable superheat effects on the finned
tube performance under the present experimental conditions with inlet
superheat up to 14°C.

The additional experiments performed were to study the superheat
effect on heat transfer coefficients when the temperature difference
became smaller, i.e., the desuperheating zone was large. As with
the previous cases, higher superheat level increased heat transfer
coefficients, other things being held constant. The heat flux distribu-
tion followed the same pattern as in the previous cases.
Fig. 71. Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void in superheat effect study, Tubes 5 and 6.
Fig. 72. Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in superheat effect study, Tube 5.
Fig. 73. Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in superheat effect study, Tube 6.
In conclusion, with complete condensation, inlet superheat up to 14°C does not affect the performance of the finned tubes. However, as the desuperheating zone extends further downstream of the test condenser, the heat transfer mechanism is modified and heat transfer coefficients increase with increasing superheat level.

**Effect of heat flux**

The experimental heat transfer coefficient(s) at the section(s) with inlet quality less than unity in those experiments for the superheat effect study without complete condensation were used to study the heat flux effect at higher quality. Figures 74 and 75 present plots of these experimental values versus the calculated values from the modified Boyko and Kruzhilin correlation for Tubes 5 and 6, respectively. These figures show a small adverse effect of low heat flux at medium and high quality range. This effect at low quality range is illustrated in Figs. 76 and 77 from two other series with wet vapor condensing. Although the accompanying effects with these series, as previously noted, impose a conservative judgement, they do suggest that there is some small effect of heat flux on the finned tube performance. The modified Dukler II correlated satisfactorily the experimental pressure drop results for both tubes, as shown in Fig. 78. This suggests that pressure drop is not sensitive to the heat flux effect.

In conclusion, in contrast to the corresponding experiments in the smooth tube with and without the twisted tapes, there is a
Fig. 74. Comparison of sectional heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in heat flux study with incomplete condensation, Tube 5.
Fig. 75. Comparison of sectional heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in heat flux study with incomplete condensation, Tube 6.
Fig. 76. Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void in heat flux study with wet inlet vapor, Tubes 5 and 6.
Fig. 77. Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in heat flux study with wet inlet vapor, Tube 5.
Fig. 78. Comparison of sectional and overall heat transfer coefficients with predictions of modified Boyko and Kruzhilin correlation, Eq. (6.1), in heat flux study with wet inlet vapor, Tube 6.
tendency that lower heat flux will slightly worsen the heat transfer performance of the finned tubes. More experiments are needed to provide a plausible explanation for this finding.
CHAPTER VII. THE ROUGH TUBES

In an attempt to exploit the well-established performance of rough tubes in single-phase flow, the present study also included tests of rough tubes with repeated rib roughness in in-tube condensation. The heat transfer augmentation and pressure drop increase were to be determined and correlated.

General Considerations

The effect of surface roughness on pressure drop and heat transfer depends on the condensate thickness relative to the roughness height and on the roughness pitch. With the boundary-layer characteristics of the condensate flow at higher qualities, the flow would be expected to undergo fully rough, transition, and hydraulically smooth regimes as the condensate film thickens. However, the flow would be subjected to modifications due to interfacial shear, gravity and surface tension. In addition, the flow is complicated by boundary layer separation and reattachment and/or skimming effects.

It was decided to test two tubes with repeated-rib roughness. The sizing of these tubes for condensation of R-113 was based on Webb's work for single-phase flow [143] in tubes with repeated-rib roughness. In place of the usual Reynolds number, the equivalent Reynolds number introduced by Akers et al. [90] was utilized, Eq. (2.36a). The results suggested that a height-to-diameter ratio, e/D, of 0.01
yielded a relatively high heat transfer performance with a modest increase in pressure drop. Further increase in height was accompanied by larger proportional increase in pressure drop than improvement in heat transfer performance. As for the pitch-to-diameter ratio, p/D, the single-phase study of Webb [143] suggested that the value of 10 gave the best heat transfer performance. Accordingly, Tubes 7 and 8 were sized for e/D of about 0.01 and 0.02, with p/D of about 10 and 20, respectively, so that the analytical guidelines could be tested.

The equivalent smooth tube inside diameter and the similar procedures for data reduction and calculations as in the previous experiments were adopted.

Results and Discussion

The experimental investigation produced 55 valid runs for Tube 7 and 41 for Tube 8, each at five inlet pressures: 2.41, 3.45, 4.48, 5.52, and 6.55 bar. Nine runs (Runs 7.047 - 7.055) were for the superheat effect study with complete condensation or with varied outlet quality; 7 runs (Runs 7.056 - 7.059, Runs 8.044-8.046) were for the heat flux study. The experimental results along with the experimental conditions are given in Appendix I.

Although several studies [193,194] cited that roughness has a small effect on flow pattern transition, no attempt was made to use the results of those studies to predict the present flow regimes. The roughness did not extend into the sight glass so that a proper
comparison between predicted and observed flow regimes could not be made. Also, flow regime studies are not as important as in the smooth tube experiment.

In contrast to the previous experiments, two distinct patterns were observed in the heat flux distribution at all pressure levels. At low flow rates, the heat fluxes at Section 3 were always lower than those at Sections 2 and 4. At higher flow rates, the heat fluxes at Section 3 were generally higher than those at Section 2. Sectional heat transfer coefficients had similar trends as the sectional heat fluxes. Distributions of test fluid static pressures indicated that major pressure drop increases occurred in Sections 2, 3, and 4.

Typical temperature distributions are shown in Figs. 79 and 80 for Tubes 7 and 8, respectively. Wall temperature variation at a thermocouple station away from both ends of the test condenser is small as in the finned tube experiments.

Figures 81 and 82 present the overall pressure drop versus mass velocity. The pressure drop data at low flow rates exhibit considerable scatter. This is attributable to the ineffectiveness of the pressure taps for pressure drop measurements. In addition to the inherent "unsteadiness" of pressure drop measurements in two-phase flow, the presence of roughness elements near the pressure tap "enhanced" the unsteadiness owing to form drag variation near the taps. At low flow rates, the fluctuations of pressure drop were comparable to the average pressure drop most of the time. Generally,
Fig. 79. Typical temperature distributions along test condenser, Tube 7.
Fig. 80. Typical temperature distributions along test condenser, Tube 8.
Fig. 81. Experimental overall pressure drops versus mass flux, Tube 7, all inlet pressures.
Fig. 82. Experimental overall pressure drops versus mass flux, Tube 8, all inlet pressures.
a higher pressure drop is associated with a higher value of e/D.

Overall heat transfer coefficients plotted against mass velocity in Figs. 83 and 84 exhibit another feature of the rough tubes which is very similar to that in single-phase flow [143,144]. The heat transfer coefficient decreases slightly and then increases moderately with increasing mass velocity. The minimum point shifts to lower mass velocity as roughness height increases; this corresponds to the shift of the maximum Stanton number in the transition region with increasing roughness values, as reported in previous single-phase studies [143,144]. As indicated in Figs. 83 and 84, higher heat transfer coefficients occur with Tube 8 which has higher e/D. The speculation that a small increase in heat transfer coefficient would accompany even higher increase in pressure drop when e/D > 0.01 cannot be justified here because of different p/D values and limited geometrical variations for a specified type of roughness tested.

Because of the unusual behavior of the rough tube heat transfer performance, the constant C' and the exponent n' of Eq. (4.10b) have to be determined separately in each region. These values and the log-linear curve fit parameters for the pressure drop are tabulated in Tables G.3 and G.2, respectively.

Correlations of Experimental Results

As with the previous augmented tube studies, the purpose of the correlations was to provide predictive equations for the heat transfer
Fig. 83. Experimental overall heat transfer coefficients versus mass flux, Tube 7, all inlet pressures.
Fig. 84. Experimental overall heat transfer coefficients versus mass flux, Tube 8, all inlet pressures.
improvement and pressure drop increase. The correlations were then applied to study the superheat and heat flux effects.

In view of the heat transfer behavior of the rough tubes, a treatment similar to that described in Chapter 2 for single-phase flow could have been applied with some modifications. This requires appropriate definition of the Reynolds number and friction factor. Also required is a set of well-controlled experimental data which is composed of experimental results from a specified type of roughness with wider variation of e/D and p/D. Since the data in the present study are limited, this approach was discarded.

Another possibility would be to use the velocity distribution on a rough surface in an analysis parallel to that used by Traviss et al. [7] in their study of in-tube condensation inside smooth tube. However, the velocity distribution near the wall is not known and, in addition, it varies with the type of roughness. Thus, a natural course that followed was to modify the existing correlations. This was done separately for the pressure drop and heat transfer coefficient as described in the following sections.

Pressure drop

An attempt was made to use the single-phase friction factor for repeated-rib tubes in [143]. The experimental results were always over-predicted. A similar conclusion was reached by Royal [2] in his effort to predict experimental results for internally finned tubes using a single-phase friction factor. This was probably due to
improper use of some physical quantities in the definition of friction factor and Reynolds number and the relationship between them.

The methodology of using equivalent diameter was thus adopted. The equivalent diameter, defined as

$$D_e = \frac{4 \text{(flow area)}}{\text{wetted perimeter}}$$

degrees as the flow area reduces and the wetted perimeter increases.

For transverse repeated-rib roughness, Webb [143] found that the use of $D_e = D - e$ in both friction factor and Reynolds number could reduce the scatter of their correlated pressure drop results. For helical repeated-rib roughness used in this study, it was found that modified Dukler II correlation with $D_e = D - 2e$ better correlated the experimental results, as shown in Figs. 85 and 86. The experimental results were generally under-predicted at high flow rates. The relatively large scatter of the data at low flow rates was caused by the several factors described before.

**Heat transfer coefficient**

Before any attempt was made to correlate the experimental heat transfer results, the analysis for sizing the rough tubes was applied to predict the experimental results. The calculated values were found to be consistently lower than the experimental values for most of the data points. This suggested that an equivalent Reynolds number, when appropriately defined, could be used with Webb's semiempirical
Fig. 85. Comparison of overall pressures drops with predictions of modified Dukler II - homogeneous void, Tube 7.
Fig. 86. Comparison of overall pressures drops with predictions of modified Dukler II - homogeneous void, Tube 8.
correlation to predict the heat transfer results.

The reasonable agreement of the Boyko and Kruzhilin correlation in its modified form with the augmented tube experiments thus far demonstrates the appropriateness of the way which the two-phase flow effects are incorporated into a single-phase smooth tube correlation. Boyko and Kruzhilin [92] did not introduce the idea of equivalent Reynolds number, but a similar idea could be applied to their correlation. In their study, Boyko and Kruzhilin found that the condensing coefficient was related to the single-phase coefficient for liquid flow as follows:

\[ h_c = h \sqrt{\frac{\rho}{\rho_m}} \]

where

\[ \frac{\rho}{\rho_m} = 1 + x(\rho_1 - \rho_g) / \rho_g \]

The equivalent Reynolds number derived from the above expression is

\[ Re_e = \frac{GD}{\mu} \left( \frac{\rho}{\rho_m} \right)^{0.625} \quad (7.1) \]

This equivalent Reynolds number was thus incorporated into Webb's correlation to predict the heat transfer performance of the rough tubes. After a number of trials, it was found that the experimental results
were better correlated if the exponent of $p/p_m$ in Eq. (7.1) is 0.5. Thus, the equivalent Reynolds number in the form

$$Re_e = \frac{GD}{\mu_1} \left( \frac{\rho}{\rho_m} \right)^{0.5}$$

was combined with Eqs. (2.66) and (2.67), with a small adjustment, to predict the experimental heat transfer results. These two equations are repeated here for convenience:

$$R(e^+, p/e) = 0.95(p/e)^{0.53} \quad \text{for } e^+ > 35 \quad (2.66)$$

$$g(e^+, Pr) = 4.5(e^+)^{0.28} \quad Pr^{0.57} \quad (2.67)$$

The adjustment was to use Eq. (2.67) for all values of $e^+$ instead of for $e^+ > 25$ as suggested in [143]. For the present experiments, most of the values of $e^+$ calculated from sectional and overall average experimental conditions are greater than 25. The value of $R(e^+, p/e)$ was directly read off Fig. 6.15 in [143] for $e^+ < 35$. The values of the pitch-to-roughness height ratio in the present experiment were inside the range of same ratio in [143]. The calculations required iteration but converged in only a few steps.

Figures 87 and 88 present the calculated values versus the experimental values. Eighty eight percent and 85 percent of the experimental data are correlated within ±30 percent for Tubes 7 and 8, respectively. The trend of lower calculated values at Section 4 is
Fig. 87. Comparison of overall and sectional heat transfer coefficients with predictions of modified Webb correlation [143], Tube 7.
Fig. 88. Comparison of overall and sectional heat transfer coefficients with predictions of modified Webb correlation [143], Tube 8.
probably caused by film instability and/or liquid entrainment promoted by the presence of roughness elements.

In conclusion, the reasonable success of using Webb's correlation with a modified equivalent Reynolds number to correlate the experimental heat transfer results suggests that the single-phase analysis for rough tubes presented in [143,144] can be extended to in-tube condensation. More experimental results from other tube geometries and/or using different condensing medium are required to generalize the modified correlation.

**Effect of superheat**

As with some of the augmented tubes, some experiments were performed to study the superheat effect for Tube 7 with complete condensation and varied inlet superheat. The pressure drop results are plotted against the modified Dukler II correlation in Fig. 89. The heat transfer results, as compared with the calculated values from the modified Webb correlation, are shown in Fig. 90. No noticeable effect of superheat (up to 20°C) is present.

Additional experiments were performed to study the desuperheating zone for Tube 7. The heat flux distribution was the same as in the previous cases. However, the heat transfer coefficient(s) at the section(s) inside the desuperheating zone with the wall temperatures less than the saturation temperatures was found to be much lower than those at the sections with saturated vapor condensing. This is in contrast to the findings in the previous cases. Further experiments
Fig. 89. Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void in superheat effect study, Tube 7.
Fig. 90. Comparison of overall and sectional heat transfer coefficients with predictions of modified Webb correlation [143] in superheat effect study, Tube 7.
are needed to justify this trend.

**Effect of heat flux**

To study the effect of heat flux, those experiments in the superheat effect study without complete condensation were used. The calculated heat transfer coefficients versus the experimental values from the sections with inlet quality less than unity are presented in Fig. 91. No large effect is observed.

Figures 92 and 93 present the calculated and experimental values from the additional experiments with wet vapor condensing for Tubes 7 and 8, respectively. These figures show a different feature from the corresponding ones for other augmented tubes. The experimental results were in better agreement with the calculated values except for Section 3 of Tube 7. The entrance effect was still observed in these runs. Thus, the entrance effect, together with others, has to be eliminated in order to have a more definite conclusion for the effect of heat flux.

The pressure drop results from the series with wet R-113 vapor condensing are plotted against the modified Dukler II correlation in Fig. 94. The results are comparable to those for complete condensation (Figs. 85 and 86).
Fig. 91. Comparison of sectional heat transfer coefficients with predictions of modified Webb correlation [143] in heat flux study with incomplete condensation, Tube 7.
Fig. 92. Comparison of overall and sectional heat transfer coefficients with predictions of modified Webb correlation [143] in heat flux study with wet inlet vapor, Tube 7.
Fig. 93. Comparison of overall and sectional heat transfer coefficients with predictions of modified Webb correlation [143] in heat flux study with wet inlet vapor, Tube 8.
Fig. 94. Comparison of overall pressure drops with predictions of modified Dukler II - homogeneous void in heat flux study with wet inlet vapor, Tubes 7 and 8.
CHAPTER VIII. COMPARISONS OF THE AUGMENTED TUBES AND PERFORMANCE EVALUATION

The prime objectives of this study were to evaluate and to predict the performance of various techniques to augment in-tube condensation of R-113. The experimental results for twisted-tape inserts, inner-fin tubes, and tubes with repeated-rib roughness and associated correlations were presented in preceding chapters. In this chapter, these techniques are compared with each other and evaluated using performance indices suggested by Royal and Bergles [50].

Comparisons of the Augmented Tubes

In order to compare the augmentation techniques, the experimental pressure drop or the overall heat transfer coefficient versus mass flux for each tube are presented in a composite plot for same inlet pressure, as shown in Figs 95-103. These plots were readily obtained by combining Figs. 6, 42, 56, 57, 58, 81 and 82 for overall pressure drop and using Figs. 7, 43, 59, 60, 61, 81, and 84 for overall heat transfer coefficients. The data points were omitted to make the plots more legible. The straight lines shown were fitted to the data with a least-square regression technique in the form of Eqs. (4.10) with the constants $C, C'$, the exponents $n, n'$, and the standard deviations tabulated in Table G.2 and G.3.
Fig. 95. Experimental overall pressure drops versus mass flux, all tubes, $P_{in} = 3.45$ bar.
Fig. 96. Experimental overall pressure drops versus mass flux, all tubes, $P_{in} = 4.48$ bar.
Fig. 97. Experimental overall pressure drops versus mass flux, all tubes, $P_{in} = 5.52$ bar.
Fig. 98. Experimental overall pressure drops versus mass flux, all tubes, $P_{\text{in}} = 6.55$ bar.
Fig. 99. Experimental overall heat transfer coefficients versus mass flux, all tubes, $P_{in} = 2.41$ bar.
Fig. 100. Experimental overall heat transfer coefficients versus mass flux, all tubes, $P_{\text{in}} = 3.45$ bar.
Fig. 101. Experimental overall heat transfer coefficients versus mass flux, all tubes, $P_{in} = 4.48$ bar.
Fig. 102. Experimental overall heat transfer coefficients versus mass flux, all tubes, $P_{in} = 5.52$ bar.
Fig. 103. Experimental overall heat transfer coefficients versus mass flux, all tubes, $P_{in} = 6.55$ bar.
Pressure drop

The composite plots comparing the pressure drop results of the augmented tubes with the corresponding smooth tube results are presented in Figs. 95-98. Pressure level has little effect on the relative location of the drawn lines on these graphs.

For the three augmentation techniques tested, the largest increase in pressure drop is with the twisted-tape inserts. An average increase of nearly 250 percent over that of the smooth tube is found. This considerable pressure drop increase is due to the increased wetted perimeter, the spiralling flow path, and the secondary flow. Most of the increased wetted perimeter is embedded in the vapor core where high shear stress prevails. This large pressure drop makes these tubes unattractive for commercial systems.

The finned tubes, except Tube 4, and the rough tubes have modest increases in pressure drop relative to the smooth tube. The increase in overall pressure drop is highest in Tube 4, but is still less than those of Tubes 2 and 3, although the wetted perimeter is higher in Tube 4. It is believed that the immersion of the fins inside the liquid film causes this significant decrease in pressure drop as compared with the twisted tapes.

Most of the lines shown in this group of figures for the finned and rough tubes have a much larger slope than that of the smooth tube. This indicates a proportionally higher increase in pressure drop with increasing mass velocity. The smaller pressure drop with some of the augmented tubes at low flow rates when compared
with those of the smooth tube is attributable to several factors. These factors are: fluctuations of the pressure drop, low resolution of the mercury manometer, and the location of the pressure taps relative to the fins or roughness elements. Regarding the latter, it is probable that the static pressure at a pressure tap is influenced by the varied flow downstream of a spiralling fin or a repeated rib.

**Heat transfer coefficient**

Figures 99-103 present the composite plots comparing the heat transfer results of the augmented tubes with the corresponding smooth tube results. As with the pressure drop, pressure level does not significantly alter the relative location of the data.

An examination of these figures indicates that, for the twisted-tape inserts, an average increase in heat transfer coefficient of 30 percent over the smooth tube values is obtained. For Tubes 4 and 6, approximately 73 and 98 percent increases in heat transfer coefficients are found, respectively. Tube 5 has the largest increase in heat transfer coefficients with an average increase of 120 percent over the smooth tube values based on a nominal area basis. For both rough tubes, an average increase of 80 percent is observed.

As seen from Table G.1, the increases in heat transfer coefficients for the finned tubes are greater than the increases in surface area of the tubes. It is noted while higher liquid loading (low quality at high flow rates) usually degraded the augmentation effect with the finned tubes, moderate liquid loading (low quality at low
flow rates or moderate quality at high flow rates) did not hamper the augmentation effect with Tubes 4 and 6 when compared with a similar run in the smooth tube case. A similar situation was observed with the twisted tape results; however, the increase or decrease was modest. For the rough tubes, the increase in sectional heat transfer coefficient was highest for Section 4 at the flow rates considered in the present experiment.

In conclusion, Tube 5 has the largest heat transfer increase. In order, follow Tubes 6, 8, 7, 4, 2, and 3. However, the merit of a augmented surface is not decided simply on the basis of increased heat transfer coefficient, but also on other factors such as increased pressure losses, greater cost per unit length of tube, maintenance problems, etc. Of immediate interest in the present case is the pressure drop penalty. This leads to the consideration of some performance indices presented below.

Performance Evaluation

Performance criteria are required in evaluating an augmented technique so that a comparison can be made in practical terms adapted to the various constraints of industrial systems. Bergles et al. [201] suggested nine performance criteria for single-phase flow. They suggested that the proper way to evaluate a surface was to compare it directly with a reference surface at the conditions of interest. These criteria were estimated by taking the ratio of the "objective
functions" of interest between the augmented surface and the smooth surface. The parameters used to form this ratio were to be obtained for both surface with some specific variables being fixed.

For the condensing flow in this study, with complete condensation, the amount of heat transferred is fixed for a given mass flow rate. The reduced degrees of freedom in this case prohibit the direct application of the above-mentioned performance criteria without further modification. Four such criteria were developed by Royal and Bergles [2,50], and the most interesting two are employed here to evaluate the augmented tubes tested. It is noted that the development of these criteria was based on the assumption that the condensing side resistance controlled the heat transfer. The two criteria are: condenser size reduction index and pressure drop index.

Condenser size reduction index

This index is a ratio which is indicative of possible condenser size reduction through use of augmented tubes while heat duty, nominal diameter, and temperature difference are held fixed. This index is given by

\[ R_n = \frac{A_{aug}}{A_{std}} = \frac{\bar{h}}{\bar{h}_{aug}} \]  \hspace{1cm} (8.1)

This ratio is readily available from the experimental results for any inlet pressure, and is plotted in Fig. 104 for Tubes 2, 3, 4, 5, 7, and 8 at \( P_{in} = 6.55 \) bar. Tube 6 was not included in this comparison.
Fig. 104. Condenser reduction index versus mass flux, $P_{in} = 6.55$ bar.
because it had a diameter quite different from the other tubes. The values of $R_h$ for these augmented tubes are well below unity. Tube 5, which has the highest heat transfer coefficients, has the lowest values of $R_h$. The breakpoint in the curves associated with Tubes 7 and 8 corresponds to the different heat transfer performance of these tubes. (Figs. 87 and 88).

**Pressure drop index**

This index is of considerable interest because it indicates the pressure drop consequences of the choice of a augmented technique with the above-mentioned constrains. This index is

$$ R_{\Delta P} = \frac{\Delta P_{\text{aug}}}{\Delta P_{\text{std}}} $$

After subtracting the momentum contribution (analytical), the pressure drop (experimental) of augmented surface was adjusted by multiplying it by the length ratio, $R_h$. The overall pressure drop was then obtained by adding the momentum contribution to the reduced frictional pressure drop. The homogeneous momentum equation was used to estimate the momentum contribution. This ratio is presented in Fig. 105 for six augmented tubes. Tubes 5, 7, and 8 have comparable values (below unity) at high mass velocity. At low mass velocity, use of Tube 7 would result in less pressure drop although the condenser size is larger.

Therefore, it can be concluded that, on the basis of $R_h$, Tube 5
Fig. 105. Pressure drop index versus mass flux, $P_{in} = 6.55$ bar.
would provide the smallest condenser size for given duty. On the other hand, use of Tube 7 would consume less power for a given duty at low mass velocities.
CHAPTER IX. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The present study investigated augmentation of in-tube condensation of R-113 and the effects of superheat and heat flux on this process. The basic experimental facility in the Heat Transfer Laboratory was extensively modified for this purpose. A smooth tube, the smooth tube with twisted-tape inserts of two different pitches, three internally finned tubes, and two tubes with repeated-rib roughness were tested. The conclusions drawn from the study are as follows:

1. For the experimental conditions considered here, the pressure drop results were correlated reasonably well by the correlations of Dukler II [29] and Lockhart-Martinelli [35] with modification of the friction factor given by Silver and Wallis [43]. The smooth tube heat transfer results were predicted satisfactorily by the local correlations of Shai [97] and Traviss et al. [7], and by the average correlation of Boyko and Kruzhilin [92].

2. Twisted-tape inserts inside the smooth tube were found to increase heat transfer coefficients (nominal area basis) and pressure drops by approximately 30 percent and 250 percent, respectively, over those of the smooth tube.

3. The best internally finned tube was found to increase heat transfer coefficients by as much as 120 percent over that of the smooth tube. This significant increase in heat transfer coefficient
was accompanied by only a modest pressure drop increase.

4. The rough tubes were found to increase in-tube condensation heat transfer coefficients by about 80 percent. The pressure drop increase was moderate. These results are highly significant for practical application in view of the minimal amount of extra material required to form the repeated ribs.

5. Predictive methods are proposed for pressure drop increase for the augmented tubes. The Dukler II correlation, modified as in the smooth tube case and with utilization of the equivalent diameter of the augmented tubes and modified friction factor (where applicable), predicted most of the pressure drop results within ±40 percent.

6. Methods were developed to predict heat transfer improvement for the augmented tubes. The twisted tape data can be predicted by a priori modifications (Eqs. 5.1-5.6) of the applicable smooth-tube heat transfer correlations. The finned tube results were correlated by incorporating a geometrical factor in the Boyko and Kruzhilin correlation (Eq. 6.1). The rough tube data were predicted by combining Webb's results for repeated-rib roughness [143] and the Boyko and Kruzhilin correlation (Eqs. 2.66-2.67, 7.2). These equations predicted most of the experimental data within ±30 percent.

7. The improvement of heat transfer performance, as evaluated by two performance criteria, of the internally finned tubes and the rough tubes was far better than that of twisted-tape inserts. However, the twisted tapes might find applications in retrofit
situations where short sections of condensers must be enhanced.

8. When the data of this investigation are compared with previous data for condensing steam, it appears that to achieve the best performance different types of inner-fin tubes are required for water and for refrigerants. Reasons for this behavior are suggested.

9. Inlet superheat up to 22°C has little effect on heat transfer or pressure drop with complete condensation for the smooth tube and the augmented tubes considered here.

10. The level of superheat affects heat transfer performance when the wall temperature is within a few degrees of the saturation temperature. Higher heat transfer coefficients are found with higher level of superheat.

11. At high and medium quality, the heat flux level does not affect the performance of the tubes tested here when the condensate flow is turbulent. At low quality (x < 0.3), entrance effect and other factors encountered in the present study preclude a conclusive result.

Recommendations for Further Study

Despite the large amount of data obtained in the present study, this investigation was less than complete owing to limited resources and other priorities. Additional work is required to fully understand the performance of these augmented tubes and to apply them to a wide range of practical situations.
Although the performance of the augmented tubes is emphasized here, the study of smooth in-tube condensation is equally important. A better understanding of this process could improve or establish sound correlation(s) for smooth tube condensation results. The correlation(s), in turn, could provide a basis upon which predictions for the performance of augmented tubes would be developed or improved. Based on the present study, several recommendations are generated:

1. The scatter of the present smooth tube experimental results when compared with some of the more popular models/correlations indicates the inaccuracy of these models/correlations to describe the flow phenomena during smooth tube condensation. A more accurate formulation for this process would require the inclusion of flow regime transitions and incorporation of liquid entrainment, wavy interface, and drained condensate flow into a single model/correlation. Several recent studies [105,202,203] have aimed in this direction.

2. Entrance effect is important with wet vapor condensing. Further experiments are required to determine the effect on the condensing process. The erratic behavior of the heat transfer coefficients at the desuperheating zone is of interest and deserves further study.

3. The reasonable success in correlating the twisted-tape results in this study and in the condensing steam study [124] suggests that no further work appears to be necessary for twisted-tape inserts. It
is believed that the scatter experienced with the twisted tapes in this study or [2] could be reduced by improving the smooth tube condensation correlation.

4. In view of the disagreement between the steam and R-113 data, and the moderate success of the present finned-tube correlation with Vrable's data (and vice versa), it is difficult to select optimum finned tubes for a specified in-tube condensation service. Heat transfer and pressure drop data for a wider range of geometries using different fluids must be obtained and these data must be accurately correlated. This will enable the specification of key parameters, such as numbers of fins and fin height, so that an optimum finned-tube geometry can be attained for a specific duty.

To correlate finned tube results, it is suggested that the fin effect can be singled out and lumped with all other possible effects in one or several constants to be determined experimentally. However, if further interest in condensation within inner-fin tubes justifies the effort, a detailed investigation of the velocity distribution should be undertaken. This velocity (or average velocity) might then be applied to a local correlation such as the Traviss et al. correlation or a more general one to attain the heat transfer prediction.

5. The experiments with the two rough tubes tested here only provided a brief view of this technique for possible exploitation in in-tube condensation. It is obvious that more data are needed for different fluids and varied geometries for a specific roughness, i.e.,
varied roughness height and pitch for two-dimensional roughness. Based on the present study, it is speculated that an optimum geometry for two-dimensional roughness could be established such that high heat transfer coefficients are accompanied by modest increases in pressure drop only. This can be done by optimizing the roughness geometries embedded in the correlation which is developed from a broad data base.

6. Rough tube experiments should be conducted with repeated ribs produced by other processes, such as rolling in the ribs, which may be more attractive economically. Also, economic analyses should be a prominent feature of future studies.

7. For guidance in practical application of these augmented tubes, studies with other refrigerants should be considered. Test with refrigerant-oil mixture should also be undertaken as the refrigerant is, to some extent, oil-contaminated in a vapor-compression refrigeration system.
BIBLIOGRAPHY


75. Bae, S.; Maulbetsch, J. S.; and Rohsenow, W. M. "Refrigerant Forced-Convection Condensation inside Horizontal Tubes." Report No. DSR 79760-64, Engineering Projects Laboratory, Massachusetts Institute of Technology, November 1, 1969.


ACKNOWLEDGMENTS

The author wishes to express his deepest gratitude to his major professor, Dr. Arthur E. Bergles, for his guidance, assistance, and invaluable advice throughout the course of this study.

The author also wish to thank Dr. Lawrence E. Burkhart, Dr. George H. Junkhan, Dr. Richard H. Pletcher, and Dr. James E. Woods, the members of his dissertation committee, for their ready assistance and guidance throughout his Ph.D. program.

The author is appreciative of the technical assistance given him by Mr. Hap Steed and Mr. Lawrence Couture of the Department of Mechanical Engineering, and Mr. Leon Girard and associates from the Engineering Research Institute workshop.

This study was supported by the American Society of Heating, Refrigerating and Air-Conditioning Engineers initially under a grant-in-Aid and subsequently under RP-219. The author gratefully acknowledges its financial support and the assistance of Mr. David F. Geary, ASHRAE project coordinator.

Acknowledgment is also extended to the Engineering Research Institute and the Department of Mechanical Engineering for making financial support available during the early stage of this study, the Noranda Metal Industries Inc. for providing the three finned tubes, and the Bas-Tex Corporation for supplying the twisted tapes.
Last, but not the least, the author is greatly indebted to his family and his wife for their constant encouragement and affection. The author is especially grateful to his wife, Yi-Lien, for her aid, constructive criticism, and understanding.
APPENDIX A: DETAILS OF EXPERIMENTAL LOOP COMPONENTS

The experimental facility was generally described in Chapter 3. Details of the major components of the facility are presented here.

Test Condenser

The test condenser used in the present study was same as the one in the Royal study [2]. However, some positive means to stop the small coolant leakage from both ends of the test condenser were introduced. Design details of this component are described in [2]. So only a summary will be given here.

The test condenser was formed by two concentric tubes. The outer tube was Type L copper tubing with 2.54 cm (1 in.) nominal diameter. The inner tube was the test condenser tube to be tested. The test tube was equipped with five spacers to seal the ends of the annulus-tube assembly and to divide the annular tube into four sections, each approximately 0.914 m (3 ft) long. The spacers provided water-tight seals by means of Neoprene O-rings and also served to center the tube in the annulus. Also, the spacers diverted the coolant through mixing sections before the coolant proceeded to the next section. Thermocouples were used to measure coolant temperatures in the mixing sections at the entrance and exit of each condenser section.

Thirty-six thermocouples were mounted on the test condenser
tube wall to measure the wall temperatures. They were spaced axially in groups of three at one-foot intervals along the test condenser. At each station, the three thermocouples were located at the top of the tube, at 90° from the top, and at 180° from the top. These thermocouples were attached to the outside wall of the test condenser tube by first marking the place of attachment with a small hole. The diameter of the hole was slightly larger than that of the thermocouple bead. The thermocouple was then attached to the hole by soldering the preformed thermocouple bead with a low temperature silver solder.

Coming out from the hole, the thermocouple leads were then mechanically fixed to the tube wall for the first 1 in. down the leads by wrapping them with 24 gage bare copper wire. This assembly was then further anchored by running a bead of epoxy ("Devcon Plastic Steel B") along the wrapped portion of each lead. Sufficient epoxy was applied to cement the leads to the tube and to provide an insulating layer of epoxy between the leads and the coolant of approximate 2.5 mm thickness. The thermocouple leads were thus in good thermal contact with the tube wall. This arrangement was believed to provide the best compromise between practical assembly considerations and minimization of thermocouple lead conduction errors. An estimate of the error introduced by this arrangement can be found in [2].

Thermocouples were also installed at the inlet and outlet of the test condenser tube to measure temperatures of the test fluid.
These two temperatures were for reference only during the study of complete condensation with incoming saturated vapor. However, the inlet temperature had to be incorporated into data reduction for those runs with small inlet superheat or during the superheat study.

The test condenser tube was equipped to allow condensation side pressure measurements to be made at the outlet of each condenser section and at the inlet of the condenser. Each of these five pressure taps was fabricated from a 3.18 mm (1/8 in.) compression fitting. The male straight pipe threads of the compression fitting, which engaged the compression fitting nut, were cut from the fitting. This threaded portion was then milled and silver-soldered into place at 90° from the top of the test tube. Finally a small hole of 0.64 mm (0.025 in.) was drilled inside the piece, through the tube wall. The relative locations of these pressure taps, the spacers, and the thermocouples as well as the proper terminology for each test tube are shown in Fig. 106.

Boiler

The boiler, tested to 21.7 bar (300 psig), was fabricated from 15.2 cm (6 in.) diameter, 114.3 cm (45 in.) long copper tubing with compliance to the requirements of the ASME Boiler and Pressure Vessel Code for miniature boilers. The boiler was mounted vertically at the facility stand.

At the top of the boiler, a demister (York, Inconel, 15.2 cm (6 in.) thick) was located. The demister was supported by a stainless
Fig. 106. Spacer, pressure tap and thermocouple mounting detail.

STATION CORRESPONDS TO PRESSURE TAP LOCATION.
steel grid which was, in turn, held in place by small pins extended from the boiler tube wall. The demister captured any small liquid droplets entrained in the vapor generated in the boiler.

At the boiler, power was supplied by a flange-mounted Chromalox Type TMI-6 immersion element designed to deliver 12 Kw at 240 volts. The element consisted of six hairpin type electric resistance heaters. These heaters were connected in three groups of two resistors. Each group of two resistors was connected in series and were separately controlled.

The boiler also acted as an accumulator. A bronze liquid level gauge was installed at the side of the boiler to visually check and maintain the liquid level. A EEP36A model gauge made by Eugene Ernst Products Co. was modified for this purpose.

The pressure was measured by a bourdon tube pressure gauge. The outlet temperature was measured by thermocouple at a well inserted into the stream. Instrumentation for the boiler will be presented in a subsequent section.

Superheater

In order to attain slightly superheated or dry saturated vapor, a superheater was installed downstream of the boiler. The superheater was a shell-and-tube heat exchanger with steam condensing in the shell side. An American Standard BCF heat exchanger 7M302D2 was chosen for this duty.
Thermocouples were installed at the inlet and outlet of the heat exchanger to measure the temperature change of the test fluid. Usually, the heat exchanger could superheat the test fluid up to 22.2°C (40°F) above the saturation temperature.

**After-Condenser**

An after-condenser was installed to condense completely the test fluid before it entered the flow meter. The condenser heat balance also provided calculation of the test fluid enthalpy at the test condenser exit.

The condenser was a conventional four tube pass, shell-and-tube heat exchanger operated with the test fluid on the tube side. The tubes were of admiralty metal and provided 12.5 ft² of heat transfer surface. Thermocouples were placed at the inlet and outlet of the condenser at the test fluid side as well as the coolant side.

**Degassing Tank**

A degassing tank was put in the refrigerant flow loop to reduce the air content in the test fluid. A Standard Model UR-66 liquid receiver was modified for this tank.

The tank was equipped with a screw plug Chromalox, Type MT-220-3 immersion element delivering 2kw at 120 volts. The tank was mounted 1.50 cm (4.9 ft) above the pump inlet so that a positive pressure
was ensured to prevent the occurrence of cavitation inside the pump. A small condenser, cooled by water, was connected to the tank to recover most of the test fluid vapor. A simple sight glass made of small Tygon tubing was installed to check the liquid level.

Pump

The pump selected for the present study was an Oberdorfer Model 1000-32 mechanical seal gear pump. It operated on lubrication from the refrigerant so oil contamination to the apparatus was avoided. The pump was directly driven by a 1/3 hp single speed motor with carbon bearings. The flow rate to the boiler was controlled by the two flow regulating valves.

The pump could deliver up to 1.5 gpm at 100 psig differential pressure. A Nupro in-line relief valve set at 120 psig was installed near the pump outlet. Downstream from the pump, a Sporlan Model C-414 filter-dryer was used to remove any particulate matter and moisture in the test fluid.

Test Fluid

For the experimental portion of this study, R-113 was used as the test fluid. R-113 was chosen because it represents a group of industrially important liquids, e.g., refrigerants, dielectric liquids used for cooling of electronics, etc. with properties quite different from steam which was used in [2]. R-113 is characterized by low
thermal conductivity, low surface tension, and relatively large vapor-liquid density ratio. Yet, based on fluid-to-fluid modeling, the experimental results of this study may be used to stimulate in-tube condensation of steam at high pressure.

The R-113 used in this study was manufactured by Dupont. Its thermodynamic and thermophysical properties are listed in Appendix C. This fluid has a relatively high boiling temperature at atmospheric pressure; thus, there is less difficulty in handling it as compared with other refrigerants.

Air has high solubility in R-113. Because of the significant effect on heat transfer coefficients of a small quantity of noncondensable gases, these gases, mainly air in this case, had to be removed. The degassing tank was installed for this purpose.

The low surface tension and excellent wetting characteristics of R-113, together with its incompatibility with some materials, caused some operating difficulties. Leakage was the main problem. Because of the strong tendency for the fluid to evaporate, a visual detection of leakage was impossible. The leakage rate was minimized by a) use of solder-type fittings wherever possible, b) application of Teflon tape to seal threaded connections, and c) replacement of most valve seats, O-rings and gaskets of other materials with those made of Teflon.
Instrumentation

Data acquisition system

The data acquisition system in the Heat Transfer Laboratory consisted of a Hewlett-Packard Model 9825A calculator, a Hewlett-Packard Model 3495A scanner, a Hewlett-Packard Model 3455A digital voltmeter, a Hewlett-Packard Model 9871A printer, and a Kaye Instruments Model K170-36C ice-point reference.

The operation of this system was described in [204]. This system was used to monitor, to acquire, and to reduce data. The system also performed data analyses and plotting. Appropriate software was developed for these purposes. The data reduction program is listed in Appendix H.

Temperature

There were forty-nine temperature measurements per experiment. These measurements were made with the data acquisition system. With the capacity of the ice-point reference up to thirty-six junctions, a thirty-point gang switch was provided so that measurements could be made in two groups. Locations of the corresponding thermocouples were specified along with the description of the experimental loop components.

All thermocouples were made of copper-constantan with 30 gage wire diameter. Thermo Electric Duo-Wrap Hf/D-30-T thermocouple wire was used on the test condenser tubes and for measurements of test condenser coolant temperatures. This wire has limits of error
of ±0.75°F in the range from -75°F to 200°F and of ±3/8% from 200°F to 700°F. The remaining thermocouples were made from Omega Duplex TT-T-30. Its limits of error are ±1.5°F in the range from -75°F to 200°F and ±3/4% from 200°F to 700°F. Omega Miniature Thermocouple Connectors NP-COCO-MF were used for connection when necessary.

The conversion from thermocouple output voltage to temperature from 33 to 299°F was made in a three part fourth order curve fit to the tabulated data from NBS Circular 561 [205]. These equations are as follows:

if \( V \leq 1.494 \),
\[
T = 31.99925 + 46.80117V - 1.407396V^2 + 0.07802V^3 - 0.007394V^4
\]
if \( 1.494 < V \leq 3.941 \),
\[
T = 33.42956 + 44.48835V - 0.07422V^2 - 0.253895V^3 - 0.02878V^4
\]
if \( 3.941 < V \leq 6.62 \),
\[
T = 33.82822 + 45.39092V - 1.015078V^2 + 0.03592V^3 - 0.000642V^4
\]

\( T \) in °F \( V \) in millivolts.

These equations were written in function form under the code name CUOCONT in the data acquisition program.

Pressure

To make pressure measurements, the pressure measuring instruments and the pressure manifold in the previous study [2] were used with some modification. Static pressure measurements were made with an Acco Helicoil Gauge Type 410. Pressure drop measurements were made with a Meriam Single Tube Manometer Model A-203 or an
Ashcroft Differential Pressure Gauge Type 1125. An additional precision pressure gauge made by Heise was installed at the boiler for reference only. Test fluid static pressure at the test condenser inlet was read directly from the pressure gauge. Test fluid static pressure at the end of each test condenser section was then determined by subtracting the pressure drop measurement over a section from the static pressure calculated or recorded at the leading end of the section.

Before operating the manometer, the pressure manifold was dried and clean mercury was used in the differential manometer. The inlet pressure gauge was re-calibrated using an Amther Dead Weight Pressure Gauge Tester, and close agreement was found between the gauge readings and the actual readings. Hence, the gauge readings were used.

During replacement of a test condenser tube, the test fluid in the manifold evaporated easily and the manifold was filled with air. The trapped air together with the test fluid contaminated by dissolved air in the manifold had to be expelled through the manifold drain and vent during the degassing operation.

The low pressure drops and sometimes pressure recovery at low flow rates in this study had not been anticipated before actual data acquisition started. This situation precluded the use of the differential pressure gauge, which had a resolution of 2 psi. Even the relatively higher resolution (0.5 psi) of the mercury manometer
was vulnerable to inaccuracy because of the low pressure drop at low flow rates. It was not possible to replace mercury by another Meriam indicating fluid with smaller specific gravity since these fluids are miscible with R-113.

Pressure recovery was observed at the station(s) nearest the test condenser inlet in those experiments with low pressure and low mass velocities. In this case, the static pressure at each station was read directly from the inlet pressure gauge. However, because the gauge had a relatively low resolution (2 psi) which generally exceeded the magnitude of pressure recovery, additional uncertainty would be introduced into the static pressure values in these experiments.

All the above-mentioned factors plus fluctuation in pressure measurements as described in Appendix B caused scattering of the pressure drop data at low flow rates. In future studies, if pressure drop information is of great importance, it will be advisable to replace the present manometer by other instruments with higher resolution, e.g., an inclined tube manometer or an inverted U-tube with refrigerant liquid under refrigerant vapor as described [206].

Flow rate

During the course of an experiment, the test condenser coolant flow rate, the test fluid flow rate, and the after-condenser coolant flow rate were measured. The measurements for the latter two flow rates were made with rotameters. For the former one, either a rotameter or a weight tank was used, depending on the flow rate
Pertinent information about these rotameters is as follows:

**Test condenser coolant flowmeter:**
- Brooks Rotameter, Type 1114
- Tube number: R-8M-25-2
- Float number: 8-RV-3, stainless steel
  - Range 10% - 100%
  - Resolution 1.0%

**Test fluid flowmeter:**
- Brooks Rotameter, Type 1110
- Tube number: R-8M-25-2
- Float number: 8-RV-3, 8RV-31, stainless steel
  - Range 10% - 100%
  - Resolution 1.0%

**After condenser coolant flowmeter:**
- Brooks Rotameter, Type 1110
- Tube number: R-10M-25-2
- Float number: 10-RS-64
  - Range: 0 - 250 mm
  - Resolution: 1.0 mm

The test condenser coolant flowmeter was calibrated in place by timing the passage of a known mass of water using a large tank on a scale and a stop watch. A linear least-square regression technique was applied to these data. The resultant equation was
\[ \dot{m} = 2.79423M - 20.35313 \]  
\[ \dot{m} \text{ in lbm/hr} \quad M \text{ in percentage} \]

Since the calibration was done at a constant temperature (61°F), a correction factor had to be incorporated into the above equation to account for varied inlet coolant temperatures in the experiments. This factor, as suggested in the manufacturer's manual, is

\[ C_1 = \left( \frac{8.04 - \eta}{7.04\eta} \right)^{1/2} \eta \]  
\[ \text{(A.2)} \]

where

\[ \eta = \rho''/\rho' \]
\[ \rho' = \text{density of the calibrated fluid} \]
\[ \rho'' = \text{density of the metered fluid} \]

Within the range of inlet coolant temperatures, this factor varied between 0.984 and 1.003 and was thus neglected in the data reduction.

Usually the test condenser coolant flow rate exceeded the flow meter capacity; a weight tank system was thus employed. This system was operated by timing the passage of a known mass of water to a storage tank on a scale.

Over the wide range of the test fluid flow rates, one of the two floats was used with the test fluid flowmeter. This test fluid flowmeter was calibrated using both water and R-113 for the float 8RV-3. After the correction factor in Eq. (A.2) was applied to the calibration results using water, both data sets were in good agreement.
Hence, the water results were used. The resultant equation for the float 8RV-3 was

\[ \dot{m} = C_1(2.81297M - 20.21328) \quad (A.3) \]

\[ \dot{m} \text{ in lbm/hr} \quad M \text{ in percentage} \]

For the float 8RV-31,

\[ \dot{m} = C_1(8.0754M + 4.7467) \quad (A.4) \]

\[ \dot{m} \text{ in lbm/hr} \quad M \text{ in percentage} \]

As with other test flowmeters, an equation derived from linear regression to the calibration results was established for the after-condenser coolant flowmeter. The equation was

\[ \dot{m} = 15.7725M - 171.4679 \quad (A.5) \]

\[ \dot{m} \text{ in lbm/hr} \quad M \text{ in mm} \]

All these equations were incorporated into the data reduction code. In practice, the measurements of the three flow rates were satisfactorily made with the equipment described above.

**Boiler power**

Instrumentation was provided to monitor power delivered to the boiler. Since the heaters in the boiler were connected in three groups, each group could be separately controlled. Control for two of the groups was provided by on-off switches. Control of the
third group was accomplished by use of a Variac.

Power monitoring to the group controlled by the Variac was provided by an ammeter and a voltmeter installed in the circuit. This group provided power up to 4000 W. Power to each of the other two groups amounted to 3003 W with fluctuation up to 1 percent. This system of monitoring and control provided the necessary flexibility to operate the boiler at power levels from 0 to 10 kW.
APPENDIX B: EXPERIMENTAL PROCEDURE

Initial Testing

Upon completion of the modification of the apparatus, the refrigerant flow loop was checked for substantial leaks by filling the loop with compressed air at 60 psig. All seals and connections were examined for leaks using a soapy water solution. The flow loop was then cleaned by circulating hot water. By alternate applications of compressed air and evacuation by a vacuum pump, any water residue in the loop was eliminated.

Every time an installation of a new test tube was done, the test condenser was checked for fluid interchange between the inner tube and the annulus before it was connected to the loop. To do this, the annulus was filled with water and the test section was connected to an air supply which was maintained at about 5 psig. Any leak was indicated by bubbling air. Leaks occurred primarily at the pressure tap connections; they were fixed by tightening or by sealing with Epoxy.

Removal of Noncondensable Gases

The test fluid employed in the present study was R-113. Justification for its being used here and its thermodynamic and thermophysical properties are found in Appendixes A and C, respectively. A potential difficulty encountered with the operation
of the system with R-113 was the presence of noncondensable gases, particularly air.

The air content in the R-113 received was measured by a Seaton-Wilson Aire-Ometer and was typically 0.36cc/cc at 30°C(86°F) and atmospheric pressure. During the initial testing period, accumulated evidences indicated that the air content was reduced to a minimum level of 0.002cc/cc (mass fraction 2.6 x 10^{-4}) by operating the degassing tank for about 2 hours. Longer degassing times were utilized after installation of a new test tube.

Air removal from R-113 was done by boiling the fluid at the degassing tank. There was a stratification in the vapor phase due to the density difference of air and R-113 vapor, with the latter being heavier. The vapor mixtures passed through the degassing condenser and most of the R-113 was recovered. The normal procedure to reduce air content in R-113 was as follows:

1) Water was allowed to pass the after-condenser and the degassing condenser.
2) Liquid level at the degassing tank was checked. The valve at top of the degassing tank was fully opened.
3) The test fluid inlet valve and throttle valve were fully opened.
4) The valve at the bypass of the degassing tank was closed while the valve connected to the degassing tank was fully opened.
5) R-113, directed to pass the drier and filter, was circulated through the loop by operating the pump.

6) Input electric power to the degassing tank heater, controlled by a Variac, was set at its maximum level (2kW).

7) The operating temperature at the degassing tank was controlled by regulating the mass flow of R-113 through the tank at the valve connected to the tank. During the first hour of the degassing process, the temperature at the tank was several degrees below the saturation temperature at atmospheric pressure, thus allowing more fluid to go through the tank. Thereafter, the tank temperature was maintained at or near the saturation temperature.

A simple model, similar to the approach used in [207], was established to study the effect of 0.002cc/cc air concentration on the heat transfer coefficients. Under the worst possible situation, it was found that the noncondensable gas would induce a temperature drop of roughly 0.26°F at the interface. With typical temperature difference of 11°F at Section 4, this additional thermal resistance would cause 2 percent difference in the heat transfer coefficients. This resistance would have less effect on the overall heat transfer coefficient because of much higher overall temperature difference.
Details of the Experimental Procedure

Procedure

After completing the degassing process, the startup procedure for the experimental equipment was initiated. This consisted of the following steps:

1) The coolant inlet valve was fully open with the coolant exit valve only partly open.
2) The valve at the top of the degassing tank was nearly closed.
3) The valve at the bypass of the degassing tank was fully open while the valve connected to the degassing tank was closed.
4) The two valves connected to the drier and filter were then closed and the flow regulating valve, in parallel with the drier, was partly open.
5) The power at the boiler was turned on and was set at the desired level.
6) The after-condenser coolant flowmeter float was reset at a scale value of between 100 mm and 150 mm.
7) After the vapor phase was observed at the boiler sight glass, the steam inlet valves to the superheater and the coolant preheater were cracked open to discharge accumulated water in the line to the drain. These two valves were then slowly open to the desired level.
8) The test fluid throttle valve was adjusted to raise the test
condenser inlet pressure to a specified value.

9) Proper adjustments had to be made subsequently to the two flow regulating valves, the test fluid throttle valve, the coolant exit valve, and the input power to attain the desired inlet pressure, test fluid flow rate, and a tolerable exit quality.

Experiences indicated that improper start-up of the system would induce large vibration of the whole system, usually accompanied by a rising inlet pressure. This was avoided by following the above procedures and making small adjustments at step 9.

Since the variation of the heat transfer coefficient with mass velocity at a fixed inlet pressure was of interest, the test condenser inlet pressure and the test fluid flow rate were systematically varied. It was noted that the test condenser had to be operated with a two-phase flow in the condenser exit sight glass in order to assure positive exit quality and less condensate subcooling. Also, the test condenser coolant had to exit the condenser as a single-phase flow at the coolant exit sight glass to avoid boiling of the coolant.

After the system had reached steady or quasi-steady state as determined by repeated checks of the test condenser inlet pressure and temperature, the test fluid and the coolant flow rates, and the coolant outlet temperature, data acquisition started. A computer program was set up for the data acquisition system to record all temperature readings. Pressure readings, flow meter scale readings
and boiler power were manually input to the computer. Recording of the flow regime at the exit sight glass, as well as miscellaneous comments concluded the experiment.

Acceptance criteria

Because of quasi-steadiness of two-phase flow and fluctuations of some physical quantities during an experiment, criteria were established to judge the acceptance of the experiment. These criteria were purely empirical and were a compromise between ideal conditions and what were realistically obtainable.

Generally, an experiment for complete condensation was accepted when

a) The heat balance between the condensing medium and the coolant was less than ±5.0%,

b) The test fluid exit quality was greater than -2.0 percent or less than 5.0 percent, and

c) The test fluid inlet pressure varied by no more than ±2 psia during experiment.

Besides the above three criteria, the calculated overall pressure drop for an experiment had to conform to the trend exhibited by other experiments in the same set. This additional constraint was necessary because of the uncertainty in pressure measurements described in the preceding Appendix as well as in a subsequent section.

An experiment satisfying the above four criteria was called a "valid" run. However, these criteria were not inviolate, and some
experimental runs were retained under extenuating circumstances. Also, the second criterion did not apply to those experiments pertaining to the heat flux effect study.

Discussions of Experimental Facility Operation

Consistency and repeatability

The characteristics of two-phase flow, the above-mentioned acceptance criteria, and varied coolant inlet temperature and flow rate in each experiment collectively posed a great concern as to the consistency and repeatability of the data. Experience with the facility demonstrated that no experiment could be truly repeated because of fluctuations of some system parameters, i.e. inlet pressure, coolant flow rate, etc.

For a fixed heat duty (constant test fluid mass flow rate) and inlet conditions, varied coolant inlet temperatures would affect the heat flux distribution along the test condenser. This, in turn, would modify the quality distribution and flow regimes at the condenser. Consequently, the sectional average heat transfer coefficients would be different. However, how the overall average heat transfer coefficients were affected had still to be justified.

Runs 5.008/5.009 and Runs 6.021/6.022 were devised especially to study the effect of heat flux distribution on the overall average heat transfer coefficient. Each set had approximately the same conditions except the coolant inlet temperature and coolant flow
rate. The heat transfer coefficients were found to have a difference of 15 percent and 8 percent respectively. These values were close to, or within, the experimental uncertainty. On the other hand, for Tubes 1, 2, and 5, sets of experimental runs corresponding to a specific inlet pressure had a wide range of inlet coolant temperature. These occurred at 80 psia for Tube 1, 65 and 80 psia for Tube 2, and 35 and 50 psia for Tube 5. As shown in Figs. 7, 43, and 59, each set of these data exhibited an expected trend. Hence, the effect of heat flux distribution on the overall average heat transfer coefficient, if any, was so small that the effect could be considered negligible.

Varying coolant inlet temperature also brought about changes in coolant flow rate. These changes altered the thermal resistance in the annulus. Plotted in Fig. 107 was the ratio of overall average heat transfer coefficients, $\frac{h_{\text{exp}}}{h_{\text{cal}}}$, versus $\frac{(T_{s}-T_{w1})/(T_{w0}-T_{c})}{h_{\text{cal}}}$ for all smooth tube experiments, where $h_{\text{cal}}$ were calculated from the Boyko and Kruzhilin correlation. The latter ratio is directly proportional to the ratio of outside wall heat transfer coefficient and condensing heat transfer coefficient. An examination of this figure indicated that the temperature differences ratio would hardly have any effect on the experimental results.

In conclusion, within the experimental uncertainty, the experimental results were, in general, internally consistent. Expected trends were conformed to and the data were not erratic in nature.
Fig. 107. Ratio of overall heat transfer coefficients, $h_{\text{exp}}/h_{\text{cal}}$, versus $(T_s - T_w)/(T_w - T_c)$. 
System stability

The stability considered here pertained to the test facility as a whole and also to the condensing process. In general, stable operation was obtained for all experiments by properly adjusting the two flow regulating valves and the test fluid throttle valve. The occasional instability which occurred during the course of an experiment came from sudden drop or rise in coolant flow rate. Under this situation, the system would shift to another operation point. Depending on the original operating state, the system would return to this state rather quickly or slowly after the coolant flow rate was restored to the original level. At higher inlet pressures, stable operation was readily attained.

Due to the inherent stochastic nature of two-phase flow, fluctuations were detected in wall temperatures, pressure drops and inlet pressure. The magnitude of these fluctuations depended on inlet conditions as well as fluctuations of other quantities such as coolant flow rate, power supply, etc. In general, for all experiments, wall temperature fluctuations amounted to 0.02 mv only and were thus not significant. As for pressure drops and inlet pressure, larger oscillations were found in the case of the heat flux study wherein a two-phase mixture entered the test condenser directly. A maximum fluctuation of 0.8 in. Hg was observed at the mercury manometer for Section 4 and 0.5 psi at the inlet pressure gage. Usually, for the complete condensation and superheat studies, higher
oscillations were often located at the first two sections nearest the condenser inlet. A typically smaller pressure drop fluctuation of 0.02 in. Hg was found. The magnitude of the inlet pressure fluctuation was also smaller in these cases. A typical value was 0.25 psi.

Pressure drop and inlet pressure fluctuations were also affected by inlet pressure level. At lower inlet pressure, the fluctuations tended to be larger. The inlet pressure fluctuation was phenomenally augmented at $P_{\text{in}} = 2.41$ bar when the test fluid was directed to bypass the superheater and part of the supplied boiler power was used to dry the wet vapor. In some cases, as the inlet pressure oscillation became comparatively large, alternating flow regimes were observed at the exit sight glass. The same phenomenon was reported by Wedekind and Bhatt [208] in their study of transient flow surges in condensing flow.

There was no significant difference in operating stability as well as the above-mentioned fluctuations for all tubes tested at high flow rates. The stability was greater with the enhanced tubes at low flow rates. In addition, with higher pressure drops in Tubes 2, 3, 4, the relatively small pressure drop fluctuations introduced less uncertainty in the data reduction for these tubes.
Thermodynamic Properties

The thermodynamic properties of R-113 are well-tabulated in the ASHRAE Thermodynamic Properties of Refrigerants [209]. However, in order to incorporate these properties in the computer program in the form of subprograms, workable equations for these properties were desired. The equations of the properties used in this study, unless otherwise stated, were adapted from [210]. The notation in parentheses following a specific property was the subprogram name of the corresponding property used in the data reduction program. The average absolute error \( s_1 \) between the calculated values and the tabulated values in [209] within the experimental range was also included for each property. The parameter \( s_1 \) was described in Chapter 4.

Enthalpy of saturated liquid (ENTL)

This quantity was calculated by taking the difference between the enthalpy of saturated vapor and the corresponding enthalpy of vaporization; \( s_1 = 0.48 \) percent.

Enthalpy of vapor (ENTV)

\[
i = 0.07963T + 1.159 \times 10^{-4}T^2/2 + 0.18505\rho g - 0.18505(4.035V + 0.0214V^2/2) + 25.198
\]
with $s_1 = 0.14$ percent

\[ i \text{ in Btu/lbm} \]
\[ P \text{ in psia} \]
\[ T \text{ in °R} \]
\[ \rho_g \text{ in lbm/ft}^3 \]

**Enthalpy of vaporization (HFG)**

\[ i = 0.18505TP \ln 10 v_g - v_1 (4330.98/T^2 - 9.2635/(T\ln 10) + 2.0539 \cdot 10^{-3}) \]

with $s_1 = 0.53$ percent

\[ i_{lg} \text{ in Btu/lbm} \]
\[ P \text{ in psia} \]
\[ T \text{ in °R} \]
\[ v \text{ in ft}^3/\text{lbm} \]

**Density of saturated liquid (R)**

\[ \rho_1 = 103.55 - 0.0712T - 6.36 \cdot 10^{-5}T^2 \]

with $s_1 = 0.008$ percent

\[ \rho_1 \text{ in lbm/ft}^3 \]
\[ T \text{ in °F} \]

**Density of vapor (RV)**

This quantity was obtained by solving the equation of state as follows:
\[(5 \cdot 10^{-5} T - 0.0214) p_g^3 + (2.618 \cdot 10^{-3} T - 4.035) p_g^2 + (5.728 \cdot 10^{-2} T) p_g - P = 0\]

with \( s_1 = 0.13 \) percent

\( p_g \) in \( \text{lbm/ft}^3 \)

\( P \) in psia

\( T \) in \( ^\circ\text{R} \)

**Saturation temperature (TSAT)**

Since there is no explicit expression for the saturation temperature, this quantity was estimated quite accurately from the second order polynomial fitted to the tabulated data in [209], in intervals as follows:

- \( 4.374 \) psia \(< P \leq 6.607 \) psia \( T = 467.166 + 14.6133 P - 0.598693 P^2 \)
- \( 6.607 \) psia \(< P \leq 10.07 \) psia \( T = 482.038 + 10.1741 P - 0.265311 P^2 \)
- \( 10.07 \) psia \(< P \leq 14.84 \) psia \( T = 496.903 + 7.2940 P - 0.125058 P^2 \)
- \( 14.84 \) psia \(< P \leq 21.19 \) psia \( T = 511.179 + 5.42424 P - 0.06357 P^2 \)
- \( 21.19 \) psia \(< P \leq 29.48 \) psia \( T = 526.236 + 4.06482 P - 0.03277 P^2 \)
- \( 29.48 \) psia \(< P \leq 58.49 \) psia \( T = 545.741 + 2.86183 P - 0.01423 P^2 \)
- \( 58.49 \) psia \(< P \leq 108.2 \) psia \( T = 578.073 + 1.74081 P - 0.004424 P^2 \)

with \( s_1 = 0.008 \) percent

\( P \) in psia

\( T \) in \( ^\circ\text{R} \)
Saturation pressure (PSAT)

\[
\log P = 33.0655 - 4330.98/T - 9.26351 \log T + 2.0539 \cdot 10^{-3} T
\]

with \( s_1 = 0.06 \) percent

P in psia

T in °R

Thermophysical Properties

Most of the thermophysical properties of R-113, except for vapor thermoconductivity and surface tension, were well-formulated and tabulated in the ASHRAE Thermophysical Properties of Refrigerants [211]. Hence these equations, unless otherwise stated, were readily copied from this source. As with the thermodynamic properties, the average absolute error \( s_1 \) was included.

Liquid thermoconductivity (KL)

\[
k_L = 0.57789 (0.0802 - 0.000205 T)
\]

with \( s_1 = 0.09 \) percent

\( k_L \) in Btu/hr-ft-°F

T in °C

Liquid specific heat at constant pressure (CPL)

\[
c_{pl} = 0.238846(-2.68086 + 3.21075 \cdot 10^{-2} T - 9.65643 \cdot 10^{-5} T^2
\]

\[+9.99343 \cdot 10^{-8} T^3\]
with $s_1 = 0.14$ percent

\[ c_{pl,1} \text{ in Btu/lbm}^{-\circ F} \]
\[ T \text{ in } ^\circ K \]

**Vapor specific heat at constant volume (CPV)**

\[ c_{pg} = 0.238846 \left(-0.10833 + 5.81502 \cdot 10^{-3} T - 1.70256 \cdot 10^{-5} T^2 + 1.98007 \cdot 10^{-8} T^3\right) \]

with $s_1 = 0.32$ percent

\[ c_{pg} \text{ in Btu/lbm}^{-\circ F} \]
\[ T \text{ in } ^\circ K \]

**Liquid viscosity (MUL)**

This property was obtained through a second-order polynomial by fitting the tabulated values in [211] at two temperature levels.

For $T \leq 609.6 \text{ R}$,

\[ \mu_1 = 10.48364 - 0.31393 T + 2.443 \cdot 10^{-5} T^2 \]

For $T > 609.6 \text{ R}$,

\[ \mu_1 = 4.13253 - 9.97482 \cdot 10^{-3} T + 6.35 \cdot 10^{-6} T^2 \]

with $s_1 = 0.80$ percent

\[ \mu_1 \text{ in centipoise} \]
\[ T \text{ in } ^\circ R \]
Vapor viscosity (MUV)

\[ \mu_g = -0.18404 + 1.54214 \cdot 10^{-3} T - 4.0957 \cdot 10^{-6} T^2 + 3.68034 \cdot 10^{-9} T^3 \]

with \( s_1 = 1.29 \) percent

\( \mu_g \) in centipoise

\( T \) in °K

Surface tension (SIGMA)

The formulation of this property was adapted from [212]

\[ \sigma = 1.3990 \cdot 10^{-3} (\rho_1 - \rho_v) (487.25 - T - 0.9)^{0.925} \]

with \( s_1 = 0.21 \) percent

\( \sigma \) in dyne/cm

\( T \) in °K
APPENDIX D: TEMPERATURE DISTRIBUTION ALONG A SINGLE FIN

In order to estimate the heat transfer through a single fin, the temperature distribution inside the fin has to be known. Presented here is a simple analysis which is somewhat different from that presented in [213]. The assumptions involved in this analysis are

a) Steady, one-dimensional heat flow

b) Constant physical properties

c) The fin geometry for the three finned tube tested here is trapezoidal. Axial conduction along the fin is neglected.

Fig. 108. Sketch illustrating one-dimensional conduction and convection through a trapezoidal fin.
After referring to Fig. 108, the differential equation governing the temperature distribution can be written as

\[ \frac{d}{dY} \left( A(Y) \frac{dT}{dY} \right) = \frac{2h_s}{k \cos \phi} \frac{\Delta Z}{(T - T_s)} \quad (D.1) \]

and the boundary conditions are as follows:

\[ Y = 0 \quad -k \frac{dT}{dY} = h_e (T_s - T_e) \]

\[ Y = H \quad T = T_w \]

where

\[ A(Y) = \frac{(B_0 - B_1) \Delta Z}{H} \quad Y + B_1 \Delta Z \]

By introducing the new variables \( \theta, Y', \) and several dummy variables, Eq. (D.1) can be transformed into

\[ Y'^2 \frac{d^2 \theta}{dY'^2} + Y' \frac{d\theta}{dY'} - Y'^2 \theta = 0 \quad (D.2) \]

where

\[ \theta \equiv T - T_s \]

\[ Y'^2 \equiv 4K^2 \left( Y + B_1 / \beta \right) \]

\[ K^2 \equiv \omega / \beta \]

\[ \omega \equiv \frac{2h_s}{k \cos \phi} \]
The boundary conditions become

\[ \frac{d\theta}{dY} = \frac{Y e^{-h} e^{\theta e}}{2kK^2} \quad \text{at} \quad Y = Y_e = 2\sqrt{\frac{B_1}{\beta}} \]

\[ \theta = \theta_o \quad \text{at} \quad Y = Y_o = 2\sqrt{\frac{H + B_1}{\beta}} \]

(The superscript "" on Y was dropped for convenience)

Equation (D.2) is Bessel differential equation with \( v = 0 \). Thus, the solution for Eq. (D.2) is

\[ \theta = C_1 I_o(Y) + C_2 K_o(Y) \]

\( I_o \) and \( K_o \) are the modified Bessel function of the first kind and of the third kind, respectively. The constants \( C_1 \) and \( C_2 \) are determined from the boundary conditions and are given by

\[ C_1 = \frac{(Y h \theta e / 2kK^2) K_o(Y_o) + K_1(Y_e)\theta_o}{I_1(Y_e)K_o(Y_o) + I_o(Y_o)K_k(Y_e)} \]

\[ C_2 = \frac{\theta_o I_1(Y_e) - (Y h \theta e / 2kK^2) I_o(Y_o)}{I_1(Y_e)K_o(Y_o) + I_o(Y_o)K_k(Y_e)} \]
After substituting the expression of \(C_1\) and \(C_2\) into Eq. (D.2) and manipulating the dummy variables, the temperature distribution in the fin is given by

\[
\theta = \theta_0 \frac{\frac{h_e}{k} \frac{\theta_e}{\theta_0} \frac{b_1}{\omega}}{I_0(Y_o)K_1(Y_e) + I_1(Y_e)K_0(Y_o)} (K_o(Y_o)I_o(Y) - I_o(Y_o)K_o(Y))
\]

\[
+ \frac{I_1(Y_e)K_o(Y) + K_1(Y_e)I_o(Y)}{I_0(Y_o)K_1(Y_e) + I_1(Y_e)K_0(Y_o)}
\]

The heat transferred at the base of fin is

\[
q_o = -kB_o \Delta Z \frac{d\theta}{dy} \bigg|_{Y=0} = \int_0^H 2h_s \Delta Z \theta_0 \frac{dy}{\cos \phi} + h_e B \Delta Z \theta_e
\]

\[
= -kB_o \Delta Z \sqrt{\frac{\omega}{\beta H + B}} \theta_0 \left[ \frac{\frac{h_e}{k} \frac{\theta_e}{\theta_0} \frac{b_1}{\omega}}{I_0(Y_o)K_1(Y_e) + I_1(Y_e)K_0(Y_o)} (K_o(Y_o)I_1(Y_o) + I_o(Y_o)K_1(Y_o))
\]

\[
+ \frac{K_1(Y_e)I_1(Y_o) - I_1(Y_e)K_1(Y_o)}{I_0(Y_o)K_1(Y_e) + I_1(Y_e)K_0(Y_o)} \right]
\]

The temperature excess, at the edge of the fin, \(\theta_e\), is given by
An examination of these expressions indicates that values of $h_s$ and $h_e$ have to be known. For the present study, the assumption was made that $h_s = h_e$. The formulations of $I_o$, $I_1$, $K_o$, and $K_1$ are given in [214].

The fin efficiency which is defined as

$$\eta_f = \frac{\text{actual heat transferred}}{\text{heat which would be transferred if entire fin area were at base temperature}}$$

is of interest and is calculated along with the finned tube data analysis. Table D.1 presents some typical values of $\eta_f$ for the three finned tubes tested in this study. Generally, the fin efficiency is high owing to high thermal conductivity of copper.

Table D.1. Typical values of fin efficiency for the three finned tubes

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.021</td>
<td>0.994</td>
<td>0.990</td>
<td>0.989</td>
<td>0.983</td>
<td>0.991</td>
</tr>
<tr>
<td>5.023</td>
<td>0.997</td>
<td>0.995</td>
<td>0.993</td>
<td>0.990</td>
<td>0.995</td>
</tr>
<tr>
<td>6.018</td>
<td>0.993</td>
<td>0.986</td>
<td>0.984</td>
<td>0.975</td>
<td>0.987</td>
</tr>
</tbody>
</table>
APPENDIX E: SAMPLE CALCULATION OF EXPERIMENTAL DATA

To illustrate the data reduction procedure, a sample calculation is performed here. Run 1.056, which was also considered for error analysis in Appendix E, was selected for this purpose.

For convenience, all units are in fmlt engineering system, and the some symbols presented are used in this appendix only.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient pressure, $P_{\text{amb}}$</td>
<td>14.293 psia</td>
</tr>
<tr>
<td>Ambient temperature, $T_{\text{amb}}$</td>
<td>81.8°F</td>
</tr>
<tr>
<td>Tube I. D., $D_i$</td>
<td>0.527 in.</td>
</tr>
<tr>
<td>Tube O. D., $D_o$</td>
<td>0.625 in.</td>
</tr>
<tr>
<td>Tube length, $L$</td>
<td>11.969 ft.</td>
</tr>
<tr>
<td>Tube thermal conductivity, $K$</td>
<td>220 Btu/hr-ft-°F</td>
</tr>
<tr>
<td>Cross section area ratio, $R$</td>
<td>$\frac{\text{area of equivalent smooth tube}}{\text{actual flow area}} = 1.0$</td>
</tr>
<tr>
<td>Number of activated heaters, $N$</td>
<td>3</td>
</tr>
<tr>
<td>Voltage across the adjusted heater, $V$</td>
<td>134.0 v</td>
</tr>
<tr>
<td>Current through the adjusted heater, $I$</td>
<td>8.90 A</td>
</tr>
<tr>
<td>Weight of coolant to be measured at the weight tank, $W$</td>
<td>8 lb</td>
</tr>
<tr>
<td>Elapsed time, $t$</td>
<td>84.7 sec</td>
</tr>
<tr>
<td>Test fluid flow rate, $W_f$</td>
<td>36%</td>
</tr>
<tr>
<td>Coolant flow rate at after-condenser, $W_a$</td>
<td>145.0 units</td>
</tr>
</tbody>
</table>
Boiler pressure, $P_b$ 85 psi
Test section inlet pressure, $P_{in}$ 81.4 psi
$\Delta P$ at Section 1, $\Delta P_1$ 0.42 in. Hg
$\Delta P$ at Section 2, $\Delta P_2$ 0.55 in. Hg
$\Delta P$ at Section 3, $\Delta P_3$ 0.82 in. Hg
$\Delta P$ at Section 4, $\Delta P_4$ 1.0 in. Hg

Recorded experimental conditions were

Coolant temperature at Station 1, $T_1$ 158.96°F
Coolant temperature at Station 2, $T_2$ 171.91°F
Coolant temperature at Station 3, $T_3$ 185.79°F
Coolant temperature at Station 4, $T_4$ 199.01°F
Coolant temperature at Station 5, $T_5$ 210.68°F

Test fluid temperature at test condenser inlet, $T_6$ 228.06°F

Test fluid temperature at after-condenser inlet, $T_7$ 245.27°F

Test fluid temperature at boiler exit, $T_8$ 244.58°F

Test fluid temperature at superheater inlet, $T_9$ 244.54°F

Test fluid temperature at superheater exit, $T_{10}$ 245.93°F

Test fluid temperature at after-condenser exit, $T_{11}$ 70.03°F

Coolant temperature at after-condenser exit, $T_{12}$ 63.60°F

Coolant temperature at after-condenser inlet, $T_{13}$ 56.62°F
Wall temperatures:

<table>
<thead>
<tr>
<th>T_14</th>
<th>179.78</th>
<th>T_15</th>
<th>191.22</th>
<th>T_16</th>
<th>135.38</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_17</td>
<td>193.48</td>
<td>T_18</td>
<td>193.07</td>
<td>T_19</td>
<td>---</td>
</tr>
<tr>
<td>T_20</td>
<td>189.47</td>
<td>T_21</td>
<td>192.66</td>
<td>T_22</td>
<td>193.00</td>
</tr>
<tr>
<td>T_23</td>
<td>196.66</td>
<td>T_24</td>
<td>191.83</td>
<td>T_25</td>
<td>200.66</td>
</tr>
<tr>
<td>T_26</td>
<td>204.02</td>
<td>T_27</td>
<td>200.97</td>
<td>T_28</td>
<td>203.24</td>
</tr>
<tr>
<td>T_29</td>
<td>204.85</td>
<td>T_30</td>
<td>208.72</td>
<td>T_31</td>
<td>199.40</td>
</tr>
<tr>
<td>T_32</td>
<td>210.12</td>
<td>T_33</td>
<td>212.28</td>
<td>T_34</td>
<td>209.12</td>
</tr>
<tr>
<td>T_35</td>
<td>212.03</td>
<td>T_36</td>
<td>216.62</td>
<td>T_37</td>
<td>210.57</td>
</tr>
<tr>
<td>T_38</td>
<td>217.23</td>
<td>T_39</td>
<td>213.55</td>
<td>T_40</td>
<td>212.38</td>
</tr>
<tr>
<td>T_41</td>
<td>217.69</td>
<td>T_42</td>
<td>221.08</td>
<td>T_43</td>
<td>221.38</td>
</tr>
<tr>
<td>T_44</td>
<td>225.06</td>
<td>T_45</td>
<td>222.58</td>
<td>T_46</td>
<td>221.88</td>
</tr>
<tr>
<td>T_47</td>
<td>227.99</td>
<td>T_48</td>
<td>223.00</td>
<td>T_49</td>
<td>223.61</td>
</tr>
</tbody>
</table>

Heat transfer area:

\[ A = \pi D_1 \frac{L}{2} = \frac{\pi(0.527)(11.969)}{12} = 1.6513 \text{ ft}^2 \]

Cross sectional flow area:

\[ A_x = \frac{\pi D_1^2}{4} = \frac{\pi(0.527)^2}{(4)(144)} = 1.515 \cdot 10^{-3} \text{ ft}^2 \]

Input power at boiler:
\[ 3.412(3003(N-1) + VI) = 3.412(3003(3-1) + (134)(8.9)) = 24561.62 \text{ Btu/hr} \]

Coolant flow rate at test condenser:

\[ m_{tc} = \frac{3600W}{84.7} = 340.02 \text{ lbm/hr} \]

Test fluid flow rate, Eq (A.4):

\[ \dot{m}_f = C_1(8.0754W_f + 4.7467) \]

\[ C_1 = \left(\frac{8.04 - \eta}{7.04\eta}\right)^{0.5} = \left(\frac{8.04 - 1.56}{(7.04)(1.56)}\right)^{0.5} \]

\[ = 1.198 \]

\[ \dot{m}_f = (1.20) [(8.0754)(36) + 4.7467] = 353.98 \text{ lbm/hr} \]

Coolant flow rate at after-condenser, Eq. (A.5):

\[ \dot{m}_a = 15.7725W_a - 171.4679 = 2115.54 \text{ lbm/hr} \]

Boiler pressure:

\[ P_b = P_{amb} + P_{amb} = 85 + 14.293 = 99.29 \text{ psia} \]

Test fluid inlet pressure:
\[ P_5 = P_{in} + P_{amb} - 3.3275 \cdot 10^{-3} \rho_{f,amb} \]
\[ = 81.4 + 14.293 - (3.3275 \cdot 10^{-3})(97.3) \]
\[ = 95.369 \text{ psia} \]

where the last term is the factor to correct for the head of condensate due to the difference in elevation between the pressure tap and the pressure gauge.

Test fluid static pressure at Sections 1, 2, 3, and 4:

\[ P_i = P_{i+1} - 0.49116 P_i + \rho_{f,amb} \Delta P_i / (12)^3 \]

where the last term accounts for the head of condensate displaced by mercury. Thus

\[ P_4 = 95.369 - 0.49116(1.0) + (97.3)(1.0)/(12)^3 \]
\[ = 94.934 \text{ psia} \]

\[ P_3 = 94.578 \text{ psi} \]

\[ P_2 = 94.338 \text{ psi} \]

\[ P_1 = 94.156 \text{ psi} \]
Heat transfer rate at each section:

\[ q_1 = \dot{m}_c c_p (T_{i+1} - T_i) \]

Thus

\[ q_1 = \dot{m}_c c_p (T_2 - T_1) = (340.02)(1)(171.91 - 158.96) \]

\[ = 4402.87 \text{ Btu/hr} \]

\[ q_2 = 4720.88 \text{ Btu/hr} \]

\[ q_3 = 4493.63 \text{ Btu/hr} \]

\[ q_4 = 3970.12 \text{ Btu/hr} \]

The total heat transfer rate is given by

\[ q_5 = q_1 + q_2 + q_3 + q_4 = 17587.51 \text{ Btu/hr} \]

Quality at test section inlet:

\[ x_5 = \frac{i_8(P_5, T_7) - i_1(P_5, T_{s,5})}{i_{18}(P_5, T_{s,5})} \]

\[ = \frac{114.40 - 63.67}{50.53} = 1.004 \]
where \( T_{s,5} \) is the saturation temperature corresponding to \( P_5 \) and \( i \) is enthalpy.

Quality at other stations was calculated in a way that accounts for sensible heat variation of both phases in addition to \( i_{lg} \).

Quality at Section 4:

\[
x_4 = \frac{\bar{i}_{lg} + 0.5(i_{lg,5} - i_{lg,4}) + 0.5(i_{g,5} - i_{g,4}) - q/\dot{m}_f}{\bar{i}_{lg} + 0.5(i_{lg,5} - i_{lg,4}) - 0.5(i_{g,5} - i_{g,4})}
\]

where \( \bar{i}_{lg} \) is evaluated at the section inlet and outlet conditions and

\[
q = \begin{cases} 
q_4 - \dot{m}_f [i_g(P_5, P_7) - i_g(P_5, T_{s,5})] & \text{if } x_5 > 1.0 \\
q_4 & \text{if } x_5 \leq 1.0 
\end{cases}
\]

Thus

\[
x_4 = \frac{50.572 + 0.5(0.101) + 0.5(0.053) - 3886.27/353.98}{50.572 + 0.5(0.101) - 0.5(0.053)}
\]

\[= 0.779\]

Quality at Sections 1, 2, and 3:

\[
x_i = \left( \frac{\bar{i}_{lg,i} - 0.5(\Delta i_{lg,i}) + 0.5(\Delta i_{g,i})}{\bar{i}_{lg,i} + 0.5(\Delta i_{lg,i}) - 0.5(\Delta i_{g,i})} \right) x_{i+1} + (\Delta i_{lg,i}) x_{i+1} - q_i/\dot{m}_f
\]
where

\[(\Delta i)_i = i_{i+1} - i_i\]

Thus

\[x_3 = \frac{0.779[50.636-0.5(0.0835)+0.5(0.0436)]-4493.63/353.98}{50.636+0.5(0.0835)-0.5(0.0436)} = 0.530\]

\[x_2 = 0.267\]

\[x_1 = 0.023\]

Heat transfer rate at after-condenser:

\[q_a = \dot{m}_a(T_{12} - T_{13}) = 2115.54(63.60 - 56.62)\]

\[= 14760.75 \text{ Btu/hr}\]

Test fluid energy transferred:

\[q_f = \dot{m}_f[i_{P_5P_7} - i_{P_{11}T_{11}}]\]

\[= 353.98(114.40 - 22.65) = 32477.80\]

Energy balance in percentage:
\[100\left(\frac{q_f - (q_5 + q_a)}{q_5 + q_a}\right) = \frac{32477.80 - (17587.51 + 14760.75)}{17587.51 + 14760.75} = 0.40\%\]

It can be shown that the application of Simpson's rule to calculate average \(T_w\) at a thermocouple station is identical to linearly averaging the three temperature readings at the station. Therefore, the sectional average wall temperature is given by

\[\overline{T_{w,i}} = \frac{\sum_{5+9i}^{13+9i} T_i}{\sum_{1}^{n_i} j} \quad (i = 1, 2, 3, 4)\]

where \(n_i\) is number of thermocouple junction \((n_i = 9)\). In case there is/are malfunctioning thermocouple(s), the above scheme was still used with the malfunctioning thermocouple(s) eliminated from the nominator and the numbers of malfunctioning thermocouple deducted from the denominator. This may introduce some uncertainty in the sectional average wall temperature; however, the uncertainty introduced is very small for smaller variation of wall temperatures at a station as in most cases in the present study.

Therefore,
\[ \bar{T}_{w,1} = \frac{179.78 + 191.22 + 185.38 + 193.07 + 189.47}{8} + \frac{192.66 + 193.0}{8} = 189.76^\circ F \]

\[ \bar{T}_{w,2} = 201.04^\circ F \]

\[ \bar{T}_{w,3} = 212.72^\circ F \]

\[ \bar{T}_{w,4} = 222.70^\circ F \]

\[ \bar{T}_{w,5} \text{ (Tube)} = 207.03^\circ F \]

Heat fluxes are given by

\[ q_i = \frac{q_1}{\pi D_i L} \]

Thus

\[ q_1 = \frac{q_1}{\pi D_i (L/4)} = \frac{(4)(12)(4402.87)}{\pi (0.527)(11.969)} = 10664.95 \text{ Btu/hr-ft}^2 \]

\[ q_2 = 11436.26 \text{ Btu/hr-ft}^2 \]
\( \dot{q}_3 = 10884.79 \text{ Btu/hr-ft}^2 \)

\( \dot{q}_4 = 9616.72 \text{ Btu/hr-ft}^2 \)

\( \dot{q}_5 = 10650.43 \text{ Btu/hr-ft}^2 \)

The heat transfer coefficient is given by

\[
\bar{h}_i = \frac{1}{\left[ (\bar{T}_{s,i} - \bar{T}_{w,i})/q_i - \frac{D_i}{24K} \ln\left(\frac{T}{D_o}\right) \right]}
\]

where \( \bar{T}_{s,i} \) is the saturation temperature corresponding to \( \bar{P}_i = \frac{P_i + P_{i+1}}{2} \).

For the overall average, \( \bar{P}_5 = \frac{P_5 + P_1}{2} \)

Therefore,

\[
\bar{h}_1 = \frac{1}{\left[ (243.24-189.76)/10664.95 - \frac{0.527}{(24)(220)} \ln(0.527/0.625) \right]}
\]

\( = 200.08 \text{ Btu/hr-ft-°F} \)

\( \bar{h}_2 = 270.98 \text{ Btu/hr-ft}^2 \text{-°F} \)

\( \bar{h}_3 = 353.43 \text{ Btu/hr-ft}^2 \text{-°F} \)
\[ \bar{h}_4 = 453.65 \text{ Btu/hr-ft}^2\circ F \]

\[ \bar{h}_5 = 291.86 \text{ Btu/hr-ft}^2\circ F \]
APPENDIX F: ESTIMATION OF EXPERIMENTAL UNCERTAINTIES

Introduction

Experimental uncertainties arise from "errors" experienced in an experiment. There are three kinds of error: systematic error, illegitimate error, and random error. Systematic error is of consistent form and results from conditions or procedures that are improper but correctable. This type of error may generally be eliminated by calibration. Illegitimate error comes from mistakes in executing an experiment. It may be eliminated by care, proper laboratory procedures, and repetition of the measurement. Random error is accidental error that occurs in all measurements. It is characterized by its inconsistent nature and its origin can not be determined in the measurement process. This error must be estimated by statistical analysis.

In the present study, the illegitimate errors were eliminated by the well-controlled experimental procedure and care in manually recording data. The systematic errors consisted of precision of all measured or calculated physical quantities and of the instruments used. Most of these errors were estimated in [2] and can be used directly in the present study.

In a single-sample experiment, as in the present study, the random errors have to be estimated from the experience with the data
acquisition process. The probable random errors come from "scatter" in the instrument calibration data, fluctuating instrument reading and uncertainty of geometrical dimensions. All these errors together with the systematic errors were incorporated in the procedure to determine the uncertainty of the experimental quantities of interest in this experiment.

The experimental quantities of interest are heat transfer coefficient and pressure drop. The uncertainty with pressure drop measurements was directly related to the precision of the mercury manometer and measuring method used. These were discussed in Chapter 8 and Appendices A and B and is thus not presented here.

Propagation of Error

For a single-sample experiment, a procedure was suggested by Kline and McClintock [215] to estimate uncertainty in the experimental quantities which are not directly measurable. This procedure is termed propagation of error and has been considered adequate for this purpose. This procedure is illustrated here by applying it to a typical run (Run 1.056) to acquire an appreciation for the precision of the overall heat transfer coefficient calculations. The error as used here is the absolute value of maximum expected deviation. Thus, the estimation of the uncertainty is, to some extent, conservative.
From Eq. (3.1), the overall average heat transfer coefficient is calculated as

\[
\bar{h} = \frac{q}{A(T_s - \bar{T}_{wi})}
\]  

(3.1)

The uncertainty of \( \bar{h} \) is estimated as

\[
w_h = \left[ (\frac{\partial h}{\partial q} w_q)^2 + (\frac{\partial h}{\partial A} w_A)^2 + (\frac{\partial h}{\partial T_s} w_{T_s})^2 + (\frac{\partial h}{\partial T_{wi}} w_{T_{wi}})^2 \right]^{1/2}
\]

(F.1)

where

\[
\frac{\partial h}{\partial q} = \frac{1}{A(T_s - \bar{T}_{wi})}
\]

\[
\frac{\partial h}{\partial A} = -\frac{q}{A^2(T_s - \bar{T}_{wi})}
\]

\[
\frac{\partial h}{\partial T_s} = -\frac{q}{A(T_s - \bar{T}_{wi})^2}
\]

\[
\frac{\partial h}{\partial T_{wi}} = \frac{q}{A(T_s - \bar{T}_{wi})^2}
\]
w: experimental error or uncertainty

("-") is dropped for convenience.

With the experimental conditions of Run 1.056,

\[ A = \pi D_L = \pi \left( \frac{0.527}{12} \right) (11.969) = 1.65 \text{ ft}^2 \]

\[ T_s = 243.71 \text{ F} \]

\[ T_{wi} = 207.22 \text{ F} \]

\[ q = 17587.51 \text{ Btu/hr} \]

Thus,

\[ \frac{\partial h}{\partial q} = \frac{1}{1.65(243.71 - 207.22) / 60.22} = \frac{1}{60.22} \]

\[ \frac{\partial h}{\partial A} = \frac{17587.51}{(1.65)^2(243.71 - 207.22)} = -177.01 \]

\[ \frac{\partial h}{\partial T_s} = - \frac{\partial h}{\partial T_{wi}} = - \frac{17587.51}{(1.65)(243.71 - 207.22)^2} = -8.0 \]

(All units are in fmlt engineering system and are consistent. Thus, the units are not shown.)

The uncertainties \( w_q, w_A, w_{T_s}, \) and \( w_{T_{wi}} \) are estimated as in Eq. (F.1).

Estimate of \( w_q \)

\[ q = \dot{m} c_p (T_{out} - T_{in}) \]
Thus,

\[
\begin{align*}
\dot{w}_q &= \left[ \left( \frac{\partial q}{\partial \dot{m}_c} \dot{m}_c \right)^2 + \left( \frac{\partial q}{\partial c_p} c_p \right)^2 + \left( \frac{\partial q}{\partial T_{out}} T_{out} \right)^2 \right]^{1/2} \\
&\quad + \left( \frac{\partial q}{\partial T_{in}} T_{in} \right)^2 \\
&\quad + \text{heat exchange with the environment} \quad \text{(F.2)}
\end{align*}
\]

with

\[
\begin{align*}
\dot{m}_c &= 340.02 \text{ lbm/hr} \\
c_p &= 1.0 \text{ Btu/lbm}^{-\circ}\text{F} \\
T_{out} &= 210.68\circ\text{F} \\
T_{in} &= 158.96\circ\text{F}
\end{align*}
\]

Hence,

\[
\begin{align*}
\frac{\partial q}{\partial \dot{m}_c} &= c_p (T_{out} - T_{in}) = 1.0(210.68 - 158.96) \\
&= 51.72 \\
\frac{\partial q}{\partial c_p} &= \dot{m}_c (T_{out} - T_{in}) = 340.02(210.68 - 158.96) \\
&= 17585.83
\end{align*}
\]
\[
\frac{\partial q}{\partial T_{\text{out}}} = - \frac{\partial q}{\partial T_{\text{in}}} = \dot{m} c_p = 340.02
\]

The uncertainty, \( \dot{m}_c \), from using the weight tank system is calculated as

\[
\dot{m}_c = \sqrt{\left[ \left( \frac{\partial \dot{m}_c}{\partial W} w_W \right)^2 + \left( \frac{\partial \dot{m}_c}{\partial (\Delta t)} w_{\Delta t} \right)^2 \right]}
\]

\[
= \sqrt{\left[ \left( \frac{1}{\Delta t} w_W \right)^2 + \left( - \frac{w}{(\Delta t)^2} w_{\Delta t} \right)^2 \right]}
\]

with \( W = 8 \text{ lbm} \)

\( \Delta t = 84.7 \text{ sec} = 0.0235 \text{ hr} \)

\( w_W = 0.1 \text{ lbm} \)

\( w_{\Delta t} = \frac{1}{3600} \text{ hr} \)

Then,

\[
\dot{m}_c = \sqrt{\left[ \left( \frac{0.1}{0.0235} \right)^2 + \left( - \frac{8}{(0.0235)^2} \times \frac{1}{3600} \right)^2 \right]}
\]

\[
= \left[ 18.11 + 16.19 \right]^{1/2} = 5.86 \text{ lbm/hr}
\]
The uncertainty $w = 0.004 \text{ Btu/lbm-°F}$

The uncertainties $w_T_{out}$ and $w_T_{in}$ are determined by assuming that the partial derivative of each temperature ($T_{out}$ or $T_{in}$) with respect to the factors listed below is unity. Factors contributing to the uncertainty of $T_{out}$ or $T_{in}$ are

- Uncertainty due to thermocouple wire inaccuracies: ±0.75°F
- Uncertainty due to voltmeter errors: nil
- Uncertainty due to ice point reference junction: ±0.09°F
- Uncertainty due to computer conversion of mV to °F: ±0.02°F
- Uncertainty due to fin effect of thermocouple well: ±0.1°F

Therefore,

$$w_T_{out} = w_T_{in} = \left[ (0.75)^2 + (0.09)^2 + (0.02)^2 + (0.1)^2 \right]^{1/2}$$

$$= 0.76°F$$

The heat exchange with the environment was small because the outer tube of the section was insulated by Rubatex Tubing and Pipe Insulation with $k = 0.26 \text{ Btu/hr-ft-°F}$. It was estimated that the heat loss to the environment was less than 2 percent of the heat transferred. After substituting all these values into Eq. (F.2),
\[
  w_q = \left[ (51.72 \times 5.86)^2 + (17585.83 \times 0.004)^2 + (340.02 \times 0.76)^2 
    + (-340.02 \times 0.76)^2 \right]^{1/2} + 0.02 \times 17587.51
  = 831.7 \text{ Btu/hr}
\]

---

\textbf{Estimate of } w_A \textbf{A}

\[ A = \pi D_i L \]

Thus,

\[ w_A = \left[ \left( \frac{\partial A}{\partial D_i} w_{D_i} \right)^2 + \left( \frac{\partial A}{\partial L} w_L \right)^2 \right]^{1/2} \tag{F.3} \]

\[ w_A = \left[ (\pi \times D_i w_{D_i})^2 + (\pi \times D_i w_L)^2 \right]^{1/2} \]

with

\[ D_i = 0.0439 \text{ ft} \]

\[ L = 11.969 \text{ ft} \]

\[ w_{D_i} = 0.001 \text{ ft} \]

\[ w_L = 0.01 \text{ ft} \]

Then,

\[ w_A = \left[ (\pi \times 1.969 \times 0.001)^2 + (\pi \times 0.0439 \times 0.01)^2 \right]^{1/2} \]

\[ = 0.038 \text{ ft}^2 \]
Estimate of $w_{Ts}$

The average saturation temperature was derived from the arithmetic mean of inlet and exit static pressures:

$$T_s = T(\overline{P}_s)$$

Therefore

$$w_{T_s} = \left[ \left( \frac{\partial T}{\partial P_s} w_{P_s} \right)^2 \right]^{1/2} + w_{P \rightarrow T}$$

The uncertainty, $w_{P_s}$, was determined as follows:

$$\overline{P}_s = \frac{(P_{in} + P_{out})}{2}$$

$$= \left[ P_{in} + (P_{in} + \Delta P) \right] / 2$$

$$= \left[ 2P_{in} + \Delta P \right] / 2 = P_{in} + \Delta P / 2$$

Hence,

$$w_{P_s} = \left[ \left( \frac{P_s}{P_{in}} w_{P_{in}} \right)^2 + \left( \frac{P_s}{\Delta P} w_{\Delta P} \right)^2 \right]^{1/2}$$

$$= \left( w_{P_{in}}^2 + \frac{1}{4} w_{\Delta P}^2 \right)^{1/2}$$

The partial derivative of $P_{in}$ or $\Delta P$ with respect to the factor listed below is again assumed to be unity. Factors contributing to the uncertainty of $P_{in}$ are

- Uncertainty due to pressure gauge errors: ±0.5 psia
Uncertainty due to gauge resolution: ±0.2 psia

Uncertainty associated with pressure measuring system: ±0.5 psia

Therefore,

\[ w_{p_{in}} = \left[ (0.5)^2 + (0.2)^2 + (0.5)^2 \right]^{1/2} \]

\[ = 0.73 \text{ psia} \]

Factors contributing to the uncertainty of ΔP are

Uncertainty due to mercury manometer errors: ±0.1 psil

Uncertainty due to gauge resolution: ±0.1 psil

Uncertainty associated with pressure measuring system: ±0.5 psil

Thus,

\[ w_{\Delta P} = \left[ (0.1)^2 + (0.1)^2 + (0.5)^2 \right]^{1/2} \]

\[ = 0.52 \text{ psi} \]

The uncertainty \( w_p \) is

\[ w_p = \left[ (0.73)^2 + \frac{1}{4} (0.52)^2 \right]^{1/2} \]

\[ = 0.77 \text{ psia} \]

The uncertainty \( w_{p\rightarrow T} \) comes from the calculation of \( T_s \) from \( P_s \) and is obtained from Appendix C as

\[ w_{p\rightarrow T} = \frac{0.008}{100} \left( 244.26 + 459.6 \right) = 0.06^\circ F \]
With \( \frac{3T}{3P_s} = 0.9 \) calculated from the thermodynamic property formula,

\[
\omega_{T_s} = 0.9 \times 0.77 + 0.06
\]

\[
= 0.75^\circ F
\]

Estimate of \( \omega_{T_{wi}} \)

\[
\bar{T}_{T_{wi}} = \bar{T}_{T_{wo}} + \frac{q}{2\pi k L} \ln \frac{D_0}{D_1}
\]

since the heat resistance at the wall is small, the uncertainty involved is insignificant as compared to the uncertainty of \( T_{wo} \). Thus,

\[
\frac{\omega_{T_{wi}}}{\omega_{T_{wo}}} = 1
\]

In order to evaluate \( \omega_{T_{wo}} \), the uncertainty associated with a wall temperature has to be estimated first.

The uncertainty in wall temperature comes partly from the precision of the sensing devices and partly from the scheme used to measure the wall temperatures. The latter part was discussed in detail in [2] and its results can be used directly here.

As with other measured physical quantities, the partial derivative of each wall temperature with respect to the factors listed below is assumed to be unity. Factors contributing to the uncertainty of \( T_{wo} \) are
Uncertainty due to thermocouple wire inaccuracies: 0.75°F
Uncertainty due to voltmeter errors: nil
Uncertainty due to ice point reference junction: 0.09°F
Uncertainty due to computer conversion of mV to °F 0.02°F
Uncertainty associated with attachment method: 2.0°F

Therefore,

\[ w_{T_{wo}} = \left[ (0.75)^2 + (0.09)^2 + (0.02)^2 + (2.0)^2 \right]^{1/2} \]

\[ = 2.14°F \]

The uncertainty of the average wall temperature is calculated as

\[ \bar{T}_{wo} = \frac{1}{n} \sum_{i=1}^{n} T_{wo_i} \]

\[ w_{T_{wo}} = \left[ \sum_{i=1}^{n} \left( \frac{\partial \bar{T}_{wo}}{\partial T_{wo_i}} w_{T_{wo}} \right)^2 \right]^{1/2} \]

\[ = \left[ \sum_{i=1}^{n} \left( w_{T_{wo}} / n \right)^2 \right]^{1/2}. \]

with \( n = 36 \)

\[ w_{T_{wo}} = \left[ n \left( \frac{w_{T_{wo}}}{n} \right)^2 \right]^{1/2} = \left( \frac{2.14}{36} \right)^{1/2} \]

\[ = 0.24°F \]

However, this value would be higher if there was any malfunctioning.
thermocouple. Thus, the uncertainty of the individual temperature measurement is used:

\[
\begin{align*}
\frac{w}{T_w} &= 2.14^\circ F \\
\end{align*}
\]

Substituting the values of the uncertainties in Eq. (F.1),

\[
\begin{align*}
\frac{w}{h} &= \left[ \left( \frac{-1}{60.22} \times 831.7 \right)^2 + (-177.01 \times 0.038)^2 + (-8.0 \times 0.75)^2 + (8.0 \times 2.14)^2 \right]^{1/2} \\
&= 24.0 \text{ Btu/hr-ft}^2\circ F \\
\end{align*}
\]

Thus, for Run 1.056

\[
\bar{h} = 291.8 \pm 24.0 \text{ Btu/hr-ft}^2\circ F
\]

The uncertainty of the overall heat transfer coefficient is thus about \pm 10 percent for a typical experimental run. It is expected that the uncertainty increases as the temperature difference becomes smaller as happened at some sections with the augmented tubes. It is also noted the major uncertainty in the overall heat transfer coefficient arise from the energy transfer and the wall temperature measurement.
Table G.1. Selected geometrical parameters of the experimental tubes

<table>
<thead>
<tr>
<th>Tube Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Smooth</td>
<td>Twisted-Tape</td>
<td>Twisted-Tape</td>
<td>Fin</td>
<td>Fin</td>
<td>Fin</td>
<td>Repeated Rib</td>
<td>Repeated Rib</td>
</tr>
<tr>
<td>Material</td>
<td>Cu</td>
<td>Cu,SS</td>
<td>Cu,SS</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Outside Diameter</td>
<td>1.5875</td>
<td>1.5875</td>
<td>1.5875</td>
<td>1.5900</td>
<td>1.5875</td>
<td>1.2789</td>
<td>1.5875</td>
<td>1.5875</td>
</tr>
<tr>
<td>Inside Diameter</td>
<td>1.3386</td>
<td>1.3386</td>
<td>1.3386</td>
<td>1.3970</td>
<td>1.4707</td>
<td>1.1811</td>
<td>1.4605</td>
<td>1.4605</td>
</tr>
<tr>
<td>Equivalent Diameter</td>
<td>1.3843</td>
<td>0.8202</td>
<td>0.8202</td>
<td>0.6767</td>
<td>0.8260</td>
<td>0.7602</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>0.1016</td>
<td>0.1016</td>
<td>0.1016</td>
<td>0.0965</td>
<td>0.0584</td>
<td>0.0489</td>
<td>0.0635</td>
<td>0.0635</td>
</tr>
<tr>
<td>Total Wetted Perimeter</td>
<td>4.3489</td>
<td>6.9922</td>
<td>6.9922</td>
<td>8.1979</td>
<td>7.8750</td>
<td>5.3310</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Total Perimeter/ Nominal Perimeter</td>
<td>1</td>
<td>1.6078</td>
<td>1.6078</td>
<td>1.7279</td>
<td>1.7045</td>
<td>1.4368</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Cross-Sectional Area</td>
<td>1.5050</td>
<td>1.4338</td>
<td>1.4338</td>
<td>1.3864</td>
<td>1.6264</td>
<td>1.0129</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Tape Thickness</td>
<td>---</td>
<td>0.0516</td>
<td>0.0516</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

aAll dimensions in cm or cm\(^2\) as appropriate.
Table G.1. (continued)

<table>
<thead>
<tr>
<th>Tube Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Smooth</td>
<td>Twisted-Tape</td>
<td>Twisted-Tape</td>
<td>Fin</td>
<td>Fin</td>
<td>Fin</td>
<td>Repeated Rib</td>
<td>Repeated Rib</td>
</tr>
<tr>
<td>Material</td>
<td>Cu</td>
<td>Cu,SS</td>
<td>Cu,SS</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Fin Height</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.1448</td>
<td>0.0599</td>
<td>0.1735</td>
<td>0.0191</td>
<td>0.0305</td>
</tr>
<tr>
<td>Fin Base Width</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.1140</td>
<td>0.0475</td>
<td>0.1669</td>
<td>0.0218</td>
<td>0.0737</td>
</tr>
<tr>
<td>Fin Tip Width</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.0462</td>
<td>0.0277</td>
<td>0.0478</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Fin Auxiliary Dimension</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.0706</td>
<td>0.0599</td>
<td>0.0759</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Number of Fins</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>16</td>
<td>32</td>
<td>6</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Pitch, cm/360°</td>
<td>---</td>
<td>7.4498</td>
<td>12.3190</td>
<td>27.9400</td>
<td>30.4800</td>
<td>17.1450</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Distance between Repeated Ribs</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.2116</td>
<td>0.6350</td>
</tr>
<tr>
<td>Helix Angle</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>72°</td>
<td>60.5°</td>
</tr>
<tr>
<td>$P_{in}$ bar</td>
<td>Tube</td>
<td>n</td>
<td>C</td>
<td>Standard Deviation bar</td>
<td>Correlation Coefficient</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>------</td>
<td>----</td>
<td>----------</td>
<td>------------------------</td>
<td>-------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.41</td>
<td>1</td>
<td>1.956</td>
<td>1.492E-6</td>
<td>0.0013</td>
<td>0.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.036</td>
<td>1.754E-3</td>
<td>0.0172</td>
<td>0.98</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.587</td>
<td>3.640E-5</td>
<td>0.1337</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.312</td>
<td>2.565E-7</td>
<td>0.0610</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.592</td>
<td>2.597E-5</td>
<td>0.0095</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.892</td>
<td>3.659E-9</td>
<td>0.0062</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.303</td>
<td>8.866E-5</td>
<td>0.0712</td>
<td>0.82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.45</td>
<td>1</td>
<td>0.771</td>
<td>1.322E-3</td>
<td>0.0157</td>
<td>0.89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.090</td>
<td>8.143E-4</td>
<td>0.0179</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.518</td>
<td>4.252E-5</td>
<td>0.0141</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.195</td>
<td>3.904E-7</td>
<td>0.0007</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.648</td>
<td>1.242E-5</td>
<td>0.0244</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.246</td>
<td>2.087E-7</td>
<td>0.0184</td>
<td>0.94</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.404</td>
<td>1.110E-7</td>
<td>0.0050</td>
<td>0.98</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.48</td>
<td>1</td>
<td>0.883</td>
<td>7.538E-4</td>
<td>0.0060</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.108</td>
<td>5.263E-4</td>
<td>0.0296</td>
<td>0.95</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.399</td>
<td>6.582E-5</td>
<td>0.0811</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table G.2. (continued)

<table>
<thead>
<tr>
<th>Pin bar</th>
<th>Tube</th>
<th>n</th>
<th>C</th>
<th>Standard Deviation bar</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.48</td>
<td>5</td>
<td>1.860</td>
<td>2.276E-6</td>
<td>0.0126</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.823</td>
<td>3.260E-6</td>
<td>0.0103</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.059</td>
<td>4.779E-7</td>
<td>0.0079</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.060</td>
<td>6.732E-7</td>
<td>0.0158</td>
<td>0.92</td>
</tr>
<tr>
<td>5.52</td>
<td>1</td>
<td>1.456</td>
<td>1.674E-5</td>
<td>0.0191</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.474</td>
<td>4.411E-5</td>
<td>0.0612</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.317</td>
<td>1.135E-4</td>
<td>0.0194</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.320</td>
<td>8.778E-5</td>
<td>0.0115</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.531</td>
<td>1.223E-5</td>
<td>0.0161</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.019</td>
<td>7.489E-7</td>
<td>0.0172</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.528</td>
<td>2.643E-8</td>
<td>0.0378</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.682</td>
<td>1.254E-8</td>
<td>0.0478</td>
<td>0.95</td>
</tr>
<tr>
<td>6.55</td>
<td>1</td>
<td>1.487</td>
<td>1.245E-5</td>
<td>0.0115</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.085</td>
<td>9.139E-7</td>
<td>0.0792</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.254</td>
<td>1.434E-4</td>
<td>0.0447</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.253</td>
<td>1.151E-4</td>
<td>0.0153</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.852</td>
<td>1.310E-6</td>
<td>0.0341</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.812</td>
<td>2.414E-6</td>
<td>0.0430</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.102</td>
<td>2.033E-7</td>
<td>0.0140</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.014</td>
<td>5.343E-7</td>
<td>0.0180</td>
<td>0.97</td>
</tr>
</tbody>
</table>
Table G.3a. Tabulation of statistical information for curve fits to experimental overall heat transfer coefficients (Tubes 1-6)

<table>
<thead>
<tr>
<th>Pin bar (bar)</th>
<th>Tube</th>
<th>n'</th>
<th>C'</th>
<th>Standard Deviation $^2\text{W/m}^2\text{°C}$</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.41</td>
<td>1</td>
<td>0.677</td>
<td>40.721</td>
<td>190.6</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.403</td>
<td>266.423</td>
<td>168.5</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.617</td>
<td>96.100</td>
<td>23.0</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.530</td>
<td>215.909</td>
<td>249.2</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.712</td>
<td>65.788</td>
<td>51.1</td>
<td>1.00</td>
</tr>
<tr>
<td>3.45</td>
<td>1</td>
<td>0.609</td>
<td>55.737</td>
<td>8.8</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.637</td>
<td>60.115</td>
<td>7.3</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.671</td>
<td>65.294</td>
<td>65.1</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.525</td>
<td>221.941</td>
<td>77.6</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.711</td>
<td>59.544</td>
<td>162.9</td>
<td>1.00</td>
</tr>
<tr>
<td>4.48</td>
<td>1</td>
<td>0.673</td>
<td>37.625</td>
<td>77.5</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.661</td>
<td>52.687</td>
<td>147.4</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.553</td>
<td>142.185</td>
<td>485.0</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.409</td>
<td>400.272</td>
<td>331.4</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.711</td>
<td>56.467</td>
<td>132.7</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Table G.3a. (continued)

<table>
<thead>
<tr>
<th>Pin bar</th>
<th>Tube</th>
<th>n'</th>
<th>C'</th>
<th>Standard Deviation $\frac{\text{W}}{\text{m}^2 \cdot ^\circ \text{C}}$</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.25</td>
<td>1</td>
<td>0.586</td>
<td>61.450</td>
<td>45.5</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.670</td>
<td>46.940</td>
<td>78.4</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.647</td>
<td>53.038</td>
<td>167.8</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.589</td>
<td>104.390</td>
<td>128.4</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.400</td>
<td>385.887</td>
<td>870.8</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.735</td>
<td>46.182</td>
<td>209.8</td>
<td>0.99</td>
</tr>
<tr>
<td>6.55</td>
<td>1</td>
<td>0.565</td>
<td>65.281</td>
<td>99.4</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.673</td>
<td>43.453</td>
<td>99.6</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.669</td>
<td>44.379</td>
<td>54.8</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.579</td>
<td>104.740</td>
<td>185.5</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.393</td>
<td>365.791</td>
<td>153.2</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.726</td>
<td>46.361</td>
<td>90.3</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Table G.3b. Tabulation of statistical information for curve fits to experimental overall heat transfer coefficients (Tubes 7-8)

<table>
<thead>
<tr>
<th>Tube</th>
<th>$G$, kg/s-m$^2$</th>
<th>$P$, bar</th>
<th>$n'$</th>
<th>$C'$</th>
<th>Standard Deviation, W/m$^2$°C</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;231</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2.41</td>
<td>0.132</td>
<td></td>
<td>1195.447</td>
<td>81.2</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>3.45</td>
<td>0.030</td>
<td></td>
<td>2041.442</td>
<td>269.8</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
<td>-0.225</td>
<td></td>
<td>7362.950</td>
<td>36.2</td>
<td>-0.97</td>
</tr>
<tr>
<td></td>
<td>5.52</td>
<td>0.084</td>
<td></td>
<td>1464.810</td>
<td>143.0</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>6.55</td>
<td>0.100</td>
<td></td>
<td>1219.239</td>
<td>16.2</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>&gt;231</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2.41</td>
<td>0.727</td>
<td></td>
<td>49.365</td>
<td>58.7</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>3.45</td>
<td>0.690</td>
<td></td>
<td>59.810</td>
<td>289.8</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
<td>0.834</td>
<td></td>
<td>23.366</td>
<td>19.7</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>5.52</td>
<td>0.708</td>
<td></td>
<td>47.064</td>
<td>294.8</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>6.55</td>
<td>0.692</td>
<td></td>
<td>47.167</td>
<td>56.7</td>
<td>0.98</td>
</tr>
<tr>
<td>8</td>
<td>&lt;217</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.41</td>
<td>0.220</td>
<td></td>
<td>758.371</td>
<td>22.4</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>3.45</td>
<td>-0.068</td>
<td></td>
<td>3285.441</td>
<td>177.3</td>
<td>-0.26</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
<td>0.173</td>
<td></td>
<td>922.532</td>
<td>233.5</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>5.52</td>
<td>0.247</td>
<td></td>
<td>573.290</td>
<td>42.0</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>6.55</td>
<td>0.326</td>
<td></td>
<td>363.066</td>
<td>15.0</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>&gt;217</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.41</td>
<td>0.901</td>
<td></td>
<td>19.666</td>
<td>92.3</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>3.45</td>
<td>0.638</td>
<td></td>
<td>82.125</td>
<td>66.1</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
<td>0.579</td>
<td></td>
<td>111.498</td>
<td>45.5</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Table G.3b. (continued)

<table>
<thead>
<tr>
<th>Tube</th>
<th>G (kg/s·m²)</th>
<th>P (bar)</th>
<th>n'</th>
<th>C'</th>
<th>Standard Deviation (W/m²·°C)</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>&gt;217</td>
<td>5.52</td>
<td>0.603</td>
<td>89.192</td>
<td>120.7</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>6.55</td>
<td>0.622</td>
<td>74.162</td>
<td>31.5</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>
Table G.4. Statistical parameters for pressure drop calculations

<table>
<thead>
<tr>
<th>Correlations</th>
<th>$\bar{e}$</th>
<th>$s$</th>
<th>$s_1$</th>
<th>$s_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous I [8]</td>
<td>-0.740</td>
<td>0.663</td>
<td>63.44</td>
<td>-54.10</td>
</tr>
<tr>
<td>Homogeneous II [27]</td>
<td>-0.803</td>
<td>0.629</td>
<td>63.91</td>
<td>-60.41</td>
</tr>
<tr>
<td>Homogeneous III [23]</td>
<td>-0.283</td>
<td>0.636</td>
<td>52.28</td>
<td>-32.46</td>
</tr>
<tr>
<td>Homogeneous IV [29]</td>
<td>-0.719</td>
<td>0.606</td>
<td>60.15</td>
<td>-55.48</td>
</tr>
<tr>
<td>Miropol'skii et al. [31]</td>
<td>-0.328</td>
<td>0.613</td>
<td>53.28</td>
<td>-31.77</td>
</tr>
<tr>
<td>Lockhart &amp; Martinelli [35]</td>
<td>-0.663</td>
<td>0.627</td>
<td>54.21</td>
<td>-48.59</td>
</tr>
<tr>
<td>Modified Lockhart-Martinelli</td>
<td>0.184</td>
<td>0.802</td>
<td>48.94</td>
<td>-4.81</td>
</tr>
<tr>
<td>Chisholm [39]</td>
<td>0.077</td>
<td>1.485</td>
<td>95.31</td>
<td>29.97</td>
</tr>
<tr>
<td>Dukler II [29]</td>
<td>-0.524</td>
<td>0.608</td>
<td>46.31</td>
<td>-36.75</td>
</tr>
<tr>
<td>Modified Dukler II</td>
<td>-0.131</td>
<td>0.644</td>
<td>46.60</td>
<td>-22.27</td>
</tr>
</tbody>
</table>
Table G.5. Statistical parameters for comparison of the smooth-tube correlations

<table>
<thead>
<tr>
<th>Test Section</th>
<th>( e )</th>
<th>( s )</th>
<th>( s_1 )</th>
<th>( s_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akers et al. [90]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-4.16</td>
<td>22.20</td>
<td>8.43</td>
<td>-0.79</td>
</tr>
<tr>
<td>2</td>
<td>-63.71</td>
<td>65.13</td>
<td>24.54</td>
<td>23.87</td>
</tr>
<tr>
<td>3</td>
<td>-101.09</td>
<td>64.47</td>
<td>33.00</td>
<td>-32.50</td>
</tr>
<tr>
<td>4</td>
<td>-173.49</td>
<td>52.93</td>
<td>52.51</td>
<td>-52.51</td>
</tr>
<tr>
<td>Overall</td>
<td>-51.895</td>
<td>52.41</td>
<td>19.08</td>
<td>-17.76</td>
</tr>
<tr>
<td>Rosson and Myers [101]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-16.66</td>
<td>53.90</td>
<td>22.49</td>
<td>-8.85</td>
</tr>
<tr>
<td>2</td>
<td>-35.18</td>
<td>79.50</td>
<td>24.14</td>
<td>-11.85</td>
</tr>
<tr>
<td>3</td>
<td>-31.70</td>
<td>114.51</td>
<td>26.08</td>
<td>-7.96</td>
</tr>
<tr>
<td>4</td>
<td>-51.31</td>
<td>151.75</td>
<td>26.16</td>
<td>-11.27</td>
</tr>
<tr>
<td>Overall</td>
<td>-19.68</td>
<td>68.02</td>
<td>19.19</td>
<td>-4.90</td>
</tr>
<tr>
<td>Boyko and Kruzhilin [92]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>9.01</td>
<td>38.24</td>
<td>13.14</td>
<td>-1.27</td>
</tr>
<tr>
<td>2</td>
<td>72.76</td>
<td>61.01</td>
<td>19.76</td>
<td>15.13</td>
</tr>
<tr>
<td>3</td>
<td>86.38</td>
<td>70.52</td>
<td>17.37</td>
<td>15.15</td>
</tr>
<tr>
<td>4</td>
<td>30.68</td>
<td>86.09</td>
<td>13.20</td>
<td>0.26</td>
</tr>
<tr>
<td>Overall</td>
<td>32.45</td>
<td>53.98</td>
<td>12.01</td>
<td>4.89</td>
</tr>
</tbody>
</table>
Table G.5. (continued)

<table>
<thead>
<tr>
<th>Test Section</th>
<th>$\bar{e}$</th>
<th>$s$</th>
<th>$s_1$</th>
<th>$s_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soliman et al. [53]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>65.75</td>
<td>56.88</td>
<td>20.95</td>
<td>18.90</td>
</tr>
<tr>
<td>2</td>
<td>181.34</td>
<td>105.74</td>
<td>33.04</td>
<td>32.84</td>
</tr>
<tr>
<td>3</td>
<td>185.89</td>
<td>121.98</td>
<td>28.38</td>
<td>28.33</td>
</tr>
<tr>
<td>4</td>
<td>50.39</td>
<td>103.95</td>
<td>16.05</td>
<td>1.66</td>
</tr>
<tr>
<td>Overall</td>
<td>115.25</td>
<td>88.71</td>
<td>23.34</td>
<td>22.12</td>
</tr>
<tr>
<td>Traviss et al. [7]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.82</td>
<td>28.40</td>
<td>11.57</td>
<td>-3.39</td>
</tr>
<tr>
<td>2</td>
<td>83.10</td>
<td>56.86</td>
<td>20.28</td>
<td>17.92</td>
</tr>
<tr>
<td>3</td>
<td>88.01</td>
<td>66.41</td>
<td>16.68</td>
<td>15.59</td>
</tr>
<tr>
<td>4</td>
<td>8.03</td>
<td>61.75</td>
<td>10.86</td>
<td>-3.08</td>
</tr>
<tr>
<td>Overall</td>
<td>33.40</td>
<td>44.50</td>
<td>10.91</td>
<td>5.78</td>
</tr>
<tr>
<td>Azer et al. [80,81]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-119.69</td>
<td>28.60</td>
<td>138.63</td>
<td>-138.63</td>
</tr>
<tr>
<td>2</td>
<td>9.64</td>
<td>45.07</td>
<td>16.03</td>
<td>-2.33</td>
</tr>
<tr>
<td>3</td>
<td>130.02</td>
<td>87.07</td>
<td>23.75</td>
<td>21.69</td>
</tr>
<tr>
<td>4</td>
<td>176.24</td>
<td>150.07</td>
<td>23.59</td>
<td>20.38</td>
</tr>
<tr>
<td>Overall</td>
<td>-94.64</td>
<td>28.33</td>
<td>50.41</td>
<td>-50.41</td>
</tr>
</tbody>
</table>
Table G.5. (continued)

<table>
<thead>
<tr>
<th>Test Section</th>
<th>$-\bar{e}$</th>
<th>$s$</th>
<th>$s_1$</th>
<th>$s_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavallini and Zecchin [95]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>22.29</td>
<td>30.42</td>
<td>10.51</td>
<td>6.33</td>
</tr>
<tr>
<td>2</td>
<td>77.96</td>
<td>45.56</td>
<td>19.97</td>
<td>17.78</td>
</tr>
<tr>
<td>3</td>
<td>125.83</td>
<td>66.15</td>
<td>22.92</td>
<td>22.68</td>
</tr>
<tr>
<td>4</td>
<td>108.28</td>
<td>95.67</td>
<td>16.88</td>
<td>13.89</td>
</tr>
<tr>
<td>Overall</td>
<td>111.52</td>
<td>70.89</td>
<td>23.67</td>
<td>23.32</td>
</tr>
<tr>
<td>Shah [97]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-23.73</td>
<td>19.58</td>
<td>17.07</td>
<td>-16.20</td>
</tr>
<tr>
<td>2</td>
<td>45.54</td>
<td>35.39</td>
<td>14.52</td>
<td>10.44</td>
</tr>
<tr>
<td>3</td>
<td>74.09</td>
<td>47.62</td>
<td>15.34</td>
<td>14.23</td>
</tr>
<tr>
<td>4</td>
<td>9.87</td>
<td>60.07</td>
<td>10.70</td>
<td>-2.38</td>
</tr>
<tr>
<td>Overall</td>
<td>2.53</td>
<td>28.23</td>
<td>7.74</td>
<td>-2.30</td>
</tr>
</tbody>
</table>
Table G.6. Statistical parameters for comparison of the modified correlations for smooth tube with twisted tapes

<table>
<thead>
<tr>
<th>Tube</th>
<th>Section</th>
<th>$\bar{e}$</th>
<th>$s$</th>
<th>$s_1$</th>
<th>$s_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Modified Boyko and Kruzhilin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>60.924</td>
<td>67.524</td>
<td>12.657</td>
<td>9.162</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>158.621</td>
<td>97.352</td>
<td>15.549</td>
<td>15.491</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>193.232</td>
<td>118.948</td>
<td>16.722</td>
<td>16.182</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>-25.157</td>
<td>139.479</td>
<td>17.201</td>
<td>-5.032</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>86.057</td>
<td>87.250</td>
<td>10.737</td>
<td>8.334</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modified Traviss et al.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>62.180</td>
<td>41.671</td>
<td>16.370</td>
<td>15.359</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>174.482</td>
<td>62.782</td>
<td>24.292</td>
<td>24.292</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>224.680</td>
<td>106.982</td>
<td>24.466</td>
<td>24.466</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>75.865</td>
<td>89.173</td>
<td>8.472</td>
<td>6.985</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>126.483</td>
<td>70.083</td>
<td>18.553</td>
<td>18.553</td>
</tr>
</tbody>
</table>
Table G.6. (continued)

<table>
<thead>
<tr>
<th>Tube</th>
<th>Section</th>
<th>e</th>
<th>s</th>
<th>s₁</th>
<th>s₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
<td>-10.014</td>
<td>31.004</td>
<td>16.209</td>
<td>-11.463</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>63.513</td>
<td>55.334</td>
<td>14.230</td>
<td>10.697</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>67.534</td>
<td>81.224</td>
<td>13.329</td>
<td>10.593</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>-15.289</td>
<td>46.189</td>
<td>9.548</td>
<td>-6.837</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td>14.298</td>
<td>43.924</td>
<td>10.371</td>
<td>-1.290</td>
</tr>
</tbody>
</table>
APPENDIX H: DATA REDUCTION COMPUTER PROGRAM LISTING
0: dsp "Set top of form; then press CONT"; stp
1: dsp "sfgl for printing; EXC; CONT"; stp
2: wtc 6, 32
3: wtb 6, 27, 84; wtb 6, 27, 77
4: wtb 6, 27, 76, int(930/64), int(930)
5: dim A[12], L[102]; fxd 6
6: dim G[20], F[30], C[12], T[56], P[6], Q[6], X[5], U[4], H[4], I[12], J[12], C[70]
7: ent "Run no.", E; ent "Prescribed inlet pressure", P
8: fmt 1, "C", fz2.0, "E", z
9: fmt 2, "FLR7A1H03T1", z
10: for J = 0 to 9; J(J-4)(J-5)(J-6)(J-7)(J-8)(J-9) - ^A; if A#0; jmp 5
11: wrt 709.1, J
12: wrt 722.2; red 722, C
13: prt 'CUCONT'(1000C)
14: if J = 6; prt "Inlet superheat", 'CUCONT'(1000C) - 'TSAT'(P)
15: next J; spc
16: ent "0 for stable check, 1 for process", A
17: if A = 0; jmp -7
18: for J = 12 to 60; 0+L[J]; next J
19: for I = 1 to 2
20: for Y = 1 to 2
21: if Y = 2; 13+Z; jmp 2
22: 0+Z
23: for J = 30; J+12+18(Y-1) - W
24: wrt 709.1, J
25: wrt 722.2; red 722, V; (1000V+L[W])/I-L[W]
26: if I = 2; 'CUCONT'(L[W]) - T[W-11]
27: next J; 0+C
28: beep; dsp "Switch change"; wait 2000; if (1+C*C) < 6; jmp 0
29: next Y
30: wait 5000; next I
31: if flgl; jmp 2
32: jmp 8
33: wtb 6, 10, 10, 10, 10
34: fmt 2, "CHANNEL VOLTAGE, volts", 10x, "Temperature, F"; wrt 6.2
35: for J = 1 to 49; J-1+I
36: if I>30;I-18+I
37: fmt 4,"Channel #",f2.0,f10.6,10x,f10.3
38: wrt 6.4,I,L[J+11],T[J];next J
39: fmt 5,2/,"Run no.:",f10.3;wrt 6.5,E;wtb 6,12;cfg 1
40: ent "Ambient pressure, in.Hg",A;E+L[1];.49116A+A+L[2]
41: ent "Ambient Temperature,F",T;T+L[3]
42: 1+J
43: ent "Static pressure-psi",P[J];plt P[J];if P[J]=0;jmp 3
44: A+P[J]-3.327e-3'R'(T)+P[J];J+1+J;if J<5;jmp -1
45: jmp 2
46: ent "Pressure difference-in.Hg",I[J];plt I[J];jnp (J+1+J)>4
48: for J=1 to 4;5-J+B;P[B+1]-.49116P+I'R'(T)/123+P[B]
49: next J
50: for J=1 to 6;‘TSAT’(P[J])+T[50+J]
52: if J=6;gto +2
53: (P[J]+P[J+1])/2+‘TSAT’(P)+L[92+J]
54: next J
55: ent "No. of activated heater",S
56: ent "Voltage & Current",V,C;3003(S-1)+VC+P
57: ‘R’(T[11])/62.36583+V
58: ent "Weight-lb",M;ent "Elapsed time-sec",A;if M=0;jmp 2
59: 3600M/A+M;jmp 2
60: ent "Coolant flow rate",M;2.79423M-20.35313\*M
61: ent "Test fluid flow rate",F;V(2.81297F-20.21328)/(8.04-V)7.04V+F
62: ent "Aftercondenser flow rate",N;15.7725N-171.4679+M
63: 0+Q;for I=1 to 4;M(T[I+1]-T[I])+Q[I];Q+Q[I]+Q;next I
64: ('ENTV'(P[5],T[7])-’ENTL'(P[5],T[55]))/’HFG’(P[5],T[55])+X[5];T[55]+A
66: if X<5<1;ent "Inlet pressure",P;gto 16
69: for I=1 to 4;5-I+L
70: ('HFG’(P[L+1],T[51+L])+’HFG’(P[L],T[50+L]))/2+R
71: ‘ENTL’(P[L+1],T[51+L])-’ENTL’(P[L],T[50+L])\*R
if I=1; (r0+.5r1+.5r2-V/F)/(r0+.5r1-.5r2)\times X[L] ; jmp 2

((r0-.5r1+.5r2)X[L]+r1-Q[L]/F)/(r0+.5r1-.5r2)\times X[L]

next I

N(T[12]-T[13])\times Q[5]


if abs(G)>.05 or X[1]>.05 or X[1]<.01;prt 100G,X[1]; gto 16

ent "Flow regime observation", F$

ent "First run of the day; Yes=1, No=0", A

if A=0;jmp 6

ent "Inside & outside diameter - in", L[7], L[8]

ent "Length of test section - ft", L[9]

ent "Thermoconductivity of test section", r3

ent "Cross section area ratio", r4

ent "Tube geometry?", G$

ent "Date", A$

wtb 6,10,10,10; fxd 3


fmt 1,39x,"********* REDUCED DATA **********"; wrt 6.1

fmt 1,2,,"Run no. ", f10.3; wrt 6.1, L[1]

wrt 6, A$


wrt 6.1, L[2], L[3]

fmt 2, "TUBE GEOMETRY", 2x, c; wrt 6, G$

fmt 1,16x,"Di,in", f6.3, 8x, "Do, in", f6.3, 8x, "Length, ft ", f6.3; wrt 6.1, I, O, L

fmt 2, ",INPUT POWER AT BOILER, Btu/hr: ", f10.2; wrt 6.2, 3.412P

fmt 3,16x,"Test fluid", f10.2, 9x, "Coolant, AC", f10.2, 9x, "Test fluid", f10.2

wrt 6.3, M, N, P; fmt 4, ",MASS VELOCITY-1lbm/hr-ft2", f12.3; wrt 6.4, 576r4F/πI

fmt 7, "PRESSURE, psia: ", 16x, "Boiler ", f10.2; wrt 6.5, P[6]

fmt 16x,"Test section", 23x, ",1", 8x, ",2", 8x, ",3", 8x, ",4", 8x, ",5", 16x, "static pressure", 8x, 5f

wrt 6.6, P[1], P[2], P[3], P[4], P[5]

fmt 7, "TEMPERATURE, F: ", 16x, "Boiler", f10.3, 5x, "deg of superheat", f10.3

wrt 6.7, T[8], T[8]-T[56]
144: fmt 7,22x,"heat balance %",f8.2;wrt 6.7,100G
145: fmt 8,22x,"heat transfer coefficient",3x,5fl0.2
146: wrt 6.8,H[1],H[2],H[3],H[4],H
147: fmt /,"QUALITY";wrt 6
148: fmt 16x,"Test section",23x,"#1",8x,"#2",8x,"#3",8x,"#4",8x,"#5";wrt 6
149: fmt 1.45x,5fl0.3;wrt 6.1,X[1],X[2],X[3],X[4],X[5]
150: fmt /,"FLOW REGIME: ",2x,c;wrt 6.1,F$
151: ent "Comment?",C$
152: fmt /,"COMMENT: ",c;wrt 6.1,C$
154: for J=1 to 56;T[J]=L[11+J];next J;100G+L[61]
155: for J=1 to 6;P[J]=L[67+J];next J
156: for J=1 to 6;Q[J]=L[73+J];next J
157: for J=1 to 5;X[J]=L[79+J];next J
158: for J=1 to 4;U[J]=L[84+J];next J
159: for J=1 to 4;H[J]=L[88+J];next J;prt "Run no. ",L[1];spc 5
160: trk l;ent "File number",X
161: fdf X;idf Y,Y,Y,Y
162: if Y=0;gto "Mark"
163: X+1+X;jmp -2
164: "Mark":fmt /,f3.0
165: wrt 6,"Tape track: 1"," Tape file: ",X
166: mrk 1,850,A
167: if A<0;dsp "All marked";stp
168: rcf X,A$;L[*]
169: dsp "Tape recorded";stp
170: ent "Another run? Yes=1,No=0",A
171: if A=0;dsp "Run finish!";end
172: wtb 6,12;gto 7
173: "CUONT":
174: if pl<=1.494;ret 31.99925+46.80117pl-1.407396pl^2+.07802pl^3-.007394pl^4
175: if pl<=3.941;ret 33.42956+44.48835pl-.07422pl^2-.253895pl^3+.02878pl^4
176: if pl<=6.62;ret 33.82822+45.39092pl-1.015078pl^2+.0592pl^3-.00642pl^4
177: "PSAT":
178: pl+519.6+p2
179: ret 10^(33.0655-4330.98/p2-9.26351log(p2)+.0020539p2)
180: "TSAT":
181: if pl<=4.374; dsp "P<4.374 psia"; stp
182: if pl<=6.607; ret 467.165791+14.613273pl-.598593plpl-459.6
183: if pl<=10.07; ret 482.038164+10.17449pl-.265311plpl-459.6
184: if pl<=14.84; ret 496.903183+7.293994pl-.125058plpl-459.6
185: if pl<=21.19; ret 511.178705+5.424383pl-.06357plpl-459.6
186: if pl<=29.48; ret 526.236224+4.064817pl-.03277plpl-459.6
187: if pl<=58.49; ret 545.740863+2.861825pl-.01423plpl-459.6
188: if pl<=108.2; ret 578.073017+1.740811pl-.004424plpl-459.6
189: "RV":
190: p2+459.6+p2
191: if p2<=558.6;14+p3;jmp 5
192: if p2<=581.6;33+p3;jmp 4
193: if p2<=629.6;49+p3;jmp 3
194: if p2<=709.6;1+p3;jmp 2
195: if p2<=809.6;2.9+p3
197: C[K]+p3p5+p5;C[K]+p6 p6
198: for J=1 to 2;4-J+K
199: C[j]+p3p5+p5;C[j]+p6 p6;next J
201: if abs(p4)<le-7 and abs(p5)<le-7;jmp 2
202: p3-p4+p3;jmp -5
203: ret p3
204: "ENTL":
205: p2+p3;ENTV'(p1,p2)-HFG'(p1,p3)+p4;ret p4
206: "ENTV":
207: RV'(p1,p2)+p3
208: .07963p2+1.159e-4p2p2/2+.185053p1/p3-.185053(4.035p3+.0214p3p3/2)+p4
209: p2-459.6+p2
210: ret p4+25.198
211: "HFG":
212: RV'(p1,p2)+p3
213: p2-459.6+p4
214: p2(1/p3-1/R'(p4))p1ln(10)(4330.98/p2p2-9.2635/p2ln(10)+2.0539e-3)+p5
215: p2-459.6+p2
216: ret .185053p5
217: "R":
218: ret 103.55-.0712p1-6.36e-5p1p1
APPENDIX I: TABULATION OF EXPERIMENTAL DATA
Table I.1. Reduced data - heat transfer coefficients and static pressures

(Units as appropriate: kg/s sq m, W/sq m degree C, bar)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Mass Flux</th>
<th>Heat Transfer Coefficients</th>
<th>Static Pressures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1.012</td>
<td>191.5</td>
<td>1090.2</td>
<td>1469.0</td>
</tr>
<tr>
<td>1.013</td>
<td>208.2</td>
<td>1111.3</td>
<td>1506.0</td>
</tr>
<tr>
<td>1.014</td>
<td>224.8</td>
<td>1090.8</td>
<td>1557.9</td>
</tr>
<tr>
<td>1.018</td>
<td>189.5</td>
<td>761.0</td>
<td>1384.9</td>
</tr>
<tr>
<td>1.019</td>
<td>184.1</td>
<td>1310.0</td>
<td>1522.1</td>
</tr>
<tr>
<td>1.020</td>
<td>165.7</td>
<td>1053.7</td>
<td>1319.5</td>
</tr>
<tr>
<td>1.021</td>
<td>193.0</td>
<td>1162.1</td>
<td>1478.4</td>
</tr>
<tr>
<td>1.022</td>
<td>217.1</td>
<td>1178.6</td>
<td>1490.8</td>
</tr>
<tr>
<td>1.023</td>
<td>232.3</td>
<td>1190.0</td>
<td>1550.2</td>
</tr>
<tr>
<td>1.024</td>
<td>257.2</td>
<td>1277.7</td>
<td>1656.4</td>
</tr>
<tr>
<td>1.025</td>
<td>165.7</td>
<td>1227.5</td>
<td>1317.6</td>
</tr>
<tr>
<td>1.026</td>
<td>171.1</td>
<td>999.4</td>
<td>1207.7</td>
</tr>
<tr>
<td>1.027</td>
<td>195.6</td>
<td>1101.9</td>
<td>1341.2</td>
</tr>
<tr>
<td>1.028</td>
<td>211.2</td>
<td>1062.3</td>
<td>1349.1</td>
</tr>
<tr>
<td>1.031</td>
<td>232.4</td>
<td>1247.8</td>
<td>1407.1</td>
</tr>
<tr>
<td>1.033</td>
<td>111.3</td>
<td>589.2</td>
<td>991.6</td>
</tr>
<tr>
<td>1.034</td>
<td>155.2</td>
<td>683.6</td>
<td>1134.3</td>
</tr>
<tr>
<td>1.035</td>
<td>191.4</td>
<td>941.2</td>
<td>1289.3</td>
</tr>
<tr>
<td>1.036</td>
<td>122.4</td>
<td>718.6</td>
<td>1053.8</td>
</tr>
<tr>
<td>1.037</td>
<td>161.1</td>
<td>868.9</td>
<td>1131.1</td>
</tr>
<tr>
<td>1.038</td>
<td>203.4</td>
<td>887.7</td>
<td>1227.7</td>
</tr>
<tr>
<td>1.039</td>
<td>250.2</td>
<td>1056.9</td>
<td>1317.0</td>
</tr>
<tr>
<td>1.040</td>
<td>347.3</td>
<td>1380.6</td>
<td>2159.3</td>
</tr>
<tr>
<td>1.041</td>
<td>401.5</td>
<td>1446.1</td>
<td>2307.8</td>
</tr>
<tr>
<td>1.042</td>
<td>495.1</td>
<td>1700.5</td>
<td>2746.9</td>
</tr>
<tr>
<td>Run #</td>
<td>Mass Flux</td>
<td>Heat Transfer Coefficients</td>
<td>overall</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>1.043</td>
<td>586.4</td>
<td>1760.5</td>
<td>2928.3</td>
</tr>
<tr>
<td>1.044</td>
<td>406.0</td>
<td>1464.2</td>
<td>2179.3</td>
</tr>
<tr>
<td>1.045</td>
<td>484.1</td>
<td>1592.4</td>
<td>2390.7</td>
</tr>
<tr>
<td>1.046</td>
<td>590.9</td>
<td>1677.2</td>
<td>2747.2</td>
</tr>
<tr>
<td>1.047</td>
<td>330.4</td>
<td>1350.9</td>
<td>1936.0</td>
</tr>
<tr>
<td>1.048</td>
<td>313.1</td>
<td>1325.8</td>
<td>1814.8</td>
</tr>
<tr>
<td>1.049</td>
<td>414.3</td>
<td>1449.8</td>
<td>2154.6</td>
</tr>
<tr>
<td>1.050</td>
<td>492.4</td>
<td>1541.4</td>
<td>2386.3</td>
</tr>
<tr>
<td>1.051</td>
<td>591.2</td>
<td>1720.5</td>
<td>2730.5</td>
</tr>
<tr>
<td>1.052</td>
<td>325.6</td>
<td>1183.4</td>
<td>1671.0</td>
</tr>
<tr>
<td>1.053</td>
<td>409.6</td>
<td>1308.8</td>
<td>1983.6</td>
</tr>
<tr>
<td>1.054</td>
<td>507.8</td>
<td>1462.4</td>
<td>2277.4</td>
</tr>
<tr>
<td>1.055</td>
<td>603.1</td>
<td>1674.9</td>
<td>2556.3</td>
</tr>
<tr>
<td>1.056</td>
<td>335.9</td>
<td>1136.1</td>
<td>1538.6</td>
</tr>
<tr>
<td>1.057</td>
<td>407.0</td>
<td>1268.5</td>
<td>1835.4</td>
</tr>
<tr>
<td>1.058</td>
<td>498.7</td>
<td>1365.6</td>
<td>2130.8</td>
</tr>
<tr>
<td>1.059</td>
<td>596.5</td>
<td>1544.8</td>
<td>2440.9</td>
</tr>
<tr>
<td>1.060</td>
<td>321.5</td>
<td>1210.4</td>
<td>1631.2</td>
</tr>
<tr>
<td>1.061</td>
<td>321.5</td>
<td>1475.9</td>
<td>1863.2</td>
</tr>
<tr>
<td>1.062</td>
<td>321.5</td>
<td>2051.6</td>
<td>2229.9</td>
</tr>
<tr>
<td>1.063</td>
<td>319.7</td>
<td>1870.7</td>
<td>2246.2</td>
</tr>
<tr>
<td>1.064</td>
<td>321.4</td>
<td>1974.1</td>
<td>1816.8</td>
</tr>
<tr>
<td>1.065</td>
<td>321.3</td>
<td>1207.3</td>
<td>1703.4</td>
</tr>
<tr>
<td>1.066</td>
<td>322.3</td>
<td>1594.5</td>
<td>1935.9</td>
</tr>
<tr>
<td>1.067</td>
<td>321.5</td>
<td>2132.1</td>
<td>2263.1</td>
</tr>
<tr>
<td>1.068</td>
<td>321.5</td>
<td>2017.0</td>
<td>2310.9</td>
</tr>
<tr>
<td>1.069</td>
<td>317.1</td>
<td>1991.3</td>
<td>2157.6</td>
</tr>
<tr>
<td>1.070</td>
<td>321.1</td>
<td>1124.4</td>
<td>1030.7</td>
</tr>
<tr>
<td>1.071</td>
<td>322.5</td>
<td>1024.2</td>
<td>823.6</td>
</tr>
<tr>
<td>1.072</td>
<td>761.8</td>
<td>1220.2</td>
<td>1167.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run #</td>
<td>Mass Flux</td>
<td>Heat Transfer Coefficients 1</td>
<td>2</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>------------------------------</td>
<td>---</td>
</tr>
<tr>
<td>1.073</td>
<td>322.7</td>
<td>891.9</td>
<td>1349.3</td>
</tr>
<tr>
<td>1.074</td>
<td>322.7</td>
<td>1146.9</td>
<td>1603.5</td>
</tr>
<tr>
<td>1.075</td>
<td>322.2</td>
<td>1081.5</td>
<td>1516.1</td>
</tr>
<tr>
<td>1.076</td>
<td>321.9</td>
<td>1217.6</td>
<td>1668.9</td>
</tr>
<tr>
<td>1.077</td>
<td>321.9</td>
<td>1211.7</td>
<td>1678.3</td>
</tr>
<tr>
<td>1.078</td>
<td>321.8</td>
<td>1245.3</td>
<td>1725.8</td>
</tr>
<tr>
<td>1.079</td>
<td>321.8</td>
<td>1152.3</td>
<td>1677.6</td>
</tr>
<tr>
<td>2.001</td>
<td>185.5</td>
<td>1740.1</td>
<td>2307.3</td>
</tr>
<tr>
<td>2.004</td>
<td>257.1</td>
<td>1960.2</td>
<td>2632.3</td>
</tr>
<tr>
<td>2.005</td>
<td>276.8</td>
<td>2022.5</td>
<td>2635.0</td>
</tr>
<tr>
<td>2.006</td>
<td>174.9</td>
<td>1499.1</td>
<td>1751.8</td>
</tr>
<tr>
<td>2.007</td>
<td>182.3</td>
<td>1474.0</td>
<td>1770.5</td>
</tr>
<tr>
<td>2.008</td>
<td>207.7</td>
<td>1483.2</td>
<td>1947.3</td>
</tr>
<tr>
<td>2.009</td>
<td>225.3</td>
<td>1583.7</td>
<td>2044.5</td>
</tr>
<tr>
<td>2.010</td>
<td>224.3</td>
<td>1612.5</td>
<td>2036.9</td>
</tr>
<tr>
<td>2.011</td>
<td>265.0</td>
<td>1652.5</td>
<td>2219.1</td>
</tr>
<tr>
<td>2.012</td>
<td>276.8</td>
<td>1592.9</td>
<td>2219.5</td>
</tr>
<tr>
<td>2.013</td>
<td>168.1</td>
<td>1520.5</td>
<td>1664.6</td>
</tr>
<tr>
<td>2.014</td>
<td>187.2</td>
<td>1519.2</td>
<td>1843.8</td>
</tr>
<tr>
<td>2.015</td>
<td>212.1</td>
<td>1527.0</td>
<td>1921.7</td>
</tr>
<tr>
<td>2.018</td>
<td>257.1</td>
<td>1511.6</td>
<td>2112.6</td>
</tr>
<tr>
<td>2.019</td>
<td>179.2</td>
<td>1483.0</td>
<td>1648.1</td>
</tr>
<tr>
<td>2.020</td>
<td>198.5</td>
<td>1358.6</td>
<td>1602.5</td>
</tr>
<tr>
<td>2.021</td>
<td>165.1</td>
<td>1215.8</td>
<td>1474.8</td>
</tr>
<tr>
<td>2.022</td>
<td>162.7</td>
<td>1172.2</td>
<td>1397.5</td>
</tr>
<tr>
<td>2.024</td>
<td>196.9</td>
<td>1186.5</td>
<td>1520.0</td>
</tr>
<tr>
<td>2.025</td>
<td>220.1</td>
<td>1332.0</td>
<td>1701.2</td>
</tr>
<tr>
<td>2.028</td>
<td>161.4</td>
<td>1093.4</td>
<td>1323.6</td>
</tr>
<tr>
<td>2.029</td>
<td>193.0</td>
<td>1129.0</td>
<td>1478.5</td>
</tr>
<tr>
<td>2.030</td>
<td>222.3</td>
<td>1183.4</td>
<td>1606.8</td>
</tr>
<tr>
<td>Run #</td>
<td>Mass Flux</td>
<td>Heat Transfer Coefficients</td>
<td>Overall</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>----------------------------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.031</td>
<td>473.8</td>
<td>2044.0</td>
<td>3476.4</td>
</tr>
<tr>
<td>2.032</td>
<td>269.8</td>
<td>1758.6</td>
<td>2805.3</td>
</tr>
<tr>
<td>2.033</td>
<td>342.7</td>
<td>1857.3</td>
<td>3034.6</td>
</tr>
<tr>
<td>2.034</td>
<td>370.4</td>
<td>1957.5</td>
<td>3088.7</td>
</tr>
<tr>
<td>2.035</td>
<td>424.8</td>
<td>1956.5</td>
<td>3179.7</td>
</tr>
<tr>
<td>2.036</td>
<td>479.9</td>
<td>2184.9</td>
<td>3563.7</td>
</tr>
<tr>
<td>2.037</td>
<td>511.8</td>
<td>2000.3</td>
<td>3312.1</td>
</tr>
<tr>
<td>2.038</td>
<td>639.5</td>
<td>2141.8</td>
<td>4165.5</td>
</tr>
<tr>
<td>2.039</td>
<td>589.3</td>
<td>2145.3</td>
<td>3716.0</td>
</tr>
<tr>
<td>2.040</td>
<td>338.5</td>
<td>1783.3</td>
<td>2709.7</td>
</tr>
<tr>
<td>2.041</td>
<td>406.4</td>
<td>1847.5</td>
<td>2930.6</td>
</tr>
<tr>
<td>2.042</td>
<td>465.3</td>
<td>1666.8</td>
<td>2980.4</td>
</tr>
<tr>
<td>2.043</td>
<td>529.4</td>
<td>1863.0</td>
<td>3330.5</td>
</tr>
<tr>
<td>2.044</td>
<td>593.2</td>
<td>2206.7</td>
<td>3950.1</td>
</tr>
<tr>
<td>2.045</td>
<td>333.4</td>
<td>1464.2</td>
<td>2406.2</td>
</tr>
<tr>
<td>2.046</td>
<td>406.3</td>
<td>1649.2</td>
<td>2841.9</td>
</tr>
<tr>
<td>2.047</td>
<td>338.7</td>
<td>1465.0</td>
<td>2272.8</td>
</tr>
<tr>
<td>2.048</td>
<td>407.2</td>
<td>1540.6</td>
<td>2616.6</td>
</tr>
<tr>
<td>2.049</td>
<td>475.6</td>
<td>1598.9</td>
<td>2896.5</td>
</tr>
<tr>
<td>2.050</td>
<td>527.7</td>
<td>1900.6</td>
<td>3348.9</td>
</tr>
<tr>
<td>2.051</td>
<td>612.6</td>
<td>2109.9</td>
<td>3731.5</td>
</tr>
<tr>
<td>2.052</td>
<td>320.0</td>
<td>1234.2</td>
<td>2156.0</td>
</tr>
<tr>
<td>2.053</td>
<td>388.4</td>
<td>1527.2</td>
<td>2420.0</td>
</tr>
<tr>
<td>2.054</td>
<td>457.0</td>
<td>1649.9</td>
<td>2749.0</td>
</tr>
<tr>
<td>2.055</td>
<td>530.0</td>
<td>1762.1</td>
<td>3134.7</td>
</tr>
<tr>
<td>2.056</td>
<td>630.1</td>
<td>1906.0</td>
<td>3377.0</td>
</tr>
<tr>
<td>2.002</td>
<td>213.1</td>
<td>1794.8</td>
<td>2442.8</td>
</tr>
<tr>
<td>2.003</td>
<td>229.8</td>
<td>1826.8</td>
<td>2477.7</td>
</tr>
<tr>
<td>3.001</td>
<td>340.5</td>
<td>1521.9</td>
<td>2322.7</td>
</tr>
<tr>
<td>3.002</td>
<td>437.7</td>
<td>1761.5</td>
<td>2849.2</td>
</tr>
</tbody>
</table>
Table I.1. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Mass Flux</th>
<th>Heat Transfer Coefficients</th>
<th>Overall Static Pressures</th>
<th>inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3.003</td>
<td>532.4</td>
<td>1939.1</td>
<td>3190.1</td>
<td>3978.0</td>
</tr>
<tr>
<td>3.004</td>
<td>633.4</td>
<td>2277.7</td>
<td>3715.6</td>
<td>4425.1</td>
</tr>
<tr>
<td>3.005</td>
<td>339.1</td>
<td>1324.2</td>
<td>2118.0</td>
<td>2721.5</td>
</tr>
<tr>
<td>3.006</td>
<td>443.0</td>
<td>1613.1</td>
<td>2619.0</td>
<td>3051.5</td>
</tr>
<tr>
<td>3.007</td>
<td>535.2</td>
<td>1907.9</td>
<td>3101.7</td>
<td>5250.1</td>
</tr>
<tr>
<td>3.008</td>
<td>627.2</td>
<td>2186.3</td>
<td>3500.0</td>
<td>4234.3</td>
</tr>
<tr>
<td>3.009</td>
<td>120.0</td>
<td>1001.0</td>
<td>1290.2</td>
<td>1366.5</td>
</tr>
<tr>
<td>3.010</td>
<td>160.7</td>
<td>1001.1</td>
<td>1360.6</td>
<td>1577.2</td>
</tr>
<tr>
<td>3.011</td>
<td>198.1</td>
<td>1072.5</td>
<td>1494.2</td>
<td>1795.3</td>
</tr>
<tr>
<td>3.012</td>
<td>264.8</td>
<td>1229.2</td>
<td>1826.0</td>
<td>2309.3</td>
</tr>
<tr>
<td>3.013</td>
<td>123.9</td>
<td>915.6</td>
<td>1186.2</td>
<td>1311.0</td>
</tr>
<tr>
<td>3.014</td>
<td>175.0</td>
<td>1031.1</td>
<td>1392.6</td>
<td>1507.9</td>
</tr>
<tr>
<td>3.015</td>
<td>231.2</td>
<td>1095.6</td>
<td>1562.8</td>
<td>1932.9</td>
</tr>
<tr>
<td>3.016</td>
<td>276.5</td>
<td>1222.3</td>
<td>1760.7</td>
<td>2150.0</td>
</tr>
<tr>
<td>3.017</td>
<td>338.5</td>
<td>1461.9</td>
<td>2220.6</td>
<td>2815.7</td>
</tr>
<tr>
<td>3.018</td>
<td>388.4</td>
<td>2175.4</td>
<td>2653.1</td>
<td>2825.9</td>
</tr>
<tr>
<td>3.019</td>
<td>388.4</td>
<td>2865.8</td>
<td>2845.6</td>
<td>2909.1</td>
</tr>
<tr>
<td>3.020</td>
<td>388.4</td>
<td>2218.9</td>
<td>2823.8</td>
<td>2837.5</td>
</tr>
<tr>
<td>3.021</td>
<td>388.4</td>
<td>2690.0</td>
<td>2672.1</td>
<td>2973.6</td>
</tr>
<tr>
<td>3.022</td>
<td>388.0</td>
<td>1367.0</td>
<td>2262.1</td>
<td>2762.5</td>
</tr>
<tr>
<td>3.023</td>
<td>338.0</td>
<td>2201.9</td>
<td>2730.1</td>
<td>3206.8</td>
</tr>
<tr>
<td>3.024</td>
<td>341.5</td>
<td>2676.2</td>
<td>2792.1</td>
<td>2385.2</td>
</tr>
<tr>
<td>3.025</td>
<td>337.9</td>
<td>2827.4</td>
<td>2954.6</td>
<td>11742.6</td>
</tr>
<tr>
<td>3.026</td>
<td>336.3</td>
<td>2132.7</td>
<td>2530.3</td>
<td>2631.9</td>
</tr>
<tr>
<td>3.027</td>
<td>338.3</td>
<td>2123.4</td>
<td>2534.1</td>
<td>2672.1</td>
</tr>
<tr>
<td>3.028</td>
<td>338.1</td>
<td>2346.4</td>
<td>2632.3</td>
<td>2759.9</td>
</tr>
<tr>
<td>3.029</td>
<td>338.1</td>
<td>2802.2</td>
<td>2823.4</td>
<td>3072.0</td>
</tr>
<tr>
<td>3.030</td>
<td>338.1</td>
<td>2555.1</td>
<td>2893.2</td>
<td>3126.7</td>
</tr>
<tr>
<td>3.031</td>
<td>338.0</td>
<td>2414.6</td>
<td>2696.0</td>
<td>2795.0</td>
</tr>
<tr>
<td>3.032</td>
<td>338.0</td>
<td>2387.4</td>
<td>2706.3</td>
<td>2932.3</td>
</tr>
<tr>
<td>Run #</td>
<td>Mass Flux</td>
<td>Heat Transfer Coefficients 1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>-------------------------------</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>3.033</td>
<td>338.0</td>
<td>2299.7</td>
<td>2605.1</td>
<td>2729.1</td>
</tr>
<tr>
<td>3.034</td>
<td>338.0</td>
<td>2271.4</td>
<td>2573.0</td>
<td>2740.1</td>
</tr>
<tr>
<td>3.035</td>
<td>338.0</td>
<td>2265.7</td>
<td>2481.9</td>
<td>2566.2</td>
</tr>
<tr>
<td>3.036</td>
<td>338.2</td>
<td>2514.7</td>
<td>2623.4</td>
<td>2721.5</td>
</tr>
<tr>
<td>3.037</td>
<td>338.2</td>
<td>2381.6</td>
<td>1802.8</td>
<td>1709.9</td>
</tr>
<tr>
<td>3.038</td>
<td>338.6</td>
<td>1589.5</td>
<td>1662.5</td>
<td>1774.5</td>
</tr>
<tr>
<td>3.039</td>
<td>338.6</td>
<td>1204.9</td>
<td>1045.8</td>
<td>1105.0</td>
</tr>
<tr>
<td>4.001</td>
<td>327.0</td>
<td>2538.8</td>
<td>4147.4</td>
<td>4575.6</td>
</tr>
<tr>
<td>4.002</td>
<td>431.5</td>
<td>2654.0</td>
<td>5286.9</td>
<td>5814.9</td>
</tr>
<tr>
<td>4.003</td>
<td>510.7</td>
<td>3244.3</td>
<td>6412.1</td>
<td>6837.8</td>
</tr>
<tr>
<td>4.004</td>
<td>572.6</td>
<td>3457.0</td>
<td>6660.8</td>
<td>7368.1</td>
</tr>
<tr>
<td>4.005</td>
<td>327.6</td>
<td>2363.0</td>
<td>4039.6</td>
<td>3867.0</td>
</tr>
<tr>
<td>4.006</td>
<td>435.1</td>
<td>2671.4</td>
<td>4650.1</td>
<td>4888.3</td>
</tr>
<tr>
<td>4.007</td>
<td>514.3</td>
<td>3356.9</td>
<td>5404.1</td>
<td>6032.2</td>
</tr>
<tr>
<td>4.008</td>
<td>514.3</td>
<td>3100.7</td>
<td>5564.0</td>
<td>5889.8</td>
</tr>
<tr>
<td>4.009</td>
<td>604.3</td>
<td>3487.7</td>
<td>6540.0</td>
<td>6802.8</td>
</tr>
<tr>
<td>4.010</td>
<td>324.2</td>
<td>2362.7</td>
<td>3898.0</td>
<td>4524.8</td>
</tr>
<tr>
<td>4.011</td>
<td>426.5</td>
<td>2582.4</td>
<td>4315.7</td>
<td>5324.0</td>
</tr>
<tr>
<td>4.012</td>
<td>514.3</td>
<td>2858.1</td>
<td>4851.6</td>
<td>5955.4</td>
</tr>
<tr>
<td>4.013</td>
<td>617.1</td>
<td>3378.6</td>
<td>6185.9</td>
<td>7206.0</td>
</tr>
<tr>
<td>4.014</td>
<td>326.4</td>
<td>2041.1</td>
<td>3509.2</td>
<td>3717.7</td>
</tr>
<tr>
<td>4.015</td>
<td>432.0</td>
<td>2466.8</td>
<td>4422.8</td>
<td>4916.3</td>
</tr>
<tr>
<td>4.016</td>
<td>517.3</td>
<td>2729.4</td>
<td>5000.5</td>
<td>5604.4</td>
</tr>
<tr>
<td>4.017</td>
<td>603.5</td>
<td>3046.3</td>
<td>5731.2</td>
<td>6365.6</td>
</tr>
<tr>
<td>4.018</td>
<td>591.2</td>
<td>2908.2</td>
<td>5097.8</td>
<td>5800.4</td>
</tr>
<tr>
<td>4.019</td>
<td>515.8</td>
<td>2638.7</td>
<td>4650.2</td>
<td>4925.7</td>
</tr>
<tr>
<td>4.020</td>
<td>434.9</td>
<td>2358.9</td>
<td>4015.6</td>
<td>4391.2</td>
</tr>
<tr>
<td>4.021</td>
<td>338.0</td>
<td>2009.0</td>
<td>3365.4</td>
<td>3656.5</td>
</tr>
<tr>
<td>4.022</td>
<td>121.6</td>
<td>1664.6</td>
<td>2470.0</td>
<td>2174.9</td>
</tr>
<tr>
<td>4.023</td>
<td>168.7</td>
<td>1673.8</td>
<td>2715.3</td>
<td>2491.1</td>
</tr>
<tr>
<td>Run #</td>
<td>Mass Flux</td>
<td>Heat Transfer Coefficients</td>
<td>Static Pressures</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------------------------</td>
<td>------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>4.024</td>
<td>218.0</td>
<td>1839.0</td>
<td>2867.4</td>
<td>2820.8</td>
</tr>
<tr>
<td>4.025</td>
<td>263.6</td>
<td>1910.8</td>
<td>3151.1</td>
<td>3399.1</td>
</tr>
<tr>
<td>4.026</td>
<td>284.4</td>
<td>1687.3</td>
<td>2969.0</td>
<td>3163.0</td>
</tr>
<tr>
<td>4.027</td>
<td>232.4</td>
<td>1684.9</td>
<td>2929.7</td>
<td>2817.3</td>
</tr>
<tr>
<td>4.028</td>
<td>124.7</td>
<td>1496.7</td>
<td>2271.1</td>
<td>1847.5</td>
</tr>
<tr>
<td>4.029</td>
<td>180.8</td>
<td>1621.6</td>
<td>2516.0</td>
<td>2379.7</td>
</tr>
<tr>
<td>4.030</td>
<td>234.7</td>
<td>1764.2</td>
<td>2774.7</td>
<td>2905.7</td>
</tr>
<tr>
<td>4.031</td>
<td>124.5</td>
<td>1397.2</td>
<td>2211.5</td>
<td>1719.7</td>
</tr>
<tr>
<td>4.032</td>
<td>178.7</td>
<td>1501.9</td>
<td>2372.1</td>
<td>2101.8</td>
</tr>
<tr>
<td>4.033</td>
<td>225.5</td>
<td>1643.5</td>
<td>2657.1</td>
<td>2376.8</td>
</tr>
<tr>
<td>4.034</td>
<td>272.6</td>
<td>1709.5</td>
<td>2876.0</td>
<td>3010.0</td>
</tr>
<tr>
<td>4.035</td>
<td>152.7</td>
<td>1912.7</td>
<td>2587.7</td>
<td>2472.3</td>
</tr>
<tr>
<td>4.036</td>
<td>218.2</td>
<td>1957.3</td>
<td>3393.7</td>
<td>3281.3</td>
</tr>
<tr>
<td>4.037</td>
<td>282.2</td>
<td>2154.8</td>
<td>3646.8</td>
<td>4045.8</td>
</tr>
<tr>
<td>4.038</td>
<td>151.9</td>
<td>1741.9</td>
<td>2383.3</td>
<td>2082.3</td>
</tr>
<tr>
<td>4.039</td>
<td>220.7</td>
<td>2042.2</td>
<td>2770.1</td>
<td>3015.3</td>
</tr>
<tr>
<td>4.040</td>
<td>272.3</td>
<td>2250.7</td>
<td>3255.9</td>
<td>3361.0</td>
</tr>
<tr>
<td>5.002</td>
<td>132.5</td>
<td>2393.0</td>
<td>3162.4</td>
<td>5098.2</td>
</tr>
<tr>
<td>5.003</td>
<td>199.8</td>
<td>2725.4</td>
<td>3962.0</td>
<td>5429.8</td>
</tr>
<tr>
<td>5.004</td>
<td>233.1</td>
<td>2628.2</td>
<td>4006.6</td>
<td>5124.8</td>
</tr>
<tr>
<td>5.005</td>
<td>171.7</td>
<td>2551.6</td>
<td>3372.7</td>
<td>4399.8</td>
</tr>
<tr>
<td>5.007</td>
<td>229.1</td>
<td>2701.0</td>
<td>3592.9</td>
<td>4719.9</td>
</tr>
<tr>
<td>5.008</td>
<td>258.2</td>
<td>2093.3</td>
<td>3035.4</td>
<td>3833.0</td>
</tr>
<tr>
<td>5.009</td>
<td>128.3</td>
<td>2546.5</td>
<td>2875.2</td>
<td>4263.5</td>
</tr>
<tr>
<td>5.010</td>
<td>201.2</td>
<td>2536.8</td>
<td>3947.7</td>
<td>5254.0</td>
</tr>
<tr>
<td>5.011</td>
<td>199.8</td>
<td>2898.8</td>
<td>4330.0</td>
<td>5871.3</td>
</tr>
<tr>
<td>5.012</td>
<td>233.1</td>
<td>2524.5</td>
<td>4033.0</td>
<td>4961.6</td>
</tr>
<tr>
<td>5.013</td>
<td>122.9</td>
<td>2108.0</td>
<td>2847.6</td>
<td>3706.6</td>
</tr>
<tr>
<td>5.014</td>
<td>182.5</td>
<td>2103.5</td>
<td>2953.9</td>
<td>3921.7</td>
</tr>
<tr>
<td>5.015</td>
<td>238.7</td>
<td>2271.4</td>
<td>3162.9</td>
<td>4404.6</td>
</tr>
</tbody>
</table>
Table I.1. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Mass Flux</th>
<th>Heat Transfer Coefficients</th>
<th>Static Pressures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>overall</td>
<td></td>
</tr>
<tr>
<td>5.016</td>
<td>123.7</td>
<td>3086.8 3232.8 6546.5 2946.7</td>
<td>5.477 5.484 5.501 5.508 5.504</td>
</tr>
<tr>
<td>5.017</td>
<td>181.3</td>
<td>2780.5 3571.7 6543.8 2984.1</td>
<td>5.477 5.501 5.518 5.522 5.508</td>
</tr>
<tr>
<td>5.018</td>
<td>237.1</td>
<td>2056.6 3173.7 4468.2 7312.6</td>
<td>3337.8 5.546 5.559 5.584 5.604 5.584</td>
</tr>
<tr>
<td>5.019</td>
<td>135.1</td>
<td>2735.9 3178.1 6369.9 2721.4</td>
<td>6.579 6.586 6.596 6.596 6.593</td>
</tr>
<tr>
<td>5.020</td>
<td>184.7</td>
<td>2704.4 3378.6 5616.3 2772.4</td>
<td>6.523 6.530 6.544 6.550 6.550</td>
</tr>
<tr>
<td>5.021</td>
<td>238.6</td>
<td>2943.4 3630.6 5257.5 2910.3</td>
<td>6.557 6.561 6.571 6.592 6.578</td>
</tr>
<tr>
<td>5.022</td>
<td>285.5</td>
<td>3101.4 4224.5 6540.1 3296.5</td>
<td>6.549 6.549 6.564 6.585 6.585</td>
</tr>
<tr>
<td>5.023</td>
<td>376.2</td>
<td>2432.4 3663.4 5177.4 7202.7</td>
<td>3772.0 6.471 6.474 6.498 6.533 6.550</td>
</tr>
<tr>
<td>5.024</td>
<td>456.5</td>
<td>2634.4 3898.9 5707.0 7331.5</td>
<td>4009.7 6.433 6.439 6.470 6.517 6.550</td>
</tr>
<tr>
<td>5.025</td>
<td>529.8</td>
<td>2818.8 4264.3 6790.9 8268.3</td>
<td>4414.4 6.437 6.443 6.476 6.534 6.585</td>
</tr>
<tr>
<td>5.026</td>
<td>601.3</td>
<td>2970.1 4605.3 7061.5 8701.6</td>
<td>4665.7 6.335 6.339 6.395 6.469 6.550</td>
</tr>
<tr>
<td>5.027</td>
<td>282.9</td>
<td>2400.0 3507.0 4756.0 6585.7</td>
<td>3549.3 5.481 5.487 5.508 5.536 5.544</td>
</tr>
<tr>
<td>5.028</td>
<td>384.0</td>
<td>2446.8 3866.7 5654.0 7448.4</td>
<td>3874.9 5.402 5.409 5.439 5.482 5.509</td>
</tr>
<tr>
<td>5.029</td>
<td>453.7</td>
<td>2704.1 4111.8 6009.9 7703.1</td>
<td>4152.5 5.324 5.331 5.369 5.429 5.474</td>
</tr>
<tr>
<td>5.030</td>
<td>532.5</td>
<td>2941.7 4556.0 7701.7 9667.6</td>
<td>4761.4 5.254 5.260 5.302 5.380 5.457</td>
</tr>
<tr>
<td>5.031</td>
<td>649.0</td>
<td>3582.3 5658.0 10406.0 14946.1</td>
<td>5964.7 5.231 5.237 5.294 5.396 5.509</td>
</tr>
<tr>
<td>5.032</td>
<td>280.4</td>
<td>2630.6 3425.8 4658.7 6874.5</td>
<td>3797.4 4.485 4.497 4.524 4.558 4.584</td>
</tr>
<tr>
<td>5.033</td>
<td>386.9</td>
<td>2835.0 4017.8 6132.9 9042.9</td>
<td>4520.1 4.382 4.396 4.431 4.483 4.533</td>
</tr>
<tr>
<td>5.034</td>
<td>454.7</td>
<td>2797.4 4471.1 7267.4 10550.0</td>
<td>4950.9 4.315 4.330 4.373 4.445 4.515</td>
</tr>
<tr>
<td>5.035</td>
<td>532.0</td>
<td>3319.0 4905.5 7633.1 10702.6</td>
<td>5316.0 4.218 4.234 4.286 4.376 4.481</td>
</tr>
<tr>
<td>5.036</td>
<td>614.6</td>
<td>3227.0 5526.5 9417.5 13876.9</td>
<td>5902.1 4.212 4.227 4.286 4.400 4.550</td>
</tr>
<tr>
<td>5.037</td>
<td>275.8</td>
<td>2821.5 3665.1 5205.1 8010.9</td>
<td>4247.7 3.316 3.330 3.361 3.403 3.454</td>
</tr>
<tr>
<td>5.038</td>
<td>373.9</td>
<td>2828.4 4600.3 6808.2 10158.7</td>
<td>5026.2 3.208 3.223 3.264 3.330 3.396</td>
</tr>
<tr>
<td>5.039</td>
<td>451.9</td>
<td>3017.0 5258.3 8460.2 11686.7</td>
<td>5669.9 3.144 3.162 3.212 3.300 3.399</td>
</tr>
<tr>
<td>5.040</td>
<td>529.1</td>
<td>3633.9 5965.9 9569.1 13061.5</td>
<td>6246.8 3.068 3.085 3.145 3.261 3.406</td>
</tr>
<tr>
<td>5.041</td>
<td>600.9</td>
<td>3562.6 5910.2 9426.4 13830.5</td>
<td>6303.7 2.961 2.979 3.047 3.188 3.379</td>
</tr>
<tr>
<td>5.042</td>
<td>315.6</td>
<td>2367.3 4464.7 7039.7 9380.9</td>
<td>4707.5 2.246 2.261 2.303 2.371 2.446</td>
</tr>
<tr>
<td>5.043</td>
<td>439.3</td>
<td>2927.5 4816.2 7277.0 9950.6</td>
<td>5026.1 2.126 2.145 2.205 2.321 2.453</td>
</tr>
<tr>
<td>5.044</td>
<td>578.2</td>
<td>4026.9 6476.0 10948.9 16206.8</td>
<td>6747.9 1.854 1.873 1.962 2.157 2.418</td>
</tr>
<tr>
<td>5.045</td>
<td>379.6</td>
<td>2178.3 3477.7 5148.2 7826.9</td>
<td>3781.1 6.432 6.444 6.470 6.509 6.545</td>
</tr>
<tr>
<td>Run #</td>
<td>Mass Flux</td>
<td>Heat Transfer Coefficients</td>
<td>Static Pressures</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>----------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5.046</td>
<td>385.6</td>
<td>2443.2</td>
<td>3587.4</td>
</tr>
<tr>
<td>5.047</td>
<td>388.6</td>
<td>2212.2</td>
<td>3576.0</td>
</tr>
<tr>
<td>5.048</td>
<td>387.3</td>
<td>2449.0</td>
<td>3524.2</td>
</tr>
<tr>
<td>5.049</td>
<td>387.3</td>
<td>2650.9</td>
<td>3958.6</td>
</tr>
<tr>
<td>5.050</td>
<td>386.7</td>
<td>2626.4</td>
<td>3717.9</td>
</tr>
<tr>
<td>5.051</td>
<td>386.7</td>
<td>3208.3</td>
<td>4261.8</td>
</tr>
<tr>
<td>5.052</td>
<td>386.7</td>
<td>4097.2</td>
<td>4976.1</td>
</tr>
<tr>
<td>5.053</td>
<td>386.7</td>
<td>5032.8</td>
<td>6471.4</td>
</tr>
<tr>
<td>5.054</td>
<td>386.7</td>
<td>5814.7</td>
<td>6599.1</td>
</tr>
<tr>
<td>5.055</td>
<td>383.5</td>
<td>2767.3</td>
<td>3763.5</td>
</tr>
<tr>
<td>5.056</td>
<td>386.4</td>
<td>4410.1</td>
<td>5182.2</td>
</tr>
<tr>
<td>5.057</td>
<td>386.4</td>
<td>6063.1</td>
<td>6243.2</td>
</tr>
<tr>
<td>5.058</td>
<td>386.4</td>
<td>4958.8</td>
<td>5475.6</td>
</tr>
<tr>
<td>5.059</td>
<td>386.9</td>
<td>1424.3</td>
<td>1043.6</td>
</tr>
<tr>
<td>5.060</td>
<td>386.9</td>
<td>1377.4</td>
<td>1220.0</td>
</tr>
<tr>
<td>5.061</td>
<td>386.9</td>
<td>1253.4</td>
<td>1489.6</td>
</tr>
<tr>
<td>5.062</td>
<td>387.2</td>
<td>1802.9</td>
<td>2069.1</td>
</tr>
<tr>
<td>5.063</td>
<td>387.2</td>
<td>2007.4</td>
<td>2550.2</td>
</tr>
<tr>
<td>6.001</td>
<td>413.8</td>
<td>2485.5</td>
<td>4564.6</td>
</tr>
<tr>
<td>6.002</td>
<td>527.1</td>
<td>2980.1</td>
<td>5314.0</td>
</tr>
<tr>
<td>6.003</td>
<td>642.9</td>
<td>3481.2</td>
<td>6682.6</td>
</tr>
<tr>
<td>6.004</td>
<td>753.7</td>
<td>4116.7</td>
<td>7731.6</td>
</tr>
<tr>
<td>6.005</td>
<td>380.1</td>
<td>1676.8</td>
<td>3626.9</td>
</tr>
<tr>
<td>6.006</td>
<td>534.2</td>
<td>2514.0</td>
<td>5044.3</td>
</tr>
<tr>
<td>6.007</td>
<td>654.5</td>
<td>3028.9</td>
<td>5960.9</td>
</tr>
<tr>
<td>6.008</td>
<td>755.6</td>
<td>3658.1</td>
<td>6992.9</td>
</tr>
<tr>
<td>6.009</td>
<td>386.3</td>
<td>1557.8</td>
<td>3750.5</td>
</tr>
<tr>
<td>6.010</td>
<td>536.2</td>
<td>2471.4</td>
<td>5195.0</td>
</tr>
<tr>
<td>6.011</td>
<td>654.8</td>
<td>3055.6</td>
<td>5735.0</td>
</tr>
<tr>
<td>6.012</td>
<td>756.8</td>
<td>3302.3</td>
<td>6594.8</td>
</tr>
</tbody>
</table>
Table I.1. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Mass Flux</th>
<th>Heat Transfer Coefficients</th>
<th>Static Pressures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>6.013</td>
<td>398.2</td>
<td>1617.1</td>
<td>3555.9</td>
</tr>
<tr>
<td>6.014</td>
<td>533.0</td>
<td>2370.8</td>
<td>4769.6</td>
</tr>
<tr>
<td>6.015</td>
<td>647.3</td>
<td>2781.6</td>
<td>5463.0</td>
</tr>
<tr>
<td>6.016</td>
<td>731.5</td>
<td>2997.7</td>
<td>6091.7</td>
</tr>
<tr>
<td>6.017</td>
<td>736.4</td>
<td>3846.4</td>
<td>6027.6</td>
</tr>
<tr>
<td>6.018</td>
<td>366.9</td>
<td>1752.3</td>
<td>3349.1</td>
</tr>
<tr>
<td>6.019</td>
<td>494.5</td>
<td>2191.4</td>
<td>4240.2</td>
</tr>
<tr>
<td>6.020</td>
<td>610.6</td>
<td>2675.7</td>
<td>5288.5</td>
</tr>
<tr>
<td>6.021</td>
<td>739.5</td>
<td>2977.9</td>
<td>6046.0</td>
</tr>
<tr>
<td>6.022</td>
<td>739.5</td>
<td>3142.8</td>
<td>5979.2</td>
</tr>
<tr>
<td>6.023</td>
<td>136.7</td>
<td>1245.8</td>
<td>1983.3</td>
</tr>
<tr>
<td>6.024</td>
<td>211.3</td>
<td>1300.7</td>
<td>2345.6</td>
</tr>
<tr>
<td>6.025</td>
<td>297.2</td>
<td>1528.8</td>
<td>2941.3</td>
</tr>
<tr>
<td>6.026</td>
<td>378.7</td>
<td>1776.7</td>
<td>3560.4</td>
</tr>
<tr>
<td>6.027</td>
<td>144.5</td>
<td>1060.8</td>
<td>2082.9</td>
</tr>
<tr>
<td>6.028</td>
<td>219.8</td>
<td>1135.4</td>
<td>2451.3</td>
</tr>
<tr>
<td>6.029</td>
<td>295.5</td>
<td>1435.1</td>
<td>2928.9</td>
</tr>
<tr>
<td>6.030</td>
<td>379.9</td>
<td>1702.5</td>
<td>3258.4</td>
</tr>
<tr>
<td>6.031</td>
<td>142.4</td>
<td>1030.2</td>
<td>2255.7</td>
</tr>
<tr>
<td>6.032</td>
<td>217.1</td>
<td>1521.9</td>
<td>2532.6</td>
</tr>
<tr>
<td>6.033</td>
<td>304.5</td>
<td>1373.7</td>
<td>3060.0</td>
</tr>
<tr>
<td>6.034</td>
<td>373.5</td>
<td>1495.7</td>
<td>3370.0</td>
</tr>
<tr>
<td>6.035</td>
<td>139.2</td>
<td>1282.2</td>
<td>1993.2</td>
</tr>
<tr>
<td>6.036</td>
<td>212.2</td>
<td>1548.4</td>
<td>2582.5</td>
</tr>
<tr>
<td>6.037</td>
<td>289.3</td>
<td>1352.4</td>
<td>3261.8</td>
</tr>
<tr>
<td>6.038</td>
<td>360.8</td>
<td>1769.3</td>
<td>3333.1</td>
</tr>
<tr>
<td>6.039</td>
<td>151.6</td>
<td>1515.3</td>
<td>2313.4</td>
</tr>
<tr>
<td>6.040</td>
<td>205.4</td>
<td>2423.7</td>
<td>2520.8</td>
</tr>
<tr>
<td>6.041</td>
<td>311.4</td>
<td>1759.1</td>
<td>3705.3</td>
</tr>
<tr>
<td>6.042</td>
<td>379.3</td>
<td>2022.0</td>
<td>4242.3</td>
</tr>
</tbody>
</table>
Table I.1. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Mass Flux</th>
<th>Heat Transfer Coefficients</th>
<th>overall</th>
<th>Static Pressures</th>
<th>inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>6.043</td>
<td>322.1</td>
<td>1846.4</td>
<td>3453.9</td>
<td>3511.3</td>
<td>6494.4</td>
</tr>
<tr>
<td>6.044</td>
<td>322.1</td>
<td>2447.9</td>
<td>4321.6</td>
<td>3667.4</td>
<td>2325.4</td>
</tr>
<tr>
<td>6.045</td>
<td>318.7</td>
<td>3107.8</td>
<td>4258.9</td>
<td>3611.7</td>
<td>-----</td>
</tr>
<tr>
<td>6.046</td>
<td>320.8</td>
<td>3575.9</td>
<td>4318.0</td>
<td>3503.3</td>
<td>-----</td>
</tr>
<tr>
<td>6.047</td>
<td>322.2</td>
<td>1668.6</td>
<td>3086.9</td>
<td>3369.1</td>
<td>5766.2</td>
</tr>
<tr>
<td>6.048</td>
<td>322.5</td>
<td>1529.6</td>
<td>3042.1</td>
<td>3424.0</td>
<td>5982.3</td>
</tr>
<tr>
<td>6.049</td>
<td>322.1</td>
<td>1605.8</td>
<td>3130.2</td>
<td>3651.0</td>
<td>6147.6</td>
</tr>
<tr>
<td>6.050</td>
<td>321.7</td>
<td>1666.2</td>
<td>3120.9</td>
<td>3679.9</td>
<td>6279.9</td>
</tr>
<tr>
<td>6.051</td>
<td>322.1</td>
<td>1774.2</td>
<td>3362.1</td>
<td>3748.8</td>
<td>7039.0</td>
</tr>
<tr>
<td>6.052</td>
<td>322.1</td>
<td>1730.9</td>
<td>3286.8</td>
<td>3775.8</td>
<td>7100.5</td>
</tr>
<tr>
<td>6.053</td>
<td>322.2</td>
<td>1322.3</td>
<td>2264.6</td>
<td>2266.3</td>
<td>3489.2</td>
</tr>
<tr>
<td>6.054</td>
<td>322.2</td>
<td>2027.0</td>
<td>3012.3</td>
<td>2666.8</td>
<td>4168.7</td>
</tr>
<tr>
<td>6.055</td>
<td>322.2</td>
<td>459.0</td>
<td>1085.3</td>
<td>916.4</td>
<td>1313.2</td>
</tr>
<tr>
<td>7.005</td>
<td>127.6</td>
<td>1871.9</td>
<td>2321.2</td>
<td>2523.0</td>
<td>2775.5</td>
</tr>
<tr>
<td>7.006</td>
<td>171.6</td>
<td>1512.3</td>
<td>2263.3</td>
<td>2492.9</td>
<td>3300.6</td>
</tr>
<tr>
<td>7.007</td>
<td>195.8</td>
<td>1848.1</td>
<td>2206.2</td>
<td>2203.4</td>
<td>3554.4</td>
</tr>
<tr>
<td>7.008</td>
<td>229.6</td>
<td>1261.1</td>
<td>2294.7</td>
<td>3098.0</td>
<td>4490.0</td>
</tr>
<tr>
<td>7.009</td>
<td>108.7</td>
<td>1413.7</td>
<td>2072.4</td>
<td>2268.4</td>
<td>3675.6</td>
</tr>
<tr>
<td>7.010</td>
<td>108.2</td>
<td>1572.9</td>
<td>2591.3</td>
<td>3141.6</td>
<td>5204.3</td>
</tr>
<tr>
<td>7.011</td>
<td>152.6</td>
<td>1600.1</td>
<td>2675.7</td>
<td>2343.0</td>
<td>3462.8</td>
</tr>
<tr>
<td>7.012</td>
<td>150.6</td>
<td>1319.1</td>
<td>2367.9</td>
<td>2289.3</td>
<td>3152.0</td>
</tr>
<tr>
<td>7.013</td>
<td>177.4</td>
<td>1683.4</td>
<td>2235.8</td>
<td>1987.9</td>
<td>3012.9</td>
</tr>
<tr>
<td>7.014</td>
<td>120.9</td>
<td>1380.7</td>
<td>2544.0</td>
<td>2626.3</td>
<td>4771.3</td>
</tr>
<tr>
<td>7.015</td>
<td>159.0</td>
<td>1352.3</td>
<td>2466.3</td>
<td>2417.8</td>
<td>4128.0</td>
</tr>
<tr>
<td>7.016</td>
<td>185.4</td>
<td>1652.0</td>
<td>2261.3</td>
<td>1979.4</td>
<td>3489.2</td>
</tr>
<tr>
<td>7.017</td>
<td>230.1</td>
<td>1563.3</td>
<td>2109.5</td>
<td>2112.3</td>
<td>3350.1</td>
</tr>
<tr>
<td>7.018</td>
<td>124.0</td>
<td>1229.4</td>
<td>2089.2</td>
<td>2157.7</td>
<td>4708.4</td>
</tr>
<tr>
<td>7.019</td>
<td>153.2</td>
<td>1488.4</td>
<td>2382.2</td>
<td>2272.3</td>
<td>4045.5</td>
</tr>
<tr>
<td>7.020</td>
<td>192.6</td>
<td>1284.1</td>
<td>2229.8</td>
<td>1856.7</td>
<td>3320.6</td>
</tr>
<tr>
<td>7.021</td>
<td>235.7</td>
<td>1381.1</td>
<td>2422.0</td>
<td>2291.9</td>
<td>4496.4</td>
</tr>
</tbody>
</table>
### Table I.I. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Mass Flux</th>
<th>Heat Transfer Coefficients</th>
<th>Static Pressures</th>
<th>overall</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.023</td>
<td>154.4</td>
<td>1242.2</td>
<td>2035.7</td>
<td>1858.1</td>
<td>3183.3</td>
<td>1910.2</td>
<td>6.635</td>
<td>6.635</td>
<td>6.646</td>
</tr>
<tr>
<td>7.024</td>
<td>196.3</td>
<td>1382.3</td>
<td>2313.6</td>
<td>2200.4</td>
<td>3310.9</td>
<td>2123.6</td>
<td>6.615</td>
<td>6.622</td>
<td>6.628</td>
</tr>
<tr>
<td>7.025</td>
<td>226.3</td>
<td>1450.4</td>
<td>2165.2</td>
<td>2027.3</td>
<td>3594.8</td>
<td>2114.7</td>
<td>6.560</td>
<td>6.549</td>
<td>6.556</td>
</tr>
<tr>
<td>7.027</td>
<td>326.4</td>
<td>1488.8</td>
<td>2250.8</td>
<td>2588.9</td>
<td>4506.2</td>
<td>2465.3</td>
<td>6.552</td>
<td>6.549</td>
<td>6.564</td>
</tr>
<tr>
<td>7.028</td>
<td>401.5</td>
<td>2011.9</td>
<td>2789.5</td>
<td>3265.0</td>
<td>5207.3</td>
<td>3041.6</td>
<td>6.493</td>
<td>6.493</td>
<td>6.508</td>
</tr>
<tr>
<td>7.029</td>
<td>497.0</td>
<td>1979.6</td>
<td>3291.7</td>
<td>4096.9</td>
<td>6478.4</td>
<td>3513.9</td>
<td>6.448</td>
<td>6.453</td>
<td>6.474</td>
</tr>
<tr>
<td>7.030</td>
<td>273.8</td>
<td>1424.4</td>
<td>2294.8</td>
<td>2625.2</td>
<td>4352.8</td>
<td>2485.7</td>
<td>4.486</td>
<td>4.489</td>
<td>4.507</td>
</tr>
<tr>
<td>7.031</td>
<td>373.6</td>
<td>1935.4</td>
<td>2908.3</td>
<td>3716.3</td>
<td>6018.2</td>
<td>3326.9</td>
<td>4.374</td>
<td>4.380</td>
<td>4.401</td>
</tr>
<tr>
<td>7.032</td>
<td>458.9</td>
<td>2102.9</td>
<td>3332.4</td>
<td>4472.3</td>
<td>6938.2</td>
<td>3763.6</td>
<td>4.301</td>
<td>4.312</td>
<td>4.341</td>
</tr>
<tr>
<td>7.033</td>
<td>540.6</td>
<td>2443.0</td>
<td>4193.9</td>
<td>5364.2</td>
<td>8592.2</td>
<td>4512.3</td>
<td>4.211</td>
<td>4.226</td>
<td>4.269</td>
</tr>
<tr>
<td>7.034</td>
<td>303.2</td>
<td>1550.2</td>
<td>2249.9</td>
<td>2760.9</td>
<td>4430.9</td>
<td>2484.6</td>
<td>5.501</td>
<td>5.504</td>
<td>5.521</td>
</tr>
<tr>
<td>7.035</td>
<td>385.5</td>
<td>1664.5</td>
<td>2714.8</td>
<td>3521.6</td>
<td>5394.4</td>
<td>2970.0</td>
<td>5.367</td>
<td>5.373</td>
<td>5.391</td>
</tr>
<tr>
<td>7.036</td>
<td>462.1</td>
<td>2059.9</td>
<td>3333.0</td>
<td>4228.5</td>
<td>6703.0</td>
<td>3628.2</td>
<td>5.374</td>
<td>5.383</td>
<td>5.408</td>
</tr>
<tr>
<td>7.037</td>
<td>531.0</td>
<td>2545.8</td>
<td>3970.5</td>
<td>4874.9</td>
<td>7751.0</td>
<td>4256.5</td>
<td>5.318</td>
<td>5.329</td>
<td>5.362</td>
</tr>
<tr>
<td>7.038</td>
<td>230.3</td>
<td>1374.5</td>
<td>2334.2</td>
<td>2974.7</td>
<td>4720.7</td>
<td>2649.5</td>
<td>3.426</td>
<td>3.433</td>
<td>3.455</td>
</tr>
<tr>
<td>7.039</td>
<td>314.2</td>
<td>1632.6</td>
<td>2899.5</td>
<td>3351.6</td>
<td>5115.7</td>
<td>3013.0</td>
<td>3.341</td>
<td>3.354</td>
<td>3.378</td>
</tr>
<tr>
<td>7.040</td>
<td>383.4</td>
<td>1840.2</td>
<td>3091.2</td>
<td>4532.4</td>
<td>6632.6</td>
<td>3610.5</td>
<td>3.340</td>
<td>3.355</td>
<td>3.383</td>
</tr>
<tr>
<td>7.041</td>
<td>449.0</td>
<td>2307.1</td>
<td>3241.2</td>
<td>4562.9</td>
<td>7257.8</td>
<td>3873.4</td>
<td>3.299</td>
<td>3.315</td>
<td>3.354</td>
</tr>
<tr>
<td>7.042</td>
<td>513.1</td>
<td>2617.2</td>
<td>4302.4</td>
<td>5714.8</td>
<td>8821.2</td>
<td>4692.3</td>
<td>3.275</td>
<td>3.291</td>
<td>3.336</td>
</tr>
<tr>
<td>7.043</td>
<td>267.0</td>
<td>1713.3</td>
<td>2605.6</td>
<td>3811.6</td>
<td>5193.0</td>
<td>2992.0</td>
<td>2.302</td>
<td>2.321</td>
<td>2.354</td>
</tr>
<tr>
<td>7.044</td>
<td>376.4</td>
<td>2092.7</td>
<td>3255.4</td>
<td>4550.9</td>
<td>6481.7</td>
<td>3610.6</td>
<td>2.257</td>
<td>2.278</td>
<td>2.321</td>
</tr>
<tr>
<td>7.045</td>
<td>456.6</td>
<td>2213.0</td>
<td>3843.3</td>
<td>5477.4</td>
<td>8003.6</td>
<td>4151.0</td>
<td>2.208</td>
<td>2.227</td>
<td>2.275</td>
</tr>
<tr>
<td>7.046</td>
<td>515.0</td>
<td>2599.3</td>
<td>4473.2</td>
<td>6345.0</td>
<td>9428.8</td>
<td>4756.0</td>
<td>2.107</td>
<td>2.126</td>
<td>2.182</td>
</tr>
<tr>
<td>7.047</td>
<td>322.3</td>
<td>1585.4</td>
<td>2323.1</td>
<td>2695.7</td>
<td>4297.8</td>
<td>2507.9</td>
<td>6.492</td>
<td>6.499</td>
<td>6.518</td>
</tr>
<tr>
<td>7.048</td>
<td>322.3</td>
<td>1628.4</td>
<td>2300.8</td>
<td>2737.8</td>
<td>4320.6</td>
<td>2525.6</td>
<td>6.489</td>
<td>6.497</td>
<td>6.516</td>
</tr>
<tr>
<td>7.049</td>
<td>322.3</td>
<td>1614.6</td>
<td>2376.0</td>
<td>2837.5</td>
<td>4604.7</td>
<td>2604.2</td>
<td>6.488</td>
<td>6.496</td>
<td>6.514</td>
</tr>
<tr>
<td>7.050</td>
<td>322.3</td>
<td>1692.7</td>
<td>2417.9</td>
<td>2987.8</td>
<td>4827.4</td>
<td>2697.4</td>
<td>6.491</td>
<td>6.497</td>
<td>6.513</td>
</tr>
<tr>
<td>7.051</td>
<td>322.2</td>
<td>1564.6</td>
<td>2472.0</td>
<td>3003.9</td>
<td>4610.9</td>
<td>2662.0</td>
<td>6.488</td>
<td>6.494</td>
<td>6.512</td>
</tr>
<tr>
<td>Run #</td>
<td>Mass Flux</td>
<td>Heat Transfer Coefficients</td>
<td>Static Pressures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>-----------------------------</td>
<td>------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>overall</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>7.052</td>
<td>322.2</td>
<td>1790.5</td>
<td>2446.7</td>
<td>3009.7</td>
<td>4816.9</td>
<td>2745.6</td>
<td>6.489</td>
<td>6.496</td>
<td>6.514</td>
</tr>
<tr>
<td>7.053</td>
<td>321.6</td>
<td>2175.5</td>
<td>2736.0</td>
<td>2867.9</td>
<td>4722.3</td>
<td>2881.6</td>
<td>6.470</td>
<td>6.481</td>
<td>6.504</td>
</tr>
<tr>
<td>7.054</td>
<td>322.3</td>
<td>3017.0</td>
<td>3113.9</td>
<td>1987.5</td>
<td>-------</td>
<td>4917.8</td>
<td>6.435</td>
<td>6.472</td>
<td>6.514</td>
</tr>
<tr>
<td>7.055</td>
<td>322.3</td>
<td>2730.8</td>
<td>2504.0</td>
<td>1616.3</td>
<td>-------</td>
<td>5872.2</td>
<td>6.507</td>
<td>6.544</td>
<td>6.586</td>
</tr>
<tr>
<td>7.057</td>
<td>322.1</td>
<td>1836.8</td>
<td>2061.7</td>
<td>985.7</td>
<td>4467.0</td>
<td>1942.2</td>
<td>6.542</td>
<td>6.548</td>
<td>6.567</td>
</tr>
<tr>
<td>7.058</td>
<td>322.6</td>
<td>2128.0</td>
<td>2110.0</td>
<td>1067.6</td>
<td>3126.8</td>
<td>2064.5</td>
<td>6.484</td>
<td>6.498</td>
<td>6.520</td>
</tr>
<tr>
<td>7.059</td>
<td>322.3</td>
<td>1702.4</td>
<td>2171.7</td>
<td>1679.7</td>
<td>3195.1</td>
<td>2036.9</td>
<td>6.515</td>
<td>6.521</td>
<td>6.538</td>
</tr>
<tr>
<td>8.001</td>
<td>95.4</td>
<td>1548.4</td>
<td>2480.2</td>
<td>2479.8</td>
<td>2823.5</td>
<td>2268.3</td>
<td>2.379</td>
<td>2.395</td>
<td>2.417</td>
</tr>
<tr>
<td>8.002</td>
<td>118.3</td>
<td>1539.1</td>
<td>2258.9</td>
<td>1834.4</td>
<td>2342.9</td>
<td>1934.1</td>
<td>2.369</td>
<td>2.369</td>
<td>2.393</td>
</tr>
<tr>
<td>8.003</td>
<td>145.5</td>
<td>1819.0</td>
<td>2110.4</td>
<td>1891.0</td>
<td>2806.7</td>
<td>2098.3</td>
<td>2.396</td>
<td>2.395</td>
<td>2.419</td>
</tr>
<tr>
<td>8.004</td>
<td>190.7</td>
<td>1778.1</td>
<td>2265.5</td>
<td>2562.5</td>
<td>3469.0</td>
<td>2418.2</td>
<td>2.375</td>
<td>2.382</td>
<td>2.403</td>
</tr>
<tr>
<td>8.005</td>
<td>124.8</td>
<td>1754.5</td>
<td>2432.3</td>
<td>2043.2</td>
<td>3083.6</td>
<td>2270.5</td>
<td>2.434</td>
<td>2.439</td>
<td>2.452</td>
</tr>
<tr>
<td>8.007</td>
<td>216.7</td>
<td>1832.9</td>
<td>2318.2</td>
<td>2749.4</td>
<td>4124.7</td>
<td>2623.4</td>
<td>2.402</td>
<td>2.407</td>
<td>2.427</td>
</tr>
<tr>
<td>8.008</td>
<td>215.8</td>
<td>1876.5</td>
<td>2523.2</td>
<td>3017.4</td>
<td>3844.9</td>
<td>2448.4</td>
<td>2.368</td>
<td>2.380</td>
<td>2.406</td>
</tr>
<tr>
<td>8.009</td>
<td>112.1</td>
<td>1578.0</td>
<td>2872.6</td>
<td>2678.8</td>
<td>3312.8</td>
<td>2513.3</td>
<td>3.432</td>
<td>3.436</td>
<td>3.436</td>
</tr>
<tr>
<td>8.010</td>
<td>148.6</td>
<td>917.8</td>
<td>2548.9</td>
<td>2317.8</td>
<td>3400.9</td>
<td>2188.5</td>
<td>3.470</td>
<td>3.470</td>
<td>3.470</td>
</tr>
<tr>
<td>8.011</td>
<td>174.8</td>
<td>1322.2</td>
<td>2371.1</td>
<td>2276.0</td>
<td>3096.1</td>
<td>2199.0</td>
<td>3.450</td>
<td>3.456</td>
<td>3.460</td>
</tr>
<tr>
<td>8.012</td>
<td>211.8</td>
<td>1283.0</td>
<td>2364.2</td>
<td>2537.3</td>
<td>4022.6</td>
<td>2437.4</td>
<td>3.466</td>
<td>3.470</td>
<td>3.485</td>
</tr>
<tr>
<td>8.013</td>
<td>114.4</td>
<td>1268.8</td>
<td>2350.2</td>
<td>2331.2</td>
<td>3369.8</td>
<td>2225.3</td>
<td>4.457</td>
<td>4.461</td>
<td>4.457</td>
</tr>
<tr>
<td>8.014</td>
<td>144.1</td>
<td>1207.9</td>
<td>2165.5</td>
<td>2209.5</td>
<td>2970.7</td>
<td>2038.5</td>
<td>4.471</td>
<td>4.472</td>
<td>4.467</td>
</tr>
<tr>
<td>8.015</td>
<td>190.2</td>
<td>1269.3</td>
<td>1903.1</td>
<td>2157.3</td>
<td>3559.0</td>
<td>2106.6</td>
<td>4.447</td>
<td>4.450</td>
<td>4.456</td>
</tr>
<tr>
<td>8.016</td>
<td>224.4</td>
<td>1979.6</td>
<td>2138.3</td>
<td>2448.1</td>
<td>4208.0</td>
<td>2550.5</td>
<td>4.409</td>
<td>4.409</td>
<td>4.412</td>
</tr>
<tr>
<td>8.017</td>
<td>115.2</td>
<td>961.0</td>
<td>1889.2</td>
<td>1970.2</td>
<td>3136.9</td>
<td>1843.1</td>
<td>5.471</td>
<td>5.471</td>
<td>5.474</td>
</tr>
<tr>
<td>8.018</td>
<td>149.5</td>
<td>1083.0</td>
<td>2273.1</td>
<td>2143.7</td>
<td>2984.5</td>
<td>2008.0</td>
<td>5.546</td>
<td>5.540</td>
<td>5.549</td>
</tr>
<tr>
<td>8.019</td>
<td>184.9</td>
<td>1270.3</td>
<td>2210.2</td>
<td>1941.4</td>
<td>2964.1</td>
<td>2008.0</td>
<td>5.526</td>
<td>5.516</td>
<td>5.522</td>
</tr>
<tr>
<td>8.020</td>
<td>220.5</td>
<td>1482.5</td>
<td>2140.1</td>
<td>2167.4</td>
<td>3531.3</td>
<td>2204.7</td>
<td>5.474</td>
<td>5.478</td>
<td>5.488</td>
</tr>
<tr>
<td>8.021</td>
<td>118.1</td>
<td>1023.1</td>
<td>1797.2</td>
<td>1768.3</td>
<td>3130.8</td>
<td>1721.7</td>
<td>6.559</td>
<td>6.552</td>
<td>6.559</td>
</tr>
<tr>
<td>8.022</td>
<td>144.2</td>
<td>1094.4</td>
<td>2018.1</td>
<td>2151.1</td>
<td>2654.1</td>
<td>1831.5</td>
<td>6.573</td>
<td>6.559</td>
<td>6.580</td>
</tr>
<tr>
<td>8.023</td>
<td>183.4</td>
<td>1344.6</td>
<td>2183.9</td>
<td>1998.8</td>
<td>2730.4</td>
<td>1964.7</td>
<td>6.552</td>
<td>6.539</td>
<td>6.556</td>
</tr>
<tr>
<td>Run #</td>
<td>Mass Flux</td>
<td>Heat Transfer Coefficients</td>
<td>Static Pressures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>----------------------------</td>
<td>------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>overall</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>8.024</td>
<td>221.2</td>
<td>1381.6</td>
<td>2168.3</td>
<td>2288.5</td>
<td>3257.2</td>
<td>2119.4</td>
<td>6.539</td>
<td>6.532</td>
<td>6.559</td>
</tr>
<tr>
<td>8.025</td>
<td>279.1</td>
<td>1512.8</td>
<td>2519.7</td>
<td>2424.6</td>
<td>4195.4</td>
<td>2454.2</td>
<td>6.472</td>
<td>6.475</td>
<td>6.493</td>
</tr>
<tr>
<td>8.026</td>
<td>344.5</td>
<td>1759.2</td>
<td>2660.2</td>
<td>2926.5</td>
<td>5041.4</td>
<td>2824.2</td>
<td>6.494</td>
<td>6.501</td>
<td>6.519</td>
</tr>
<tr>
<td>8.027</td>
<td>413.0</td>
<td>2008.9</td>
<td>2793.8</td>
<td>3342.0</td>
<td>5923.8</td>
<td>3159.3</td>
<td>6.488</td>
<td>6.505</td>
<td>6.526</td>
</tr>
<tr>
<td>8.028</td>
<td>561.5</td>
<td>2327.0</td>
<td>3347.4</td>
<td>4315.7</td>
<td>6894.7</td>
<td>3770.6</td>
<td>6.380</td>
<td>6.401</td>
<td>6.428</td>
</tr>
<tr>
<td>8.029</td>
<td>292.0</td>
<td>2187.4</td>
<td>2812.0</td>
<td>2746.2</td>
<td>4715.2</td>
<td>2928.8</td>
<td>5.552</td>
<td>5.556</td>
<td>5.571</td>
</tr>
<tr>
<td>8.030</td>
<td>340.6</td>
<td>1893.2</td>
<td>2756.4</td>
<td>3356.7</td>
<td>5236.8</td>
<td>3042.7</td>
<td>5.458</td>
<td>5.472</td>
<td>5.492</td>
</tr>
<tr>
<td>8.031</td>
<td>426.6</td>
<td>1918.9</td>
<td>2936.4</td>
<td>3867.3</td>
<td>6405.8</td>
<td>3404.2</td>
<td>5.386</td>
<td>5.411</td>
<td>5.443</td>
</tr>
<tr>
<td>8.032</td>
<td>512.3</td>
<td>2163.4</td>
<td>3221.3</td>
<td>4179.3</td>
<td>7393.6</td>
<td>3772.0</td>
<td>5.343</td>
<td>5.371</td>
<td>5.408</td>
</tr>
<tr>
<td>8.033</td>
<td>281.3</td>
<td>2122.1</td>
<td>2713.2</td>
<td>3167.7</td>
<td>5536.2</td>
<td>3047.5</td>
<td>5.465</td>
<td>5.478</td>
<td>5.500</td>
</tr>
<tr>
<td>8.034</td>
<td>354.2</td>
<td>2054.2</td>
<td>3045.8</td>
<td>4282.1</td>
<td>6559.4</td>
<td>3535.3</td>
<td>5.371</td>
<td>5.392</td>
<td>5.420</td>
</tr>
<tr>
<td>8.035</td>
<td>430.7</td>
<td>2158.5</td>
<td>3403.2</td>
<td>4993.6</td>
<td>7608.2</td>
<td>3979.4</td>
<td>5.308</td>
<td>5.341</td>
<td>5.381</td>
</tr>
<tr>
<td>8.036</td>
<td>516.4</td>
<td>2094.7</td>
<td>3557.0</td>
<td>5465.4</td>
<td>8822.4</td>
<td>4283.1</td>
<td>5.159</td>
<td>5.202</td>
<td>5.255</td>
</tr>
<tr>
<td>8.037</td>
<td>287.0</td>
<td>1931.1</td>
<td>2652.0</td>
<td>3046.4</td>
<td>5050.8</td>
<td>2949.7</td>
<td>4.397</td>
<td>4.418</td>
<td>4.448</td>
</tr>
<tr>
<td>8.038</td>
<td>353.6</td>
<td>2026.3</td>
<td>2870.9</td>
<td>3927.6</td>
<td>6191.4</td>
<td>3390.4</td>
<td>4.347</td>
<td>4.377</td>
<td>4.410</td>
</tr>
<tr>
<td>8.039</td>
<td>423.4</td>
<td>1946.7</td>
<td>3181.5</td>
<td>4423.5</td>
<td>7187.6</td>
<td>3716.2</td>
<td>4.257</td>
<td>4.288</td>
<td>4.326</td>
</tr>
<tr>
<td>8.040</td>
<td>513.6</td>
<td>2168.5</td>
<td>3453.9</td>
<td>4988.6</td>
<td>8298.3</td>
<td>4103.3</td>
<td>4.244</td>
<td>4.279</td>
<td>4.321</td>
</tr>
<tr>
<td>8.041</td>
<td>270.2</td>
<td>2093.2</td>
<td>2977.9</td>
<td>3433.2</td>
<td>5143.5</td>
<td>3183.4</td>
<td>2.203</td>
<td>2.235</td>
<td>2.274</td>
</tr>
<tr>
<td>8.042</td>
<td>339.4</td>
<td>2465.1</td>
<td>3186.5</td>
<td>4188.8</td>
<td>6288.7</td>
<td>3684.2</td>
<td>2.155</td>
<td>2.197</td>
<td>2.242</td>
</tr>
<tr>
<td>8.043</td>
<td>320.7</td>
<td>1332.2</td>
<td>2117.3</td>
<td>1818.3</td>
<td>2992.0</td>
<td>1921.9</td>
<td>6.586</td>
<td>6.587</td>
<td>6.598</td>
</tr>
<tr>
<td>8.045</td>
<td>320.7</td>
<td>1319.8</td>
<td>2058.4</td>
<td>1636.2</td>
<td>2756.6</td>
<td>1840.3</td>
<td>6.593</td>
<td>6.596</td>
<td>6.606</td>
</tr>
<tr>
<td>8.046</td>
<td>320.8</td>
<td>1145.3</td>
<td>1857.1</td>
<td>1440.4</td>
<td>2619.8</td>
<td>1669.2</td>
<td>6.599</td>
<td>6.602</td>
<td>6.609</td>
</tr>
</tbody>
</table>
Table I.2. Reduced data - saturation temperatures, inside wall temperatures and flow regime observations

(Unit: degree C)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Saturation Temperatures</th>
<th>Wall Temperatures</th>
<th>Flow Regime Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1.012</td>
<td>75.9</td>
<td>76.0</td>
<td>76.2</td>
</tr>
<tr>
<td>1.013</td>
<td>76.3</td>
<td>76.5</td>
<td>76.6</td>
</tr>
<tr>
<td>1.014</td>
<td>75.0</td>
<td>75.3</td>
<td>75.7</td>
</tr>
<tr>
<td>1.018</td>
<td>75.4</td>
<td>75.6</td>
<td>75.9</td>
</tr>
<tr>
<td>1.019</td>
<td>76.4</td>
<td>76.6</td>
<td>76.8</td>
</tr>
<tr>
<td>1.020</td>
<td>89.7</td>
<td>89.9</td>
<td>90.1</td>
</tr>
<tr>
<td>1.021</td>
<td>89.2</td>
<td>89.5</td>
<td>89.8</td>
</tr>
<tr>
<td>1.022</td>
<td>89.0</td>
<td>89.3</td>
<td>89.7</td>
</tr>
<tr>
<td>1.023</td>
<td>89.3</td>
<td>89.5</td>
<td>89.8</td>
</tr>
<tr>
<td>1.024</td>
<td>88.9</td>
<td>89.2</td>
<td>89.6</td>
</tr>
<tr>
<td>1.025</td>
<td>100.0</td>
<td>100.2</td>
<td>100.5</td>
</tr>
<tr>
<td>1.026</td>
<td>100.2</td>
<td>100.3</td>
<td>100.7</td>
</tr>
<tr>
<td>1.027</td>
<td>100.2</td>
<td>100.4</td>
<td>100.7</td>
</tr>
<tr>
<td>1.028</td>
<td>99.7</td>
<td>99.9</td>
<td>100.2</td>
</tr>
<tr>
<td>1.031</td>
<td>109.1</td>
<td>109.3</td>
<td>109.7</td>
</tr>
<tr>
<td>1.033</td>
<td>109.6</td>
<td>109.6</td>
<td>109.7</td>
</tr>
<tr>
<td>1.034</td>
<td>109.7</td>
<td>109.7</td>
<td>109.8</td>
</tr>
<tr>
<td>1.035</td>
<td>109.7</td>
<td>109.7</td>
<td>109.8</td>
</tr>
<tr>
<td>1.036</td>
<td>118.0</td>
<td>118.0</td>
<td>118.1</td>
</tr>
<tr>
<td>1.037</td>
<td>117.5</td>
<td>117.5</td>
<td>117.6</td>
</tr>
<tr>
<td>1.038</td>
<td>118.1</td>
<td>118.2</td>
<td>118.2</td>
</tr>
<tr>
<td>1.039</td>
<td>117.5</td>
<td>117.6</td>
<td>117.7</td>
</tr>
<tr>
<td>1.040</td>
<td>72.9</td>
<td>73.7</td>
<td>74.7</td>
</tr>
<tr>
<td>1.041</td>
<td>73.1</td>
<td>73.9</td>
<td>74.9</td>
</tr>
<tr>
<td>1.042</td>
<td>73.2</td>
<td>73.7</td>
<td>74.7</td>
</tr>
<tr>
<td>Run #</td>
<td>Saturation Temperatures</td>
<td>Wall Temperatures</td>
<td>Flow Regime</td>
</tr>
<tr>
<td>------</td>
<td>------------------------</td>
<td>------------------</td>
<td>-------------</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1.043</td>
<td>71.6</td>
<td>72.1</td>
<td>73.2</td>
</tr>
<tr>
<td>1.044</td>
<td>89.7</td>
<td>89.9</td>
<td>90.3</td>
</tr>
<tr>
<td>1.045</td>
<td>88.7</td>
<td>88.9</td>
<td>89.4</td>
</tr>
<tr>
<td>1.046</td>
<td>88.1</td>
<td>88.3</td>
<td>88.9</td>
</tr>
<tr>
<td>1.047</td>
<td>89.9</td>
<td>90.2</td>
<td>90.6</td>
</tr>
<tr>
<td>1.048</td>
<td>99.7</td>
<td>99.9</td>
<td>100.2</td>
</tr>
<tr>
<td>1.049</td>
<td>99.3</td>
<td>99.6</td>
<td>100.0</td>
</tr>
<tr>
<td>1.050</td>
<td>99.1</td>
<td>99.3</td>
<td>99.8</td>
</tr>
<tr>
<td>1.051</td>
<td>98.7</td>
<td>99.0</td>
<td>99.5</td>
</tr>
<tr>
<td>1.052</td>
<td>109.3</td>
<td>109.5</td>
<td>109.7</td>
</tr>
<tr>
<td>1.053</td>
<td>108.9</td>
<td>109.1</td>
<td>109.3</td>
</tr>
<tr>
<td>1.054</td>
<td>108.7</td>
<td>108.9</td>
<td>109.2</td>
</tr>
<tr>
<td>1.055</td>
<td>108.6</td>
<td>108.8</td>
<td>109.1</td>
</tr>
<tr>
<td>1.056</td>
<td>117.4</td>
<td>117.5</td>
<td>117.6</td>
</tr>
<tr>
<td>1.057</td>
<td>117.1</td>
<td>117.2</td>
<td>117.4</td>
</tr>
<tr>
<td>1.058</td>
<td>116.8</td>
<td>116.9</td>
<td>117.2</td>
</tr>
<tr>
<td>1.059</td>
<td>116.6</td>
<td>116.8</td>
<td>117.0</td>
</tr>
<tr>
<td>1.060</td>
<td>117.6</td>
<td>117.7</td>
<td>117.9</td>
</tr>
<tr>
<td>1.061</td>
<td>117.3</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>1.062</td>
<td>117.7</td>
<td>117.9</td>
<td>118.1</td>
</tr>
<tr>
<td>1.063</td>
<td>117.5</td>
<td>117.7</td>
<td>117.9</td>
</tr>
<tr>
<td>1.064</td>
<td>117.5</td>
<td>117.7</td>
<td>117.9</td>
</tr>
<tr>
<td>1.065</td>
<td>117.3</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>1.066</td>
<td>117.5</td>
<td>117.7</td>
<td>117.9</td>
</tr>
<tr>
<td>1.067</td>
<td>117.5</td>
<td>117.7</td>
<td>117.9</td>
</tr>
<tr>
<td>1.068</td>
<td>117.1</td>
<td>117.3</td>
<td>117.5</td>
</tr>
<tr>
<td>1.069</td>
<td>117.2</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>1.070</td>
<td>117.6</td>
<td>117.7</td>
<td>117.8</td>
</tr>
<tr>
<td>1.071</td>
<td>117.5</td>
<td>117.5</td>
<td>117.6</td>
</tr>
<tr>
<td>1.072</td>
<td>117.4</td>
<td>117.5</td>
<td>117.6</td>
</tr>
</tbody>
</table>
Table I.2. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Saturation Temperatures</th>
<th>Wall Temperatures</th>
<th>Flow Regime Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 overall</td>
<td>1 2 3 4 overall</td>
<td></td>
</tr>
<tr>
<td>1.073</td>
<td>117.4 117.5 117.6 117.7 117.6</td>
<td>103.7 107.2 110.2 112.4 108.5</td>
<td>semiannular</td>
</tr>
<tr>
<td>1.074</td>
<td>117.3 117.4 117.6 117.7 117.5</td>
<td>105.2 108.3 111.2 113.2 109.6</td>
<td>semiannular</td>
</tr>
<tr>
<td>1.075</td>
<td>117.3 117.4 117.6 117.7 117.6</td>
<td>84.9 92.7 101.4 106.0 96.3</td>
<td>semiannular</td>
</tr>
<tr>
<td>1.076</td>
<td>117.2 117.3 117.4 117.6 117.4</td>
<td>83.0 92.3 101.4 106.7 95.9</td>
<td>wavy</td>
</tr>
<tr>
<td>1.077</td>
<td>117.2 117.3 117.4 117.6 117.4</td>
<td>83.0 92.5 100.9 106.8 96.3</td>
<td>wavy</td>
</tr>
<tr>
<td>1.078</td>
<td>117.2 117.3 117.4 117.6 117.4</td>
<td>83.5 92.7 100.9 105.2 95.7</td>
<td>wavy</td>
</tr>
<tr>
<td>1.079</td>
<td>117.2 117.3 117.4 117.6 117.4</td>
<td>82.0 92.0 100.0 105.1 94.9</td>
<td>wavy</td>
</tr>
<tr>
<td>2.001</td>
<td>71.6 73.1 74.7 76.1 73.9</td>
<td>51.5 62.6 68.8 73.3 64.1</td>
<td>slug</td>
</tr>
<tr>
<td>2.004</td>
<td>67.4 70.6 73.2 75.2 71.3</td>
<td>48.1 57.1 63.9 69.6 59.7</td>
<td>slug</td>
</tr>
<tr>
<td>2.005</td>
<td>66.9 70.5 73.3 75.4 71.0</td>
<td>47.5 55.8 62.6 68.7 58.7</td>
<td>slug</td>
</tr>
<tr>
<td>2.006</td>
<td>87.2 88.1 88.9 89.6 88.4</td>
<td>61.0 76.8 83.8 87.4 77.3</td>
<td>slug</td>
</tr>
<tr>
<td>2.007</td>
<td>87.0 87.9 88.8 89.6 88.3</td>
<td>60.1 75.7 82.9 86.8 76.4</td>
<td>plug</td>
</tr>
<tr>
<td>2.008</td>
<td>87.6 88.4 89.2 89.9 88.7</td>
<td>59.3 74.7 82.4 86.9 75.8</td>
<td>plug</td>
</tr>
<tr>
<td>2.009</td>
<td>86.5 87.5 88.4 89.2 87.8</td>
<td>59.3 73.2 80.5 84.9 74.5</td>
<td>slug</td>
</tr>
<tr>
<td>2.010</td>
<td>86.5 87.5 88.5 89.4 87.9</td>
<td>59.9 73.9 81.4 85.8 75.3</td>
<td>wavy</td>
</tr>
<tr>
<td>2.011</td>
<td>86.8 87.9 88.8 89.6 88.2</td>
<td>59.3 72.7 80.4 85.4 74.5</td>
<td>slug</td>
</tr>
<tr>
<td>2.012</td>
<td>86.3 87.4 88.3 89.1 87.6</td>
<td>56.9 70.2 78.1 83.9 72.3</td>
<td>plug</td>
</tr>
<tr>
<td>2.013</td>
<td>99.5 99.9 100.4 100.7 100.1</td>
<td>70.8 90.2 96.9 99.6 89.4</td>
<td>plug</td>
</tr>
<tr>
<td>2.014</td>
<td>98.2 98.8 99.4 99.9 99.0</td>
<td>68.8 88.0 95.2 98.5 87.6</td>
<td>slug</td>
</tr>
<tr>
<td>2.015</td>
<td>99.3 99.7 100.2 100.6 100.0</td>
<td>68.1 87.6 95.5 99.5 87.7</td>
<td>plug</td>
</tr>
<tr>
<td>2.016</td>
<td>97.8 98.3 99.1 99.8 98.9</td>
<td>65.6 83.3 91.7 96.5 84.8</td>
<td>plug</td>
</tr>
<tr>
<td>2.019</td>
<td>108.5 108.7 109.0 109.3 108.9</td>
<td>76.9 99.1 105.4 107.8 97.9</td>
<td>slug</td>
</tr>
<tr>
<td>2.020</td>
<td>108.8 109.0 109.3 109.6 109.2</td>
<td>73.2 96.1 104.1 107.6 95.9</td>
<td>bubble</td>
</tr>
<tr>
<td>2.021</td>
<td>109.3 109.5 109.7 109.9 109.6</td>
<td>74.2 98.2 105.8 109.0 97.4</td>
<td>bubble</td>
</tr>
<tr>
<td>2.022</td>
<td>108.7 108.9 109.1 109.3 109.0</td>
<td>87.0 95.5 101.2 105.1 97.6</td>
<td>slug</td>
</tr>
<tr>
<td>2.024</td>
<td>109.0 109.2 109.5 109.7 109.3</td>
<td>84.5 93.7 99.9 104.7 96.1</td>
<td>slug</td>
</tr>
<tr>
<td>2.027</td>
<td>108.8 109.0 109.4 109.7 109.2</td>
<td>82.6 91.1 97.6 102.9 93.9</td>
<td>slug</td>
</tr>
<tr>
<td>2.028</td>
<td>118.3 118.4 118.5 118.5 118.4</td>
<td>94.8 104.3 110.0 114.2 106.1</td>
<td>plug</td>
</tr>
<tr>
<td>2.029</td>
<td>117.6 117.7 117.9 118.0 117.8</td>
<td>92.2 102.4 108.6 113.4 104.5</td>
<td>plug</td>
</tr>
<tr>
<td>2.030</td>
<td>117.8 117.9 118.1 118.3 118.0</td>
<td>90.9 101.6 108.1 113.1 103.8</td>
<td>plug</td>
</tr>
</tbody>
</table>
Table I.2. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Saturation Temperatures</th>
<th>Wall Temperatures</th>
<th>Flow Regime</th>
<th>Flow Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4 overall</td>
</tr>
<tr>
<td>2.031</td>
<td>58.7</td>
<td>62.7</td>
<td>68.3</td>
<td>74.1</td>
</tr>
<tr>
<td>2.032</td>
<td>68.3</td>
<td>70.5</td>
<td>73.0</td>
<td>75.7</td>
</tr>
<tr>
<td>2.033</td>
<td>64.6</td>
<td>67.2</td>
<td>70.6</td>
<td>74.0</td>
</tr>
<tr>
<td>2.034</td>
<td>63.2</td>
<td>66.2</td>
<td>70.1</td>
<td>73.9</td>
</tr>
<tr>
<td>2.035</td>
<td>62.1</td>
<td>65.3</td>
<td>69.8</td>
<td>74.3</td>
</tr>
<tr>
<td>2.036</td>
<td>59.8</td>
<td>63.7</td>
<td>68.9</td>
<td>74.2</td>
</tr>
<tr>
<td>2.037</td>
<td>82.2</td>
<td>83.9</td>
<td>86.6</td>
<td>89.3</td>
</tr>
<tr>
<td>2.038</td>
<td>12.3</td>
<td>78.9</td>
<td>83.2</td>
<td>87.6</td>
</tr>
<tr>
<td>2.039</td>
<td>78.6</td>
<td>81.1</td>
<td>85.0</td>
<td>88.6</td>
</tr>
<tr>
<td>2.040</td>
<td>84.9</td>
<td>86.1</td>
<td>87.7</td>
<td>89.4</td>
</tr>
<tr>
<td>2.041</td>
<td>83.9</td>
<td>85.3</td>
<td>87.5</td>
<td>89.4</td>
</tr>
<tr>
<td>2.042</td>
<td>96.4</td>
<td>97.3</td>
<td>98.6</td>
<td>100.0</td>
</tr>
<tr>
<td>2.043</td>
<td>95.1</td>
<td>96.3</td>
<td>96.0</td>
<td>99.7</td>
</tr>
<tr>
<td>2.044</td>
<td>93.7</td>
<td>95.1</td>
<td>97.5</td>
<td>99.9</td>
</tr>
<tr>
<td>2.045</td>
<td>98.6</td>
<td>99.1</td>
<td>99.9</td>
<td>100.6</td>
</tr>
<tr>
<td>2.046</td>
<td>97.6</td>
<td>98.3</td>
<td>99.3</td>
<td>100.3</td>
</tr>
<tr>
<td>2.047</td>
<td>108.3</td>
<td>108.7</td>
<td>109.3</td>
<td>109.9</td>
</tr>
<tr>
<td>2.048</td>
<td>108.4</td>
<td>108.9</td>
<td>109.6</td>
<td>110.4</td>
</tr>
<tr>
<td>2.049</td>
<td>107.0</td>
<td>107.5</td>
<td>108.6</td>
<td>109.7</td>
</tr>
<tr>
<td>2.050</td>
<td>105.6</td>
<td>106.4</td>
<td>107.7</td>
<td>109.1</td>
</tr>
<tr>
<td>2.051</td>
<td>104.9</td>
<td>105.8</td>
<td>107.4</td>
<td>109.2</td>
</tr>
<tr>
<td>2.052</td>
<td>116.5</td>
<td>116.8</td>
<td>117.2</td>
<td>117.6</td>
</tr>
<tr>
<td>2.053</td>
<td>116.2</td>
<td>116.5</td>
<td>117.1</td>
<td>117.6</td>
</tr>
<tr>
<td>2.054</td>
<td>115.6</td>
<td>116.0</td>
<td>116.8</td>
<td>117.5</td>
</tr>
<tr>
<td>2.055</td>
<td>114.8</td>
<td>114.5</td>
<td>114.6</td>
<td>114.7</td>
</tr>
<tr>
<td>2.056</td>
<td>113.7</td>
<td>114.4</td>
<td>115.7</td>
<td>117.1</td>
</tr>
<tr>
<td>2.002</td>
<td>70.1</td>
<td>71.8</td>
<td>73.7</td>
<td>75.6</td>
</tr>
<tr>
<td>2.003</td>
<td>69.1</td>
<td>70.9</td>
<td>72.9</td>
<td>74.8</td>
</tr>
<tr>
<td>3.001</td>
<td>108.1</td>
<td>108.5</td>
<td>109.1</td>
<td>109.7</td>
</tr>
<tr>
<td>3.002</td>
<td>107.4</td>
<td>107.9</td>
<td>108.7</td>
<td>109.6</td>
</tr>
</tbody>
</table>
Table I.2. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Saturation Temperatures</th>
<th>Wall Temperatures</th>
<th>Flow Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3.003</td>
<td>107.0</td>
<td>107.6</td>
<td>108.7</td>
</tr>
<tr>
<td>3.004</td>
<td>104.7</td>
<td>105.6</td>
<td>107.1</td>
</tr>
<tr>
<td>3.005</td>
<td>116.6</td>
<td>116.9</td>
<td>117.3</td>
</tr>
<tr>
<td>3.006</td>
<td>116.1</td>
<td>116.5</td>
<td>117.1</td>
</tr>
<tr>
<td>3.007</td>
<td>115.3</td>
<td>115.8</td>
<td>116.6</td>
</tr>
<tr>
<td>3.008</td>
<td>114.5</td>
<td>115.1</td>
<td>116.2</td>
</tr>
<tr>
<td>3.009</td>
<td>108.8</td>
<td>108.9</td>
<td>109.1</td>
</tr>
<tr>
<td>3.010</td>
<td>109.2</td>
<td>109.4</td>
<td>109.6</td>
</tr>
<tr>
<td>3.011</td>
<td>109.0</td>
<td>109.2</td>
<td>109.5</td>
</tr>
<tr>
<td>3.012</td>
<td>109.5</td>
<td>109.8</td>
<td>110.1</td>
</tr>
<tr>
<td>3.013</td>
<td>117.1</td>
<td>117.2</td>
<td>117.3</td>
</tr>
<tr>
<td>3.014</td>
<td>116.9</td>
<td>117.1</td>
<td>117.3</td>
</tr>
<tr>
<td>3.015</td>
<td>116.8</td>
<td>117.0</td>
<td>117.3</td>
</tr>
<tr>
<td>3.016</td>
<td>116.6</td>
<td>116.8</td>
<td>117.1</td>
</tr>
<tr>
<td>3.017</td>
<td>117.3</td>
<td>117.5</td>
<td>117.9</td>
</tr>
<tr>
<td>3.018</td>
<td>117.0</td>
<td>117.4</td>
<td>117.8</td>
</tr>
<tr>
<td>3.019</td>
<td>117.1</td>
<td>117.5</td>
<td>117.8</td>
</tr>
<tr>
<td>3.020</td>
<td>117.4</td>
<td>117.7</td>
<td>117.9</td>
</tr>
<tr>
<td>3.021</td>
<td>117.5</td>
<td>117.7</td>
<td>117.9</td>
</tr>
<tr>
<td>3.022</td>
<td>116.7</td>
<td>116.9</td>
<td>117.3</td>
</tr>
<tr>
<td>3.023</td>
<td>116.2</td>
<td>116.6</td>
<td>117.0</td>
</tr>
<tr>
<td>3.024</td>
<td>116.6</td>
<td>116.7</td>
<td>117.1</td>
</tr>
<tr>
<td>3.025</td>
<td>116.2</td>
<td>116.6</td>
<td>116.9</td>
</tr>
<tr>
<td>3.026</td>
<td>117.4</td>
<td>117.7</td>
<td>118.2</td>
</tr>
<tr>
<td>3.027</td>
<td>116.3</td>
<td>116.7</td>
<td>117.2</td>
</tr>
<tr>
<td>3.028</td>
<td>116.3</td>
<td>116.7</td>
<td>117.2</td>
</tr>
<tr>
<td>3.029</td>
<td>116.2</td>
<td>116.7</td>
<td>117.1</td>
</tr>
<tr>
<td>3.030</td>
<td>116.2</td>
<td>116.6</td>
<td>117.1</td>
</tr>
<tr>
<td>3.031</td>
<td>116.5</td>
<td>117.0</td>
<td>117.4</td>
</tr>
<tr>
<td>3.032</td>
<td>116.3</td>
<td>116.7</td>
<td>117.1</td>
</tr>
<tr>
<td>Run #</td>
<td>Saturation Temperatures</td>
<td>Wall Temperatures</td>
<td>Flow Regime observation</td>
</tr>
<tr>
<td>-------</td>
<td>-------------------------</td>
<td>------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td></td>
<td>1 2 3 4 overall</td>
<td>1 2 3 4 overall</td>
<td></td>
</tr>
<tr>
<td>3.033</td>
<td>116.2 116.7 117.1 117.5 116.9</td>
<td>99.1 105.8 110.4 113.4 107.7</td>
<td>semiannular</td>
</tr>
<tr>
<td>3.034</td>
<td>116.3 116.7 117.2 117.6 117.0</td>
<td>98.9 105.8 110.5 113.5 107.7</td>
<td>semiannular</td>
</tr>
<tr>
<td>3.035</td>
<td>116.2 116.7 117.1 117.5 116.9</td>
<td>96.4 106.5 112.0 114.9 108.1</td>
<td>semiannular</td>
</tr>
<tr>
<td>3.036</td>
<td>115.8 116.3 116.8 117.3 116.5</td>
<td>105.4 109.4 112.3 114.5 110.6</td>
<td>annular</td>
</tr>
<tr>
<td>3.037</td>
<td>117.0 117.5 118.0 118.5 117.7</td>
<td>111.1 113.8 115.5 116.8 114.3</td>
<td>annular</td>
</tr>
<tr>
<td>3.038</td>
<td>117.0 117.2 117.4 117.7 117.4</td>
<td>106.9 110.3 112.7 114.4 111.1</td>
<td>wavy</td>
</tr>
<tr>
<td>3.039</td>
<td>117.2 117.4 117.6 117.8 117.6</td>
<td>106.2 110.6 112.8 114.3 111.0</td>
<td>wavy</td>
</tr>
</tbody>
</table>
Table I.2. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Saturation Temperatures</th>
<th>Wall Temperatures</th>
<th>Flow Regime Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>4.024</td>
<td>100.7</td>
<td>100.9</td>
<td>101.2</td>
</tr>
<tr>
<td>4.025</td>
<td>99.5</td>
<td>99.7</td>
<td>100.1</td>
</tr>
<tr>
<td>4.026</td>
<td>108.8</td>
<td>108.9</td>
<td>109.3</td>
</tr>
<tr>
<td>4.027</td>
<td>109.4</td>
<td>109.6</td>
<td>109.8</td>
</tr>
<tr>
<td>4.028</td>
<td>109.3</td>
<td>109.4</td>
<td>109.5</td>
</tr>
<tr>
<td>4.029</td>
<td>109.0</td>
<td>109.2</td>
<td>109.3</td>
</tr>
<tr>
<td>4.030</td>
<td>109.4</td>
<td>109.6</td>
<td>109.8</td>
</tr>
<tr>
<td>4.031</td>
<td>117.0</td>
<td>117.1</td>
<td>117.2</td>
</tr>
<tr>
<td>4.032</td>
<td>117.5</td>
<td>117.6</td>
<td>117.7</td>
</tr>
<tr>
<td>4.033</td>
<td>117.4</td>
<td>117.5</td>
<td>117.7</td>
</tr>
<tr>
<td>4.034</td>
<td>116.8</td>
<td>117.0</td>
<td>117.2</td>
</tr>
<tr>
<td>4.035</td>
<td>74.4</td>
<td>74.8</td>
<td>75.3</td>
</tr>
<tr>
<td>4.036</td>
<td>73.6</td>
<td>74.2</td>
<td>74.9</td>
</tr>
<tr>
<td>4.037</td>
<td>72.9</td>
<td>73.6</td>
<td>74.7</td>
</tr>
<tr>
<td>4.038</td>
<td>89.0</td>
<td>89.3</td>
<td>89.6</td>
</tr>
<tr>
<td>4.039</td>
<td>88.6</td>
<td>88.9</td>
<td>89.4</td>
</tr>
<tr>
<td>4.040</td>
<td>87.9</td>
<td>88.3</td>
<td>89.0</td>
</tr>
<tr>
<td>5.002</td>
<td>76.2</td>
<td>76.3</td>
<td>76.4</td>
</tr>
<tr>
<td>5.003</td>
<td>76.1</td>
<td>76.2</td>
<td>76.6</td>
</tr>
<tr>
<td>5.004</td>
<td>75.4</td>
<td>75.7</td>
<td>76.1</td>
</tr>
<tr>
<td>5.006</td>
<td>89.6</td>
<td>89.8</td>
<td>90.0</td>
</tr>
<tr>
<td>5.007</td>
<td>89.8</td>
<td>90.0</td>
<td>90.2</td>
</tr>
<tr>
<td>5.008</td>
<td>90.0</td>
<td>90.2</td>
<td>90.3</td>
</tr>
<tr>
<td>5.009</td>
<td>90.0</td>
<td>90.2</td>
<td>90.2</td>
</tr>
<tr>
<td>5.010</td>
<td>76.1</td>
<td>76.3</td>
<td>76.7</td>
</tr>
<tr>
<td>5.011</td>
<td>75.8</td>
<td>76.0</td>
<td>76.3</td>
</tr>
<tr>
<td>5.012</td>
<td>75.2</td>
<td>75.5</td>
<td>75.9</td>
</tr>
<tr>
<td>5.013</td>
<td>100.7</td>
<td>100.8</td>
<td>100.9</td>
</tr>
<tr>
<td>5.014</td>
<td>100.6</td>
<td>100.7</td>
<td>100.8</td>
</tr>
<tr>
<td>5.015</td>
<td>100.0</td>
<td>100.2</td>
<td>100.5</td>
</tr>
</tbody>
</table>
Table I.2. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Saturation Temperatures</th>
<th>Wall Temperatures</th>
<th>Flow Regime Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 overall</td>
<td>1 2 3 4 overall</td>
<td></td>
</tr>
<tr>
<td>5.016</td>
<td>109.4 109.5 109.6 109.6</td>
<td>100.7 104.6 106.1</td>
<td></td>
</tr>
<tr>
<td>5.017</td>
<td>109.5 109.6 109.7 109.7</td>
<td>97.2 101.4 104.6</td>
<td></td>
</tr>
<tr>
<td>5.018</td>
<td>110.0 110.1 110.3 110.1</td>
<td>95.1 100.5 104.8</td>
<td></td>
</tr>
<tr>
<td>5.019</td>
<td>118.0 118.0 118.1 118.1</td>
<td>107.5 112.1 114.7</td>
<td></td>
</tr>
<tr>
<td>5.020</td>
<td>117.6 117.6 117.7 117.8</td>
<td>104.3 109.1 112.8</td>
<td></td>
</tr>
<tr>
<td>5.021</td>
<td>117.8 117.9 118.0 117.9</td>
<td>100.9 107.3 111.6</td>
<td></td>
</tr>
<tr>
<td>5.022</td>
<td>117.7 117.8 117.9 117.9</td>
<td>100.7 106.4 110.8</td>
<td></td>
</tr>
<tr>
<td>5.023</td>
<td>117.2 117.3 117.5 117.7</td>
<td>97.3 104.3 109.7</td>
<td></td>
</tr>
<tr>
<td>5.024</td>
<td>116.9 117.0 117.3 117.6</td>
<td>94.4 102.3 108.9</td>
<td></td>
</tr>
<tr>
<td>5.025</td>
<td>116.9 117.1 117.4 117.8</td>
<td>92.4 101.6 108.8</td>
<td></td>
</tr>
<tr>
<td>5.026</td>
<td>116.2 116.4 116.9 117.4</td>
<td>89.7 99.7 107.4</td>
<td></td>
</tr>
<tr>
<td>5.027</td>
<td>109.4 109.5 109.7 109.7</td>
<td>92.7 98.9 103.5</td>
<td></td>
</tr>
<tr>
<td>5.028</td>
<td>108.8 108.9 109.2 109.2</td>
<td>87.5 95.6 101.6</td>
<td></td>
</tr>
<tr>
<td>5.029</td>
<td>108.1 108.3 108.7 109.1</td>
<td>84.8 93.4 100.1</td>
<td></td>
</tr>
<tr>
<td>5.030</td>
<td>107.5 107.7 108.2 108.9</td>
<td>83.4 92.6 100.2</td>
<td></td>
</tr>
<tr>
<td>5.031</td>
<td>107.3 107.6 108.2 108.5</td>
<td>83.3 92.9 101.2</td>
<td></td>
</tr>
<tr>
<td>5.032</td>
<td>100.6 100.8 101.1 101.4</td>
<td>86.7 90.8 94.3</td>
<td></td>
</tr>
<tr>
<td>5.033</td>
<td>99.6 99.9 100.3 100.8</td>
<td>83.2 88.3 92.9</td>
<td></td>
</tr>
<tr>
<td>5.034</td>
<td>99.0 99.3 99.8 100.5</td>
<td>80.9 86.8 92.0</td>
<td></td>
</tr>
<tr>
<td>5.035</td>
<td>98.1 98.4 99.1 100.0</td>
<td>78.3 85.2 90.9</td>
<td></td>
</tr>
<tr>
<td>5.036</td>
<td>98.0 98.4 99.2 100.5</td>
<td>76.7 84.4 90.9</td>
<td></td>
</tr>
<tr>
<td>5.037</td>
<td>88.3 88.6 89.0 89.6</td>
<td>76.5 79.3 82.5</td>
<td></td>
</tr>
<tr>
<td>5.038</td>
<td>87.0 87.4 88.0 88.8</td>
<td>72.5 76.6 80.5</td>
<td></td>
</tr>
<tr>
<td>5.039</td>
<td>86.2 86.7 87.5 88.7</td>
<td>70.5 75.4 79.9</td>
<td></td>
</tr>
<tr>
<td>5.040</td>
<td>85.3 85.8 86.9 88.5</td>
<td>68.3 73.9 79.4</td>
<td></td>
</tr>
<tr>
<td>5.041</td>
<td>83.9 84.5 85.8 87.9</td>
<td>65.2 70.9 76.8</td>
<td></td>
</tr>
<tr>
<td>5.042</td>
<td>73.6 74.0 74.9 76.0</td>
<td>60.0 64.3 68.7</td>
<td></td>
</tr>
<tr>
<td>5.043</td>
<td>71.7 72.4 73.7 75.6</td>
<td>55.0 60.2 65.2</td>
<td></td>
</tr>
<tr>
<td>5.044</td>
<td>67.0 68.0 70.5 74.1</td>
<td>50.1 55.9 62.7</td>
<td></td>
</tr>
<tr>
<td>5.045</td>
<td>116.9 117.1 117.3 117.6</td>
<td>98.3 103.9 108.9</td>
<td></td>
</tr>
<tr>
<td>Run #</td>
<td>Saturation Temperatures</td>
<td>Wall Temperatures</td>
<td>Flow Regime</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------</td>
<td>------------------</td>
<td>-------------</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>5.046</td>
<td>117.0</td>
<td>117.1</td>
<td>117.4</td>
</tr>
<tr>
<td>5.047</td>
<td>116.9</td>
<td>117.1</td>
<td>117.4</td>
</tr>
<tr>
<td>5.048</td>
<td>117.0</td>
<td>117.1</td>
<td>117.4</td>
</tr>
<tr>
<td>5.049</td>
<td>117.1</td>
<td>117.2</td>
<td>117.5</td>
</tr>
<tr>
<td>5.050</td>
<td>117.1</td>
<td>117.3</td>
<td>117.6</td>
</tr>
<tr>
<td>5.051</td>
<td>116.8</td>
<td>117.0</td>
<td>117.3</td>
</tr>
<tr>
<td>5.052</td>
<td>116.7</td>
<td>117.1</td>
<td>117.4</td>
</tr>
<tr>
<td>5.053</td>
<td>116.7</td>
<td>117.1</td>
<td>117.4</td>
</tr>
<tr>
<td>5.054</td>
<td>116.8</td>
<td>117.2</td>
<td>117.6</td>
</tr>
<tr>
<td>5.055</td>
<td>117.0</td>
<td>117.2</td>
<td>117.5</td>
</tr>
<tr>
<td>5.056</td>
<td>116.8</td>
<td>117.1</td>
<td>117.5</td>
</tr>
<tr>
<td>5.057</td>
<td>116.5</td>
<td>116.9</td>
<td>117.2</td>
</tr>
<tr>
<td>5.058</td>
<td>116.5</td>
<td>116.9</td>
<td>117.2</td>
</tr>
<tr>
<td>5.059</td>
<td>117.1</td>
<td>117.2</td>
<td>117.3</td>
</tr>
<tr>
<td>5.060</td>
<td>117.0</td>
<td>117.1</td>
<td>117.3</td>
</tr>
<tr>
<td>5.061</td>
<td>117.0</td>
<td>117.1</td>
<td>117.3</td>
</tr>
<tr>
<td>5.062</td>
<td>117.0</td>
<td>117.2</td>
<td>117.3</td>
</tr>
<tr>
<td>5.063</td>
<td>118.1</td>
<td>118.2</td>
<td>118.4</td>
</tr>
<tr>
<td>6.001</td>
<td>71.5</td>
<td>72.4</td>
<td>73.9</td>
</tr>
<tr>
<td>6.002</td>
<td>66.6</td>
<td>68.3</td>
<td>71.3</td>
</tr>
<tr>
<td>6.003</td>
<td>62.7</td>
<td>64.9</td>
<td>69.1</td>
</tr>
<tr>
<td>6.004</td>
<td>61.0</td>
<td>63.6</td>
<td>68.3</td>
</tr>
<tr>
<td>6.005</td>
<td>87.6</td>
<td>88.0</td>
<td>88.7</td>
</tr>
<tr>
<td>6.006</td>
<td>85.3</td>
<td>86.0</td>
<td>87.3</td>
</tr>
<tr>
<td>6.007</td>
<td>82.9</td>
<td>83.9</td>
<td>86.0</td>
</tr>
<tr>
<td>6.008</td>
<td>81.4</td>
<td>82.7</td>
<td>85.5</td>
</tr>
<tr>
<td>6.009</td>
<td>99.6</td>
<td>99.9</td>
<td>100.3</td>
</tr>
<tr>
<td>6.010</td>
<td>98.3</td>
<td>98.7</td>
<td>99.5</td>
</tr>
<tr>
<td>6.011</td>
<td>96.8</td>
<td>97.4</td>
<td>98.6</td>
</tr>
<tr>
<td>6.012</td>
<td>95.1</td>
<td>95.8</td>
<td>97.6</td>
</tr>
<tr>
<td>Run #</td>
<td>Saturation Temperatures</td>
<td>Wall Temperatures</td>
<td>Flow Regime observation</td>
</tr>
<tr>
<td>-------</td>
<td>--------------------------</td>
<td>------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>6.013</td>
<td>108.9</td>
<td>109.1</td>
<td>109.5</td>
</tr>
<tr>
<td>6.014</td>
<td>108.4</td>
<td>108.7</td>
<td>109.3</td>
</tr>
<tr>
<td>6.015</td>
<td>108.1</td>
<td>108.5</td>
<td>109.4</td>
</tr>
<tr>
<td>6.016</td>
<td>107.2</td>
<td>107.7</td>
<td>108.3</td>
</tr>
<tr>
<td>6.017</td>
<td>107.6</td>
<td>108.0</td>
<td>108.9</td>
</tr>
<tr>
<td>6.018</td>
<td>117.2</td>
<td>117.3</td>
<td>117.5</td>
</tr>
<tr>
<td>6.019</td>
<td>116.5</td>
<td>116.7</td>
<td>117.1</td>
</tr>
<tr>
<td>6.020</td>
<td>115.8</td>
<td>116.1</td>
<td>116.8</td>
</tr>
<tr>
<td>6.021</td>
<td>114.9</td>
<td>115.3</td>
<td>116.2</td>
</tr>
<tr>
<td>6.022</td>
<td>115.1</td>
<td>115.5</td>
<td>116.3</td>
</tr>
<tr>
<td>6.023</td>
<td>117.5</td>
<td>117.6</td>
<td>117.6</td>
</tr>
<tr>
<td>6.024</td>
<td>118.4</td>
<td>118.5</td>
<td>118.6</td>
</tr>
<tr>
<td>6.025</td>
<td>117.3</td>
<td>117.5</td>
<td>117.7</td>
</tr>
<tr>
<td>6.026</td>
<td>116.8</td>
<td>117.0</td>
<td>117.4</td>
</tr>
<tr>
<td>6.027</td>
<td>109.9</td>
<td>109.9</td>
<td>110.0</td>
</tr>
<tr>
<td>6.028</td>
<td>109.5</td>
<td>109.5</td>
<td>109.7</td>
</tr>
<tr>
<td>6.029</td>
<td>109.3</td>
<td>109.5</td>
<td>109.7</td>
</tr>
<tr>
<td>6.030</td>
<td>108.6</td>
<td>108.8</td>
<td>109.2</td>
</tr>
<tr>
<td>6.031</td>
<td>100.5</td>
<td>100.5</td>
<td>100.7</td>
</tr>
<tr>
<td>6.032</td>
<td>100.3</td>
<td>100.4</td>
<td>100.6</td>
</tr>
<tr>
<td>6.033</td>
<td>100.1</td>
<td>100.3</td>
<td>100.6</td>
</tr>
<tr>
<td>6.034</td>
<td>98.8</td>
<td>99.1</td>
<td>99.6</td>
</tr>
<tr>
<td>6.035</td>
<td>89.6</td>
<td>89.7</td>
<td>89.9</td>
</tr>
<tr>
<td>6.036</td>
<td>89.3</td>
<td>89.5</td>
<td>89.9</td>
</tr>
<tr>
<td>6.037</td>
<td>88.5</td>
<td>88.8</td>
<td>89.3</td>
</tr>
<tr>
<td>6.038</td>
<td>87.7</td>
<td>88.2</td>
<td>88.9</td>
</tr>
<tr>
<td>6.039</td>
<td>75.9</td>
<td>76.2</td>
<td>76.5</td>
</tr>
<tr>
<td>6.040</td>
<td>74.7</td>
<td>75.1</td>
<td>75.6</td>
</tr>
<tr>
<td>6.041</td>
<td>73.4</td>
<td>74.0</td>
<td>75.0</td>
</tr>
<tr>
<td>6.042</td>
<td>71.8</td>
<td>72.5</td>
<td>73.8</td>
</tr>
</tbody>
</table>
Table I.2. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Saturation Temperatures 1 2 3 4 overall</th>
<th>Wall Temperatures 1 2 3 4 overall</th>
<th>Flow Regime observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.043</td>
<td>117.1 117.3 117.6 117.8 117.5</td>
<td>103.6 107.9 110.2 113.0 108.7</td>
<td></td>
</tr>
<tr>
<td>6.044</td>
<td>117.0 117.3 117.6 117.9 117.4</td>
<td>110.1 112.3 113.7 115.7 112.9</td>
<td></td>
</tr>
<tr>
<td>6.045</td>
<td>116.7 117.1 117.4 117.6 117.1</td>
<td>111.6 113.8 115.1 117.8 114.6</td>
<td></td>
</tr>
<tr>
<td>6.046</td>
<td>117.1 117.4 117.7 117.9 117.5</td>
<td>112.7 115.0 116.2 119.4 115.8</td>
<td></td>
</tr>
<tr>
<td>6.047</td>
<td>116.6 116.8 117.1 117.3 117.0</td>
<td>101.3 106.4 109.4 112.3 107.4</td>
<td></td>
</tr>
<tr>
<td>6.048</td>
<td>116.7 116.9 117.2 117.4 117.1</td>
<td>100.6 106.0 109.3 112.4 107.1</td>
<td></td>
</tr>
<tr>
<td>6.049</td>
<td>117.3 117.5 117.7 118.0 117.7</td>
<td>101.2 106.9 110.2 113.1 107.8</td>
<td></td>
</tr>
<tr>
<td>6.050</td>
<td>117.0 117.2 117.5 117.7 117.4</td>
<td>100.7 106.4 109.9 112.9 107.5</td>
<td></td>
</tr>
<tr>
<td>6.051</td>
<td>117.3 117.5 117.8 118.0 117.7</td>
<td>101.6 107.4 110.3 113.7 108.2</td>
<td></td>
</tr>
<tr>
<td>6.052</td>
<td>117.3 117.5 117.8 118.0 117.7</td>
<td>101.0 106.7 110.2 113.6 107.9</td>
<td></td>
</tr>
<tr>
<td>6.053</td>
<td>116.3 116.5 116.7 116.9 116.7</td>
<td>106.3 109.9 112.0 113.4 110.4</td>
<td></td>
</tr>
<tr>
<td>6.054</td>
<td>117.0 117.2 117.4 117.6 117.3</td>
<td>109.9 113.2 114.7 115.7 113.4</td>
<td></td>
</tr>
<tr>
<td>6.055</td>
<td>116.6 116.7 116.8 116.9 116.8</td>
<td>105.5 111.1 113.2 114.3 111.0</td>
<td></td>
</tr>
<tr>
<td>7.005</td>
<td>76.8 76.9 76.9 76.9 76.8</td>
<td>66.5 68.6 71.3 70.9 69.3</td>
<td></td>
</tr>
<tr>
<td>7.006</td>
<td>76.9 77.0 77.1 77.1 77.0</td>
<td>63.8 66.2 67.9 69.1 66.8</td>
<td></td>
</tr>
<tr>
<td>7.007</td>
<td>76.4 76.5 76.6 76.7 76.5</td>
<td>62.4 64.3 66.7 68.4 65.5</td>
<td></td>
</tr>
<tr>
<td>7.008</td>
<td>76.1 76.1 76.3 76.3 76.4</td>
<td>61.1 63.1 66.0 67.7 64.4</td>
<td></td>
</tr>
<tr>
<td>7.009</td>
<td>90.3 90.4 90.5 90.5 90.4</td>
<td>80.9 83.0 85.2 86.0 83.8</td>
<td></td>
</tr>
<tr>
<td>7.010</td>
<td>90.1 90.1 90.2 90.2 90.1</td>
<td>82.7 84.1 86.3 87.0 85.0</td>
<td></td>
</tr>
<tr>
<td>7.011</td>
<td>90.1 90.1 90.2 90.2 90.1</td>
<td>78.5 81.4 82.9 83.9 81.7</td>
<td></td>
</tr>
<tr>
<td>7.012</td>
<td>89.8 89.9 89.9 90.0 89.9</td>
<td>77.6 80.0 82.0 82.8 80.6</td>
<td></td>
</tr>
<tr>
<td>7.013</td>
<td>89.5 89.6 89.6 89.6 89.5</td>
<td>76.2 78.6 80.2 81.1 79.0</td>
<td></td>
</tr>
<tr>
<td>7.014</td>
<td>100.5 100.6 100.6 100.6 100.5</td>
<td>91.7 93.7 95.8 96.7 94.5</td>
<td></td>
</tr>
<tr>
<td>7.015</td>
<td>100.1 100.2 100.3 100.3 100.2</td>
<td>88.6 91.1 93.2 94.8 91.9</td>
<td></td>
</tr>
<tr>
<td>7.016</td>
<td>100.8 100.8 100.9 100.9 100.9</td>
<td>86.9 89.8 91.6 93.1 90.4</td>
<td></td>
</tr>
<tr>
<td>7.017</td>
<td>100.5 100.6 100.7 100.8 100.6</td>
<td>85.6 86.6 88.7 90.7 87.9</td>
<td></td>
</tr>
<tr>
<td>7.018</td>
<td>109.8 109.8 109.8 109.8 109.8</td>
<td>100.2 102.4 104.4 105.8 103.2</td>
<td></td>
</tr>
<tr>
<td>7.019</td>
<td>109.7 109.8 109.8 109.8 109.8</td>
<td>98.6 101.2 103.4 104.5 101.9</td>
<td></td>
</tr>
<tr>
<td>7.020</td>
<td>109.2 109.3 109.3 109.3 109.2</td>
<td>95.3 97.7 99.5 101.0 98.4</td>
<td></td>
</tr>
<tr>
<td>7.021</td>
<td>108.6 108.7 108.8 108.8 108.7</td>
<td>93.0 95.7 97.7 100.1 96.6</td>
<td></td>
</tr>
<tr>
<td>Run #</td>
<td>Saturation Temperatures 1</td>
<td>Saturation Temperatures 2</td>
<td>Saturation Temperatures 3</td>
</tr>
<tr>
<td>-------</td>
<td>---------------------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>7.022</td>
<td>117.8</td>
<td>117.9</td>
<td>117.9</td>
</tr>
<tr>
<td>7.023</td>
<td>118.4</td>
<td>118.4</td>
<td>118.5</td>
</tr>
<tr>
<td>7.024</td>
<td>118.2</td>
<td>118.3</td>
<td>118.3</td>
</tr>
<tr>
<td>7.025</td>
<td>117.8</td>
<td>117.8</td>
<td>117.6</td>
</tr>
<tr>
<td>7.026</td>
<td>117.6</td>
<td>117.7</td>
<td>117.8</td>
</tr>
<tr>
<td>7.027</td>
<td>117.7</td>
<td>117.8</td>
<td>117.9</td>
</tr>
<tr>
<td>7.028</td>
<td>117.3</td>
<td>117.4</td>
<td>117.5</td>
</tr>
<tr>
<td>7.029</td>
<td>117.0</td>
<td>117.1</td>
<td>117.4</td>
</tr>
<tr>
<td>7.030</td>
<td>100.6</td>
<td>100.7</td>
<td>100.9</td>
</tr>
<tr>
<td>7.031</td>
<td>99.5</td>
<td>99.7</td>
<td>99.9</td>
</tr>
<tr>
<td>7.032</td>
<td>98.9</td>
<td>99.0</td>
<td>99.4</td>
</tr>
<tr>
<td>7.033</td>
<td>98.0</td>
<td>98.3</td>
<td>98.8</td>
</tr>
<tr>
<td>7.034</td>
<td>109.6</td>
<td>109.7</td>
<td>109.8</td>
</tr>
<tr>
<td>7.035</td>
<td>108.5</td>
<td>108.6</td>
<td>108.8</td>
</tr>
<tr>
<td>7.036</td>
<td>108.5</td>
<td>108.7</td>
<td>109.0</td>
</tr>
<tr>
<td>7.037</td>
<td>108.1</td>
<td>108.2</td>
<td>108.6</td>
</tr>
<tr>
<td>7.038</td>
<td>89.6</td>
<td>89.8</td>
<td>90.0</td>
</tr>
<tr>
<td>7.039</td>
<td>88.6</td>
<td>88.9</td>
<td>89.2</td>
</tr>
<tr>
<td>7.040</td>
<td>88.6</td>
<td>88.9</td>
<td>89.3</td>
</tr>
<tr>
<td>7.041</td>
<td>88.1</td>
<td>88.5</td>
<td>89.1</td>
</tr>
<tr>
<td>7.042</td>
<td>87.9</td>
<td>88.2</td>
<td>88.9</td>
</tr>
<tr>
<td>7.043</td>
<td>74.5</td>
<td>74.9</td>
<td>75.5</td>
</tr>
<tr>
<td>7.044</td>
<td>73.8</td>
<td>74.3</td>
<td>75.1</td>
</tr>
<tr>
<td>7.045</td>
<td>73.0</td>
<td>73.6</td>
<td>74.6</td>
</tr>
<tr>
<td>7.046</td>
<td>71.4</td>
<td>72.0</td>
<td>73.4</td>
</tr>
<tr>
<td>7.047</td>
<td>117.3</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>7.048</td>
<td>117.3</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>7.049</td>
<td>117.3</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>7.050</td>
<td>117.3</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>7.051</td>
<td>117.3</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>Run #</td>
<td>Saturation Temperatures</td>
<td>Wall Temperatures</td>
<td>Flow Regime Observation</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------</td>
<td>------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>7.052</td>
<td>117.3</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>7.053</td>
<td>117.2</td>
<td>117.3</td>
<td>117.5</td>
</tr>
<tr>
<td>7.054</td>
<td>117.0</td>
<td>117.3</td>
<td>117.6</td>
</tr>
<tr>
<td>7.055</td>
<td>117.6</td>
<td>117.8</td>
<td>118.1</td>
</tr>
<tr>
<td>7.056</td>
<td>118.0</td>
<td>118.0</td>
<td>118.2</td>
</tr>
<tr>
<td>7.057</td>
<td>117.7</td>
<td>117.8</td>
<td>117.9</td>
</tr>
<tr>
<td>7.058</td>
<td>117.3</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>7.059</td>
<td>117.5</td>
<td>117.6</td>
<td>117.7</td>
</tr>
<tr>
<td>8.001</td>
<td>75.6</td>
<td>75.9</td>
<td>76.2</td>
</tr>
<tr>
<td>8.002</td>
<td>75.4</td>
<td>75.6</td>
<td>75.9</td>
</tr>
<tr>
<td>8.003</td>
<td>75.8</td>
<td>75.9</td>
<td>76.3</td>
</tr>
<tr>
<td>8.004</td>
<td>75.5</td>
<td>75.7</td>
<td>76.1</td>
</tr>
<tr>
<td>8.005</td>
<td>76.4</td>
<td>76.5</td>
<td>76.7</td>
</tr>
<tr>
<td>8.007</td>
<td>75.9</td>
<td>76.1</td>
<td>76.5</td>
</tr>
<tr>
<td>8.008</td>
<td>75.4</td>
<td>75.7</td>
<td>76.2</td>
</tr>
<tr>
<td>8.009</td>
<td>89.7</td>
<td>89.7</td>
<td>89.7</td>
</tr>
<tr>
<td>8.010</td>
<td>90.1</td>
<td>90.2</td>
<td>90.3</td>
</tr>
<tr>
<td>8.011</td>
<td>89.9</td>
<td>89.9</td>
<td>90.0</td>
</tr>
<tr>
<td>8.012</td>
<td>90.0</td>
<td>90.2</td>
<td>90.4</td>
</tr>
<tr>
<td>8.013</td>
<td>100.3</td>
<td>100.3</td>
<td>100.5</td>
</tr>
<tr>
<td>8.014</td>
<td>100.4</td>
<td>100.4</td>
<td>100.4</td>
</tr>
<tr>
<td>8.015</td>
<td>100.2</td>
<td>100.3</td>
<td>100.3</td>
</tr>
<tr>
<td>8.016</td>
<td>99.8</td>
<td>99.8</td>
<td>100.0</td>
</tr>
<tr>
<td>8.017</td>
<td>109.3</td>
<td>109.3</td>
<td>109.4</td>
</tr>
<tr>
<td>8.018</td>
<td>109.9</td>
<td>109.9</td>
<td>110.0</td>
</tr>
<tr>
<td>8.019</td>
<td>109.7</td>
<td>109.7</td>
<td>109.8</td>
</tr>
<tr>
<td>8.020</td>
<td>109.3</td>
<td>109.4</td>
<td>109.6</td>
</tr>
<tr>
<td>8.021</td>
<td>117.8</td>
<td>117.8</td>
<td>117.9</td>
</tr>
<tr>
<td>8.022</td>
<td>117.9</td>
<td>117.9</td>
<td>118.0</td>
</tr>
<tr>
<td>8.023</td>
<td>117.7</td>
<td>117.7</td>
<td>117.9</td>
</tr>
<tr>
<td>Run #</td>
<td>Saturation Temperatures</td>
<td>Wall Temperatures</td>
<td>Flow Regime observation</td>
</tr>
<tr>
<td>-------</td>
<td>-------------------------</td>
<td>------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>8.024</td>
<td>117.6</td>
<td>117.7</td>
<td>117.9</td>
</tr>
<tr>
<td>8.025</td>
<td>117.2</td>
<td>117.3</td>
<td>117.4</td>
</tr>
<tr>
<td>8.026</td>
<td>117.4</td>
<td>117.4</td>
<td>117.6</td>
</tr>
<tr>
<td>8.027</td>
<td>117.3</td>
<td>117.5</td>
<td>117.7</td>
</tr>
<tr>
<td>8.028</td>
<td>116.6</td>
<td>116.7</td>
<td>117.1</td>
</tr>
<tr>
<td>8.029</td>
<td>110.0</td>
<td>110.1</td>
<td>110.2</td>
</tr>
<tr>
<td>8.030</td>
<td>109.3</td>
<td>109.4</td>
<td>109.6</td>
</tr>
<tr>
<td>8.031</td>
<td>108.7</td>
<td>108.9</td>
<td>109.3</td>
</tr>
<tr>
<td>8.032</td>
<td>108.3</td>
<td>108.6</td>
<td>109.0</td>
</tr>
<tr>
<td>8.033</td>
<td>90.1</td>
<td>90.3</td>
<td>90.6</td>
</tr>
<tr>
<td>8.034</td>
<td>89.0</td>
<td>89.3</td>
<td>89.8</td>
</tr>
<tr>
<td>8.035</td>
<td>87.1</td>
<td>87.6</td>
<td>88.3</td>
</tr>
<tr>
<td>8.036</td>
<td>86.6</td>
<td>87.2</td>
<td>88.1</td>
</tr>
<tr>
<td>8.037</td>
<td>99.8</td>
<td>100.1</td>
<td>100.4</td>
</tr>
<tr>
<td>8.038</td>
<td>99.4</td>
<td>99.7</td>
<td>100.1</td>
</tr>
<tr>
<td>8.039</td>
<td>98.5</td>
<td>98.9</td>
<td>99.3</td>
</tr>
<tr>
<td>8.040</td>
<td>98.4</td>
<td>98.8</td>
<td>99.4</td>
</tr>
<tr>
<td>8.041</td>
<td>73.1</td>
<td>73.6</td>
<td>74.4</td>
</tr>
<tr>
<td>8.042</td>
<td>72.4</td>
<td>73.1</td>
<td>74.0</td>
</tr>
<tr>
<td>8.044</td>
<td>118.0</td>
<td>118.0</td>
<td>118.2</td>
</tr>
<tr>
<td>8.045</td>
<td>118.1</td>
<td>118.1</td>
<td>118.2</td>
</tr>
<tr>
<td>8.046</td>
<td>118.1</td>
<td>118.1</td>
<td>118.2</td>
</tr>
</tbody>
</table>
Table I.3. Reduced data - heat fluxes and energy transfers

(Units as appropriate: W/sq m, W)

<table>
<thead>
<tr>
<th>Run</th>
<th>Heat Fluxes</th>
<th>Energy Transfers</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1.012</td>
<td>31702.4</td>
<td>26972.9</td>
<td>21282.6</td>
</tr>
<tr>
<td>1.013</td>
<td>31763.8</td>
<td>28364.3</td>
<td>22491.1</td>
</tr>
<tr>
<td>1.014</td>
<td>31656.8</td>
<td>30665.7</td>
<td>26054.6</td>
</tr>
<tr>
<td>1.018</td>
<td>26457.7</td>
<td>29370.7</td>
<td>25426.4</td>
</tr>
<tr>
<td>1.019</td>
<td>33796.3</td>
<td>23033.6</td>
<td>16148.8</td>
</tr>
<tr>
<td>1.020</td>
<td>36495.0</td>
<td>23195.6</td>
<td>13047.1</td>
</tr>
<tr>
<td>1.021</td>
<td>38547.9</td>
<td>26693.7</td>
<td>16254.5</td>
</tr>
<tr>
<td>1.022</td>
<td>40359.5</td>
<td>30298.0</td>
<td>20811.2</td>
</tr>
<tr>
<td>1.023</td>
<td>40209.0</td>
<td>31289.6</td>
<td>22823.0</td>
</tr>
<tr>
<td>1.024</td>
<td>43019.8</td>
<td>35883.7</td>
<td>27609.8</td>
</tr>
<tr>
<td>1.025</td>
<td>38982.3</td>
<td>15158.2</td>
<td>5937.0</td>
</tr>
<tr>
<td>1.026</td>
<td>38216.3</td>
<td>20940.1</td>
<td>9918.5</td>
</tr>
<tr>
<td>1.027</td>
<td>42146.2</td>
<td>25050.5</td>
<td>13526.1</td>
</tr>
<tr>
<td>1.028</td>
<td>42110.6</td>
<td>28754.6</td>
<td>18275.1</td>
</tr>
<tr>
<td>1.031</td>
<td>43149.7</td>
<td>27228.9</td>
<td>13933.3</td>
</tr>
<tr>
<td>1.033</td>
<td>10151.0</td>
<td>13255.5</td>
<td>11834.7</td>
</tr>
<tr>
<td>1.034</td>
<td>16037.7</td>
<td>20340.2</td>
<td>18287.3</td>
</tr>
<tr>
<td>1.035</td>
<td>22046.3</td>
<td>23363.2</td>
<td>20205.6</td>
</tr>
<tr>
<td>1.036</td>
<td>13549.7</td>
<td>14614.1</td>
<td>11254.2</td>
</tr>
<tr>
<td>1.037</td>
<td>19602.5</td>
<td>18971.5</td>
<td>15319.3</td>
</tr>
<tr>
<td>1.038</td>
<td>25006.7</td>
<td>25590.0</td>
<td>21154.6</td>
</tr>
<tr>
<td>1.039</td>
<td>30911.3</td>
<td>28523.4</td>
<td>24152.6</td>
</tr>
<tr>
<td>1.040</td>
<td>42920.7</td>
<td>49818.8</td>
<td>48775.2</td>
</tr>
<tr>
<td>1.041</td>
<td>45210.3</td>
<td>54273.1</td>
<td>52893.2</td>
</tr>
<tr>
<td>1.042</td>
<td>58686.4</td>
<td>72144.9</td>
<td>71247.5</td>
</tr>
<tr>
<td>Run</td>
<td>Heat Fluxes</td>
<td>Energy Transfer</td>
<td>After condenser</td>
</tr>
<tr>
<td>------</td>
<td>--------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td></td>
<td>#</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1.043</td>
<td>64396.6</td>
<td>83091.0</td>
<td>85824.4</td>
</tr>
<tr>
<td>1.044</td>
<td>53465.1</td>
<td>57450.8</td>
<td>50243.1</td>
</tr>
<tr>
<td>1.045</td>
<td>60955.5</td>
<td>66846.1</td>
<td>61949.7</td>
</tr>
<tr>
<td>1.046</td>
<td>68557.9</td>
<td>32835.2</td>
<td>77036.1</td>
</tr>
<tr>
<td>1.047</td>
<td>47195.3</td>
<td>45898.5</td>
<td>37257.0</td>
</tr>
<tr>
<td>1.048</td>
<td>41602.2</td>
<td>41395.7</td>
<td>35963.9</td>
</tr>
<tr>
<td>1.049</td>
<td>49643.8</td>
<td>54640.6</td>
<td>49326.5</td>
</tr>
<tr>
<td>1.050</td>
<td>57395.1</td>
<td>66600.9</td>
<td>61116.6</td>
</tr>
<tr>
<td>1.051</td>
<td>65156.1</td>
<td>76392.1</td>
<td>70785.9</td>
</tr>
<tr>
<td>1.052</td>
<td>33942.3</td>
<td>38307.2</td>
<td>36182.9</td>
</tr>
<tr>
<td>1.053</td>
<td>43745.1</td>
<td>51752.9</td>
<td>48639.5</td>
</tr>
<tr>
<td>1.054</td>
<td>50231.2</td>
<td>61781.5</td>
<td>61149.3</td>
</tr>
<tr>
<td>1.055</td>
<td>62065.7</td>
<td>73478.7</td>
<td>71475.7</td>
</tr>
<tr>
<td>1.056</td>
<td>33637.3</td>
<td>36066.8</td>
<td>34330.6</td>
</tr>
<tr>
<td>1.057</td>
<td>42136.3</td>
<td>47261.5</td>
<td>44668.3</td>
</tr>
<tr>
<td>1.058</td>
<td>48723.5</td>
<td>58866.8</td>
<td>55213.0</td>
</tr>
<tr>
<td>1.059</td>
<td>59474.1</td>
<td>71496.6</td>
<td>66624.6</td>
</tr>
<tr>
<td>1.060</td>
<td>35003.9</td>
<td>37754.7</td>
<td>35465.3</td>
</tr>
<tr>
<td>1.061</td>
<td>30759.2</td>
<td>29752.6</td>
<td>25052.6</td>
</tr>
<tr>
<td>1.062</td>
<td>18059.3</td>
<td>14671.2</td>
<td>12045.6</td>
</tr>
<tr>
<td>1.063</td>
<td>10248.5</td>
<td>8497.4</td>
<td>5663.1</td>
</tr>
<tr>
<td>1.064</td>
<td>8758.0</td>
<td>5749.5</td>
<td>3221.2</td>
</tr>
<tr>
<td>1.065</td>
<td>36292.1</td>
<td>40569.0</td>
<td>37373.3</td>
</tr>
<tr>
<td>1.066</td>
<td>31428.9</td>
<td>28708.1</td>
<td>21525.7</td>
</tr>
<tr>
<td>1.067</td>
<td>25223.8</td>
<td>20004.2</td>
<td>13461.8</td>
</tr>
<tr>
<td>1.068</td>
<td>10161.6</td>
<td>8283.9</td>
<td>5119.7</td>
</tr>
<tr>
<td>1.069</td>
<td>8296.5</td>
<td>3920.0</td>
<td>9576.5</td>
</tr>
<tr>
<td>1.070</td>
<td>11681.8</td>
<td>6733.5</td>
<td>3721.7</td>
</tr>
<tr>
<td>1.071</td>
<td>11647.2</td>
<td>5546.7</td>
<td>2903.2</td>
</tr>
<tr>
<td>1.072</td>
<td>10940.0</td>
<td>13371.2</td>
<td>9186.3</td>
</tr>
<tr>
<td>Run</td>
<td>Heat Fluxes</td>
<td>Energy Transfers</td>
<td>Error</td>
</tr>
<tr>
<td>-----</td>
<td>-------------</td>
<td>------------------</td>
<td>-------</td>
</tr>
<tr>
<td>#</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1.073</td>
<td>12203.4</td>
<td>13899.9</td>
<td>9149.5</td>
</tr>
<tr>
<td>1.074</td>
<td>13853.0</td>
<td>14631.1</td>
<td>9137.8</td>
</tr>
<tr>
<td>1.075</td>
<td>35100.0</td>
<td>37398.3</td>
<td>32758.1</td>
</tr>
<tr>
<td>1.076</td>
<td>41578.5</td>
<td>41650.3</td>
<td>33821.2</td>
</tr>
<tr>
<td>1.077</td>
<td>41442.2</td>
<td>41518.3</td>
<td>34690.1</td>
</tr>
<tr>
<td>1.078</td>
<td>41938.6</td>
<td>42327.7</td>
<td>34752.0</td>
</tr>
<tr>
<td>1.079</td>
<td>40533.3</td>
<td>42360.0</td>
<td>35659.9</td>
</tr>
<tr>
<td>2.001</td>
<td>35034.4</td>
<td>24158.3</td>
<td>16235.7</td>
</tr>
<tr>
<td>2.004</td>
<td>37861.0</td>
<td>35480.4</td>
<td>28743.4</td>
</tr>
<tr>
<td>2.005</td>
<td>39156.0</td>
<td>38669.5</td>
<td>33179.0</td>
</tr>
<tr>
<td>2.006</td>
<td>39250.4</td>
<td>19726.0</td>
<td>9909.6</td>
</tr>
<tr>
<td>2.007</td>
<td>39698.9</td>
<td>21632.0</td>
<td>11832.9</td>
</tr>
<tr>
<td>2.008</td>
<td>42000.4</td>
<td>26680.4</td>
<td>16108.7</td>
</tr>
<tr>
<td>2.009</td>
<td>43057.5</td>
<td>29126.2</td>
<td>17996.9</td>
</tr>
<tr>
<td>2.010</td>
<td>42995.3</td>
<td>27750.2</td>
<td>16502.2</td>
</tr>
<tr>
<td>2.011</td>
<td>45510.4</td>
<td>33552.0</td>
<td>22170.4</td>
</tr>
<tr>
<td>2.012</td>
<td>46935.2</td>
<td>38113.9</td>
<td>26896.7</td>
</tr>
<tr>
<td>2.013</td>
<td>43726.6</td>
<td>16099.5</td>
<td>6116.9</td>
</tr>
<tr>
<td>2.014</td>
<td>44719.1</td>
<td>19959.5</td>
<td>8491.8</td>
</tr>
<tr>
<td>2.015</td>
<td>47640.4</td>
<td>23288.6</td>
<td>10947.6</td>
</tr>
<tr>
<td>2.018</td>
<td>48606.1</td>
<td>31791.8</td>
<td>18452.2</td>
</tr>
<tr>
<td>2.019</td>
<td>46776.5</td>
<td>15883.3</td>
<td>5458.1</td>
</tr>
<tr>
<td>2.020</td>
<td>48304.1</td>
<td>20663.6</td>
<td>8071.5</td>
</tr>
<tr>
<td>2.021</td>
<td>42720.5</td>
<td>16682.1</td>
<td>6067.1</td>
</tr>
<tr>
<td>2.023</td>
<td>25474.1</td>
<td>18677.6</td>
<td>12964.1</td>
</tr>
<tr>
<td>2.024</td>
<td>28997.7</td>
<td>23489.2</td>
<td>17746.1</td>
</tr>
<tr>
<td>2.027</td>
<td>33713.8</td>
<td>34596.0</td>
<td>28062.0</td>
</tr>
<tr>
<td>2.028</td>
<td>25682.0</td>
<td>18642.9</td>
<td>12496.9</td>
</tr>
<tr>
<td>2.029</td>
<td>28736.4</td>
<td>22738.6</td>
<td>15877.2</td>
</tr>
<tr>
<td>2.030</td>
<td>31764.1</td>
<td>26219.4</td>
<td>19012.5</td>
</tr>
</tbody>
</table>
Table I.3. (continued)

<table>
<thead>
<tr>
<th>Run</th>
<th>Heat Fluxes</th>
<th>Energy Transfers</th>
<th>Condenser</th>
<th>Coolant</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>#1</td>
<td>#2</td>
<td>#3</td>
<td>#4</td>
</tr>
<tr>
<td>2.031</td>
<td>47187.6</td>
<td>61862.7</td>
<td>66163.1</td>
<td>64639.3</td>
</tr>
<tr>
<td>2.032</td>
<td>36763.4</td>
<td>35980.1</td>
<td>29315.8</td>
<td>21986.2</td>
</tr>
<tr>
<td>2.033</td>
<td>40260.0</td>
<td>46030.7</td>
<td>44591.3</td>
<td>38277.3</td>
</tr>
<tr>
<td>2.034</td>
<td>42127.6</td>
<td>48191.0</td>
<td>47614.1</td>
<td>41840.0</td>
</tr>
<tr>
<td>2.035</td>
<td>45556.9</td>
<td>56306.7</td>
<td>57087.7</td>
<td>53074.4</td>
</tr>
<tr>
<td>2.036</td>
<td>48337.4</td>
<td>61319.1</td>
<td>63523.5</td>
<td>61218.2</td>
</tr>
<tr>
<td>2.037</td>
<td>62690.5</td>
<td>71032.5</td>
<td>65519.3</td>
<td>54890.2</td>
</tr>
<tr>
<td>2.038</td>
<td>58018.7</td>
<td>84452.5</td>
<td>89735.9</td>
<td>92053.3</td>
</tr>
<tr>
<td>2.039</td>
<td>67906.9</td>
<td>83500.5</td>
<td>78737.4</td>
<td>69368.1</td>
</tr>
<tr>
<td>2.040</td>
<td>51017.9</td>
<td>45941.8</td>
<td>33834.5</td>
<td>22996.3</td>
</tr>
<tr>
<td>2.041</td>
<td>54055.9</td>
<td>57151.9</td>
<td>47231.0</td>
<td>36160.9</td>
</tr>
<tr>
<td>2.042</td>
<td>43536.9</td>
<td>57108.6</td>
<td>56217.8</td>
<td>53994.1</td>
</tr>
<tr>
<td>2.043</td>
<td>51165.8</td>
<td>67404.2</td>
<td>65760.1</td>
<td>62822.7</td>
</tr>
<tr>
<td>2.044</td>
<td>60196.1</td>
<td>78252.9</td>
<td>75233.5</td>
<td>71428.5</td>
</tr>
<tr>
<td>2.045</td>
<td>34250.0</td>
<td>41115.6</td>
<td>38095.6</td>
<td>34383.0</td>
</tr>
<tr>
<td>2.046</td>
<td>40375.7</td>
<td>50598.1</td>
<td>47126.8</td>
<td>44048.6</td>
</tr>
<tr>
<td>2.047</td>
<td>34527.9</td>
<td>39159.2</td>
<td>36599.8</td>
<td>34134.4</td>
</tr>
<tr>
<td>2.048</td>
<td>40121.4</td>
<td>49032.2</td>
<td>44953.3</td>
<td>41342.4</td>
</tr>
<tr>
<td>2.049</td>
<td>46791.4</td>
<td>59671.9</td>
<td>54035.0</td>
<td>49296.6</td>
</tr>
<tr>
<td>2.050</td>
<td>54348.2</td>
<td>67451.2</td>
<td>59505.7</td>
<td>53841.7</td>
</tr>
<tr>
<td>2.051</td>
<td>61095.3</td>
<td>76279.5</td>
<td>70428.6</td>
<td>65211.0</td>
</tr>
<tr>
<td>2.052</td>
<td>29322.2</td>
<td>35798.6</td>
<td>31610.2</td>
<td>32314.0</td>
</tr>
<tr>
<td>2.053</td>
<td>40059.7</td>
<td>45845.7</td>
<td>39716.6</td>
<td>36369.8</td>
</tr>
<tr>
<td>2.054</td>
<td>45271.7</td>
<td>53906.3</td>
<td>47218.1</td>
<td>42654.6</td>
</tr>
<tr>
<td>2.055</td>
<td>51417.2</td>
<td>64204.6</td>
<td>56726.5</td>
<td>50528.5</td>
</tr>
<tr>
<td>2.056</td>
<td>60397.8</td>
<td>77323.9</td>
<td>70326.9</td>
<td>64322.0</td>
</tr>
<tr>
<td>2.002</td>
<td>36674.4</td>
<td>29806.3</td>
<td>21798.7</td>
<td>13395.4</td>
</tr>
<tr>
<td>2.003</td>
<td>36781.1</td>
<td>30750.3</td>
<td>23816.6</td>
<td>16201.1</td>
</tr>
<tr>
<td>3.001</td>
<td>39746.5</td>
<td>42294.6</td>
<td>34859.9</td>
<td>28880.1</td>
</tr>
<tr>
<td>3.002</td>
<td>49511.5</td>
<td>53824.4</td>
<td>45328.0</td>
<td>37118.4</td>
</tr>
</tbody>
</table>
Table I.3. (continued)

<table>
<thead>
<tr>
<th>Run</th>
<th>Heat Fluxes</th>
<th>Energy Transfers</th>
<th>Condenser coolant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3.003</td>
<td>57403.2</td>
<td>66435.0</td>
<td>58180.3</td>
</tr>
<tr>
<td>3.004</td>
<td>68454.9</td>
<td>80986.2</td>
<td>71675.1</td>
</tr>
<tr>
<td>3.005</td>
<td>32518.2</td>
<td>38493.4</td>
<td>34321.4</td>
</tr>
<tr>
<td>3.006</td>
<td>44570.1</td>
<td>51755.9</td>
<td>44720.1</td>
</tr>
<tr>
<td>3.007</td>
<td>52617.9</td>
<td>63031.3</td>
<td>56878.2</td>
</tr>
<tr>
<td>3.008</td>
<td>62788.0</td>
<td>75153.1</td>
<td>67498.1</td>
</tr>
<tr>
<td>3.009</td>
<td>15052.8</td>
<td>14301.5</td>
<td>10986.3</td>
</tr>
<tr>
<td>3.010</td>
<td>18011.2</td>
<td>18407.7</td>
<td>15195.5</td>
</tr>
<tr>
<td>3.011</td>
<td>22883.9</td>
<td>23665.7</td>
<td>19664.7</td>
</tr>
<tr>
<td>3.012</td>
<td>30609.6</td>
<td>32049.9</td>
<td>27064.4</td>
</tr>
<tr>
<td>3.013</td>
<td>14070.0</td>
<td>13321.5</td>
<td>10920.8</td>
</tr>
<tr>
<td>3.014</td>
<td>20760.8</td>
<td>20604.2</td>
<td>15965.7</td>
</tr>
<tr>
<td>3.015</td>
<td>26076.4</td>
<td>26813.6</td>
<td>22524.1</td>
</tr>
<tr>
<td>3.016</td>
<td>31351.7</td>
<td>32824.1</td>
<td>26644.1</td>
</tr>
<tr>
<td>3.017</td>
<td>37541.3</td>
<td>41357.2</td>
<td>35357.1</td>
</tr>
<tr>
<td>3.018</td>
<td>33442.7</td>
<td>29596.7</td>
<td>21660.6</td>
</tr>
<tr>
<td>3.019</td>
<td>22775.8</td>
<td>18038.6</td>
<td>12110.3</td>
</tr>
<tr>
<td>3.020</td>
<td>10768.6</td>
<td>9117.9</td>
<td>5575.8</td>
</tr>
<tr>
<td>3.021</td>
<td>11299.9</td>
<td>6003.6</td>
<td>3032.7</td>
</tr>
<tr>
<td>3.022</td>
<td>31680.7</td>
<td>41901.5</td>
<td>40220.2</td>
</tr>
<tr>
<td>3.023</td>
<td>32940.4</td>
<td>30821.2</td>
<td>24523.0</td>
</tr>
<tr>
<td>3.024</td>
<td>34435.7</td>
<td>25059.9</td>
<td>17704.5</td>
</tr>
<tr>
<td>3.025</td>
<td>10879.7</td>
<td>7408.6</td>
<td>5379.2</td>
</tr>
<tr>
<td>3.026</td>
<td>35422.4</td>
<td>29366.0</td>
<td>20696.5</td>
</tr>
<tr>
<td>3.027</td>
<td>35563.9</td>
<td>29476.2</td>
<td>20962.5</td>
</tr>
<tr>
<td>3.028</td>
<td>35621.7</td>
<td>27794.0</td>
<td>19550.4</td>
</tr>
<tr>
<td>3.029</td>
<td>36054.6</td>
<td>27594.4</td>
<td>19149.6</td>
</tr>
<tr>
<td>3.030</td>
<td>36205.6</td>
<td>27625.0</td>
<td>19334.7</td>
</tr>
<tr>
<td>3.031</td>
<td>39436.7</td>
<td>27855.9</td>
<td>18545.6</td>
</tr>
<tr>
<td>3.032</td>
<td>39595.6</td>
<td>28019.5</td>
<td>18513.9</td>
</tr>
<tr>
<td>Run</td>
<td>Heat Fluxes</td>
<td>Energy Transfers</td>
<td>Error %</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>------------------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td># 1 2 3 4 overall fluid test condenser test condenser coolant after</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.033</td>
<td>39272.2 28186.2 18343.0 15099.2 25225.2</td>
<td>9826.8 3871.0 5761.8</td>
<td>9632.9 2.01</td>
</tr>
<tr>
<td>3.034</td>
<td>39504.1 28286.8 18496.5 15190.3 25369.4</td>
<td>9737.6 3893.2 5627.4</td>
<td>9520.5 2.28</td>
</tr>
<tr>
<td>3.035</td>
<td>44938.9 25147.0 13143.9 8874.3 23026.0</td>
<td>9734.7 3533.5 5814.3</td>
<td>9347.8 4.14</td>
</tr>
<tr>
<td>3.036</td>
<td>26173.1 17981.9 12244.3 9786.9 16546.5</td>
<td>9523.9 2539.2 6635.7</td>
<td>9174.9 3.80</td>
</tr>
<tr>
<td>3.037</td>
<td>14163.2 6758.1 4245.4 4244.1 7352.7</td>
<td>9539.4 1128.3 7737.8</td>
<td>8866.1 7.59</td>
</tr>
<tr>
<td>3.038</td>
<td>16049.8 11414.2 8381.7 7366.6 10803.1</td>
<td>7309.8 1657.8 4864.4</td>
<td>6522.2 12.08</td>
</tr>
<tr>
<td>3.039</td>
<td>13254.4 7145.8 5318.8 5113.0 7708.0</td>
<td>6630.4 1182.9 4474.3</td>
<td>5657.1 17.20</td>
</tr>
<tr>
<td>3.040</td>
<td>6967.1 2841.0 483.3 1517.9 3452.3</td>
<td>6129.5 529.8 5472.5</td>
<td>6002.3 2.12</td>
</tr>
<tr>
<td>4.001</td>
<td>49173.0 44674.3 35704.5 26405.5</td>
<td>38989.3 8604.5 6244.4</td>
<td>2128.1 8372.5 2.77</td>
</tr>
<tr>
<td>4.002</td>
<td>56407.0 59229.4 52481.4 42414.0</td>
<td>52633.0 11324.4 8429.5</td>
<td>2467.9 10897.4 3.92</td>
</tr>
<tr>
<td>4.003</td>
<td>64209.6 66448.4 63950.5 55490.6</td>
<td>62524.8 13417.8 10013.7</td>
<td>2333.8 12847.6 4.44</td>
</tr>
<tr>
<td>4.004</td>
<td>68057.3 79158.3 87521.0 86573.1</td>
<td>80327.4 15669.7 12864.9</td>
<td>2685.0 15549.9 0.77</td>
</tr>
<tr>
<td>4.005</td>
<td>56787.7 47180.1 31749.2 21296.0</td>
<td>39253.3 9060.5 6286.6</td>
<td>2566.8 8943.5 1.31</td>
</tr>
<tr>
<td>4.006</td>
<td>66086.3 61768.0 46088.2 33920.7</td>
<td>51965.8 11951.1 8322.6</td>
<td>3454.6 11777.2 1.48</td>
</tr>
<tr>
<td>4.007</td>
<td>77345.2 69852.0 57043.5 43253.8</td>
<td>61873.7 14125.7 9909.4</td>
<td>4099.8 14009.2 0.83</td>
</tr>
<tr>
<td>4.008</td>
<td>76513.2 71126.5 58862.4 45978.9</td>
<td>63120.3 14218.5 10109.1</td>
<td>4004.5 14113.5 0.74</td>
</tr>
<tr>
<td>4.009</td>
<td>81564.0 80536.4 69616.0 57220.6</td>
<td>72234.2 16585.1 11568.7</td>
<td>4620.2 16188.9 2.45</td>
</tr>
<tr>
<td>4.010</td>
<td>41341.3 39717.0 31931.6 26656.6</td>
<td>34911.6 9083.2 5591.3</td>
<td>3288.0 8879.4 2.30</td>
</tr>
<tr>
<td>4.011</td>
<td>53098.4 53516.3 45537.9 39238.6</td>
<td>47847.8 12056.8 7663.1</td>
<td>4155.8 11819.0 2.01</td>
</tr>
<tr>
<td>4.012</td>
<td>59868.0 63389.7 53601.6 51022.6</td>
<td>57695.5 14613.2 9240.3</td>
<td>4943.0 14183.3 3.03</td>
</tr>
<tr>
<td>4.013</td>
<td>72243.1 70730.0 69873.4 63858.4</td>
<td>70762.0 17498.0 11333.0</td>
<td>5802.0 17135.0 2.12</td>
</tr>
<tr>
<td>4.014</td>
<td>38030.4 40471.2 31292.4 28282.9</td>
<td>34769.2 9380.6 5568.5</td>
<td>3635.6 9204.1 1.92</td>
</tr>
<tr>
<td>4.015</td>
<td>48465.3 52251.9 41224.9 37946.3</td>
<td>44972.4 12355.2 7202.6</td>
<td>4803.9 12006.4 2.90</td>
</tr>
<tr>
<td>4.016</td>
<td>59922.9 64223.1 51391.7 46142.5</td>
<td>55420.1 14788.7 8875.9</td>
<td>5557.0 14432.9 2.47</td>
</tr>
<tr>
<td>4.017</td>
<td>70503.8 76027.0 61716.4 55858.8</td>
<td>66026.5 17389.0 10574.5</td>
<td>6347.2 16921.8 2.76</td>
</tr>
<tr>
<td>4.018</td>
<td>67463.7 70759.9 56444.9 51766.6</td>
<td>61608.8 17182.2 9867.0</td>
<td>7050.8 16917.8 1.56</td>
</tr>
<tr>
<td>4.019</td>
<td>58681.1 60639.7 47058.3 42493.1</td>
<td>52218.1 15044.9 8363.0</td>
<td>6257.2 14620.2 2.91</td>
</tr>
<tr>
<td>4.020</td>
<td>51344.3 52336.0 39455.3 35459.0</td>
<td>44648.7 12710.1 7150.8</td>
<td>5271.2 12422.0 2.32</td>
</tr>
<tr>
<td>4.021</td>
<td>40419.3 39888.6 28258.6 25411.6</td>
<td>33494.5 9903.9 5364.4</td>
<td>4218.0 9582.3 3.36</td>
</tr>
<tr>
<td>4.022</td>
<td>18755.0 14691.6 8343.1 12730.0</td>
<td>3431.9 2038.8 1362.0</td>
<td>3400.7 0.92</td>
</tr>
<tr>
<td>Run #</td>
<td>Heat Fluxes</td>
<td>Energy Transfers</td>
<td>Error %</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>------------------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>test fluid</td>
<td>overall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>test condenser</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>after condenser</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>coolant</td>
<td></td>
</tr>
<tr>
<td>4.023</td>
<td>23347.1</td>
<td>18486.3</td>
<td>14886.3</td>
</tr>
<tr>
<td>4.024</td>
<td>27904.2</td>
<td>18486.5</td>
<td>17414.0</td>
</tr>
<tr>
<td>4.025</td>
<td>33402.1</td>
<td>25431.4</td>
<td>23192.4</td>
</tr>
<tr>
<td>4.026</td>
<td>30771.9</td>
<td>35424.0</td>
<td>27349.0</td>
</tr>
<tr>
<td>4.027</td>
<td>27370.3</td>
<td>28438.8</td>
<td>20439.7</td>
</tr>
<tr>
<td>4.028</td>
<td>19175.2</td>
<td>15349.5</td>
<td>8137.6</td>
</tr>
<tr>
<td>4.029</td>
<td>26895.2</td>
<td>14580.3</td>
<td>12858.4</td>
</tr>
<tr>
<td>4.030</td>
<td>32735.1</td>
<td>29673.1</td>
<td>20303.3</td>
</tr>
<tr>
<td>4.031</td>
<td>17220.2</td>
<td>15131.2</td>
<td>8071.1</td>
</tr>
<tr>
<td>4.032</td>
<td>23810.1</td>
<td>21850.7</td>
<td>13489.6</td>
</tr>
<tr>
<td>4.033</td>
<td>29514.2</td>
<td>27331.0</td>
<td>17658.5</td>
</tr>
<tr>
<td>4.034</td>
<td>34822.0</td>
<td>34656.4</td>
<td>23693.8</td>
</tr>
<tr>
<td>4.035</td>
<td>33445.2</td>
<td>19480.0</td>
<td>10806.6</td>
</tr>
<tr>
<td>4.036</td>
<td>37973.9</td>
<td>31445.8</td>
<td>19517.8</td>
</tr>
<tr>
<td>4.037</td>
<td>44691.8</td>
<td>39689.4</td>
<td>30219.9</td>
</tr>
<tr>
<td>4.038</td>
<td>39445.9</td>
<td>17781.9</td>
<td>7493.4</td>
</tr>
<tr>
<td>4.039</td>
<td>47374.5</td>
<td>27751.9</td>
<td>15154.9</td>
</tr>
<tr>
<td>4.040</td>
<td>52593.0</td>
<td>35775.0</td>
<td>22052.8</td>
</tr>
<tr>
<td>5.002</td>
<td>36738.7</td>
<td>18161.9</td>
<td>8880.2</td>
</tr>
<tr>
<td>5.003</td>
<td>44617.3</td>
<td>30778.1</td>
<td>18322.0</td>
</tr>
<tr>
<td>5.004</td>
<td>45539.9</td>
<td>37015.6</td>
<td>23614.4</td>
</tr>
<tr>
<td>5.006</td>
<td>47263.1</td>
<td>23178.5</td>
<td>11475.3</td>
</tr>
<tr>
<td>5.007</td>
<td>53642.8</td>
<td>32485.7</td>
<td>18040.0</td>
</tr>
<tr>
<td>5.008</td>
<td>19176.9</td>
<td>17950.8</td>
<td>13554.8</td>
</tr>
<tr>
<td>5.009</td>
<td>40418.0</td>
<td>13823.1</td>
<td>5478.9</td>
</tr>
<tr>
<td>5.010</td>
<td>43631.7</td>
<td>13907.5</td>
<td>19116.6</td>
</tr>
<tr>
<td>5.011</td>
<td>45165.5</td>
<td>29467.9</td>
<td>17504.5</td>
</tr>
<tr>
<td>5.012</td>
<td>44031.8</td>
<td>36511.2</td>
<td>24356.7</td>
</tr>
<tr>
<td>5.013</td>
<td>17010.8</td>
<td>15258.2</td>
<td>12076.1</td>
</tr>
<tr>
<td>5.014</td>
<td>24765.0</td>
<td>23630.7</td>
<td>20009.5</td>
</tr>
</tbody>
</table>

Table I.3. (continued)
<table>
<thead>
<tr>
<th>Run</th>
<th>Heat Fluxes</th>
<th>Energy Transfers</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>after</td>
<td>%</td>
</tr>
<tr>
<td>#</td>
<td>overall fluid</td>
<td>condenser coolant</td>
<td></td>
</tr>
<tr>
<td>5.015</td>
<td>32791.3</td>
<td>31038.7</td>
<td>26723.8</td>
</tr>
<tr>
<td>5.016</td>
<td>15881.9</td>
<td>14997.4</td>
<td>11243.1</td>
</tr>
<tr>
<td>5.017</td>
<td>23404.5</td>
<td>22995.0</td>
<td>18362.0</td>
</tr>
<tr>
<td>5.018</td>
<td>30592.9</td>
<td>30536.0</td>
<td>24482.1</td>
</tr>
<tr>
<td>5.019</td>
<td>19883.3</td>
<td>16348.4</td>
<td>10646.8</td>
</tr>
<tr>
<td>5.020</td>
<td>26019.1</td>
<td>22890.6</td>
<td>16617.5</td>
</tr>
<tr>
<td>5.021</td>
<td>34274.4</td>
<td>31087.0</td>
<td>23036.4</td>
</tr>
<tr>
<td>5.022</td>
<td>37210.4</td>
<td>35287.3</td>
<td>29956.1</td>
</tr>
<tr>
<td>5.023</td>
<td>48411.0</td>
<td>47660.8</td>
<td>40266.2</td>
</tr>
<tr>
<td>5.024</td>
<td>59395.2</td>
<td>57298.4</td>
<td>51185.1</td>
</tr>
<tr>
<td>5.025</td>
<td>69124.3</td>
<td>66022.8</td>
<td>58301.4</td>
</tr>
<tr>
<td>5.026</td>
<td>78553.2</td>
<td>77046.4</td>
<td>67224.2</td>
</tr>
<tr>
<td>5.027</td>
<td>40108.3</td>
<td>37358.4</td>
<td>29583.0</td>
</tr>
<tr>
<td>5.028</td>
<td>52088.5</td>
<td>51475.9</td>
<td>43206.7</td>
</tr>
<tr>
<td>5.029</td>
<td>62919.4</td>
<td>61158.3</td>
<td>51743.6</td>
</tr>
<tr>
<td>5.030</td>
<td>70865.2</td>
<td>68810.8</td>
<td>61637.8</td>
</tr>
<tr>
<td>5.031</td>
<td>85331.0</td>
<td>82697.6</td>
<td>73324.2</td>
</tr>
<tr>
<td>5.032</td>
<td>36707.5</td>
<td>34351.7</td>
<td>31566.3</td>
</tr>
<tr>
<td>5.033</td>
<td>46527.1</td>
<td>46516.8</td>
<td>45405.2</td>
</tr>
<tr>
<td>5.034</td>
<td>50675.0</td>
<td>50633.9</td>
<td>56714.2</td>
</tr>
<tr>
<td>5.035</td>
<td>65697.6</td>
<td>64983.4</td>
<td>62862.6</td>
</tr>
<tr>
<td>5.036</td>
<td>68774.9</td>
<td>77103.7</td>
<td>78331.1</td>
</tr>
<tr>
<td>5.037</td>
<td>33499.1</td>
<td>33963.6</td>
<td>34232.5</td>
</tr>
<tr>
<td>5.038</td>
<td>41051.6</td>
<td>49454.3</td>
<td>51081.6</td>
</tr>
<tr>
<td>5.039</td>
<td>47508.6</td>
<td>59523.1</td>
<td>64265.9</td>
</tr>
<tr>
<td>5.040</td>
<td>61840.7</td>
<td>70664.7</td>
<td>71264.0</td>
</tr>
<tr>
<td>5.041</td>
<td>66470.1</td>
<td>80166.2</td>
<td>84596.8</td>
</tr>
<tr>
<td>5.042</td>
<td>35931.4</td>
<td>43410.4</td>
<td>43674.7</td>
</tr>
<tr>
<td>5.043</td>
<td>49123.4</td>
<td>58592.0</td>
<td>62227.1</td>
</tr>
<tr>
<td>5.044</td>
<td>68038.9</td>
<td>78183.2</td>
<td>86061.5</td>
</tr>
</tbody>
</table>
Table I.3. (continued)

<table>
<thead>
<tr>
<th>Run #1</th>
<th>Heat Fluxes</th>
<th>Energy Transfers</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.045</td>
<td>40545.8</td>
<td>45821.1</td>
<td>43471.2</td>
</tr>
<tr>
<td>5.046</td>
<td>44216.7</td>
<td>45870.7</td>
<td>41978.6</td>
</tr>
<tr>
<td>5.047</td>
<td>41233.0</td>
<td>49277.0</td>
<td>47846.6</td>
</tr>
<tr>
<td>5.048</td>
<td>48304.8</td>
<td>49582.5</td>
<td>46063.6</td>
</tr>
<tr>
<td>5.049</td>
<td>52585.2</td>
<td>52100.8</td>
<td>47051.4</td>
</tr>
<tr>
<td>5.050</td>
<td>43659.9</td>
<td>43787.2</td>
<td>37604.0</td>
</tr>
<tr>
<td>5.051</td>
<td>48510.2</td>
<td>41622.6</td>
<td>34928.5</td>
</tr>
<tr>
<td>5.052</td>
<td>31418.3</td>
<td>25329.2</td>
<td>19921.0</td>
</tr>
<tr>
<td>5.053</td>
<td>19826.7</td>
<td>12291.3</td>
<td>6887.5</td>
</tr>
<tr>
<td>5.054</td>
<td>17034.4</td>
<td>8292.6</td>
<td>4303.4</td>
</tr>
<tr>
<td>5.055</td>
<td>48575.0</td>
<td>45724.5</td>
<td>40966.5</td>
</tr>
<tr>
<td>5.056</td>
<td>34420.7</td>
<td>26587.7</td>
<td>20027.0</td>
</tr>
<tr>
<td>5.057</td>
<td>20483.9</td>
<td>14428.7</td>
<td>8730.7</td>
</tr>
<tr>
<td>5.058</td>
<td>16179.4</td>
<td>9057.0</td>
<td>5516.0</td>
</tr>
<tr>
<td>5.059</td>
<td>4370.4</td>
<td>2262.7</td>
<td>880.8</td>
</tr>
<tr>
<td>5.060</td>
<td>3550.9</td>
<td>2349.5</td>
<td>1069.5</td>
</tr>
<tr>
<td>5.061</td>
<td>3076.2</td>
<td>2760.9</td>
<td>1449.9</td>
</tr>
<tr>
<td>5.062</td>
<td>6148.2</td>
<td>5449.9</td>
<td>3347.8</td>
</tr>
<tr>
<td>5.063</td>
<td>17390.9</td>
<td>16163.4</td>
<td>12846.4</td>
</tr>
<tr>
<td>6.001</td>
<td>34331.9</td>
<td>43398.0</td>
<td>45278.6</td>
</tr>
<tr>
<td>6.002</td>
<td>43755.3</td>
<td>56300.1</td>
<td>60001.0</td>
</tr>
<tr>
<td>6.003</td>
<td>42830.7</td>
<td>63684.7</td>
<td>80591.7</td>
</tr>
<tr>
<td>6.004</td>
<td>49196.9</td>
<td>70716.1</td>
<td>88752.3</td>
</tr>
<tr>
<td>6.005</td>
<td>22921.6</td>
<td>36373.0</td>
<td>40759.0</td>
</tr>
<tr>
<td>6.006</td>
<td>38122.8</td>
<td>54518.8</td>
<td>57892.7</td>
</tr>
<tr>
<td>6.007</td>
<td>46258.9</td>
<td>65047.8</td>
<td>70630.7</td>
</tr>
<tr>
<td>6.008</td>
<td>53843.2</td>
<td>74240.4</td>
<td>78775.9</td>
</tr>
<tr>
<td>6.009</td>
<td>22009.8</td>
<td>38966.9</td>
<td>36723.5</td>
</tr>
<tr>
<td>6.010</td>
<td>37935.4</td>
<td>54856.7</td>
<td>51973.1</td>
</tr>
<tr>
<td>6.011</td>
<td>49241.8</td>
<td>63649.7</td>
<td>64348.7</td>
</tr>
<tr>
<td>Run</td>
<td>Heat Fluxes</td>
<td>Energy Transfers</td>
<td>Error</td>
</tr>
<tr>
<td>-----</td>
<td>-------------</td>
<td>------------------</td>
<td>-------</td>
</tr>
<tr>
<td>#</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>6.012</td>
<td>52701.0</td>
<td>71621.0</td>
<td>74109.0</td>
</tr>
<tr>
<td>6.013</td>
<td>25768.5</td>
<td>39623.3</td>
<td>36043.4</td>
</tr>
<tr>
<td>6.014</td>
<td>40988.2</td>
<td>54519.9</td>
<td>49817.5</td>
</tr>
<tr>
<td>6.015</td>
<td>52107.9</td>
<td>64778.5</td>
<td>60101.9</td>
</tr>
<tr>
<td>6.016</td>
<td>54121.2</td>
<td>73173.7</td>
<td>70962.7</td>
</tr>
<tr>
<td>6.017</td>
<td>55075.1</td>
<td>73770.5</td>
<td>71633.4</td>
</tr>
<tr>
<td>6.018</td>
<td>27899.3</td>
<td>37035.0</td>
<td>30686.1</td>
</tr>
<tr>
<td>6.019</td>
<td>37415.6</td>
<td>49963.3</td>
<td>42780.3</td>
</tr>
<tr>
<td>6.020</td>
<td>49577.4</td>
<td>61844.5</td>
<td>53661.8</td>
</tr>
<tr>
<td>6.021</td>
<td>60998.7</td>
<td>75598.5</td>
<td>67775.7</td>
</tr>
<tr>
<td>6.022</td>
<td>55702.0</td>
<td>72157.7</td>
<td>68109.6</td>
</tr>
<tr>
<td>6.023</td>
<td>12732.1</td>
<td>13826.1</td>
<td>9346.0</td>
</tr>
<tr>
<td>6.024</td>
<td>16921.6</td>
<td>21424.4</td>
<td>16816.2</td>
</tr>
<tr>
<td>6.025</td>
<td>22381.0</td>
<td>29807.5</td>
<td>24573.6</td>
</tr>
<tr>
<td>6.026</td>
<td>27901.7</td>
<td>38135.0</td>
<td>33023.7</td>
</tr>
<tr>
<td>6.027</td>
<td>9954.4</td>
<td>15321.1</td>
<td>10527.7</td>
</tr>
<tr>
<td>6.028</td>
<td>12052.9</td>
<td>21158.7</td>
<td>17763.5</td>
</tr>
<tr>
<td>6.029</td>
<td>17483.2</td>
<td>27975.2</td>
<td>26050.9</td>
</tr>
<tr>
<td>6.030</td>
<td>24303.1</td>
<td>35555.1</td>
<td>37106.6</td>
</tr>
<tr>
<td>6.031</td>
<td>9143.9</td>
<td>15366.0</td>
<td>10998.7</td>
</tr>
<tr>
<td>6.032</td>
<td>17870.1</td>
<td>22521.6</td>
<td>18737.8</td>
</tr>
<tr>
<td>6.033</td>
<td>18161.8</td>
<td>29665.7</td>
<td>23029.1</td>
</tr>
<tr>
<td>6.034</td>
<td>20106.7</td>
<td>32971.8</td>
<td>37471.8</td>
</tr>
<tr>
<td>6.035</td>
<td>11418.2</td>
<td>14504.9</td>
<td>12192.0</td>
</tr>
<tr>
<td>6.036</td>
<td>16681.3</td>
<td>21803.4</td>
<td>19277.3</td>
</tr>
<tr>
<td>6.037</td>
<td>15704.0</td>
<td>27947.6</td>
<td>31934.3</td>
</tr>
<tr>
<td>6.038</td>
<td>23530.8</td>
<td>32999.0</td>
<td>37529.3</td>
</tr>
<tr>
<td>6.039</td>
<td>12814.3</td>
<td>15832.5</td>
<td>14996.6</td>
</tr>
<tr>
<td>6.040</td>
<td>23038.8</td>
<td>18853.2</td>
<td>16436.8</td>
</tr>
<tr>
<td>6.041</td>
<td>18890.8</td>
<td>29852.5</td>
<td>33552.8</td>
</tr>
</tbody>
</table>
Table I.3. (continued)

<table>
<thead>
<tr>
<th>Run</th>
<th>Heat Fluxes</th>
<th>Energy Transfers</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>test fluid</td>
<td>test condenser</td>
</tr>
<tr>
<td>#</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>6.042</td>
<td>22532.2</td>
<td>36426.5</td>
<td>42483.7</td>
</tr>
<tr>
<td>6.043</td>
<td>24938.7</td>
<td>32288.3</td>
<td>25673.3</td>
</tr>
<tr>
<td>6.044</td>
<td>16908.9</td>
<td>21342.3</td>
<td>14279.7</td>
</tr>
<tr>
<td>6.045</td>
<td>16059.4</td>
<td>14042.5</td>
<td>8171.7</td>
</tr>
<tr>
<td>6.046</td>
<td>15242.7</td>
<td>10257.8</td>
<td>5272.8</td>
</tr>
<tr>
<td>6.047</td>
<td>25558.3</td>
<td>32071.3</td>
<td>25630.4</td>
</tr>
<tr>
<td>6.048</td>
<td>24732.9</td>
<td>33109.7</td>
<td>26889.9</td>
</tr>
<tr>
<td>6.049</td>
<td>25292.8</td>
<td>33250.3</td>
<td>27427.9</td>
</tr>
<tr>
<td>6.050</td>
<td>27143.1</td>
<td>33635.2</td>
<td>27907.5</td>
</tr>
<tr>
<td>6.051</td>
<td>27867.3</td>
<td>33939.2</td>
<td>27889.9</td>
</tr>
<tr>
<td>6.052</td>
<td>28309.8</td>
<td>35351.5</td>
<td>28523.9</td>
</tr>
<tr>
<td>6.053</td>
<td>13243.3</td>
<td>14974.1</td>
<td>10504.1</td>
</tr>
<tr>
<td>6.054</td>
<td>14296.8</td>
<td>12042.6</td>
<td>7237.3</td>
</tr>
<tr>
<td>6.055</td>
<td>5082.5</td>
<td>6103.2</td>
<td>3311.2</td>
</tr>
<tr>
<td>7.005</td>
<td>19318.9</td>
<td>19136.3</td>
<td>14169.2</td>
</tr>
<tr>
<td>7.006</td>
<td>19765.8</td>
<td>24281.8</td>
<td>22845.4</td>
</tr>
<tr>
<td>7.007</td>
<td>25946.0</td>
<td>26911.5</td>
<td>21817.3</td>
</tr>
<tr>
<td>7.008</td>
<td>18979.7</td>
<td>29599.2</td>
<td>31937.1</td>
</tr>
<tr>
<td>7.009</td>
<td>13419.2</td>
<td>15325.3</td>
<td>12073.5</td>
</tr>
<tr>
<td>7.010</td>
<td>11604.5</td>
<td>15515.1</td>
<td>12138.5</td>
</tr>
<tr>
<td>7.011</td>
<td>18560.9</td>
<td>23374.0</td>
<td>17076.4</td>
</tr>
<tr>
<td>7.012</td>
<td>16178.4</td>
<td>23327.9</td>
<td>18233.0</td>
</tr>
<tr>
<td>7.013</td>
<td>22320.4</td>
<td>24499.1</td>
<td>18810.8</td>
</tr>
<tr>
<td>7.014</td>
<td>12165.1</td>
<td>17561.0</td>
<td>12541.9</td>
</tr>
<tr>
<td>7.015</td>
<td>15560.7</td>
<td>22467.7</td>
<td>17280.7</td>
</tr>
<tr>
<td>7.016</td>
<td>22837.7</td>
<td>24909.9</td>
<td>18304.6</td>
</tr>
<tr>
<td>7.017</td>
<td>23306.1</td>
<td>29580.6</td>
<td>25315.6</td>
</tr>
<tr>
<td>7.018</td>
<td>11794.3</td>
<td>15449.4</td>
<td>11573.0</td>
</tr>
<tr>
<td>7.019</td>
<td>16640.0</td>
<td>20434.1</td>
<td>14600.7</td>
</tr>
<tr>
<td>7.020</td>
<td>17864.4</td>
<td>25744.2</td>
<td>18196.3</td>
</tr>
<tr>
<td>Run</td>
<td>Heat Fluxes</td>
<td>Energy Transfers</td>
<td>Error %</td>
</tr>
<tr>
<td>-----</td>
<td>-------------</td>
<td>-----------------</td>
<td>--------</td>
</tr>
<tr>
<td></td>
<td>#</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>7.021</td>
<td>21484.0</td>
<td>31357.1</td>
<td>25383.9</td>
</tr>
<tr>
<td>7.022</td>
<td>11774.8</td>
<td>13630.6</td>
<td>9457.8</td>
</tr>
<tr>
<td>7.023</td>
<td>16191.1</td>
<td>19984.8</td>
<td>13638.1</td>
</tr>
<tr>
<td>7.024</td>
<td>20580.7</td>
<td>26450.0</td>
<td>18703.9</td>
</tr>
<tr>
<td>7.025</td>
<td>24513.1</td>
<td>29786.2</td>
<td>22195.8</td>
</tr>
<tr>
<td>7.026</td>
<td>25224.8</td>
<td>32128.8</td>
<td>26456.8</td>
</tr>
<tr>
<td>7.027</td>
<td>30415.1</td>
<td>39275.4</td>
<td>37338.6</td>
</tr>
<tr>
<td>7.028</td>
<td>41630.9</td>
<td>48407.6</td>
<td>45242.9</td>
</tr>
<tr>
<td>7.029</td>
<td>48615.3</td>
<td>64870.4</td>
<td>61671.7</td>
</tr>
<tr>
<td>7.030</td>
<td>24075.9</td>
<td>34041.7</td>
<td>33324.2</td>
</tr>
<tr>
<td>7.031</td>
<td>36337.5</td>
<td>46857.8</td>
<td>49693.5</td>
</tr>
<tr>
<td>7.032</td>
<td>44333.8</td>
<td>58896.3</td>
<td>62598.2</td>
</tr>
<tr>
<td>7.033</td>
<td>49768.0</td>
<td>69337.8</td>
<td>70536.7</td>
</tr>
<tr>
<td>7.034</td>
<td>30518.4</td>
<td>36919.9</td>
<td>35074.7</td>
</tr>
<tr>
<td>7.035</td>
<td>37165.2</td>
<td>50594.4</td>
<td>50013.3</td>
</tr>
<tr>
<td>7.036</td>
<td>43607.1</td>
<td>57423.6</td>
<td>56962.7</td>
</tr>
<tr>
<td>7.037</td>
<td>55615.8</td>
<td>68431.6</td>
<td>67867.2</td>
</tr>
<tr>
<td>7.038</td>
<td>18881.0</td>
<td>28466.0</td>
<td>31515.6</td>
</tr>
<tr>
<td>7.039</td>
<td>27843.5</td>
<td>38934.8</td>
<td>41258.6</td>
</tr>
<tr>
<td>7.040</td>
<td>34430.1</td>
<td>49214.6</td>
<td>58110.1</td>
</tr>
<tr>
<td>7.041</td>
<td>45088.4</td>
<td>53535.4</td>
<td>60252.2</td>
</tr>
<tr>
<td>7.042</td>
<td>52360.1</td>
<td>70137.6</td>
<td>74389.1</td>
</tr>
<tr>
<td>7.043</td>
<td>28660.9</td>
<td>39633.7</td>
<td>41421.5</td>
</tr>
<tr>
<td>7.044</td>
<td>39378.5</td>
<td>50218.7</td>
<td>54001.5</td>
</tr>
<tr>
<td>7.045</td>
<td>45409.6</td>
<td>62548.3</td>
<td>67537.9</td>
</tr>
<tr>
<td>7.046</td>
<td>50901.0</td>
<td>70718.2</td>
<td>75585.7</td>
</tr>
<tr>
<td>7.047</td>
<td>32274.6</td>
<td>40102.4</td>
<td>36424.5</td>
</tr>
<tr>
<td>7.048</td>
<td>33115.0</td>
<td>39551.7</td>
<td>36703.5</td>
</tr>
<tr>
<td>7.049</td>
<td>32911.2</td>
<td>41240.4</td>
<td>38402.5</td>
</tr>
<tr>
<td>7.050</td>
<td>36201.6</td>
<td>43685.4</td>
<td>41593.2</td>
</tr>
<tr>
<td>#</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>----</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>7.051</td>
<td>33091.3</td>
<td>44665.2</td>
<td>42609.2</td>
</tr>
<tr>
<td>7.052</td>
<td>36560.3</td>
<td>42088.4</td>
<td>40237.0</td>
</tr>
<tr>
<td>7.053</td>
<td>34653.0</td>
<td>35689.8</td>
<td>27965.7</td>
</tr>
<tr>
<td>7.054</td>
<td>10769.2</td>
<td>7825.3</td>
<td>3267.6</td>
</tr>
<tr>
<td>7.055</td>
<td>8402.5</td>
<td>5198.8</td>
<td>1964.0</td>
</tr>
<tr>
<td>7.056</td>
<td>14333.4</td>
<td>7434.4</td>
<td>3161.2</td>
</tr>
<tr>
<td>7.057</td>
<td>12867.7</td>
<td>7401.5</td>
<td>2734.4</td>
</tr>
<tr>
<td>7.058</td>
<td>13260.1</td>
<td>6942.2</td>
<td>2419.5</td>
</tr>
<tr>
<td>7.059</td>
<td>17221.3</td>
<td>15131.7</td>
<td>8664.8</td>
</tr>
<tr>
<td>8.001</td>
<td>11813.1</td>
<td>14674.4</td>
<td>11072.9</td>
</tr>
<tr>
<td>8.002</td>
<td>15882.0</td>
<td>18211.2</td>
<td>13586.4</td>
</tr>
<tr>
<td>8.003</td>
<td>20232.8</td>
<td>19594.5</td>
<td>15510.6</td>
</tr>
<tr>
<td>8.004</td>
<td>23452.8</td>
<td>26640.6</td>
<td>25352.6</td>
</tr>
<tr>
<td>8.005</td>
<td>16512.0</td>
<td>17856.9</td>
<td>13893.6</td>
</tr>
<tr>
<td>8.007</td>
<td>24695.4</td>
<td>27370.7</td>
<td>28889.2</td>
</tr>
<tr>
<td>8.008</td>
<td>39089.8</td>
<td>32112.4</td>
<td>24427.4</td>
</tr>
<tr>
<td>8.009</td>
<td>11329.2</td>
<td>17343.0</td>
<td>12496.4</td>
</tr>
<tr>
<td>8.010</td>
<td>9279.8</td>
<td>21618.7</td>
<td>18674.3</td>
</tr>
<tr>
<td>8.011</td>
<td>16437.1</td>
<td>26161.8</td>
<td>23451.4</td>
</tr>
<tr>
<td>8.012</td>
<td>17513.7</td>
<td>28883.5</td>
<td>28567.1</td>
</tr>
<tr>
<td>8.013</td>
<td>10779.1</td>
<td>16275.5</td>
<td>13054.0</td>
</tr>
<tr>
<td>8.014</td>
<td>12850.5</td>
<td>16020.0</td>
<td>16579.7</td>
</tr>
<tr>
<td>8.015</td>
<td>16887.9</td>
<td>21918.5</td>
<td>22253.4</td>
</tr>
<tr>
<td>8.016</td>
<td>26919.7</td>
<td>25517.2</td>
<td>24317.1</td>
</tr>
<tr>
<td>8.017</td>
<td>9986.0</td>
<td>16278.7</td>
<td>13370.1</td>
</tr>
<tr>
<td>8.018</td>
<td>12759.9</td>
<td>21943.6</td>
<td>16807.3</td>
</tr>
<tr>
<td>8.019</td>
<td>16772.2</td>
<td>24343.8</td>
<td>18918.2</td>
</tr>
<tr>
<td>8.020</td>
<td>22259.1</td>
<td>28004.7</td>
<td>24045.3</td>
</tr>
<tr>
<td>8.021</td>
<td>11594.7</td>
<td>15304.4</td>
<td>11096.6</td>
</tr>
<tr>
<td>8.022</td>
<td>14087.4</td>
<td>19507.3</td>
<td>15269.7</td>
</tr>
<tr>
<td>Run #</td>
<td>Heat Fluxes</td>
<td>Energy Transfers</td>
<td>Error %</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>------------------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.023</td>
<td>19707.5</td>
<td>25071.9</td>
<td>19370.2</td>
</tr>
<tr>
<td>8.024</td>
<td>23944.9</td>
<td>30156.3</td>
<td>25344.1</td>
</tr>
<tr>
<td>8.025</td>
<td>27894.3</td>
<td>37760.2</td>
<td>30483.1</td>
</tr>
<tr>
<td>8.026</td>
<td>34601.9</td>
<td>43536.2</td>
<td>38807.6</td>
</tr>
<tr>
<td>8.027</td>
<td>41427.1</td>
<td>49817.4</td>
<td>45833.6</td>
</tr>
<tr>
<td>8.028</td>
<td>55661.9</td>
<td>67819.6</td>
<td>67904.6</td>
</tr>
<tr>
<td>8.029</td>
<td>35612.5</td>
<td>38035.2</td>
<td>30607.8</td>
</tr>
<tr>
<td>8.030</td>
<td>35269.3</td>
<td>44091.4</td>
<td>42940.2</td>
</tr>
<tr>
<td>8.031</td>
<td>37492.5</td>
<td>49614.3</td>
<td>52684.0</td>
</tr>
<tr>
<td>8.032</td>
<td>47098.2</td>
<td>60225.5</td>
<td>62987.7</td>
</tr>
<tr>
<td>8.033</td>
<td>34372.3</td>
<td>37133.6</td>
<td>34197.8</td>
</tr>
<tr>
<td>8.034</td>
<td>35796.6</td>
<td>45110.6</td>
<td>48647.0</td>
</tr>
<tr>
<td>8.035</td>
<td>42248.5</td>
<td>56767.9</td>
<td>64793.7</td>
</tr>
<tr>
<td>8.036</td>
<td>40821.4</td>
<td>59653.8</td>
<td>71366.8</td>
</tr>
<tr>
<td>8.037</td>
<td>29493.1</td>
<td>34536.0</td>
<td>33190.2</td>
</tr>
<tr>
<td>8.038</td>
<td>34997.3</td>
<td>43435.8</td>
<td>46918.7</td>
</tr>
<tr>
<td>8.039</td>
<td>37116.8</td>
<td>52724.5</td>
<td>58427.3</td>
</tr>
<tr>
<td>8.040</td>
<td>45854.1</td>
<td>61859.9</td>
<td>69482.8</td>
</tr>
<tr>
<td>8.041</td>
<td>28753.9</td>
<td>36004.0</td>
<td>35423.7</td>
</tr>
<tr>
<td>8.042</td>
<td>36702.6</td>
<td>43088.8</td>
<td>45168.3</td>
</tr>
<tr>
<td>8.044</td>
<td>15940.8</td>
<td>18802.5</td>
<td>12754.1</td>
</tr>
<tr>
<td>8.045</td>
<td>13222.9</td>
<td>15863.1</td>
<td>10032.7</td>
</tr>
<tr>
<td>8.046</td>
<td>9769.1</td>
<td>12131.4</td>
<td>7678.2</td>
</tr>
</tbody>
</table>

Note: The table continues with more rows, but they are not shown here.
<table>
<thead>
<tr>
<th>Run #</th>
<th>Coolant Flow Rate</th>
<th>Coolant Temperatures 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>exit</th>
<th>Qualities 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.012</td>
<td>59.27</td>
<td>10.7</td>
<td>28.3</td>
<td>43.3</td>
<td>55.2</td>
<td>62.9</td>
<td>0.024</td>
<td>0.354</td>
<td>0.634</td>
<td>0.855</td>
<td>1.000</td>
</tr>
<tr>
<td>1.013</td>
<td>61.94</td>
<td>10.8</td>
<td>27.7</td>
<td>42.8</td>
<td>54.8</td>
<td>62.9</td>
<td>0.064</td>
<td>0.367</td>
<td>0.639</td>
<td>0.854</td>
<td>1.003</td>
</tr>
<tr>
<td>1.014</td>
<td>71.95</td>
<td>10.7</td>
<td>25.2</td>
<td>39.3</td>
<td>51.2</td>
<td>59.8</td>
<td>0.057</td>
<td>0.335</td>
<td>0.604</td>
<td>0.834</td>
<td>1.003</td>
</tr>
<tr>
<td>1.018</td>
<td>66.95</td>
<td>10.7</td>
<td>23.8</td>
<td>38.2</td>
<td>50.8</td>
<td>59.6</td>
<td>-0.037</td>
<td>0.239</td>
<td>0.547</td>
<td>0.813</td>
<td>1.002</td>
</tr>
<tr>
<td>1.019</td>
<td>48.60</td>
<td>10.9</td>
<td>33.8</td>
<td>49.4</td>
<td>60.4</td>
<td>67.1</td>
<td>0.104</td>
<td>0.469</td>
<td>0.718</td>
<td>0.893</td>
<td>1.001</td>
</tr>
<tr>
<td>1.020</td>
<td>36.78</td>
<td>10.8</td>
<td>43.5</td>
<td>64.3</td>
<td>76.0</td>
<td>82.8</td>
<td>-0.006</td>
<td>0.452</td>
<td>0.742</td>
<td>0.905</td>
<td>1.000</td>
</tr>
<tr>
<td>1.021</td>
<td>42.75</td>
<td>10.6</td>
<td>40.4</td>
<td>61.0</td>
<td>73.5</td>
<td>80.8</td>
<td>0.025</td>
<td>0.439</td>
<td>0.725</td>
<td>0.898</td>
<td>0.998</td>
</tr>
<tr>
<td>1.022</td>
<td>50.47</td>
<td>10.5</td>
<td>36.9</td>
<td>56.7</td>
<td>70.3</td>
<td>78.2</td>
<td>0.015</td>
<td>0.399</td>
<td>0.687</td>
<td>0.884</td>
<td>0.996</td>
</tr>
<tr>
<td>1.023</td>
<td>53.65</td>
<td>10.6</td>
<td>35.3</td>
<td>54.6</td>
<td>68.6</td>
<td>77.1</td>
<td>0.037</td>
<td>0.396</td>
<td>0.675</td>
<td>0.877</td>
<td>1.001</td>
</tr>
<tr>
<td>1.024</td>
<td>63.79</td>
<td>10.5</td>
<td>32.7</td>
<td>51.3</td>
<td>65.6</td>
<td>74.8</td>
<td>0.003</td>
<td>0.349</td>
<td>0.636</td>
<td>0.857</td>
<td>0.998</td>
</tr>
<tr>
<td>1.025</td>
<td>24.37</td>
<td>11.0</td>
<td>63.8</td>
<td>84.3</td>
<td>92.3</td>
<td>96.7</td>
<td>0.180</td>
<td>0.686</td>
<td>0.882</td>
<td>0.958</td>
<td>0.999</td>
</tr>
<tr>
<td>1.026</td>
<td>29.96</td>
<td>11.0</td>
<td>53.0</td>
<td>76.1</td>
<td>87.0</td>
<td>93.8</td>
<td>0.052</td>
<td>0.535</td>
<td>0.798</td>
<td>0.922</td>
<td>0.998</td>
</tr>
<tr>
<td>1.027</td>
<td>35.79</td>
<td>10.7</td>
<td>49.5</td>
<td>72.6</td>
<td>85.1</td>
<td>92.7</td>
<td>0.021</td>
<td>0.485</td>
<td>0.760</td>
<td>0.908</td>
<td>0.999</td>
</tr>
<tr>
<td>1.028</td>
<td>41.61</td>
<td>10.6</td>
<td>44.0</td>
<td>66.8</td>
<td>81.3</td>
<td>89.9</td>
<td>-0.016</td>
<td>0.411</td>
<td>0.704</td>
<td>0.889</td>
<td>0.998</td>
</tr>
<tr>
<td>1.031</td>
<td>36.29</td>
<td>10.4</td>
<td>55.4</td>
<td>80.2</td>
<td>92.8</td>
<td>101.0</td>
<td>0.046</td>
<td>0.521</td>
<td>0.781</td>
<td>0.913</td>
<td>0.996</td>
</tr>
<tr>
<td>1.033</td>
<td>103.57</td>
<td>83.8</td>
<td>87.0</td>
<td>91.2</td>
<td>95.0</td>
<td>99.0</td>
<td>0.042</td>
<td>0.246</td>
<td>0.512</td>
<td>0.750</td>
<td>1.001</td>
</tr>
<tr>
<td>1.034</td>
<td>117.51</td>
<td>75.3</td>
<td>79.8</td>
<td>85.5</td>
<td>90.7</td>
<td>95.7</td>
<td>-0.045</td>
<td>0.186</td>
<td>0.479</td>
<td>0.743</td>
<td>1.007</td>
</tr>
<tr>
<td>1.035</td>
<td>120.96</td>
<td>72.2</td>
<td>78.2</td>
<td>84.5</td>
<td>90.1</td>
<td>95.3</td>
<td>0.006</td>
<td>0.264</td>
<td>0.537</td>
<td>0.773</td>
<td>1.012</td>
</tr>
<tr>
<td>1.036</td>
<td>82.03</td>
<td>87.3</td>
<td>92.8</td>
<td>98.6</td>
<td>103.2</td>
<td>107.7</td>
<td>0.038</td>
<td>0.294</td>
<td>0.571</td>
<td>0.784</td>
<td>1.002</td>
</tr>
<tr>
<td>1.037</td>
<td>86.46</td>
<td>80.2</td>
<td>87.7</td>
<td>94.9</td>
<td>100.8</td>
<td>105.9</td>
<td>0.032</td>
<td>0.314</td>
<td>0.586</td>
<td>0.805</td>
<td>1.011</td>
</tr>
<tr>
<td>1.038</td>
<td>97.23</td>
<td>72.5</td>
<td>81.0</td>
<td>89.7</td>
<td>96.9</td>
<td>103.4</td>
<td>-0.038</td>
<td>0.247</td>
<td>0.538</td>
<td>0.779</td>
<td>1.009</td>
</tr>
<tr>
<td>1.039</td>
<td>97.23</td>
<td>67.0</td>
<td>77.5</td>
<td>87.1</td>
<td>93.5</td>
<td>102.3</td>
<td>0.053</td>
<td>0.338</td>
<td>0.602</td>
<td>0.825</td>
<td>1.016</td>
</tr>
<tr>
<td>1.040</td>
<td>153.69</td>
<td>13.2</td>
<td>22.4</td>
<td>33.1</td>
<td>43.6</td>
<td>52.4</td>
<td>-0.022</td>
<td>0.218</td>
<td>0.497</td>
<td>0.770</td>
<td>1.000</td>
</tr>
<tr>
<td>1.041</td>
<td>167.48</td>
<td>13.2</td>
<td>22.1</td>
<td>32.8</td>
<td>43.2</td>
<td>51.9</td>
<td>0.050</td>
<td>0.268</td>
<td>0.531</td>
<td>0.787</td>
<td>1.000</td>
</tr>
<tr>
<td>1.042</td>
<td>248.36</td>
<td>12.9</td>
<td>20.7</td>
<td>30.3</td>
<td>39.7</td>
<td>48.1</td>
<td>0.021</td>
<td>0.253</td>
<td>0.538</td>
<td>0.818</td>
<td>1.066</td>
</tr>
</tbody>
</table>
Table I.4. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Coolant Flow Rate</th>
<th>Coolant Temperatures 1 2 3 4 exit</th>
<th>Qualities 1 2 3 4 inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.043</td>
<td>326.59</td>
<td>12.8 19.3 27.7 36.4 44.4</td>
<td>0.021 0.236 0.511 0.793 1.054</td>
</tr>
<tr>
<td>1.044</td>
<td>120.96</td>
<td>13.2 27.7 43.4 57.1 67.8</td>
<td>0.018 0.291 0.584 0.839 1.038</td>
</tr>
<tr>
<td>1.045</td>
<td>155.34</td>
<td>13.1 26.0 40.2 53.4 63.9</td>
<td>0.019 0.279 0.564 0.827 1.037</td>
</tr>
<tr>
<td>1.046</td>
<td>204.12</td>
<td>13.0 24.1 37.5 49.9 60.3</td>
<td>0.018 0.258 0.546 0.812 1.035</td>
</tr>
<tr>
<td>1.047</td>
<td>87.73</td>
<td>13.4 31.1 48.4 62.4 72.5</td>
<td>0.016 0.312 0.599 0.832 1.008</td>
</tr>
<tr>
<td>1.048</td>
<td>117.31</td>
<td>41.6 53.3 64.9 75.0 83.1</td>
<td>0.012 0.297 0.581 0.827 1.022</td>
</tr>
<tr>
<td>1.049</td>
<td>161.88</td>
<td>39.1 49.3 60.4 70.4 78.8</td>
<td>0.018 0.274 0.556 0.810 1.020</td>
</tr>
<tr>
<td>1.050</td>
<td>187.43</td>
<td>34.7 44.8 56.6 67.3 76.3</td>
<td>-0.008 0.243 0.532 0.796 1.016</td>
</tr>
<tr>
<td>1.051</td>
<td>225.86</td>
<td>34.7 44.3 55.4 65.8 74.6</td>
<td>0.019 0.254 0.529 0.783 1.012</td>
</tr>
<tr>
<td>1.052</td>
<td>182.96</td>
<td>65.3 71.4 78.3 84.8 91.1</td>
<td>0.023 0.255 0.517 0.764 1.003</td>
</tr>
<tr>
<td>1.053</td>
<td>200.98</td>
<td>57.1 64.3 72.8 80.8 88.0</td>
<td>-0.002 0.236 0.517 0.780 1.018</td>
</tr>
<tr>
<td>1.054</td>
<td>272.16</td>
<td>58.2 64.3 71.7 79.2 86.1</td>
<td>0.013 0.233 0.503 0.770 1.020</td>
</tr>
<tr>
<td>1.055</td>
<td>281.95</td>
<td>52.0 59.3 67.9 76.2 83.9</td>
<td>0.014 0.242 0.513 0.775 1.015</td>
</tr>
<tr>
<td>1.056</td>
<td>154.23</td>
<td>70.5 77.7 85.4 92.8 99.3</td>
<td>0.023 0.267 0.530 0.779 1.004</td>
</tr>
<tr>
<td>1.057</td>
<td>192.11</td>
<td>66.5 73.7 81.8 89.5 96.4</td>
<td>0.013 0.251 0.518 0.771 1.010</td>
</tr>
<tr>
<td>1.058</td>
<td>218.31</td>
<td>62.0 69.4 78.2 86.6 94.2</td>
<td>0.020 0.244 0.516 0.770 1.009</td>
</tr>
<tr>
<td>1.059</td>
<td>250.84</td>
<td>58.3 66.1 75.5 84.3 92.2</td>
<td>0.008 0.237 0.512 0.768 1.004</td>
</tr>
<tr>
<td>1.060</td>
<td>173.72</td>
<td>72.8 79.5 86.7 93.4 99.6</td>
<td>0.075 0.326 0.597 0.852 1.088</td>
</tr>
<tr>
<td>1.061</td>
<td>147.11</td>
<td>80.4 87.3 94.0 99.6 104.7</td>
<td>0.312 0.532 0.745 0.924 1.087</td>
</tr>
<tr>
<td>1.062</td>
<td>114.98</td>
<td>96.4 101.6 105.8 109.3 112.8</td>
<td>0.679 0.808 0.913 0.999 1.086</td>
</tr>
<tr>
<td>1.063</td>
<td>91.53</td>
<td>102.9 106.5 109.6 111.7 114.7</td>
<td>0.854 0.927 0.988 1.028 1.087</td>
</tr>
<tr>
<td>1.064</td>
<td>69.73</td>
<td>103.7 107.9 110.6 112.1 115.1</td>
<td>0.917 0.979 1.020 1.041 1.086</td>
</tr>
<tr>
<td>1.065</td>
<td>171.89</td>
<td>70.3 77.2 85.0 92.2 98.8</td>
<td>0.073 0.334 0.625 0.893 1.141</td>
</tr>
<tr>
<td>1.066</td>
<td>133.85</td>
<td>80.8 88.5 95.6 100.9 106.2</td>
<td>0.400 0.626 0.831 0.986 1.140</td>
</tr>
<tr>
<td>1.067</td>
<td>114.98</td>
<td>90.0 97.2 103.0 106.8 111.2</td>
<td>0.610 0.791 0.934 1.030 1.139</td>
</tr>
<tr>
<td>1.068</td>
<td>87.73</td>
<td>102.8 106.6 109.7 111.6 115.5</td>
<td>0.900 0.972 1.030 1.066 1.140</td>
</tr>
<tr>
<td>1.069</td>
<td>76.45</td>
<td>104.3 107.9 110.7 112.4 116.5</td>
<td>0.939 0.999 1.046 1.072 1.141</td>
</tr>
<tr>
<td>1.070</td>
<td>43.37</td>
<td>92.5 101.4 106.5 109.3 112.4</td>
<td>0.251 0.335 0.383 0.409 0.437</td>
</tr>
<tr>
<td>1.071</td>
<td>35.13</td>
<td>90.1 101.1 106.3 109.0 112.2</td>
<td>0.235 0.318 0.357 0.377 0.400</td>
</tr>
<tr>
<td>1.072</td>
<td>92.16</td>
<td>92.6 96.5 101.3 104.6 108.1</td>
<td>0.223 0.301 0.396 0.462 0.530</td>
</tr>
</tbody>
</table>
Table I.4. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Coolant Flow Rate</th>
<th>Coolant Temperatures</th>
<th>Qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>exit 1 2 3 4 inlet</td>
<td>1 2 3 4 inlet</td>
</tr>
<tr>
<td>1.073</td>
<td>92.16</td>
<td>92.5 96.9 101.9 105.2 108.9</td>
<td>0.214 0.301 0.400 0.465 0.539</td>
</tr>
<tr>
<td>1.074</td>
<td>92.16</td>
<td>92.5 97.5 102.7 106.0 109.6</td>
<td>0.436 0.535 0.639 0.703 0.774</td>
</tr>
<tr>
<td>1.075</td>
<td>117.51</td>
<td>61.4 71.3 81.8 91.0 98.9</td>
<td>0.063 0.315 0.582 0.817 1.018</td>
</tr>
<tr>
<td>1.076</td>
<td>108.64</td>
<td>54.3 66.9 79.6 89.9 98.9</td>
<td>-0.016 0.282 0.580 0.822 1.034</td>
</tr>
<tr>
<td>1.077</td>
<td>114.98</td>
<td>55.8 67.7 79.6 89.6 98.3</td>
<td>-0.005 0.292 0.589 0.837 1.056</td>
</tr>
<tr>
<td>1.078</td>
<td>114.35</td>
<td>55.6 67.7 79.9 89.9 98.6</td>
<td>0.002 0.303 0.606 0.855 1.070</td>
</tr>
<tr>
<td>1.079</td>
<td>115.61</td>
<td>54.1 65.7 77.8 88.0 97.1</td>
<td>0.029 0.320 0.623 0.879 1.108</td>
</tr>
<tr>
<td>2.001</td>
<td>48.29</td>
<td>10.5 34.5 51.0 62.0 68.4</td>
<td>0.081 0.464 0.726 0.901 0.998</td>
</tr>
<tr>
<td>2.004</td>
<td>78.79</td>
<td>9.7 25.6 40.4 52.5 61.1</td>
<td>0.071 0.351 0.619 0.840 0.999</td>
</tr>
<tr>
<td>2.005</td>
<td>90.41</td>
<td>9.8 24.1 38.2 50.3 59.3</td>
<td>0.052 0.317 0.586 0.822 0.999</td>
</tr>
<tr>
<td>2.006</td>
<td>33.55</td>
<td>10.9 49.5 68.9 78.6 83.7</td>
<td>0.096 0.577 0.818 0.938 0.994</td>
</tr>
<tr>
<td>2.007</td>
<td>36.13</td>
<td>10.5 46.7 66.5 77.3 83.3</td>
<td>0.067 0.534 0.787 0.925 0.994</td>
</tr>
<tr>
<td>2.008</td>
<td>42.92</td>
<td>10.3 42.6 63.1 75.4 82.2</td>
<td>0.036 0.470 0.745 0.911 0.996</td>
</tr>
<tr>
<td>2.009</td>
<td>47.14</td>
<td>10.3 40.4 60.8 73.4 80.4</td>
<td>0.055 0.462 0.737 0.906 0.992</td>
</tr>
<tr>
<td>2.010</td>
<td>44.76</td>
<td>10.3 42.0 62.5 74.6 81.4</td>
<td>0.087 0.495 0.758 0.914 0.995</td>
</tr>
<tr>
<td>2.011</td>
<td>54.16</td>
<td>10.2 37.9 58.3 71.8 79.8</td>
<td>0.082 0.447 0.717 0.895 0.998</td>
</tr>
<tr>
<td>2.012</td>
<td>62.81</td>
<td>9.9 34.6 54.6 68.7 77.3</td>
<td>0.016 0.375 0.668 0.875 0.995</td>
</tr>
<tr>
<td>2.013</td>
<td>26.77</td>
<td>11.0 64.9 84.7 92.3 96.6</td>
<td>0.072 0.659 0.873 0.954 0.996</td>
</tr>
<tr>
<td>2.014</td>
<td>30.24</td>
<td>10.7 59.4 81.2 90.5 96.0</td>
<td>0.069 0.603 0.841 0.941 0.998</td>
</tr>
<tr>
<td>2.015</td>
<td>34.31</td>
<td>10.6 56.4 78.8 89.3 95.6</td>
<td>0.064 0.570 0.817 0.931 0.999</td>
</tr>
<tr>
<td>2.018</td>
<td>44.37</td>
<td>11.9 48.0 71.6 85.3 92.4</td>
<td>0.065 0.487 0.762 0.920 0.999</td>
</tr>
<tr>
<td>2.019</td>
<td>25.12</td>
<td>12.4 73.6 94.3 101.5 105.8</td>
<td>0.066 0.679 0.887 0.957 0.996</td>
</tr>
<tr>
<td>2.020</td>
<td>29.30</td>
<td>12.1 66.5 89.7 98.8 104.2</td>
<td>0.038 0.607 0.850 0.944 0.990</td>
</tr>
<tr>
<td>2.021</td>
<td>24.19</td>
<td>11.8 70.1 92.8 101.1 106.2</td>
<td>0.018 0.625 0.862 0.947 0.996</td>
</tr>
<tr>
<td>2.022</td>
<td>58.32</td>
<td>63.9 78.3 88.9 96.2 101.3</td>
<td>0.049 0.415 0.664 0.870 1.005</td>
</tr>
<tr>
<td>2.024</td>
<td>69.35</td>
<td>60.4 74.2 85.4 93.8 100.1</td>
<td>0.027 0.372 0.651 0.861 1.018</td>
</tr>
<tr>
<td>2.027</td>
<td>107.37</td>
<td>59.8 70.1 80.8 89.4 96.7</td>
<td>0.007 0.286 0.571 0.802 1.013</td>
</tr>
<tr>
<td>2.028</td>
<td>53.51</td>
<td>69.0 84.9 96.4 104.1 109.6</td>
<td>0.006 0.394 0.676 0.864 1.007</td>
</tr>
<tr>
<td>2.029</td>
<td>59.84</td>
<td>65.0 80.9 93.4 102.2 108.8</td>
<td>0.001 0.363 0.649 0.848 1.011</td>
</tr>
<tr>
<td>2.030</td>
<td>66.82</td>
<td>62.7 78.4 91.4 100.8 108.0</td>
<td>-0.001 0.346 0.632 0.840 1.010</td>
</tr>
<tr>
<td>Fun #</td>
<td>Coolant Flow Rate</td>
<td>Coolant Temperatures</td>
<td>Qualities</td>
</tr>
<tr>
<td>------</td>
<td>-------------------</td>
<td>----------------------</td>
<td>-----------</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2.031</td>
<td>233.28</td>
<td>13.2</td>
<td>19.9</td>
</tr>
<tr>
<td>2.032</td>
<td>84.56</td>
<td>13.0</td>
<td>27.3</td>
</tr>
<tr>
<td>2.033</td>
<td>137.22</td>
<td>12.8</td>
<td>22.5</td>
</tr>
<tr>
<td>2.034</td>
<td>149.81</td>
<td>12.5</td>
<td>21.8</td>
</tr>
<tr>
<td>2.035</td>
<td>186.62</td>
<td>12.4</td>
<td>20.4</td>
</tr>
<tr>
<td>2.036</td>
<td>214.16</td>
<td>12.3</td>
<td>19.7</td>
</tr>
<tr>
<td>2.037</td>
<td>160.09</td>
<td>12.3</td>
<td>25.2</td>
</tr>
<tr>
<td>2.038</td>
<td>384.23</td>
<td>32.9</td>
<td>37.8</td>
</tr>
<tr>
<td>2.039</td>
<td>204.12</td>
<td>12.3</td>
<td>23.2</td>
</tr>
<tr>
<td>2.040</td>
<td>80.76</td>
<td>12.6</td>
<td>33.4</td>
</tr>
<tr>
<td>2.041</td>
<td>111.18</td>
<td>12.6</td>
<td>28.6</td>
</tr>
<tr>
<td>2.042</td>
<td>279.94</td>
<td>56.2</td>
<td>61.3</td>
</tr>
<tr>
<td>2.043</td>
<td>296.90</td>
<td>51.3</td>
<td>57.0</td>
</tr>
<tr>
<td>2.044</td>
<td>313.17</td>
<td>47.4</td>
<td>53.7</td>
</tr>
<tr>
<td>2.045</td>
<td>192.11</td>
<td>59.4</td>
<td>65.3</td>
</tr>
<tr>
<td>2.046</td>
<td>233.28</td>
<td>57.5</td>
<td>63.2</td>
</tr>
<tr>
<td>2.047</td>
<td>186.62</td>
<td>68.8</td>
<td>74.9</td>
</tr>
<tr>
<td>2.048</td>
<td>206.70</td>
<td>65.0</td>
<td>71.4</td>
</tr>
<tr>
<td>2.049</td>
<td>217.73</td>
<td>58.0</td>
<td>65.1</td>
</tr>
<tr>
<td>2.050</td>
<td>232.37</td>
<td>55.5</td>
<td>63.2</td>
</tr>
<tr>
<td>2.051</td>
<td>285.12</td>
<td>56.1</td>
<td>63.2</td>
</tr>
<tr>
<td>2.052</td>
<td>171.17</td>
<td>77.7</td>
<td>83.4</td>
</tr>
<tr>
<td>2.053</td>
<td>179.45</td>
<td>72.0</td>
<td>79.4</td>
</tr>
<tr>
<td>2.054</td>
<td>200.25</td>
<td>69.0</td>
<td>76.5</td>
</tr>
<tr>
<td>2.055</td>
<td>220.94</td>
<td>65.2</td>
<td>72.9</td>
</tr>
<tr>
<td>2.056</td>
<td>271.75</td>
<td>61.8</td>
<td>69.1</td>
</tr>
<tr>
<td>2.002</td>
<td>61.51</td>
<td>10.3</td>
<td>30.0</td>
</tr>
<tr>
<td>2.003</td>
<td>67.69</td>
<td>10.2</td>
<td>28.1</td>
</tr>
<tr>
<td>3.001</td>
<td>140.77</td>
<td>60.8</td>
<td>70.1</td>
</tr>
<tr>
<td>3.002</td>
<td>170.86</td>
<td>57.2</td>
<td>66.7</td>
</tr>
</tbody>
</table>
Table I.4. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Coolant Flow Rate</th>
<th>Coolant Temperatures</th>
<th>Qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Exit 1 2 3 4</td>
<td>1 2 3 4 inlet</td>
</tr>
<tr>
<td>3.003</td>
<td>224.13</td>
<td>56.5 65.0 74.8 83.3 90.6</td>
<td>0.021 0.269 0.554 0.802 1.015</td>
</tr>
<tr>
<td>3.004</td>
<td>275.02</td>
<td>52.9 61.1 70.8 79.4 86.9</td>
<td>0.008 0.253 0.541 0.794 1.019</td>
</tr>
<tr>
<td>3.005</td>
<td>186.84</td>
<td>78.7 84.4 91.2 97.3 102.8</td>
<td>0.030 0.261 0.534 0.777 1.007</td>
</tr>
<tr>
<td>3.006</td>
<td>200.19</td>
<td>70.9 78.3 86.8 94.2 100.6</td>
<td>0.027 0.268 0.547 0.788 1.013</td>
</tr>
<tr>
<td>3.007</td>
<td>260.03</td>
<td>70.3 77.0 85.0 92.2 98.7</td>
<td>0.028 0.262 0.542 0.793 1.020</td>
</tr>
<tr>
<td>3.008</td>
<td>301.84</td>
<td>67.7 74.6 82.8 90.2 96.8</td>
<td>0.021 0.258 0.540 0.793 1.021</td>
</tr>
<tr>
<td>3.009</td>
<td>89.63</td>
<td>81.9 87.5 92.7 96.8 100.7</td>
<td>0.007 0.301 0.579 0.793 1.008</td>
</tr>
<tr>
<td>3.010</td>
<td>97.87</td>
<td>77.4 83.5 89.7 94.8 99.5</td>
<td>0.048 0.311 0.579 0.800 1.008</td>
</tr>
<tr>
<td>3.011</td>
<td>107.37</td>
<td>72.2 79.2 86.5 92.5 97.9</td>
<td>0.012 0.282 0.561 0.793 1.011</td>
</tr>
<tr>
<td>3.012</td>
<td>117.82</td>
<td>65.9 74.5 83.5 91.0 97.3</td>
<td>0.010 0.281 0.564 0.802 1.006</td>
</tr>
<tr>
<td>3.013</td>
<td>88.36</td>
<td>90.5 95.7 100.7 104.8 108.5</td>
<td>0.056 0.331 0.591 0.805 1.007</td>
</tr>
<tr>
<td>3.014</td>
<td>100.40</td>
<td>82.8 89.6 96.4 101.6 106.7</td>
<td>0.013 0.300 0.565 0.805 1.017</td>
</tr>
<tr>
<td>3.015</td>
<td>109.91</td>
<td>76.6 84.4 92.4 99.2 105.0</td>
<td>0.026 0.298 0.578 0.814 1.018</td>
</tr>
<tr>
<td>3.016</td>
<td>116.64</td>
<td>72.0 80.8 90.1 97.7 104.0</td>
<td>0.033 0.306 0.592 0.824 1.021</td>
</tr>
<tr>
<td>3.017</td>
<td>164.23</td>
<td>73.8 81.4 89.7 96.8 103.0</td>
<td>0.049 0.317 0.612 0.865 1.090</td>
</tr>
<tr>
<td>3.018</td>
<td>138.62</td>
<td>83.5 91.4 98.5 103.6 108.6</td>
<td>0.337 0.375 0.785 0.939 1.068</td>
</tr>
<tr>
<td>3.019</td>
<td>116.25</td>
<td>93.9 100.4 105.5 108.9 112.7</td>
<td>0.617 0.778 0.905 0.991 1.087</td>
</tr>
<tr>
<td>3.020</td>
<td>94.07</td>
<td>103.2 106.9 110.1 112.1 115.3</td>
<td>0.843 0.919 0.983 1.022 1.067</td>
</tr>
<tr>
<td>3.021</td>
<td>54.14</td>
<td>100.6 107.4 111.1 112.9 116.9</td>
<td>0.900 0.980 1.022 1.043 1.089</td>
</tr>
<tr>
<td>3.022</td>
<td>310.62</td>
<td>83.7 87.1 91.6 95.8 100.2</td>
<td>0.034 0.260 0.558 0.844 1.142</td>
</tr>
<tr>
<td>3.023</td>
<td>188.78</td>
<td>86.9 92.7 98.0 102.3 106.6</td>
<td>0.346 0.580 0.798 0.972 1.146</td>
</tr>
<tr>
<td>3.024</td>
<td>109.91</td>
<td>82.0 92.3 99.8 105.2 110.3</td>
<td>0.481 0.722 0.898 1.022 1.146</td>
</tr>
<tr>
<td>3.025</td>
<td>68.08</td>
<td>101.2 106.4 110.0 112.6 117.0</td>
<td>0.908 0.984 1.035 1.072 1.147</td>
</tr>
<tr>
<td>3.026</td>
<td>117.51</td>
<td>79.5 89.4 97.7 103.5 108.4</td>
<td>0.279 0.531 0.740 0.886 1.011</td>
</tr>
<tr>
<td>3.027</td>
<td>117.51</td>
<td>78.2 88.2 96.5 102.3 107.4</td>
<td>0.300 0.552 0.761 0.909 1.038</td>
</tr>
<tr>
<td>3.028</td>
<td>117.51</td>
<td>80.2 90.2 98.0 103.5 108.3</td>
<td>0.346 0.598 0.794 0.933 1.055</td>
</tr>
<tr>
<td>3.029</td>
<td>117.51</td>
<td>80.9 91.0 98.8 104.1 109.1</td>
<td>0.381 0.636 0.832 0.967 1.091</td>
</tr>
<tr>
<td>3.030</td>
<td>117.51</td>
<td>81.0 91.2 98.9 104.3 109.3</td>
<td>0.413 0.669 0.864 1.001 1.127</td>
</tr>
<tr>
<td>3.031</td>
<td>93.43</td>
<td>73.4 87.4 97.2 103.7 109.6</td>
<td>0.399 0.678 0.876 1.007 1.124</td>
</tr>
<tr>
<td>3.032</td>
<td>92.16</td>
<td>72.6 86.7 96.8 103.4 109.0</td>
<td>0.368 0.649 0.847 0.978 1.088</td>
</tr>
</tbody>
</table>
### Table I.4. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Coolant Flow Rate</th>
<th>Coolant Temperatures</th>
<th>exit</th>
<th>Qualities</th>
<th>inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>3.033</td>
<td>92.16</td>
<td>72.4</td>
<td>86.4</td>
<td>96.5</td>
<td>103.1</td>
</tr>
<tr>
<td>3.034</td>
<td>92.16</td>
<td>72.1</td>
<td>86.2</td>
<td>96.3</td>
<td>102.9</td>
</tr>
<tr>
<td>3.035</td>
<td>51.61</td>
<td>51.8</td>
<td>80.6</td>
<td>96.6</td>
<td>105.0</td>
</tr>
<tr>
<td>3.036</td>
<td>84.56</td>
<td>85.0</td>
<td>95.2</td>
<td>102.2</td>
<td>107.0</td>
</tr>
<tr>
<td>3.037</td>
<td>50.34</td>
<td>94.4</td>
<td>103.7</td>
<td>108.1</td>
<td>110.9</td>
</tr>
<tr>
<td>3.038</td>
<td>78.22</td>
<td>93.3</td>
<td>100.1</td>
<td>104.9</td>
<td>108.4</td>
</tr>
<tr>
<td>3.039</td>
<td>50.97</td>
<td>91.2</td>
<td>99.8</td>
<td>104.4</td>
<td>107.8</td>
</tr>
<tr>
<td>4.001</td>
<td>120.05</td>
<td>16.4</td>
<td>30.5</td>
<td>43.3</td>
<td>53.5</td>
</tr>
<tr>
<td>4.002</td>
<td>183.48</td>
<td>16.8</td>
<td>27.4</td>
<td>38.5</td>
<td>48.3</td>
</tr>
<tr>
<td>4.003</td>
<td>233.28</td>
<td>16.5</td>
<td>26.0</td>
<td>35.8</td>
<td>45.2</td>
</tr>
<tr>
<td>4.004</td>
<td>371.13</td>
<td>16.6</td>
<td>23.0</td>
<td>30.3</td>
<td>38.4</td>
</tr>
<tr>
<td>4.005</td>
<td>89.63</td>
<td>16.9</td>
<td>38.7</td>
<td>56.8</td>
<td>69.0</td>
</tr>
<tr>
<td>4.006</td>
<td>127.58</td>
<td>16.7</td>
<td>34.5</td>
<td>51.2</td>
<td>63.6</td>
</tr>
<tr>
<td>4.007</td>
<td>157.77</td>
<td>16.2</td>
<td>33.1</td>
<td>48.3</td>
<td>60.8</td>
</tr>
<tr>
<td>4.008</td>
<td>164.53</td>
<td>16.2</td>
<td>32.2</td>
<td>47.0</td>
<td>59.4</td>
</tr>
<tr>
<td>4.009</td>
<td>200.36</td>
<td>16.0</td>
<td>30.1</td>
<td>43.9</td>
<td>55.9</td>
</tr>
<tr>
<td>4.010</td>
<td>177.17</td>
<td>61.5</td>
<td>69.5</td>
<td>77.2</td>
<td>83.4</td>
</tr>
<tr>
<td>4.011</td>
<td>222.39</td>
<td>55.9</td>
<td>64.1</td>
<td>72.4</td>
<td>79.5</td>
</tr>
<tr>
<td>4.012</td>
<td>293.57</td>
<td>56.3</td>
<td>63.3</td>
<td>70.8</td>
<td>77.4</td>
</tr>
<tr>
<td>4.013</td>
<td>335.31</td>
<td>51.5</td>
<td>58.9</td>
<td>66.9</td>
<td>74.0</td>
</tr>
<tr>
<td>4.014</td>
<td>185.56</td>
<td>71.2</td>
<td>78.5</td>
<td>86.0</td>
<td>91.8</td>
</tr>
<tr>
<td>4.015</td>
<td>235.20</td>
<td>69.7</td>
<td>76.8</td>
<td>84.4</td>
<td>90.4</td>
</tr>
<tr>
<td>4.016</td>
<td>248.25</td>
<td>63.2</td>
<td>71.5</td>
<td>80.4</td>
<td>87.6</td>
</tr>
<tr>
<td>4.017</td>
<td>275.08</td>
<td>58.5</td>
<td>67.3</td>
<td>76.9</td>
<td>84.6</td>
</tr>
<tr>
<td>4.018</td>
<td>270.93</td>
<td>69.4</td>
<td>78.0</td>
<td>87.0</td>
<td>94.2</td>
</tr>
<tr>
<td>4.019</td>
<td>237.43</td>
<td>72.3</td>
<td>80.8</td>
<td>89.6</td>
<td>96.4</td>
</tr>
<tr>
<td>4.020</td>
<td>196.07</td>
<td>72.3</td>
<td>81.4</td>
<td>90.6</td>
<td>97.5</td>
</tr>
<tr>
<td>4.021</td>
<td>146.32</td>
<td>74.6</td>
<td>84.1</td>
<td>93.5</td>
<td>100.1</td>
</tr>
<tr>
<td>4.022</td>
<td>76.96</td>
<td>72.9</td>
<td>81.3</td>
<td>87.9</td>
<td>91.9</td>
</tr>
<tr>
<td>4.023</td>
<td>109.91</td>
<td>69.9</td>
<td>77.2</td>
<td>84.0</td>
<td>88.7</td>
</tr>
</tbody>
</table>
Table I.4. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Coolant Flow Rate</th>
<th>Coolant Temperatures</th>
<th>Qualities</th>
<th>inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>exit</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>4.024</td>
<td>127.97</td>
<td>68.7</td>
<td>66.1</td>
<td>1.007</td>
</tr>
<tr>
<td>4.025</td>
<td>153.67</td>
<td>64.1</td>
<td>86.6</td>
<td>1.014</td>
</tr>
<tr>
<td>4.026</td>
<td>200.12</td>
<td>77.0</td>
<td>88.6</td>
<td>1.005</td>
</tr>
<tr>
<td>4.027</td>
<td>156.71</td>
<td>79.0</td>
<td>90.8</td>
<td>1.003</td>
</tr>
<tr>
<td>4.028</td>
<td>67.07</td>
<td>79.9</td>
<td>104.8</td>
<td>1.008</td>
</tr>
<tr>
<td>4.029</td>
<td>89.63</td>
<td>72.7</td>
<td>102.4</td>
<td>1.017</td>
</tr>
<tr>
<td>4.030</td>
<td>112.44</td>
<td>70.1</td>
<td>101.0</td>
<td>1.018</td>
</tr>
<tr>
<td>4.031</td>
<td>79.49</td>
<td>90.3</td>
<td>111.8</td>
<td>1.009</td>
</tr>
<tr>
<td>4.032</td>
<td>96.98</td>
<td>84.4</td>
<td>105.4</td>
<td>1.014</td>
</tr>
<tr>
<td>4.033</td>
<td>108.01</td>
<td>79.6</td>
<td>108.6</td>
<td>1.018</td>
</tr>
<tr>
<td>4.034</td>
<td>117.82</td>
<td>73.5</td>
<td>106.8</td>
<td>1.021</td>
</tr>
<tr>
<td>4.035</td>
<td>45.27</td>
<td>17.2</td>
<td>70.5</td>
<td>1.003</td>
</tr>
<tr>
<td>4.036</td>
<td>69.35</td>
<td>16.8</td>
<td>67.2</td>
<td>0.998</td>
</tr>
<tr>
<td>4.037</td>
<td>101.04</td>
<td>16.4</td>
<td>62.8</td>
<td>0.999</td>
</tr>
<tr>
<td>4.038</td>
<td>34.63</td>
<td>18.2</td>
<td>86.1</td>
<td>1.001</td>
</tr>
<tr>
<td>4.039</td>
<td>51.61</td>
<td>17.5</td>
<td>83.2</td>
<td>0.996</td>
</tr>
<tr>
<td>4.040</td>
<td>66.82</td>
<td>17.0</td>
<td>80.6</td>
<td>0.995</td>
</tr>
<tr>
<td>5.002</td>
<td>42.97</td>
<td>15.5</td>
<td>72.8</td>
<td>0.999</td>
</tr>
<tr>
<td>5.003</td>
<td>70.62</td>
<td>15.1</td>
<td>68.8</td>
<td>1.004</td>
</tr>
<tr>
<td>5.004</td>
<td>87.09</td>
<td>15.0</td>
<td>65.7</td>
<td>0.999</td>
</tr>
<tr>
<td>5.006</td>
<td>45.28</td>
<td>15.6</td>
<td>85.6</td>
<td>1.016</td>
</tr>
<tr>
<td>5.007</td>
<td>61.47</td>
<td>15.3</td>
<td>82.8</td>
<td>1.018</td>
</tr>
<tr>
<td>5.008</td>
<td>152.61</td>
<td>68.7</td>
<td>84.0</td>
<td>1.013</td>
</tr>
<tr>
<td>5.009</td>
<td>31.56</td>
<td>16.3</td>
<td>87.7</td>
<td>0.996</td>
</tr>
<tr>
<td>5.010</td>
<td>72.58</td>
<td>15.1</td>
<td>68.3</td>
<td>1.000</td>
</tr>
<tr>
<td>5.011</td>
<td>69.69</td>
<td>15.2</td>
<td>68.8</td>
<td>1.001</td>
</tr>
<tr>
<td>5.012</td>
<td>88.36</td>
<td>15.0</td>
<td>54.0</td>
<td>0.999</td>
</tr>
<tr>
<td>5.013</td>
<td>168.87</td>
<td>83.3</td>
<td>92.8</td>
<td>1.011</td>
</tr>
<tr>
<td>5.014</td>
<td>199.75</td>
<td>76.5</td>
<td>92.6</td>
<td>1.007</td>
</tr>
<tr>
<td>5.015</td>
<td>217.73</td>
<td>71.0</td>
<td>90.4</td>
<td>1.012</td>
</tr>
</tbody>
</table>
Table I.4. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Coolant Flow Rate</th>
<th>Coolant Temperatures</th>
<th>Qualities</th>
<th>inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5.016</td>
<td>158.03</td>
<td>91.6</td>
<td>94.7</td>
<td>98.1</td>
</tr>
<tr>
<td>5.017</td>
<td>178.22</td>
<td>84.3</td>
<td>89.1</td>
<td>93.8</td>
</tr>
<tr>
<td>5.018</td>
<td>175.94</td>
<td>77.4</td>
<td>83.7</td>
<td>90.0</td>
</tr>
<tr>
<td>5.019</td>
<td>116.88</td>
<td>93.7</td>
<td>99.9</td>
<td>105.0</td>
</tr>
<tr>
<td>5.020</td>
<td>143.24</td>
<td>88.3</td>
<td>94.9</td>
<td>100.7</td>
</tr>
<tr>
<td>5.021</td>
<td>152.61</td>
<td>80.7</td>
<td>88.9</td>
<td>96.2</td>
</tr>
<tr>
<td>5.022</td>
<td>227.25</td>
<td>84.7</td>
<td>90.6</td>
<td>96.2</td>
</tr>
<tr>
<td>5.023</td>
<td>255.15</td>
<td>78.1</td>
<td>85.0</td>
<td>91.8</td>
</tr>
<tr>
<td>5.024</td>
<td>251.22</td>
<td>69.7</td>
<td>78.3</td>
<td>86.5</td>
</tr>
<tr>
<td>5.025</td>
<td>256.15</td>
<td>63.6</td>
<td>73.4</td>
<td>82.7</td>
</tr>
<tr>
<td>5.026</td>
<td>270.28</td>
<td>57.1</td>
<td>67.6</td>
<td>77.9</td>
</tr>
<tr>
<td>5.027</td>
<td>188.01</td>
<td>71.8</td>
<td>79.5</td>
<td>86.7</td>
</tr>
<tr>
<td>5.028</td>
<td>214.86</td>
<td>62.2</td>
<td>71.0</td>
<td>79.6</td>
</tr>
<tr>
<td>5.029</td>
<td>237.04</td>
<td>56.9</td>
<td>66.5</td>
<td>75.9</td>
</tr>
<tr>
<td>5.030</td>
<td>285.12</td>
<td>56.3</td>
<td>65.3</td>
<td>74.1</td>
</tr>
<tr>
<td>5.031</td>
<td>308.11</td>
<td>52.1</td>
<td>62.2</td>
<td>71.9</td>
</tr>
<tr>
<td>5.032</td>
<td>396.35</td>
<td>76.5</td>
<td>79.9</td>
<td>83.0</td>
</tr>
<tr>
<td>5.033</td>
<td>459.99</td>
<td>71.1</td>
<td>74.8</td>
<td>78.5</td>
</tr>
<tr>
<td>5.034</td>
<td>500.25</td>
<td>66.9</td>
<td>70.6</td>
<td>74.6</td>
</tr>
<tr>
<td>5.035</td>
<td>522.27</td>
<td>62.7</td>
<td>67.3</td>
<td>71.3</td>
</tr>
<tr>
<td>5.036</td>
<td>532.13</td>
<td>58.8</td>
<td>63.5</td>
<td>68.7</td>
</tr>
<tr>
<td>5.037</td>
<td>628.06</td>
<td>68.9</td>
<td>70.8</td>
<td>72.8</td>
</tr>
<tr>
<td>5.038</td>
<td>671.08</td>
<td>62.6</td>
<td>64.8</td>
<td>67.4</td>
</tr>
<tr>
<td>5.039</td>
<td>709.98</td>
<td>59.2</td>
<td>61.7</td>
<td>64.7</td>
</tr>
<tr>
<td>5.040</td>
<td>709.98</td>
<td>55.1</td>
<td>58.3</td>
<td>61.9</td>
</tr>
<tr>
<td>5.041</td>
<td>791.74</td>
<td>51.0</td>
<td>54.0</td>
<td>57.7</td>
</tr>
<tr>
<td>5.042</td>
<td>531.91</td>
<td>49.2</td>
<td>51.7</td>
<td>54.6</td>
</tr>
<tr>
<td>5.043</td>
<td>653.18</td>
<td>42.5</td>
<td>45.2</td>
<td>48.4</td>
</tr>
<tr>
<td>5.044</td>
<td>829.44</td>
<td>36.1</td>
<td>39.1</td>
<td>42.5</td>
</tr>
<tr>
<td>5.045</td>
<td>371.83</td>
<td>84.3</td>
<td>88.2</td>
<td>92.7</td>
</tr>
</tbody>
</table>
Table I.4. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Coolant Flow Rate</th>
<th>Coolant Temperatures</th>
<th>Qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 2 3 4 exit</td>
<td>1 2 3 4 inlet</td>
</tr>
<tr>
<td>5.046</td>
<td>365.93</td>
<td>84.0 88.4 92.9 97.1 101.5</td>
<td>0.037 0.288 0.547 0.785 1.036</td>
</tr>
<tr>
<td>5.047</td>
<td>371.13</td>
<td>82.5 86.5 91.3 96.0 100.7</td>
<td>0.005 0.237 0.514 0.783 1.054</td>
</tr>
<tr>
<td>5.048</td>
<td>373.25</td>
<td>81.4 86.1 90.9 95.4 100.1</td>
<td>0.001 0.274 0.553 0.813 1.087</td>
</tr>
<tr>
<td>5.049</td>
<td>349.92</td>
<td>79.9 85.3 90.7 95.6 100.6</td>
<td>0.004 0.302 0.596 0.861 1.134</td>
</tr>
<tr>
<td>5.050</td>
<td>294.89</td>
<td>83.4 88.7 94.1 98.7 103.3</td>
<td>0.119 0.366 0.613 0.825 1.035</td>
</tr>
<tr>
<td>5.051</td>
<td>262.67</td>
<td>82.5 89.1 94.9 99.7 104.3</td>
<td>0.142 0.416 0.651 0.847 1.037</td>
</tr>
<tr>
<td>5.052</td>
<td>213.92</td>
<td>93.4 96.8 103.0 106.4 109.9</td>
<td>0.492 0.668 0.810 0.921 1.036</td>
</tr>
<tr>
<td>5.053</td>
<td>100.40</td>
<td>96.9 104.0 108.5 111.0 113.8</td>
<td>0.774 0.884 0.952 0.989 1.033</td>
</tr>
<tr>
<td>5.054</td>
<td>68.08</td>
<td>96.8 105.8 110.3 112.5 115.1</td>
<td>0.845 0.940 0.985 1.008 1.034</td>
</tr>
<tr>
<td>5.055</td>
<td>296.90</td>
<td>81.1 87.0 92.6 97.6 102.5</td>
<td>0.087 0.364 0.625 0.858 1.086</td>
</tr>
<tr>
<td>5.056</td>
<td>225.86</td>
<td>93.8 99.3 103.6 106.8 110.2</td>
<td>0.516 0.710 0.859 0.971 1.091</td>
</tr>
<tr>
<td>5.057</td>
<td>114.98</td>
<td>96.7 103.2 107.7 110.5 114.2</td>
<td>0.781 0.895 0.975 1.023 1.089</td>
</tr>
<tr>
<td>5.058</td>
<td>78.22</td>
<td>97.9 105.4 109.5 112.1 116.1</td>
<td>0.873 0.963 1.012 1.042 1.089</td>
</tr>
<tr>
<td>5.059</td>
<td>49.07</td>
<td>107.2 110.4 112.1 112.8 113.8</td>
<td>0.149 0.173 0.184 0.188 0.194</td>
</tr>
<tr>
<td>5.060</td>
<td>59.60</td>
<td>108.7 110.9 112.3 112.9 114.0</td>
<td>0.205 0.224 0.236 0.241 0.249</td>
</tr>
<tr>
<td>5.061</td>
<td>82.13</td>
<td>109.8 111.1 112.3 113.0 114.2</td>
<td>0.198 0.214 0.229 0.236 0.250</td>
</tr>
<tr>
<td>5.062</td>
<td>131.27</td>
<td>108.0 109.7 111.3 112.2 113.7</td>
<td>0.134 0.170 0.200 0.217 0.247</td>
</tr>
<tr>
<td>5.063</td>
<td>233.04</td>
<td>101.2 103.9 106.4 108.4 110.8</td>
<td>0.065 0.163 0.254 0.326 0.413</td>
</tr>
<tr>
<td>6.001</td>
<td>343.06</td>
<td>42.7 45.6 49.3 53.2 57.5</td>
<td>0.005 0.200 0.450 0.704 1.008</td>
</tr>
<tr>
<td>6.002</td>
<td>420.87</td>
<td>35.3 38.4 42.3 46.4 51.3</td>
<td>0.001 0.191 0.432 0.686 1.007</td>
</tr>
<tr>
<td>6.003</td>
<td>923.23</td>
<td>40.9 42.3 44.3 46.8 50.2</td>
<td>0.007 0.155 0.371 0.641 1.015</td>
</tr>
<tr>
<td>6.004</td>
<td>$ $$ $$ $$</td>
<td>39.4 40.8 42.9 45.5 49.0</td>
<td>0.054 0.197 0.397 0.645 1.013</td>
</tr>
<tr>
<td>6.005</td>
<td>535.40</td>
<td>65.0 66.2 68.3 70.5 73.5</td>
<td>0.009 0.159 0.413 0.680 1.022</td>
</tr>
<tr>
<td>6.006</td>
<td>587.40</td>
<td>59.1 61.0 63.7 66.5 70.0</td>
<td>0.009 0.185 0.436 0.699 1.021</td>
</tr>
<tr>
<td>6.007</td>
<td>634.16</td>
<td>54.8 57.0 60.0 63.2 67.0</td>
<td>0.022 0.194 0.433 0.689 1.008</td>
</tr>
<tr>
<td>6.008</td>
<td>669.44</td>
<td>52.5 54.8 58.0 61.4 65.6</td>
<td>0.049 0.221 0.453 0.695 1.008</td>
</tr>
<tr>
<td>6.009</td>
<td>461.61</td>
<td>76.1 77.5 80.0 82.3 85.5</td>
<td>0.017 0.166 0.430 0.678 1.020</td>
</tr>
<tr>
<td>6.010</td>
<td>511.10</td>
<td>71.0 73.2 76.3 79.2 83.0</td>
<td>0.003 0.187 0.450 0.699 1.018</td>
</tr>
<tr>
<td>6.011</td>
<td>559.87</td>
<td>66.7 69.3 72.6 75.9 80.0</td>
<td>0.006 0.199 0.447 0.695 1.010</td>
</tr>
<tr>
<td>6.012</td>
<td>590.73</td>
<td>63.8 66.4 69.9 73.6 77.9</td>
<td>0.046 0.223 0.461 0.704 1.011</td>
</tr>
</tbody>
</table>
6.013 280.58 78.6 81.3 85.4 89.2 93.5 0.047 0.223 0.492 0.737 1.022
6.014 327.68 73.3 77.0 81.8 86.2 91.2 0.005 0.213 0.489 0.739 1.021
6.015 398.28 71.5 75.3 80.1 84.5 89.4 0.001 0.218 0.487 0.734 1.015
6.016 471.19 71.0 74.4 78.9 83.3 88.2 0.006 0.204 0.471 0.725 1.016
6.017 471.36 70.7 74.1 78.7 83.1 88.0 -0.019 0.183 0.451 0.709 1.012
6.018 242.28 86.8 90.1 94.6 98.3 102.5 0.009 0.224 0.508 0.743 1.015
6.019 263.99 80.6 84.8 90.3 95.0 100.2 0.014 0.226 0.509 0.750 1.017
6.020 278.19 75.3 80.4 86.9 92.5 98.3 0.014 0.241 0.523 0.766 1.020
6.021 301.93 68.8 74.7 82.0 88.5 95.0 0.003 0.232 0.514 0.765 1.019
6.022 441.34 79.0 82.7 87.4 91.9 96.8 0.006 0.215 0.485 0.737 1.018
6.023 92.16 94.6 98.6 103.0 106.0 109.2 0.059 0.322 0.608 0.801 1.014
6.024 145.80 92.6 96.0 100.3 103.6 107.2 0.036 0.262 0.550 0.776 1.019
6.025 187.91 88.0 91.5 96.1 99.9 104.2 0.008 0.220 0.502 0.734 1.014
6.026 250.26 86.2 89.4 93.8 97.7 102.0 0.010 0.216 0.499 0.743 1.021
6.027 166.97 92.0 93.8 96.4 98.3 101.0 0.047 0.236 0.526 0.726 1.021
6.028 322.56 92.0 93.1 95.0 96.6 99.0 0.042 0.192 0.455 0.676 1.013
6.029 413.41 89.8 91.0 93.0 94.8 97.3 0.035 0.196 0.454 0.694 1.015
6.030 486.24 86.2 87.6 89.7 92.0 94.7 0.004 0.177 0.431 0.695 1.018
6.031 169.39 82.8 84.3 87.0 88.9 91.7 0.051 0.220 0.505 0.708 1.019
6.032 222.93 78.1 80.5 83.4 85.9 88.9 0.010 0.227 0.500 0.726 1.015
6.033 331.23 77.1 78.7 81.3 83.9 87.2 0.025 0.181 0.437 0.697 1.016
6.034 435.46 75.9 77.2 79.4 81.9 85.1 0.052 0.192 0.421 0.682 1.013
6.035 220.67 73.2 74.7 76.7 78.3 80.5 0.009 0.217 0.481 0.703 1.014
6.036 320.97 70.8 72.3 74.2 76.0 78.3 0.027 0.226 0.485 0.714 1.018
6.037 462.16 69.4 70.3 72.1 74.1 76.6 0.019 0.155 0.397 0.674 1.021
6.038 600.63 66.8 68.0 69.6 71.4 73.9 0.009 0.172 0.400 0.658 1.016
6.039 289.02 60.7 62.0 63.6 65.1 67.0 0.007 0.209 0.459 0.695 0.998
6.040 403.65 58.8 60.5 61.8 63.0 64.7 0.045 0.316 0.537 0.729 0.997
6.041 535.40 55.4 56.4 58.0 59.9 62.2 0.045 0.189 0.417 0.673 1.000
6.042 649.93 52.7 53.7 55.3 57.2 59.6 0.041 0.181 0.407 0.669 1.000

Table I.4. (continued)
### Table I.4. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Coolant Flow Rate</th>
<th>Coolant Temperatures</th>
<th>exit</th>
<th>Qualities</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>6.043</td>
<td>219.19</td>
<td>88.7</td>
<td>92.1</td>
<td>96.3</td>
<td>99.7</td>
</tr>
<tr>
<td>6.044</td>
<td>183.89</td>
<td>97.7</td>
<td>100.3</td>
<td>103.7</td>
<td>106.0</td>
</tr>
<tr>
<td>6.045</td>
<td>89.63</td>
<td>96.2</td>
<td>101.4</td>
<td>106.0</td>
<td>108.6</td>
</tr>
<tr>
<td>6.046</td>
<td>63.01</td>
<td>96.0</td>
<td>103.2</td>
<td>107.9</td>
<td>110.4</td>
</tr>
<tr>
<td>6.047</td>
<td>175.21</td>
<td>84.5</td>
<td>88.7</td>
<td>94.0</td>
<td>98.3</td>
</tr>
<tr>
<td>6.048</td>
<td>179.05</td>
<td>83.7</td>
<td>87.7</td>
<td>93.1</td>
<td>97.5</td>
</tr>
<tr>
<td>6.049</td>
<td>177.11</td>
<td>83.8</td>
<td>88.1</td>
<td>93.6</td>
<td>98.1</td>
</tr>
<tr>
<td>6.050</td>
<td>177.50</td>
<td>82.9</td>
<td>87.4</td>
<td>92.9</td>
<td>97.5</td>
</tr>
<tr>
<td>6.051</td>
<td>177.50</td>
<td>83.2</td>
<td>87.7</td>
<td>93.3</td>
<td>97.9</td>
</tr>
<tr>
<td>6.052</td>
<td>175.40</td>
<td>81.9</td>
<td>86.6</td>
<td>92.5</td>
<td>97.2</td>
</tr>
<tr>
<td>6.053</td>
<td>109.23</td>
<td>94.2</td>
<td>97.8</td>
<td>101.8</td>
<td>104.6</td>
</tr>
<tr>
<td>6.054</td>
<td>73.15</td>
<td>94.5</td>
<td>100.2</td>
<td>104.9</td>
<td>107.8</td>
</tr>
<tr>
<td>6.055</td>
<td>38.93</td>
<td>97.2</td>
<td>101.0</td>
<td>105.6</td>
<td>108.0</td>
</tr>
<tr>
<td>7.005</td>
<td>346.39</td>
<td>61.0</td>
<td>63.0</td>
<td>65.0</td>
<td>66.5</td>
</tr>
<tr>
<td>7.006</td>
<td>424.15</td>
<td>57.4</td>
<td>59.1</td>
<td>61.1</td>
<td>63.1</td>
</tr>
<tr>
<td>7.007</td>
<td>476.78</td>
<td>55.7</td>
<td>57.7</td>
<td>59.7</td>
<td>61.4</td>
</tr>
<tr>
<td>7.008</td>
<td>546.92</td>
<td>54.1</td>
<td>55.4</td>
<td>57.3</td>
<td>59.4</td>
</tr>
<tr>
<td>7.009</td>
<td>275.22</td>
<td>75.7</td>
<td>77.4</td>
<td>79.5</td>
<td>81.0</td>
</tr>
<tr>
<td>7.010</td>
<td>279.14</td>
<td>77.1</td>
<td>78.6</td>
<td>80.6</td>
<td>82.2</td>
</tr>
<tr>
<td>7.011</td>
<td>366.96</td>
<td>72.4</td>
<td>74.3</td>
<td>76.6</td>
<td>78.2</td>
</tr>
<tr>
<td>7.012</td>
<td>369.03</td>
<td>71.4</td>
<td>73.0</td>
<td>75.3</td>
<td>77.1</td>
</tr>
<tr>
<td>7.013</td>
<td>453.60</td>
<td>70.4</td>
<td>72.2</td>
<td>74.1</td>
<td>75.6</td>
</tr>
<tr>
<td>7.014</td>
<td>283.99</td>
<td>86.4</td>
<td>87.9</td>
<td>90.2</td>
<td>91.7</td>
</tr>
<tr>
<td>7.015</td>
<td>330.73</td>
<td>82.1</td>
<td>83.8</td>
<td>86.3</td>
<td>88.2</td>
</tr>
<tr>
<td>7.016</td>
<td>390.49</td>
<td>80.4</td>
<td>82.5</td>
<td>84.8</td>
<td>86.5</td>
</tr>
<tr>
<td>7.017</td>
<td>470.40</td>
<td>77.4</td>
<td>79.2</td>
<td>81.4</td>
<td>83.4</td>
</tr>
<tr>
<td>7.018</td>
<td>257.84</td>
<td>94.8</td>
<td>96.6</td>
<td>98.8</td>
<td>100.2</td>
</tr>
<tr>
<td>7.019</td>
<td>302.40</td>
<td>92.4</td>
<td>94.4</td>
<td>96.3</td>
<td>98.5</td>
</tr>
<tr>
<td>7.020</td>
<td>421.41</td>
<td>89.2</td>
<td>90.7</td>
<td>92.9</td>
<td>94.5</td>
</tr>
<tr>
<td>7.021</td>
<td>527.83</td>
<td>86.6</td>
<td>88.0</td>
<td>90.2</td>
<td>91.9</td>
</tr>
<tr>
<td>Run #</td>
<td>Coolant Flow Rate</td>
<td>Coolant Temperatures</td>
<td>exit</td>
<td>Qualities</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------------------</td>
<td>----------------------</td>
<td>------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>7.022</td>
<td>154.05</td>
<td>100.3 103.0</td>
<td>106.2 108.4</td>
<td>111.7</td>
<td>0.049 0.278 0.542 0.726 1.012</td>
</tr>
<tr>
<td>7.023</td>
<td>221.17</td>
<td>97.4 100.0</td>
<td>103.2 105.5</td>
<td>108.6</td>
<td>0.048 0.272 0.547 0.734 1.000</td>
</tr>
<tr>
<td>7.024</td>
<td>271.03</td>
<td>94.3 97.0</td>
<td>100.6 103.0</td>
<td>106.3</td>
<td>0.022 0.244 0.531 0.733 1.005</td>
</tr>
<tr>
<td>7.025</td>
<td>343.78</td>
<td>92.0 94.5</td>
<td>97.6 100.0</td>
<td>103.2</td>
<td>-0.012 0.219 0.498 0.709 1.004</td>
</tr>
<tr>
<td>7.026</td>
<td>399.68</td>
<td>91.1 93.4</td>
<td>96.2 98.6</td>
<td>101.8</td>
<td>0.012 0.225 0.487 0.709 1.016</td>
</tr>
<tr>
<td>7.027</td>
<td>487.45</td>
<td>88.6 90.8</td>
<td>93.7 96.5</td>
<td>100.1</td>
<td>-0.013 0.185 0.440 0.682 1.013</td>
</tr>
<tr>
<td>7.028</td>
<td>544.32</td>
<td>86.6 89.4</td>
<td>92.6 95.5</td>
<td>99.2</td>
<td>0.018 0.237 0.492 0.730 1.025</td>
</tr>
<tr>
<td>7.029</td>
<td>644.59</td>
<td>82.0 84.7</td>
<td>88.4 91.8</td>
<td>96.0</td>
<td>-0.048 0.159 0.434 0.695 1.017</td>
</tr>
<tr>
<td>7.030</td>
<td>680.40</td>
<td>77.7 79.0</td>
<td>80.8 82.6</td>
<td>84.9</td>
<td>0.013 0.187 0.432 0.672 1.009</td>
</tr>
<tr>
<td>7.031</td>
<td>882.68</td>
<td>74.1 75.5</td>
<td>77.4 79.5</td>
<td>82.1</td>
<td>-0.016 0.175 0.422 0.683 1.023</td>
</tr>
<tr>
<td>7.032</td>
<td>911.42</td>
<td>69.8 71.5</td>
<td>73.8 76.3</td>
<td>79.4</td>
<td>-0.015 0.175 0.426 0.692 1.022</td>
</tr>
<tr>
<td>7.033</td>
<td>976.98</td>
<td>68.5 70.3</td>
<td>72.9 75.5</td>
<td>78.7</td>
<td>0.027 0.207 0.456 0.709 1.026</td>
</tr>
<tr>
<td>7.034</td>
<td>396.90</td>
<td>79.8 82.6</td>
<td>85.9 89.1</td>
<td>93.0</td>
<td>0.014 0.221 0.470 0.706 1.013</td>
</tr>
<tr>
<td>7.035</td>
<td>540.72</td>
<td>76.1 78.5</td>
<td>81.9 85.2</td>
<td>89.3</td>
<td>-0.025 0.172 0.439 0.702 1.021</td>
</tr>
<tr>
<td>7.036</td>
<td>653.18</td>
<td>77.2 79.6</td>
<td>82.8 85.9</td>
<td>89.8</td>
<td>0.012 0.205 0.457 0.707 1.017</td>
</tr>
<tr>
<td>7.037</td>
<td>760.70</td>
<td>75.5 78.1</td>
<td>81.3 84.6</td>
<td>84.4</td>
<td>-0.023 0.190 0.451 0.709 1.023</td>
</tr>
<tr>
<td>7.038</td>
<td>672.40</td>
<td>69.8 70.8</td>
<td>72.3 74.0</td>
<td>76.3</td>
<td>0.025 0.181 0.415 0.674 1.020</td>
</tr>
<tr>
<td>7.039</td>
<td>868.60</td>
<td>65.8 67.0</td>
<td>68.6 70.3</td>
<td>72.5</td>
<td>0.050 0.217 0.451 0.698 1.022</td>
</tr>
<tr>
<td>7.040</td>
<td>964.93</td>
<td>63.2 64.5</td>
<td>66.4 68.5</td>
<td>71.1</td>
<td>-0.043 0.126 0.368 0.653 1.012</td>
</tr>
<tr>
<td>7.041</td>
<td>1046.8</td>
<td>61.5 63.1</td>
<td>64.9 67.0</td>
<td>69.7</td>
<td>0.007 0.196 0.419 0.670 1.009</td>
</tr>
<tr>
<td>7.042</td>
<td>1113.4</td>
<td>59.7 61.4</td>
<td>63.7 66.1</td>
<td>69.0</td>
<td>-0.031 0.161 0.416 0.688 1.021</td>
</tr>
<tr>
<td>7.043</td>
<td>520.05</td>
<td>49.0 51.0</td>
<td>53.6 56.4</td>
<td>59.6</td>
<td>-0.023 0.170 0.420 0.699 1.014</td>
</tr>
<tr>
<td>7.044</td>
<td>628.06</td>
<td>44.9 47.2</td>
<td>50.0 53.1</td>
<td>56.7</td>
<td>0.018 0.206 0.444 0.700 1.006</td>
</tr>
<tr>
<td>7.045</td>
<td>747.92</td>
<td>42.1 44.3</td>
<td>47.3 50.6</td>
<td>54.4</td>
<td>0.005 0.183 0.427 0.689 1.005</td>
</tr>
<tr>
<td>7.046</td>
<td>850.50</td>
<td>41.0 43.1</td>
<td>46.1 49.3</td>
<td>53.2</td>
<td>0.010 0.186 0.429 0.686 1.007</td>
</tr>
<tr>
<td>7.047</td>
<td>460.92</td>
<td>87.8 90.3</td>
<td>93.4 96.3</td>
<td>99.9</td>
<td>-0.005 0.207 0.470 0.708 1.018</td>
</tr>
<tr>
<td>7.048</td>
<td>460.92</td>
<td>87.7 90.3</td>
<td>93.3 96.2</td>
<td>99.9</td>
<td>0.012 0.230 0.489 0.729 1.037</td>
</tr>
<tr>
<td>7.049</td>
<td>480.28</td>
<td>87.6 90.0</td>
<td>93.1 96.0</td>
<td>99.7</td>
<td>-0.004 0.212 0.482 0.734 1.055</td>
</tr>
<tr>
<td>7.050</td>
<td>492.70</td>
<td>86.3 89.0</td>
<td>92.2 95.2</td>
<td>99.0</td>
<td>-0.048 0.190 0.477 0.749 1.090</td>
</tr>
<tr>
<td>7.051</td>
<td>488.49</td>
<td>86.0 88.5</td>
<td>91.7 94.9</td>
<td>98.7</td>
<td>-0.004 0.213 0.506 0.785 1.129</td>
</tr>
<tr>
<td>Run #</td>
<td>Coolant Flow Rate</td>
<td>Coolant Temperatures 1</td>
<td>Coolant Temperatures 2</td>
<td>Coolant Temperatures 3</td>
<td>Coolant Temperatures 4</td>
</tr>
<tr>
<td>------</td>
<td>------------------</td>
<td>------------------------</td>
<td>------------------------</td>
<td>------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>7.052</td>
<td>476.28</td>
<td>86.9</td>
<td>89.6</td>
<td>92.8</td>
<td>95.8</td>
</tr>
<tr>
<td>7.053</td>
<td>333.26</td>
<td>89.6</td>
<td>93.3</td>
<td>97.2</td>
<td>100.2</td>
</tr>
<tr>
<td>7.054</td>
<td>108.64</td>
<td>104.6</td>
<td>108.2</td>
<td>110.8</td>
<td>111.8</td>
</tr>
<tr>
<td>7.055</td>
<td>75.69</td>
<td>105.4</td>
<td>109.4</td>
<td>111.9</td>
<td>112.8</td>
</tr>
<tr>
<td>7.056</td>
<td>60.44</td>
<td>96.9</td>
<td>105.4</td>
<td>109.9</td>
<td>111.7</td>
</tr>
<tr>
<td>7.057</td>
<td>60.70</td>
<td>97.4</td>
<td>105.0</td>
<td>109.4</td>
<td>111.0</td>
</tr>
<tr>
<td>7.058</td>
<td>59.08</td>
<td>97.1</td>
<td>105.1</td>
<td>109.4</td>
<td>110.8</td>
</tr>
<tr>
<td>7.059</td>
<td>130.85</td>
<td>95.9</td>
<td>100.6</td>
<td>104.8</td>
<td>107.2</td>
</tr>
<tr>
<td>8.001</td>
<td>263.38</td>
<td>62.9</td>
<td>64.5</td>
<td>66.5</td>
<td>68.0</td>
</tr>
<tr>
<td>8.002</td>
<td>314.03</td>
<td>59.1</td>
<td>61.0</td>
<td>63.0</td>
<td>64.6</td>
</tr>
<tr>
<td>8.003</td>
<td>352.80</td>
<td>58.1</td>
<td>60.2</td>
<td>62.2</td>
<td>63.8</td>
</tr>
<tr>
<td>8.004</td>
<td>466.56</td>
<td>55.7</td>
<td>57.5</td>
<td>59.6</td>
<td>61.5</td>
</tr>
<tr>
<td>8.005</td>
<td>401.55</td>
<td>62.2</td>
<td>63.7</td>
<td>65.3</td>
<td>66.5</td>
</tr>
<tr>
<td>8.007</td>
<td>716.21</td>
<td>57.5</td>
<td>58.7</td>
<td>60.1</td>
<td>61.5</td>
</tr>
<tr>
<td>8.008</td>
<td>90.90</td>
<td>18.3</td>
<td>33.7</td>
<td>46.5</td>
<td>56.1</td>
</tr>
<tr>
<td>8.009</td>
<td>491.86</td>
<td>79.1</td>
<td>80.0</td>
<td>81.2</td>
<td>82.1</td>
</tr>
<tr>
<td>8.010</td>
<td>589.21</td>
<td>75.9</td>
<td>76.4</td>
<td>77.8</td>
<td>78.9</td>
</tr>
<tr>
<td>8.011</td>
<td>716.21</td>
<td>73.3</td>
<td>74.1</td>
<td>75.4</td>
<td>76.6</td>
</tr>
<tr>
<td>8.012</td>
<td>816.48</td>
<td>71.9</td>
<td>72.7</td>
<td>74.0</td>
<td>75.2</td>
</tr>
<tr>
<td>8.013</td>
<td>423.05</td>
<td>88.0</td>
<td>88.9</td>
<td>90.3</td>
<td>91.4</td>
</tr>
<tr>
<td>8.014</td>
<td>496.99</td>
<td>85.7</td>
<td>86.6</td>
<td>88.0</td>
<td>89.2</td>
</tr>
<tr>
<td>8.015</td>
<td>613.89</td>
<td>82.2</td>
<td>83.2</td>
<td>84.4</td>
<td>85.7</td>
</tr>
<tr>
<td>8.016</td>
<td>628.06</td>
<td>80.8</td>
<td>82.3</td>
<td>83.8</td>
<td>85.2</td>
</tr>
<tr>
<td>8.017</td>
<td>371.13</td>
<td>95.2</td>
<td>96.1</td>
<td>97.7</td>
<td>99.0</td>
</tr>
<tr>
<td>8.018</td>
<td>405.34</td>
<td>93.3</td>
<td>94.4</td>
<td>96.4</td>
<td>97.8</td>
</tr>
<tr>
<td>8.019</td>
<td>454.86</td>
<td>91.1</td>
<td>92.4</td>
<td>94.4</td>
<td>95.9</td>
</tr>
<tr>
<td>8.020</td>
<td>517.03</td>
<td>88.1</td>
<td>89.6</td>
<td>91.6</td>
<td>93.3</td>
</tr>
<tr>
<td>8.021</td>
<td>201.60</td>
<td>100.1</td>
<td>102.2</td>
<td>104.9</td>
<td>106.9</td>
</tr>
<tr>
<td>8.022</td>
<td>231.08</td>
<td>98.0</td>
<td>100.2</td>
<td>103.3</td>
<td>105.6</td>
</tr>
<tr>
<td>8.023</td>
<td>281.85</td>
<td>94.7</td>
<td>97.2</td>
<td>100.4</td>
<td>102.9</td>
</tr>
</tbody>
</table>
Table I.4. (continued)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Coolant Flow Rate</th>
<th>Coolant Temperatures</th>
<th>exit Temperatures</th>
<th>Qualities</th>
<th>inlet</th>
<th>Qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>8.024</td>
<td>320.19</td>
<td>91.2</td>
<td>93.9</td>
<td>97.3</td>
<td>100.1</td>
<td>103.5</td>
</tr>
<tr>
<td>8.025</td>
<td>431.14</td>
<td>90.3</td>
<td>92.6</td>
<td>95.8</td>
<td>98.3</td>
<td>101.8</td>
</tr>
<tr>
<td>8.026</td>
<td>486.00</td>
<td>88.2</td>
<td>90.8</td>
<td>94.0</td>
<td>96.9</td>
<td>100.6</td>
</tr>
<tr>
<td>8.027</td>
<td>522.55</td>
<td>85.9</td>
<td>88.7</td>
<td>92.2</td>
<td>95.3</td>
<td>99.5</td>
</tr>
<tr>
<td>8.028</td>
<td>648.00</td>
<td>81.1</td>
<td>84.2</td>
<td>87.9</td>
<td>91.7</td>
<td>96.2</td>
</tr>
<tr>
<td>8.029</td>
<td>466.56</td>
<td>85.0</td>
<td>87.8</td>
<td>90.7</td>
<td>93.1</td>
<td>96.2</td>
</tr>
<tr>
<td>8.030</td>
<td>544.32</td>
<td>81.6</td>
<td>83.9</td>
<td>86.8</td>
<td>89.6</td>
<td>93.1</td>
</tr>
<tr>
<td>8.031</td>
<td>666.79</td>
<td>80.2</td>
<td>82.2</td>
<td>84.8</td>
<td>87.7</td>
<td>91.3</td>
</tr>
<tr>
<td>8.032</td>
<td>813.21</td>
<td>77.8</td>
<td>79.9</td>
<td>82.5</td>
<td>85.3</td>
<td>89.0</td>
</tr>
<tr>
<td>8.033</td>
<td>492.70</td>
<td>65.2</td>
<td>67.7</td>
<td>70.4</td>
<td>72.9</td>
<td>76.0</td>
</tr>
<tr>
<td>8.034</td>
<td>602.57</td>
<td>62.4</td>
<td>64.6</td>
<td>67.3</td>
<td>70.2</td>
<td>73.6</td>
</tr>
<tr>
<td>8.035</td>
<td>799.82</td>
<td>58.9</td>
<td>60.8</td>
<td>63.3</td>
<td>66.3</td>
<td>69.7</td>
</tr>
<tr>
<td>8.036</td>
<td>949.40</td>
<td>58.6</td>
<td>60.1</td>
<td>62.4</td>
<td>65.1</td>
<td>68.6</td>
</tr>
<tr>
<td>8.037</td>
<td>577.31</td>
<td>77.3</td>
<td>79.2</td>
<td>81.3</td>
<td>83.4</td>
<td>86.1</td>
</tr>
<tr>
<td>8.038</td>
<td>661.12</td>
<td>73.8</td>
<td>75.7</td>
<td>78.0</td>
<td>80.6</td>
<td>83.7</td>
</tr>
<tr>
<td>8.039</td>
<td>769.15</td>
<td>70.6</td>
<td>72.4</td>
<td>74.8</td>
<td>77.6</td>
<td>81.0</td>
</tr>
<tr>
<td>8.040</td>
<td>852.44</td>
<td>68.0</td>
<td>70.0</td>
<td>72.6</td>
<td>75.5</td>
<td>79.2</td>
</tr>
<tr>
<td>8.041</td>
<td>651.32</td>
<td>52.4</td>
<td>54.0</td>
<td>56.0</td>
<td>58.0</td>
<td>60.4</td>
</tr>
<tr>
<td>8.042</td>
<td>777.60</td>
<td>50.6</td>
<td>52.3</td>
<td>54.3</td>
<td>56.4</td>
<td>59.0</td>
</tr>
<tr>
<td>8.043</td>
<td>198.34</td>
<td>97.0</td>
<td>99.9</td>
<td>103.3</td>
<td>105.6</td>
<td>108.7</td>
</tr>
<tr>
<td>8.045</td>
<td>198.34</td>
<td>100.3</td>
<td>102.7</td>
<td>105.6</td>
<td>107.4</td>
<td>110.0</td>
</tr>
<tr>
<td>8.046</td>
<td>198.34</td>
<td>103.7</td>
<td>105.5</td>
<td>107.7</td>
<td>109.1</td>
<td>111.2</td>
</tr>
</tbody>
</table>