Studies in efficiency of the air-stream atomization phenomena

Henry Francis Hrubecky

Iowa State College

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

Part of the Mathematics Commons, and the Mechanical Engineering Commons

Recommended Citation
Hrubecky, Henry Francis, "Studies in efficiency of the air-stream atomization phenomena " (1953). Retrospective Theses and Dissertations. 13283.
https://lib.dr.iastate.edu/rtd/13283

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.
STUDIES IN EFFICIENCY OF THE
AIR-STREAM ATOMIZATION PHENOMENA

by

Henry Francis Hrubecky

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

Major Subjects: Mathematics
               Mechanical Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Heads of Major Departments

Signature was redacted for privacy.

Dean of Graduate College

Iowa State College

1953
INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI Microform DP12401
Copyright 2005 by ProQuest Information and Learning Company.
All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOMENCLATURE</td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>vi</td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>A. Some General Features of Atomization</td>
<td>1</td>
</tr>
<tr>
<td>B. The Need for Atomization</td>
<td>4</td>
</tr>
<tr>
<td>C. Pertinent Variables in Air-Stream Atomization</td>
<td>6</td>
</tr>
<tr>
<td>II. OBJECT OF THE INVESTIGATION</td>
<td>10</td>
</tr>
<tr>
<td>III. REVIEW OF LITERATURE</td>
<td>12</td>
</tr>
<tr>
<td>IV. DESCRIPTION OF APPARATUS</td>
<td>25</td>
</tr>
<tr>
<td>A. General Layout</td>
<td>25</td>
</tr>
<tr>
<td>B. Air Flow Apparatus</td>
<td>30</td>
</tr>
<tr>
<td>C. Liquid Flow Apparatus</td>
<td>33</td>
</tr>
<tr>
<td>D. Liquid Nozzles and Their Supports</td>
<td>35</td>
</tr>
<tr>
<td>E. Methods of Liquid Injection</td>
<td>37</td>
</tr>
<tr>
<td>F. Duct for Spray Discharge</td>
<td>37</td>
</tr>
<tr>
<td>G. Droplet Sampling Method</td>
<td>39</td>
</tr>
<tr>
<td>V. DISCUSSION OF TEST AND PROCEDURE</td>
<td>44</td>
</tr>
<tr>
<td>A. Calibration of Convergent Air Nozzles</td>
<td>44</td>
</tr>
<tr>
<td>B. The Experimental Tests</td>
<td>45</td>
</tr>
<tr>
<td>VI. EXPERIMENTAL RESULTS</td>
<td>49</td>
</tr>
<tr>
<td>A. Variation of Point of Water Injection</td>
<td>49</td>
</tr>
<tr>
<td>B. Variation of Method of Liquid Injection</td>
<td>55</td>
</tr>
</tbody>
</table>

T10708
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>VII. DISCUSSION AND INTERPRETATION OF RESULTS</td>
<td>74</td>
</tr>
<tr>
<td>A. Comparison with Previous Investigations</td>
<td>74</td>
</tr>
<tr>
<td>B. Effect of Liquid Tube Position on Atomization</td>
<td>80</td>
</tr>
<tr>
<td>C. Effect of Method of Liquid Injection Upon Atomization</td>
<td>83</td>
</tr>
<tr>
<td>VIII. CONCLUSIONS</td>
<td>89</td>
</tr>
<tr>
<td>IX. ACKNOWLEDGEMENTS</td>
<td>92</td>
</tr>
<tr>
<td>X. LITERATURE CITED</td>
<td>93</td>
</tr>
<tr>
<td>XI. APPENDICES</td>
<td>99</td>
</tr>
<tr>
<td>Appendix A. Nomenclature</td>
<td>100</td>
</tr>
<tr>
<td>Appendix B. Development of the Atomization Number</td>
<td>101</td>
</tr>
</tbody>
</table>
**NOMENCLATURE**

\[
\bar{x} = \text{significant mean-diameter of drop, microns.}
\]

\[
v_a = \text{air velocity, m. per sec.}
\]

\[
v_l = \text{liquid velocity, m. per sec.}
\]

\[
m_a = \text{air mass rate of flow, gm. per sec.}
\]

\[
m_l = \text{liquid mass rate of flow, gm. per sec.}
\]

\[
\rho_l = \text{density of liquid, gm. per cm.}^3
\]

\[
\mu = \text{liquid viscosity, dyne-sec. per cm.}^2
\]

\[
\sigma = \text{interfacial tension between air and liquid, dynes per cm.}
\]

\[
D_a = \text{exit diameter of air nozzle.}
\]

\[
D_l = \text{exit diameter of liquid nozzle.}
\]

\[
m = \text{mass of droplet, gm.}
\]

\[
t = \text{time, sec.}
\]

\[
x = \text{diameter of liquid droplet, microns.}
\]

\[
\Delta n = \text{fractional count of total number of drops.}
\]

\[
r = \text{radius of the liquid jet at time, t.}
\]

\[
a = \text{amplitude of the disturbance at time, t.}
\]

\[
a = \text{initial radius of the liquid jet.}
\]

\[
i = -1
\]

\[
J_0(x) = 1 - \frac{1-x^2}{2^2} + \frac{x^4}{2^2 \cdot 4^2} - \frac{x^6}{2^2 \cdot 4^2 \cdot 6^2} + \cdots, \text{Bessel's function of zero order.}
\]

---

1 Symbols arranged according to occurrence in text.
$V =$ potential energy per unit length of the liquid cylinder from the equilibrium position.

$\phi =$ velocity potential.

$q =$ frequency of the disturbance.

$T =$ kinetic energy per unit length of the liquid cylinder.

$v =$ relative velocity between air and liquid, m. per sec.

$K =$ "atomizing characteristic", fundamental dimension of one over length.

$d_0 = \frac{2x^3 \Delta n}{x^2 \Delta n}$, the diameter of a single drop having the same volume-surface ratio as the total sum of the drops, where $\Delta n$ represents the number of drops of diameter $x$ such that, $x-\Delta x < x < x+\Delta x$.

$q_a =$ air volume rate of flow, cm.$^3$ per sec.

$q_w =$ water volume rate of flow, cm.$^3$ per sec.

$q_l =$ liquid volume rate of flow, cm.$^3$ per sec.

$\bar{\sigma}_w =$ mean surface tension of water, dynes per cm.

$A_N =$ atomization number, $\frac{\rho_a d_0 q_a}{12 \bar{\sigma}_w q_w v_a^2}$.

$\rho_a =$ air density at exit of the air nozzle, gm. per cm.$^3$. 
ABSTRACT

An experimental investigation was conducted in which distilled water under normal atmospheric conditions was atomized by a high velocity air stream. The atomizing unit (which also could be used for solid-injection atomization) consisted of a glass convergent air nozzle with a short straight section and a concentric hypodermic tube for the purpose of water injection. The purpose of the investigation was to determine the effect upon the efficacy and comparative degree of atomization by using various methods of water injection, and by varying the injection position along the axis of air flow, for use in possible engineering applications. The sprayed droplets were collected on magnesium oxide coated glass slides, housed in a specially constructed sampling apparatus which exposed the slides for an appropriate time. Three samples were taken for each test at the horizontal axis of the spray, and under a calibrated microscope counted until no appreciable difference in droplet distribution was noted. From the droplet distribution the volume-surface or Sauter mean-diameter, \( d_o \), in microns was evaluated. Precautions were taken against drop evaporation and possible settling out of drops before reaching the sampling apparatus.

The air velocity, \( v_a \), was varied from 106 to 316 m. per
sec. The air to water volume ratio, $\frac{Q_a}{Q_w}$ was varied from 1,000 to 20,000. The water rates used were small, and, consequently, the water velocity never exceeded one m. per sec. Four different methods of injection were used: one utilized water injection parallel to the ambient air stream and the others with various types of orifices used injection normal to the air stream.

In light of this investigation, the following conclusions can be made. Liquid injection parallel to the air stream results in a better degree of atomization than liquid injection normal to the ambient air stream. The former method does not seem to impair the normal process of attenuation of the liquid surface, ligament formation, and drop formation as does the latter method. Differences in the degree of atomization in the latter methods depend principally upon the amount of liquid surface that comes in contact with the high velocity air.

With liquid injection parallel to the ambient air stream, for the best degree of atomization the mass of liquid should enter the region of maximum velocity. For the convergent nozzle used, the maximum $v_a$ attainable is acoustic. At this velocity and for $\frac{Q_a}{Q_w} > 5000$, $d_o$ tends towards a lower limit. This lower limit may range between 5 and 7 microns for the atomizing unit used. These low values for $d_o$ in the proximate vicinity of the acoustic velocity is not in agreement with the experiments of Nukiyama and Tanasawa. Their
empirical equation predicts higher values, but otherwise present experimental results compare favorably with the investigators mentioned. For \( v_a < 100 \text{ m. per sec.} \) and \( Q_a/Q_w < 1000 \) the degree of uniformity of the drops decreases rapidly. For \( Q_a/Q_w > 5000 \), \( d_o \) is independent of the liquid rate and depends on \( v_a \) (for low liquid velocities), decreasing as \( v_a \) increases.

The angle of spray dispersion increases as the point of liquid injection is varied from upstream of the exit of the nozzle and on through the straight section of the nozzle. For \( v_a > 150 \text{ m. per sec.} \), \( d_o \) does not appreciably vary over an interval, which with respect to the nozzle exit extends through the straight section and one-half an inch downstream. Consequently, the spray angle may be varied by manual adjustment without appreciably varying the droplet size.

A dimensionless number is developed and is termed the atomization number, \( A_N \). It is in effect, the ratio of the kinetic energy of the air to the actual superficial potential energy of the droplets formed, and it serves as an adequate index of the efficacy and comparative degree of air-stream atomization for various atomizing units.
I. INTRODUCTION

A. Some General Features of Atomization

The phenomenon of liquid atomization\(^1\) is accomplished by forces acting on a constrained static or moving liquid, whose characteristic is such that during some stage of the process the main bulk of the liquid emerges in the form of an attenuated film. Observation indicates an initiation of small disturbances at the surface of the liquid in the nature of ripples or protuberances. The further action of air pressure and tangential forces on these disturbances appear to attenuate the film, drawing it out into fine ligaments. These ligaments eventually collapse into smaller fragments and in time form droplets\(^2\) of a spherical nature which are under the action of surface tension itself. During this process a given bulk or volume of the liquid undergoes a considerable change in exposed surface area in

---

\(^1\) This should be more correctly termed "comminution" since liquid breakup into atoms is not implied. The term atomization has come to mean the breakup of liquids into very fine drops, and it is in this general light that the phenomenon is so viewed here.

\(^2\) By specifying the term droplets an attempt is made to eliminate the extreme situations such as macroscopic magnitudes wherein large individual drops or slugs of liquid predominate, and the microscopic case wherein dispersion is of molecular order.
forming the liquid spray.\(^1\) For example, suppose that one cubic centimeter of a liquid substance in the form of a sphere is split into uniformly fine drops whose diameters are one micron each. A few simple calculations indicate the diameter of the original drop to be 1.24 centimeters. Its surface area is 4.63 square centimeters. The above atomization would result in approximately \(1.91 \times 10^{12}\) drops being formed whose total surface area is \(6 \times 10^4\) square centimeters, or approximately 12,500 times the original surface area. This was given as an extreme example; normally an atomized spray may contain droplets varying from 5 to 500 microns. Although the exposed surface area would normally be smaller than the case cited, it still would be considerably larger than the original, possibly ranging up to 1500 square centimeters.

This desire for high surface transformation has found its application in many mechanical units as well as in a diversity of fields and industries. A partial list may include: combustion equipment, such as carburetors, air-injection Diesel engines, gas turbines, and jet engines; horticultural and agricultural spray equipment for the distribution of insecticides. Further industrial uses may be: pneumatic sprayers for application of paints and

\(^1\) A spray is defined as an aggregate of individual liquid droplets in a fluid continuous phase.
protective coatings, spray type absorptive equipment in refrigerators, dust extraction in ventilation, air conditioning and filtration plants, steam cooling for mechanical-stoker grates, and many others.

Atomization may be divided into two broad classifications based upon the manner in which the atomization is accomplished: (1) gas or vapor stream atomization, in which a high velocity stream such as air or steam comes in contact with the main mass of liquid, effecting the liquid breakup; (2) solid injection, in which a liquid under high pressure is passed through a nozzle or orifice into a certain atmosphere and the energy change due to the pressure drop is utilized in promoting the atomized spray. Experiment and observation indicate a similar pattern of liquid disruption for the two types of atomization, that is, the attenuation of the liquid into a film followed by a ligament growth and final disruption into liquid droplets. It may be mentioned that for low viscosity liquids such as kerosines, gas oils, and diesel oils, atomization is readily effected at atmospheric temperatures without the need of abnormally high supply pressures or high air or steam velocities, but the more viscous grades of fuel have to be preheated so as to conform to the atomization pattern described above. Also, at some level of viscosity, no amount of applied force will allow the liquid to break up into a spray of droplets; it simply flows as liquid out of the nozzle.
B. The Need for Atomization

Many physical phenomena, such as combustion, in which liquid fuels are utilized require atomization for proper promulgation. A large exposed liquid surface is necessary since in many instances wherein combustion occurs the chamber space is restricted or as in internal combustion engines a rapid explosion and not slow burning over a space is desirable. For example, a small beaker of kerosene will not ignite if its exposed surface contacts the flame of a lighted match, but if this given fuel is passed under pressure through a nozzle or orifice into the atmosphere or comes in contact with a high velocity air stream the atomized fluid is readily ignited by the match and burns. If the pressure or air velocity is gradually reduced, the resulting droplets become larger until a point is reached where a flame cannot be sustained. Manifestly, the exposed surface area and consequently the droplet diameter is an important criterion in defining the quality of the combustion process. Of course, a liquid fuel could be prepared for combustion without the necessity of the intervening atomization process. Prior to or during its admixture with air, the liquid could be vaporized by heating it beyond the saturation point of its heaviest hydrocarbon. The use of vaporizers for this purpose would necessarily be confined to low-residue fuels to mitigate the frequent cleaning of the vaporizer burners.
Vaporizers historically antedate atomizers, but the latter are used almost exclusively where combustion of high residue fuels is utilized.

Further momentary pursuance of pertinent factors requiring consideration in combustion will be given, illustrating, thereby, its relation to the atomization process. Briefly, experimental investigations (28, 33, 36, 53, 58) indicate that for proper combustion the following is desirable:

1. The droplet sizes should be as small as possible and of uniform distribution. Large drops (even in a fine spray) have a detrimental effect upon combustion. These fine droplets are of paramount importance since they ignite readily and serve to act, so to speak, as a catalyst in promulgating a stable continuous combustion to the remainder of the spray.

2. The shape and direction of the spray should be of such a nature as to penetrate all parts of the combustion chamber.

3. The degree of droplet penetration should be such that the larger droplets have sufficient momentum to penetrate the furthest part of the combustion chamber. This requirement opposes the first since the droplet distribution may be so fine that these rapidly lose their momentum and burn near the nozzle exit.

The above statements serve to illustrate the importance of such influencing factors as droplet size and their
distribution, spray penetration, chamber density containing the spray, shape and direction of the spray, etc., when applied to a specific phenomenon such as combustion. Another example of the importance of particle size to a totally different field of applicability is in the large scale spraying of insecticides. Experiments indicate, for instance, that there is a certain optimum particle size of a given insecticidal concentration to produce a certain kill of the common mosquito. A larger droplet would be wasteful, and a smaller one ineffective.

C. Pertinent Variables in Air-Stream Atomization

The ultimate definition of the atomization process in terms of fundamental mechanisms remains incomplete. Aside from this considerable experimental work has been done concerning the atomization process, principally in solid injection with emphasis in application to combustion of fuels in Diesel engines. Numerous nozzle designs exist which claim optimum atomization for their specific applications. However, experimental evidence relating the particular design and various physical, geometric, and dynamic variables involved with particle size or distribution is far from adequate. Until relatively recently the gas-vapor stream atomization process was only slightly explored, while in the solid injection field much of the performance data has been
privately retained by the manufacturers concerned.

Since in this study the atomization was accomplished by a high velocity air stream, it is important to note the pertinent physical, dynamic, and geometric variables involved. It may be of interest to determine a functional relationship between various independent and controlled variables in terms of a dependent variable such as some significant mean diameter \( \bar{x} \) of the droplet size. For a given design and consequent orientation of position of liquid injection with respect to the passing air stream, this mean diameter may be a function of the following variables: the air velocity, \( v_a \); the liquid velocity, \( v_1 \); the density of the liquid, \( \rho_l \); the density of the atmosphere into which the liquid is sprayed, \( \rho_{atm} \); the mass rate of flow of air, \( m_a \); the mass rate of flow of the liquid, \( m_1 \); the viscosity of the liquid, \( \mu \); the surface tension between air and the liquid, \( \sigma \); some significant dimension of the air nozzle such as the throat diameter, \( D_a \); and finally some significant dimension of the liquid nozzle (if circular) the diameter, \( D_1 \). Symbolically the functional relation may be,

\[
\bar{x} = f(v_a, v_1, m_a, m_1, \rho_l, \rho_{atm}, \mu, \sigma, D_a, D_1)
\]

Which of these variables are found to be pertinent to the atomization process under a given set of conditions as given by previous experimental investigations will be
reviewed later. Since the droplet distribution is rarely of uniform size, and rather than relate the experimentally controlled variables to a non-uniform drop distribution, it is of advantage to seek some significant mean drop diameter. Obviously, in any investigation involving a non-uniform droplet distribution the significant droplet size will depend on the nature of the field of application, and must be readily calculable from the drop size distribution equation.\(^1\) For example, if the application be to an evaporative process, the Langmuir equation for the evaporation of a single drop is

\[
\frac{dm}{dt} = -cx
\]

and for a number of droplets of different diameters

\[
\frac{d(\sum_{n} x_n \Delta n)}{dt} = -c(\sum_{n} x_n \Delta n)
\]

and dividing by the total number of drops

\[
\frac{dm}{dt} = -c \frac{\sum_{n} x_n \Delta n}{\Delta n}
\]

where \(\Delta n\) represents the total number of drops whose diameter is \(x\).

The linear mean diameter or the average diameter \(\bar{x}_{ave}\)

---

\(^1\) Considerable work relating the significant drop diameters for various physical processes to the pertinent drop size distribution equations has been done by numerous investigators (9,14,17,18,19,44,51,56,57,67).
is \( \frac{E x \cdot \Delta n}{\Delta n} \) and represents the diameter which when multiplied by the total count of drops will give the same result as adding the products of the separate group counts by the mean diameters of the separate groups.

If the subject of investigation is concerned with atomization efficiency as is the case in this study, a representative diameter may be derived as follows: suppose a portion \( E \) of the energy lost in pressure drop \( \Delta p \) is used to form a new surface whose surface energy is then equal to \( \sigma A \).

For a single drop this is

\[
\frac{E(x^3 \Delta p)}{6} = \pi x^2 \sigma, 
\]

and for a number of drops

\[
E \Delta p \frac{E x^3 \cdot \Delta n}{E x^2 \cdot \Delta n} = 6 \sigma x^2 \Delta n, 
\]

indicating the representative diameter of atomizing efficiency may be given as \( d_o = \frac{E x^3 \cdot \Delta n}{E x^2 \cdot \Delta n} \), referred to as the Sauter mean diameter or the mean volume-surface diameter.
II. OBJECT OF THE INVESTIGATION

Three principal objectives were proposed in this investigation. The first was the construction of an atomizing unit which with the minimum of alterations could be capable of handling experiments dealing with either air-stream or solid injection atomization. However, the present study dealt only with air-stream atomization, and with this in mind the flow unit was constructed. For satisfactory atomization the atomizing unit must be of good design, rigid and durable in construction, and correct in assembly. Furthermore, with a view toward extensive investigations, it must contain a basic simplicity and flexibility in construction. These latter features, and necessarily so, permit the ready interchangeability of various parts of the air and liquid flow units, such as air nozzles and liquid nozzles.

What may be classed as the second and third objectives of the investigation dealt principally with the experimental aspects of air-stream atomization. The purpose of these experiments, essentially of a model nature, was to present certain knowledge, as to the effect of the method and manner of liquid injection upon the air-stream atomization phenomenon. This knowledge was to be presented in terms of various controllable pertinent factors such as air velocity,
liquid velocity, liquid and air flow rates, etc., and their
effect upon the droplet size distribution. Furthermore, it
was desired to obtain a relation between these factors and a
certain particle size mean diameter which may serve as a
measure of the atomizing process.

In all the experiments a glass convergent air nozzle
was used. The first class of experiments, utilizing paral-
lel flow of liquid and air, dealt with the effect upon
atomization of varying the position of liquid injection
along the axis of air flow. This gave, analogous to that of
the velocity profile within a duct, so to speak, a map of
the atomization's variation.

The second class of experiments dealt with the effect
upon atomization in varying the manner in which the liquid
is injected into the air-stream, that is to say, the type of
geometrical liquid surface presented to the passing air-
stream. In each case the liquid surface was presented normal
to the passing air-stream.

It was hoped in proposing and executing these experi-
ments, that some certain specific features of the above
knowledge, though conducted under model conditions, could be
incorporated into prototype industrial designs of air-stream
atomization units.
III. REVIEW OF LITERATURE

J. A. F. Plateau in 1873 studied in his researches the action of liquid jets in a non-gravity system, and found that a cylindrical column of liquid whose length exceeds its circumference is unstable and will eventually collapse under the influence of any disturbance. Lord Rayleigh (54,55) in the pioneer analytical work on liquid jets was principally interested in the mode of disintegration of an infinite liquid cylinder subjected to a given disturbance, and the number of liquid masses and possible drops that may be formed from a finite length of this liquid cylinder. Rayleigh considered an infinite cylinder whose surface varying with time $t$ took the form

$$ r = a + a \cos k z , $$

where $z$ is the length along the axis of the cylinder, $a$ is the amplitude varying with time, and $k = \frac{2\pi}{\lambda}$ where $\lambda$ is the wave length of the original disturbance. The potential energy of the above surface subjected only to the tension force of its own envelope may be expressed from its equilibrium position as,

$$ V = - \sigma \frac{ka^2}{2a} (1-k^2a^2) . $$

The velocity potential for the above surface is of the
form \( \phi = A J_0(ika) \cos \kappa z \), where \( A \) is evaluated from the boundary condition that the outwards normal velocity at the surface of the cylinder is \( \ddot{a} \cos \kappa z \). From the above the kinetic energy of the cylinder per unit length is

\[
T = \frac{1}{2} \rho \pi a^2 \frac{J_0'(ika) \cdot \dot{a}^2}{ika J_0''(ika)}.
\]

By La Grange's method with a proportional to \( e^{qt} \),

\[
q^2 = \frac{\sigma}{\rho a^3} \frac{(1-k^2 a^2) \cdot ika \cdot J_0'(ika)}{J_0''(ika)}
\]

which determines the law of falling away from equilibrium for a disturbance of wave-length \( \lambda \). Rayleigh solved for the value of \( ka \) for which \( q^2 \) is a maximum. This is tantamount to the condition for slowly collapsing jets. The maximized \( q^2 \) value gives \( \frac{\lambda}{2a} = 4.508 \) or the ratio of wave length to diameter for the kind of disturbance which leads rapidly to the collapse of a liquid jet. As previously mentioned, Rayleigh's analysis is more applicable to slowly collapsing jets. Castleman (5,6,7), recognizing the possibility of employing this analysis to rapidly collapsing jets, or as is the case in air-stream atomization, did so with success. This procedure employed the physical data of Scheubel (63) and Sauter (60,61,62). However, as pointed out by Schweitzer (64,65) this analysis is permissible only in cases where there exists a stable laminar flow or a liquid
at rest and the consequent assumption of the existence of a velocity potential is valid. In solid injection the liquid passes through the nozzle with a velocity proportional to the pressure difference existing between inlet and exit sections of the nozzle. In many instances this velocity may be great. High velocity combined with low viscosity fluids may produce Reynolds numbers of considerable magnitude and consequent turbulent flow. For this condition a velocity potential is not applicable.

Castleman (6, p. 376) qualitatively describes the process of atomization in an air-stream as follows:

A portion of the large mass is caught up (say, at a point where its surface is ruffled) by the air stream and, being anchored at the other end, is drawn out into a fine ligament. This ligament is quickly cut off by the rapid growth of a dent in its surface, and the detached mass, being quite small, is swiftly drawn up into a spherical drop. Within limits, the higher the air speed, the finer the ligaments, the shorter their lives, and the smaller the drops formed.

The above description was substantiated and extended in scope by Nukiyama and Tanasawa (49) who took stereoscopic instantaneous photograms of liquid jets which were atomized in variable speed air streams. Various liquids for a set liquid flow were subjected to an air stream whose velocity was gradually increased. Each liquid gave the same atomizing form as indicated in Figure 1. The atomizing form may be divided into three successive stages.
Figure 1. Air-Stream Atomization Pattern [Nukiyama and Tanasawa (49, p. 7)]
1. Dropwise Atomization. At very low velocities the end of the liquid cylinder exhibits bead-like swellings and contractions with continuously increasing amplitude culminating in several large spherical drops, Figure 1 (1)-(2). This is as predicted by the Rayleigh theory.

2. Twisted Ribbon-Like Atomization. As the velocity of the air stream is increased the amplitude rapidly increases resulting in a twisted ribbon-like pattern. The process continues as described by Castleman above and as seen in Figure 1 (3)-(4).

3. Filmwise Atomization. As the air velocity is further increased the twisted ribbon is flattened to form a thin cob-web-like film which disintegrates into numerous liquid particles as shown in Figure 1 (5)-(6). A further increase in velocity increases the number of films whose size as well as the droplet size becomes smaller, Figure 1 (7)-(8).

Many experimenters have attempted to relate the physical and dynamic properties of the fluids involved with some significant dimension of the particle size in air-stream and solid-injection atomization phenomena. The work in the former has not been nearly as extensive as in the latter. The more notable work in the latter field contains a long list of experimenters, some of whom are: Bryan (3), Dellales (11), Glendenning (13), Haenlein (16), Juhasz (29), Kuehn (33), Lee (36,37,38), and Woltjin (71). Some of the earliest experiments conducted in air-stream atomization
were by Scheibel (63). His purpose was to relate the various pertinent factors involved with the possible improvement in carburetor jet design. He tested water and alcohol, the former because of its high surface tension, and the latter to simulate the properties of customary fuels like gasoline and benzol. The significant factor of air-stream atomization was termed the "atomizing characteristic" and expressed as, \( \frac{K}{2} = \frac{\rho v^2}{2\sigma} \), or the static pressure of the air stream per surface tension of the liquid. Drop sizes of the sprays were determined by utilizing spark photography. Assuming an ideal liquid or negligible viscous forces, a functional relationship for the "mean drop diameter" \( d \) was expressed as

\[
d = f(\rho, v, \sigma)
\]

The application of dimensional analysis gives \( d = \frac{c_2}{\rho v^2} \), where \( c \) is a dimensionless constant. The above considered only the effect of inertia and capillary forces, and consequently the correlation between variables considered and particle diameters was poor. To account for the effect of viscosity a new dimensionless quantity was introduced of the form \( \frac{\sigma}{\mu v} \). The mean drop diameter was then expressed as

\[
d = c \frac{\sigma}{\mu v} \frac{\sigma}{\rho v^2}
\]

where \( c \), a constant, takes different values for different
forms of exit nozzle. The above relation lacks in general-
ity; for instance, it omits the consideration of the mass
rates of flow of air and liquid. The published data is
incomplete. However, Scheubel arrived at some qualitative
conclusions:

1. The outstanding quantity of the whole atomization
problem is the "atomizing characteristic" K. The higher its
value the better the atomization. One should if possible
avoid a value of K less than 300 to 400 cm.\(^{-1}\).

2. The shape of the venturi plays a secondary role,
but the increase of the divergent section beyond the throat
had best not be too abrupt.

3. It is advantageous to introduce the liquid in front
of the sharp-edged widening of the air stream, so that it
enters the region of highest velocity as gradually as
possible.

It may be mentioned that in the foregoing dimensionless
relation no account is taken of the external force of air
friction of the ambient atmosphere upon the degree of air-
stream atomization. Any liquid jet in a finite time will
eventually disintegrate due to surface irregularities
encountered, principally by the combined effect of air fric-
tion and surface tension. However, in the more usual situ-
tions where we may say air-stream atomization occurs, the
life period of the ligaments is very short. Since the mag-
nitude of the external force is proportional to the length
and consequent life period of the ligaments, the effect of the ambient atmosphere into which the high velocity air stream and liquid stream are injected is quite small. A number of experiments (10,16,29,30,31,37,38) where pressure injection was utilized were conducted, in which the spray was dispersed into variable density atmospheres. These experiments illustrate the effect of the ambient atmosphere upon atomization, and show conclusively, that in pressure injection, air friction alone is not responsible for jet disintegration. For a complete analytical discussion of the effect of mode of flow in pressure jet nozzles, see Schweitzer (64). Little experimental data exists wherein a variable density ambient atmosphere is employed in atomization by an air stream.

In the years 1937 through 1939, a number of extensive and notable experiments were carried out by Nukiyama and Tanasawa (45,46,47,48,49,50) and their associates in air-stream atomization. Because of their importance and scope these will be reviewed at length. In the first of these the atomization was accomplished by injecting water from a nozzle into the throat of a convergent air nozzle, the throat of the air nozzle being located some distance upstream of the water nozzle's outlet. The sprayed drops impacted upon a deck glass coated with a specially prepared oil solution. This glass was inserted in a cylindrical shutter whose exposure time could be adjusted from 0.002 to
0.01 seconds. The above unit was attached to a traveller whose position could be adjusted with respect to the longitudinal axis of the conically shaped sprayed jet. Photomicrograms were taken of the sprayed droplets and counted. The exit diameters of the water nozzles were varied as well as the throat diameters of the nozzles.

The diameter \( d_0 \) in microns, which is the diameter of a single drop having the same volume to surface ratio as the total sum of the drops, was determined from

\[
d_0 = \frac{\frac{E x^3 \Delta n}{E x^2 \Delta n}}
\]

where \( \Delta n \) is the number of drops whose diameters lie between \( x \) and \( x + \Delta x \). In all the tests the injected liquid flowed parallel to the air stream. Some of the conclusions reached are as follows:

1. The drop distributions indicate a uniformity of the mean diameters with the exception of the atomized jet's outer surface extremity.

2. Atomization is completed in the near vicinity or at the throat of the convergent air nozzle.

3. The mean diameter \( d_0 \) is principally affected by the ratio \( \frac{Q_a}{Q_w} \) and not by \( v_w \) or the diameter of the water nozzle when the relative velocity \( v_a - v_w \) is kept constant.

4. When the ratio \( \frac{Q_a}{Q_w} \) is much larger than 5000 the
experimental results may be expressed by $d_o = \frac{5300}{v}$.

In another experiment the air flow unit was varied. Sharp-edged orifices and cylindrical nozzles were used. In all cases the liquid was injected in a direction parallel to the flowing air. The same preceding equation is obtained for the sharp-edged orifice as for the convergent air nozzle. An additional study was made of the effect of the size of the air and water nozzles. Keeping the relative velocity between air and water constant as well as the ratio $\frac{Q_a}{D_w}$, samples were taken of the sprayed droplets but no appreciable effect was noted due to varying $\frac{D_a}{D_w}$.

Nukiyama and Tanasawa (48) extended their foregoing technique in studying the effect of physical properties upon the air-stream atomization phenomena. The experiments utilized sharp-edged orifices and cylindrical nozzles. The liquid was ejected from a cylindrical nozzle in a direction parallel to the flowing air stream. Atomization was accomplished at the throat of the sharp-edged orifice. The sprayed drops were collected near the center-line of the jet on a specially prepared oil and were photographed. The effect of viscosity $\mu$ was measured with 40 to 80 per cent glycerine-water solutions since the surface tension is almost constant within the above range. The effect of surface tension $\sigma$ was measured with ethyl and methyl-alcohol-water solutions, and the combined effect of $\sigma$ and $\mu$ was
checked with alcohol-water-glycerine solutions. The following expression was obtained for the mean diameter \( d_0 \) of the drops.

\[
d_0 = 585 \frac{\sqrt{\sigma}}{v \sqrt{\rho}} + 597 \left( \frac{\mu}{\sqrt{\sigma \rho}} \right)^{0.45} \left( 1000 \frac{q_1}{q_a} \right)^{1.5}.\]

The conclusions reached as a result of the above expression are:

1. The magnitude of the drops is mainly governed by the quantity \( \frac{\sqrt{\sigma}}{v \sqrt{\rho}} \) when \( \frac{q_a}{q_1} \) is large. Thus the viscosity under these circumstances is of minor significance.

2. When \( \frac{q_a}{q_1} \) is small, the magnitude of the drops is principally governed by the quantity \( \left( \frac{\mu}{\sqrt{\sigma \rho}} \right)^{0.45} \left( 1000 \frac{q_1}{q_a} \right)^{1.5} \). Thus under these circumstances the surface tension is of minor importance. The Japanese authors state that the above empirical relation is valid for \( 0.8 < \rho < 1.2 \) grams per cubic centimeter, \( 30 < \sigma < 73 \) dyne per centimeter, and \( 0.01 < \mu < 0.3 \) dyne-seconds per square centimeter.

Sauter (62) performed experiments on several commercial carburetors and an atomizing unit consisting of a Venturi wherein liquid is injected into the throat of the Venturi in a direction parallel to the air flow. No drop distribution data is given, since the method used for determining the mean diameter \( d_0 \) depended on the degree of absorption of a
beam of light passed through the spray. Complete data was
given for the Venturi atomizing unit. Comparative calcula-
tions between the above empirical equation and Sauter's
data indicate that the magnitude of the drop sizes as given
by the latter is approximately 25 to 35 per cent of those of
the former. As Lewis and others (39) pointed out this is
quite possibly due to certain dubious assumptions involved
in Sauter's calculations, namely:

1. The drop distribution is uniform over a given
cross-section of the atomized spray. Later experiments
show that the main portion of spray is concentrated near the
longitudinal axis of the conical spray and gradually becomes
less dense as the extremities of the spray are approached.

2. The drops passing the beam of light are spherical.
As Castleman pointed out, ligament formation is a necessary
intermediate step in the atomization process as the main
mass of liquid is changed to droplets. This takes a finite
time. This was verified by the high-speed photography of a
number of investigators (1,16,20,21,27,34,49).

Some interesting experiments were conducted by Lewis
and others (39) on practical atomizing units that may be
employed in field spray work. In one unit the atomization
was accomplished by utilizing the hot exhaust gases from a
truck engine passed through a Venturi with 0.5 inch throat
diameter. Consequently, it was expected that the correspond-
ing mean diameters $d_0$ would be higher since for these gases
the density is less and the viscosity greater when compared to atmospheric air conditions. The results indicated this to be true at low liquid rates when the first term of the Nukiyama-Tanasawa equation is the controlling factor. However, at high liquid rates when the other term is controlling the observed diameters $d_0$ were considerably less than those predicted by the equation. As the authors mention this latter result was principally due to heat being transferred from the hot gases to the sprayed liquid. From a practical aspect this suggests the advisability of utilizing hot gases or vapors to improve the atomization of heavy oils at high liquid rates.

Taking into cognizance the possibility of utilizing hot gases or vapors for atomization suited for practical purposes, it seems the Nukiyama-Tanasawa equation could be further generalized by including the dimensionless quantity of the mass rate of flow fair to that of liquid instead of the ratio of the volume rates. This would permit a greater latitude of gas and liquid densities. Of course, for consistent results it would be necessary to control the fluid temperatures to mitigate or even obviate the heat transfer effect between the liquid and the gas or vapor.
IV. DESCRIPTION OF APPARATUS

A. General Layout

The main portion of the experimental equipment was located on the second floor of the Mechanical Engineering Laboratory at Iowa State College. This experimental room was well insulated on all sides, and this feature together with the room's low ceiling construction minimized to a large extent the effect of thermal currents upon the atomized spray. The compressed air utilized in the experiments was furnished by a motor driven air compressor located on the first floor of this same laboratory. The compressor was of the single stage type with cooling supplied by a water jacketed cylinder. An automatic cutoff kept the maximum pressure at 120 lb. per sq. in. gage, and in time as the pressure dropped the same mechanism kept the minimum pressure at 90 lb. per sq. in. A standard one inch pipe supplied the compressed air to the experimental unit, the magnitude of which was noted by a pressure gage on the supply line. The entire experimental unit either rested on or was supported by a specially constructed wooden table.

Figures 2, 3, and 4 give appropriate vantage points in regard to the overall arrangement of the experimental apparatus while Figure 5 illustrates the schematic arrangement of
Figure 2. Over-all View of Experimental Apparatus
Figure 4. Air Nozzle Unit and Liquid Flow Tube
Figure 5: Schematic Flow Diagram
All Standard A.S.H.V.E. Symbols

Legend

A - Air Line
B - Pressure Gages
C - Motor Compressor
    Reciprocating Direct Connected
D - Valves
E - Filter Strainer Unit
F - Pressure Reducer
G - Air Receiver
H - Liquid Meter
J - Liquid Tube
K - Thermometer
L - Liquid Line
N - Thermometer
P - Spray Sampling Apparatus
Q - 20 inch Circular Duct
R - Atmospheric Relief
S - Duct Exhaust and Spray
    Absorption Equipment
the experimental unit. These illustrations indicate the
main portion of the high pressure air to be directly sup-
plied through the one inch pipe line to the air pressure
reducer mechanism. However, through an appropriate tee a
portion of the high pressure air is channeled through a
one-fourth inch line located at a right angle to the main
line. This channeled air in turn flows in two directions,
namely: to the atmosphere by way of a standard one-fourth
inch atmospheric relief needle valve and to the liquid flow
meter. The latter line is parallel to the direction of flow
of the main mass of air. This arrangement provided the
means for accurate manual control of the pressure exerted
upon the liquid. A detailed discussion of liquid flow con-
trol apparatus will be considered later.

B. Air Flow Apparatus

As previously mentioned, the main mass of the high
pressure air entered a filter and reducer. With the aid of
the pressure reducer the pressure on the downstream side
could be manually adjusted to the desired magnitude ranging
from 0 to 120 lb. per sq. in. gage. Leaving the pressure
reducer the air entered a galvanized iron cylindrical air
receiver whose external dimensions are approximately one
foot in diameter and 21 inches in length. This relatively
large diameter when compared to the air nozzle's throat
diameter insured a negligible velocity within the air receiver. Provision was made to measure the static pressure within the air receiver both by a Bourdon pressure gage as well as a mercury manometer for a more accurate determination. In addition, it was possible to make a pitot-tube traverse of the existing flow conditions within the air receiver. A calibrated mercury-in-glass thermometer indicated the air temperature leaving the air receiver. Upon leaving the air receiver the air enters and flows through a glass convergent type of nozzle. The nozzle was blown from a standard one inch pyrex glass pipe in a manner suited for smooth entry of the air through the throat of the nozzle. The throat dimensions were 0.203 inches in diameter and a hollow ground straight section of 0.203 inches as indicated in Figure 6. The glass to metal connection was accomplished by using circular metal flanges whose inner faces were smoothly machine finished. A threaded metal coupling whose inner surface was smoothly finished and led to the air receiver by means of a suitable connection was inserted into one of the flanges to secure the metal portion of the joint. The glass nozzle inserted through the other flange was

1 A special pressure tested hypodermic stainless steel pitot-static pressure tube dimensionally modified according to National Physics Laboratory and ASHVE standards. Diameter 1/16 in. O.D.; stem 11 inches; head 7/8 inches; static outlet 2 inches.
Figure 6. Glass Convergent Air Nozzle
Full Scale

Figure 7. Liquid Injection Positions
Full Scale
brought to bear against the end of the threaded coupling
with rubber gasketing interposed between the two surfaces.
A temporary liquid outer seal coated and secured the faces
of the glass nozzle and the threaded coupling. The flanges
were bolted and thus secured a good seal and one easily
removable (Figure 8).

C. Liquid Flow Apparatus

As previously mentioned, a portion of the main mass of
air is channeled through a one-fourth inch line to serve as
a source of pressure exerted upon the liquid. Approximately
at the midpoint of this compressed air line is located a
standard one-fourth needle valve which is manually con-
trolled. Upstream of the valve a pressure gage records the
pressure in the upstream end of the line. This pressure is
determined by the joint action of the atmospheric relief
valve and the above mentioned valve. The latter valve con-
trols the pressure on the downstream side to a value as
small as desired. In this section of the air line a tap is
provided to record the static pressure. This is done with
the aid of a small mercury manometer (the pressure exerted
on the liquid never exceeded 6 inches of mercury gage)
mounted on the control board which also supports the liquid
meter. The liquid meter consists of a nickel plated thick
walled brass cylinder provided with a glass gage and scale
Figure 8. Top Cross-Sectional View of Air Nozzle Unit and Liquid Tube. Full Scale.
to note the level of the liquid at all times. The capacity of the cylinder is approximately 215 cubic centimeters. A thermometer well extends along the longitudinal center line of the cylinder for about one-half its length. The compressed air enters at the cylinder's top through a suitable connection between the air pipe line and cylinder. A tap is also provided for liquid filling at the top of the cylinder. At the base of the cylinder another one-fourth inch needle valve is provided for control of the exit flow rate of the liquid. The liquid flows through the valve and enters the liquid tube via flexible rubber tubing from whence it is discharged into the air stream. All metal to metal and metal to rubber connections were thoroughly sealed.

D. Liquid Nozzles and Their Supports

As previously mentioned, four different ways of liquid entry into the air stream were tested. All of the liquid nozzles were fashioned from 1/4 gage hypodermic stainless steel tubing, with an inside diameter of 0.063 inch and an outside diameter of 0.083 inch. The steel had a high nickel alloy content and the tubes' walls were extremely hard and of high strength.

The tubes used were all approximately 10 inches long. The liquid tube was supported such that its longitudinal axis was collinear with that of the convergent air nozzle, and
consequently, the air flowed in an annular manner with respect to the inner surface of the air nozzle and outer surface of the liquid tube. The liquid tube could be moved horizontally along this axis of flow. The liquid tube had two main supports. One of these was a steel block mounted on a cast iron channel, the latter in turn being supported by the table on which the entire experimental unit rested. The liquid tube passed through a rubber lined drilled hole of the block, entered and passed through the second support consisting of a rubber packed brass fitting which was inserted into a 90 degree elbow. The latter connection joins the exit line of the air receiver and that of the pipe coupled flange. Both of these supports were quite long, about 3.5 inches of total support length. This length was found necessary since one of the major problems with this construction arose from possible vibrations of the liquid tube while the liquid and air are in motion. The tube acts as a cantilever with possible oscillations of the free end. These vibratory forces are influenced by the moving liquid and air, the liquid's weight, and the weight of the tube itself. These vibratory effects were mitigated by using low liquid rates, light tube metal, and the long and rubber packed supports. All observations indicated vibratory effects were insignificant.
E. Methods of Liquid Injection

1. One method of liquid injection allowed the liquid to flow through the open end of the tube parallel to that of the surrounding flowing air (Figure 9a).

In the remaining methods the liquid entered the air stream at right angles to it. The manner of liquid surface presented to the high velocity air stream was varied.

2. The free end of the liquid tube being closed, the liquid enters the air stream through two opposingly-spaced rectangular slits each of which are 0.02 inch wide and 0.08 inch long (Figure 9b).

3. The free end again being closed, the liquid enters the air stream through four equally spaced circular orifices each of which is 0.0315 inch in diameter (Figure 9c).

4. As in the preceding two cases, the free end is closed. The liquid enters the air stream through two 135 degree oppositely spaced slots which are 0.0295 inch long.

In each of the above cases the exit cross-sectional area of liquid flow is the same.

F. Duct for Spray Discharge

The atomized spray discharged into a 20 inch circular sheet metal duct whose entry section was located approximately 12 inches downstream from the throat of the
Figure 9a. Air to Liquid Parallel Flow

Figure 9b. Air to Liquid Normal Flow

Figure 9c. 4-0.0315" Circular Holes, Equally Spaced

Figure 9d. 2 Oppositely Spaced 135° Slots, 0.0295" Long

Figure 9c and 9d. Air to Liquid Normal Flow

(Stainless Steel Hypodermic Tube, I.D. = 0.063"; O.D. = 0.083")
convergent air nozzle. The duct was used principally to eliminate unnecessary spray penetration to various parts of the experimental room and to serve as a housing for the droplet sampling apparatus. The duct was L-shaped, one leg of which was parallel to the longitudinal axis of the existing conically shaped spray, while the other projected vertically downward. Some distance above the base of the latter leg of the duct, a circular opening normal to the downward flow of the liquid served as an exhaust for any spray not collected along the duct walls. This vertical leg of the duct had a specially constructed base which served as a support as well as collector for the excess liquid. It simply consisted of two sheet metal cylinders annularly spaced and soldered to a circular plate. The outer annular space was tightly packed with absorbent material which also supported the duct periphery, while the inner annular space was more loosely packed with the same absorbent material and could easily be removed.

G. Droplet Sampling Method

The liquid droplets were received on ordinary biological glass slides which were coated with magnesium oxide. This was done simply by burning magnesium metal ribbon and passing the slide back and forth over the smoke. This gave a smooth and uniform coating. The coating in each case was
quite thick, approximately 1/16 inch, which is much greater than the diameter of any droplet measured. By using a thick coat of oxide and noting that the individual grains are very fine and loosely packed, this was found to give an accurate indication of the droplet's true size. The droplet penetrates and enters the oxide coat much as a pellet would in passing through a blanket of snow. What is measured is the surface diameter of penetration as the droplet will tend to spread as its impact energy is reduced to zero. This spread occurs considerably below the surface if the coating is thick enough.

These slides were placed in a specially constructed shutter mechanism, the principle of which is quite simple (Figure 10). It consisted of a rectangular piece of heavy gage sheet metal, the long ends of which are bent back upon themselves through 180 degrees forming guides in which another flat plate may be inserted and caused to slide freely. In the plate which serves as the guide, three appropriately spaced and located circular holes ranging in diameter from 0.1 to 0.5 centimeters were drilled. Directly behind these holes a holder was fashioned to house the inserted glass slide. The long flat plate with a rectangular slit appropriately placed is made to slide freely within the guides, and consequently acts as a sort of shutter arrangement whereby the rectangular slit exposes the circular holes and oxide coated slide for a fraction of a second.
Figure 10. Particle Sampling Unit. Half Scale.
The vertically downward velocity of the sliding plate may be expressed as

\[ v_p = \sqrt{2gh - F}, \]

where

- \( v_p \) = vertical velocity of the plate in feet per second;
- \( h \) = vertical distance of fall in feet;
- \( g \) = acceleration due to gravity in feet per second;

and \( F \) may be thought of as frictional factor proportional to the vertical free fall velocity of the plate. The magnitude of this factor is affected by the friction developed between the flat plate and guides. This can be obviated to a large extent by lubricating the guides and reducing the area of contact. The former was done and the latter is small by virtue of material chosen and relative thinness of plate. The other factor influencing the velocity of the plate would be the horizontal pressure exerted by discharged spray. This, of course, was eliminated by virtue of the design itself since the spray never came in contact with the falling plate. Obviously, air resistance is negligible. For all practical purposes, the plate acquired a free fall velocity. For example, if the horizontal center line of the rectangular slit slides through a distance of 6 inches with respect to the horizontal center line of the shutter openings its velocity is approximately 5.68 feet per second. Thus the 1/10 centimeter shutter opening is exposed for an average
time of approximately $5.78 \times 10^{-3}$ seconds. Consequently, by varying the height of fall as well as the shutter size opening a range of average time exposures for the slides could be determined. For each test conducted the shutter unit was covered with a highly absorbent paper to prevent any interference caused by any possible deflections of the liquid particles striking the shutter unit. These were renewed after each test.

Filter paper in the form of cylinders was inserted into the spray to obtain some measure of the angle made by the spray's extremities.

Particle measurements were made by using a Bausch and Lamb metallurgical microscope with a 215 millimeter tube length, 10.25 millimeter objective lens, and 12.5 eyepiece. Both direct and side lighting were used.
V. DISCUSSION OF TEST AND PROCEDURE

A. Calibration of Convergent Air Nozzles

Prior to the actual experimental tests, a group of convergent air nozzles with varying throat diameter were calibrated. The nozzles tested had throat diameters as follows: 0.126 inch, 0.203 inch, 0.372 inch, and 0.448 inch. The nozzle unit was calibrated with the liquid feed tubes in their actual test positions. The procedure involved the determination of the energy loss measured as head loss between a given section of the air receiver where the velocity was negligible and a section at the nozzle's exit. Consequently, the calibration is not of the air nozzle itself, but of the flow unit included between the two above named sections. In this manner it was possible to determine throat velocities in the nozzle in terms of head of air in feet at some upstream section. As expected the velocity profile at the nozzle's exit was quite uniform. This was determined with the hypodermic type of pitot tube previously mentioned. It was found for this nozzle unit that the head losses were quite small, so that for all practical purposes a reversible adiabatic type of expansion could be assumed. However, in the computation of the experimental results these energy losses due to frictional effects (though small
in comparison with total head available) were considered.

For the velocity traverse of the nozzle throat the following relation was used in determining the point or local velocities assuming reversible adiabatic deceleration of the air. See Stoever (66, p. 394) or Kiefer and Stuart (32, p. 253).

\[
V_1 = \sqrt{\frac{2gkRT_1}{(k-1)} \left( \frac{p_2}{p_1} \right) \frac{k-1}{k} - 1},
\]

where

- \( p_2 \) = total pressure at point of nozzle exit,
- \( p_1 \) = static pressure at nozzle exit,
- \( T_1 \) = absolute temperature of air at nozzle exit,
- \( R \) = gas constant, and
- \( k \) = ratio of constant pressure and volume specific heats, respectively.

B. The Experimental Tests

The first class of experiments consisted of varying the point along the axis of air flow at which liquid is injected into the air stream. This was done at the positions, with respect to the nozzle throat, as illustrated in Figure 7. With the compressor in operation, the pressure reducer valve was manually adjusted to give the desired air receiver pressure and consequent throat velocity. The air unit was allowed to arrive at steady state operation.
The liquid utilized in all the tests was distilled water which was colored with fuchsin powder. The concentration found suitable for a well defined and measurable spray was about five grams per liter. The temperature of the dyed solution was brought to that of the temperature of the exit air to minimize any heat transfer effects. The liquid meter was then filled and the temperature again checked. By the mutual adjustment of the atmospheric relief valve and the valve in the air line leading to the liquid meter the pressure acting on the liquid was determined and measured to give the desired flow rate for a given exit meter valve setting.

During the course of the test initial and final liquid meter readings were taken, the time, and liquid pressure. In addition, the pressure and temperature at the inlet to the nozzle unit were taken.

Since as pointed out previously the atomization is essentially completed at the air nozzle throat, the sampling apparatus was located approximately 2 feet beyond the nozzle exit. The magnesium oxide coated slides were inserted into the shutter mechanism and knowing the average velocity of the exit spray the time exposures of the slides were adjusted accordingly. These samples were taken at the center of the spray. A form of qualitative check may be had of the proper time exposure, since if the exposure is too long this will be indicated on the slide by droplet interference and
accumulation of one on top of the other. If the exposure is too short the slide will appear streaked, or in the extreme none of course should appear.

In each test three separate samples were made to serve as checks. The particles were then counted and their distribution obtained by a linear traverse with the aid of the metallurgical microscope described and calibrated scale to read in microns.

An absorbent paper wound in the form of a cylinder was placed in the sprayed jet. The chief interest of this was to give some indication of the spray angle at which notable concentration of the spray exists.

The second class of experiments varied the method of liquid injection or the manner in which the liquid surface is presented to the air stream. In each case the liquid was injected at the throat of the convergent air nozzle and enters normal to the direction of the air stream flow (Figure 9b, 9c, and 9d). The exit area of the liquid nozzles was the same in all the experimental tests or approximately 0.0032 square inch. Also, the convergent air nozzle was the same with a throat diameter of 0.203 inch. The maximum air velocity encountered was the acoustic velocity since a convergent air nozzle was used. A similar procedure for liquid and air control and droplet sampling was used as in the first class of experiments described.
From the preceding experimental measurements the pertinent properties and variables could be calculated. These include the liquid properties, viscosity \( \mu \), the density \( \rho_w \), and the surface tension \( \sigma \) between the liquid and air, which are essentially functions of temperature for the moderate pressures encountered and were very nearly constant over the entire range of experiments. Further properties and variables calculated were the liquid velocity \( v_w \), air nozzle throat velocity \( v_a \), the volume rate of air flow \( Q_a \), the volume rate of liquid flow \( Q_w \), the air density at inlet and exit from the nozzle \( \rho_a \), the mass rate of flow of air \( \dot{w}_a \), and the mass rate of flow of water \( \dot{w}_w \).
VI. EXPERIMENTAL RESULTS

A. Variation of Point of Water Injection

In this series of experiments the point at which water is injected into the ambient air stream was varied. This was done by manually moving the liquid tube along the axis of air flow. At each point the liquid was injected in a direction parallel to the surrounding air flow. Figure 7 indicates the various positions with respect to the exit of the air nozzle where the liquid was injected. Samples of the spray were taken and from a count of droplets the volume-surface mean diameter $d_o$ was determined for various conditions of air velocity $v_a$ and air to water volume ratio $\frac{Q_a}{Q_w}$. Since the atomization is substantially completed in the proximate vicinity of the point of liquid injection, samples were taken approximately two feet downstream of the exit of the nozzle and at the horizontal axis of air flow.

Table 1 illustrates these results for liquid rates $Q_w$ less than 0.5 cm.$^3$ per sec. and for increasing air velocities and consequent increasing $\frac{Q_a}{Q_w}$. In each case distilled water at approximately 20° C. was used. Hence the interfacial tension between air and water, the water viscosity, and the water density for all practical purposes were kept constant.
Table 1.

Effect of Liquid Tube Position Upon Droplet Mean Diameter

<table>
<thead>
<tr>
<th>Water-tube position</th>
<th>Air vel. (v_a) m./sec.</th>
<th>Water rate (Q_w) cm.³/sec.</th>
<th>Air-water ratio Q_a/Q_w</th>
<th>Drop mean dia. (d_o) microns</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-a</td>
<td>140</td>
<td>0.13</td>
<td>23,300</td>
<td>52.4</td>
</tr>
<tr>
<td>c-c</td>
<td>140</td>
<td>0.20</td>
<td>13,680</td>
<td>36.4</td>
</tr>
<tr>
<td>t-t</td>
<td>140</td>
<td>0.14</td>
<td>18,720</td>
<td>28.6</td>
</tr>
<tr>
<td>e-e</td>
<td>134</td>
<td>0.20</td>
<td>12,400</td>
<td>33.9</td>
</tr>
<tr>
<td>a-a</td>
<td>189</td>
<td>0.21</td>
<td>17,350</td>
<td>45.8</td>
</tr>
<tr>
<td>c-c</td>
<td>189</td>
<td>0.25</td>
<td>14,600</td>
<td>32.9</td>
</tr>
<tr>
<td>t-t</td>
<td>192</td>
<td>0.34</td>
<td>10,420</td>
<td>25.4</td>
</tr>
<tr>
<td>e-e</td>
<td>198</td>
<td>0.30</td>
<td>12,500</td>
<td>28.1</td>
</tr>
<tr>
<td>a-a</td>
<td>226</td>
<td>0.18</td>
<td>23,650</td>
<td>36.5</td>
</tr>
<tr>
<td>c-c</td>
<td>228</td>
<td>0.38</td>
<td>11,240</td>
<td>20.9</td>
</tr>
<tr>
<td>t-t</td>
<td>228</td>
<td>0.26</td>
<td>13,580</td>
<td>17.5</td>
</tr>
<tr>
<td>e-e</td>
<td>233</td>
<td>0.32</td>
<td>13,900</td>
<td>20.6</td>
</tr>
<tr>
<td>a-a</td>
<td>278</td>
<td>0.29</td>
<td>17,880</td>
<td>29.8</td>
</tr>
<tr>
<td>c-c</td>
<td>276</td>
<td>0.27</td>
<td>18,850</td>
<td>17.6</td>
</tr>
<tr>
<td>t-t</td>
<td>280</td>
<td>0.23</td>
<td>22,700</td>
<td>8.6</td>
</tr>
<tr>
<td>e-e</td>
<td>276</td>
<td>0.37</td>
<td>14,070</td>
<td>11.6</td>
</tr>
<tr>
<td>a-a</td>
<td>316^a</td>
<td>0.34</td>
<td>17,570</td>
<td>13</td>
</tr>
<tr>
<td>c-c</td>
<td>316</td>
<td>0.34</td>
<td>17,200</td>
<td>8.4</td>
</tr>
<tr>
<td>t-t</td>
<td>316</td>
<td>0.56</td>
<td>10,630</td>
<td>7.3</td>
</tr>
<tr>
<td>e-e</td>
<td>316</td>
<td>0.53</td>
<td>11,230</td>
<td>7.5</td>
</tr>
</tbody>
</table>

^a Acoustic velocity for existing conditions of pressure and temperature.
that point had not as yet attained the maximum velocity, which was expected, the results indicated that the air at
which the traverse was made at section e-e, or at the point
greater than at section e-e and less than at section f-f. The
result for section o-o, where the velocities will be
very small at any degree of accuracy would be still
lower.

According to the determination of this average
exact of the nozzle would be considered to be less than at sec-
onal values of the traverse at these sections. The average
were not the average of all sections 1-1. Consequent.
ally, the nozzle at section e-e, or at section e-e, and e-e
were taken with reference to the velocity at the exit of the
meter read the nozzle, but the results obtained indicated
pressure of which acts upon the water. Thus made the low water levels
at section f-f there is slight condensation at the surface of the nozzle.
that the nozzle to impinge upon the gases was a tendency for
poor and incomprehensible atomication. The results were a

At the values of the traverse at these sections 2-2 and 2-
attenuated the progression of taught injection are indicated in
water level used was small in comparison to the exit velocities.

Consequently, the exit water velocity in m. per sec. for the
The exit area of the nozzle tube was only 0.0205 cm. 2,
Data and results for section b-b were not included in Table 1 because obvious trends in the results can be clearly seen without their inclusion.

In Table 2 higher liquid rates are included. Otherwise the arrangement of the pertinent quantities is the same as in Table 1. These liquid rates range between 0.5 cm.\(^3\) per sec. and 1.0 cm.\(^3\) per sec. This gave air to water volume ratios for Table 2 greater than 10,000 while in Table 1 these ratios are less than 10,000. In both tables the results are arranged in terms of increasing air velocity.

For similar liquid rates the results indicated a decrease in the mean-diameter \(d_o\) with increasing air velocity. This is true for each section along the axis of air flow. The minimum drop mean-diameter was attained at section t-t for a given water rate and air velocity while the maximum occurred at section a-a. For air to water volume ratios greater than 5000 the drop mean-diameter was higher at section c-c than at section e-e. It was observed that at the lower air velocities and higher liquid rates there was a tendency for some of the atomized droplets at section e-e to strike the surface of the straight section of the nozzle. This may have resulted in a certain coalescence of the smaller drops to form larger drops. This condition was substantially mitigated as the air velocities were increased. Consequently, for air to water volume ratios less than 5000 and at the lower velocities the drop mean-diameter at section e-e
and temperature.*

*Acoustic velocity for exercising conditions of pressure

Then given in Table 1.

The values at velocities but at higher liquid rates

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Acoustic Velocity</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7580</td>
<td>88.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>15</td>
<td>5206</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>20</td>
<td>5256</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>25</td>
<td>5810</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>30</td>
<td>6600</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>35</td>
<td>7520</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>40</td>
<td>8600</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>45</td>
<td>1000</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>50</td>
<td>1150</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>55</td>
<td>1300</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>60</td>
<td>1480</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>65</td>
<td>1600</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>70</td>
<td>1750</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>75</td>
<td>1920</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
<tr>
<td>80</td>
<td>2100</td>
<td>96.0</td>
<td>96.0</td>
<td>316</td>
</tr>
</tbody>
</table>

Table 2.
appears greater than at section c-c. The drop sizes between these two sections were not substantially different for air velocities between 190 and 240 m. per sec. and for a $\frac{Q_a}{Q_w}$ in the neighborhood of 5000. Furthermore, the results indicated a decrease in the difference of the drop mean-diameters between sections a-a and c-c and those at section t-t as the air velocity was increased at similar water rates. This resulted in very little difference between the drop mean-diameters at acoustic conditions or a velocity of 316 m. per sec. and values of $\frac{Q_a}{Q_w}$ greater than 9000. This latter condition may also be true for $5000 < \frac{Q_a}{Q_w} < 9000$ at a similar condition of velocity. For $\frac{Q_a}{Q_w}$ greater than 5000 and for a given air velocity a comparison between the results in Tables 1 and 2 indicates only small differences in the drop mean-diameters at section t-t. Thus it appears that for these values of $\frac{Q_a}{Q_w}$ that the droplet mean diameter is principally dependent upon the air velocity and in an inverse manner.

Although the results are not included in either of the tables, an attempt was made to determine the angle of spray dispersion when water was injected at each of the three sections, c-c, t-t, and e-e. However, certain qualitative trends were noted. It was found that for a given condition of air velocity and $\frac{Q_a}{Q_w}$ the angle of spray dispersion was greater when the injection took place at section e-e than at the exit of the nozzle. This may be accounted for in part
as follows: The atomized spray in traveling through the short straight section of the air nozzle tends to follow the flow lines of the air and upon reaching the nozzle exit expands in a greater arc than if the liquid injection occurs in the region of sudden expansion. Although in this case the dispersion angle for a given condition was larger a proportionately greater number of larger drops occurred in the outer surface extremities of the spray than with injection at the nozzle exit. Furthermore, injection downstream of the exit of the nozzle or at section c-c produced a smaller angle of dispersion than with injection at the exit of the nozzle. This is in keeping with the foregoing view. Also, because of the decreasing air velocity downstream the water particles were larger along with a high concentration of larger particles at the outer surface extremities of the spray.

B. Variation of Method of Liquid Injection

In this series of experiments four different methods of injection were utilized. In each case the liquid was injected at the exit of the convergent air nozzle. These methods of injection are as follows:

1. Water is injected in a direction parallel to the surrounding air flow. Refer to Figure 9a. This is
designated as method A.

2. Water is injected in a direction normal to the surrounding air flow using four equally spaced circular orifices located along the periphery of the tube. Refer to Figure 9c. This is designated as method B.

3. Water is injected in a direction normal to the surrounding air flow using two oppositely spaced rectangular orifices. Refer to Figure 9b. This is designated as method C.

4. Water is injected normal to the surrounding air flow using two oppositely spaced 135 degree angular slots. Refer to Figure 9d. This is designated as method D.

The exit area of liquid flow in each of the above was the same and equal to 0.0205 cm.$^2$. The rate of water flow in each of the experiments conducted never exceeded 1.94 cm.$^3$ per sec. Consequently, the water velocity was small in comparison to the air velocity. An attempt was made to control the water temperature at approximately 20° C. Thus there was only a slight variation in the water viscosity, water density, and the interfacial tension between the air and water, and for all practical purposes these could be assumed constant. The air velocities used ranged from $106 < v_a < 316$ m. per sec. The air to water volume ratios ranged from approximately $1000 < Q_a/Q_w < 10,000$. The above range of values gave a distribution of droplet sizes ranging
from 5 to 250 microns in diameter. A further decrease in value of $v_a$ and $\frac{Q_a}{Q_w}$ from those mentioned above resulted in the formation of rapidly increasing drop sizes. Hence, from the standpoint of drop measureability and distribution, lower values for the above mentioned ranges were undesirable.

In differentiating between various methods of liquid injection as well as various designs used in air-stream atomization under various conditions, it was proposed to derive an expression (with all the pertinent variables involved), which would serve as an effective distinguisher. In many engineering applications the fineness of the drops produced may not be the prime consideration. Normally, a particular drop size or limited range of size is desired, depending upon the application. From the standpoint of practical operation, factors such as the economy of operation, simplicity of design, and durability are important. However, given a certain atomizing unit, its efficacy in performing the desired atomization will entail consideration, possibly, of the economy of operation, that is, how effectively is the energy available used in performing the desired atomization. In the air-stream atomization phenomenon the principal source of energy in converting the bulk liquid into a larger surface consisting of many droplets is the kinetic energy of the air. An expression which in effect entails the ratio of the kinetic energy of the air per unit time to the potential surface energy created per unit time.
during the droplet formation was developed. Since the drop
distribution may contain a range of sizes, the latter energy
term is based upon the actual superficial area $S_o$ produced
by the atomization of a unit volume of liquid sprayed. This
dimensionless energy ratio is termed the atomization number,
$A_N$, and with the pertinent assumptions involved is developed
in the Appendix. If so defined, large values of $A_N$ may be
considered as denoting poor efficiency or efficacy of the
atomization. This number is applied to a unit utilizing a
certain liquid under various conditions of air velocity and
air to liquid volume ratio to produce a certain volume-surf-
fase mean diameter $d_o$.

Thus, for water

$$A_N = \rho_a \frac{d_o}{Q_w} \frac{Q_w^2}{v_a} \frac{v_a}{870},$$

where in this instance $\rho_a$ was calculated by assuming an
ideal adiabatic expansion between inlet and exit air nozzle
conditions.

For $Q_a/Q_w$ less than 10,000 and $Q_w$ less than 1 cm.$^3$ per
sec., the experimental results are included in Table 3.
Table 3 is arranged in order of increasing air velocities.
Under similar conditions of $Q_a$, $Q_a/Q_w$, and $v_a$, it is
apparent that method A of liquid injection gives the lowest
value of $d_o$ and $A_N$. For method A at a given liquid rate the
value of $d_o$ steadily decreases as the air velocity is
Table 3.
Variation of Method of Injection Upon Air-Stream Atomization of Water

<table>
<thead>
<tr>
<th>Method of water injection</th>
<th>Air vel. ($v_a$)</th>
<th>Water rate ($Q_w$)</th>
<th>Air-water ratio ($Q_a/Q_w$)</th>
<th>Drop mean-dia. ($d_o$)</th>
<th>Atom number ($A_N \times 10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>107</td>
<td>0.79</td>
<td>2560</td>
<td>46.1</td>
<td>1.72</td>
</tr>
<tr>
<td>B</td>
<td>106</td>
<td>0.70</td>
<td>2860</td>
<td>101</td>
<td>4.26</td>
</tr>
<tr>
<td>C</td>
<td>107</td>
<td>0.98</td>
<td>2060</td>
<td>123.7</td>
<td>3.78</td>
</tr>
<tr>
<td>D</td>
<td>106</td>
<td>0.99</td>
<td>2020</td>
<td>91.1</td>
<td>2.78</td>
</tr>
<tr>
<td>A</td>
<td>132</td>
<td>0.90</td>
<td>2780</td>
<td>42.5</td>
<td>2.69</td>
</tr>
<tr>
<td>B</td>
<td>132</td>
<td>0.89</td>
<td>2815</td>
<td>94.5</td>
<td>6.36</td>
</tr>
<tr>
<td>C</td>
<td>130</td>
<td>0.80</td>
<td>3030</td>
<td>117</td>
<td>7.83</td>
</tr>
<tr>
<td>D</td>
<td>136</td>
<td>0.83</td>
<td>3070</td>
<td>86.3</td>
<td>6.80</td>
</tr>
<tr>
<td>A</td>
<td>140</td>
<td>0.71</td>
<td>3740</td>
<td>38.2</td>
<td>3.90</td>
</tr>
<tr>
<td>B</td>
<td>152</td>
<td>0.66</td>
<td>4280</td>
<td>79.8</td>
<td>10.85</td>
</tr>
<tr>
<td>C</td>
<td>136</td>
<td>0.78</td>
<td>3270</td>
<td>113</td>
<td>9.45</td>
</tr>
<tr>
<td>D</td>
<td>153</td>
<td>0.96</td>
<td>3010</td>
<td>71</td>
<td>7.00</td>
</tr>
</tbody>
</table>

(Continued on next page)

a Water is injected in a parallel direction to the surrounding air flow. Refer to Figure 9a.

b Water is injected in a direction normal to the surrounding air flow using four equally spaced circular orifices located along the periphery of the tube. Refer to Figure 9c.

c Water is injected in a direction normal to the surrounding air flow using two oppositely spaced rectangular orifices. Refer to Figure 9b.

d Water is injected in a direction normal to the surrounding air flow using two oppositely spaced 135° angular slots. Refer to Figure 9d.
Table 3. (Continued)

<table>
<thead>
<tr>
<th>Method of water injection</th>
<th>Air vel. (v_a) m./sec.</th>
<th>Water rate (Q_w) cm.³/sec.</th>
<th>Air-water ratio (Q_a/Q_w)</th>
<th>Drop mean-dia. (d_o) microns</th>
<th>Atom number (A_n x 10⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>183</td>
<td>0.64</td>
<td>5370</td>
<td>25.8</td>
<td>6.45</td>
</tr>
<tr>
<td>B</td>
<td>174</td>
<td>0.84</td>
<td>3920</td>
<td>71.4</td>
<td>11.70</td>
</tr>
<tr>
<td>C</td>
<td>174</td>
<td>0.70</td>
<td>4680</td>
<td>79.1</td>
<td>15.90</td>
</tr>
<tr>
<td>D</td>
<td>171</td>
<td>0.84</td>
<td>3840</td>
<td>59.5</td>
<td>9.45</td>
</tr>
<tr>
<td>A</td>
<td>190</td>
<td>0.71</td>
<td>5040</td>
<td>26.1</td>
<td>6.75</td>
</tr>
<tr>
<td>B</td>
<td>191</td>
<td>0.72</td>
<td>4970</td>
<td>52.5</td>
<td>13.28</td>
</tr>
<tr>
<td>C</td>
<td>202</td>
<td>0.57</td>
<td>6650</td>
<td>70.1</td>
<td>28.10</td>
</tr>
<tr>
<td>D</td>
<td>189</td>
<td>0.72</td>
<td>4940</td>
<td>49.3</td>
<td>12.41</td>
</tr>
<tr>
<td>A</td>
<td>235</td>
<td>0.86</td>
<td>5170</td>
<td>23.6</td>
<td>8.90</td>
</tr>
<tr>
<td>B</td>
<td>235</td>
<td>0.76</td>
<td>5830</td>
<td>43.4</td>
<td>20.2</td>
</tr>
<tr>
<td>C</td>
<td>239</td>
<td>0.57</td>
<td>7890</td>
<td>61</td>
<td>40.6</td>
</tr>
<tr>
<td>D</td>
<td>234</td>
<td>0.62</td>
<td>7170</td>
<td>32.8</td>
<td>19.0</td>
</tr>
<tr>
<td>A</td>
<td>274</td>
<td>0.90</td>
<td>5735</td>
<td>20.4</td>
<td>13.1</td>
</tr>
<tr>
<td>B</td>
<td>272</td>
<td>0.79</td>
<td>6460</td>
<td>36.9</td>
<td>27.0</td>
</tr>
<tr>
<td>C</td>
<td>271</td>
<td>0.69</td>
<td>7410</td>
<td>45</td>
<td>37.3</td>
</tr>
<tr>
<td>D</td>
<td>272</td>
<td>0.69</td>
<td>7400</td>
<td>29.4</td>
<td>24.0</td>
</tr>
<tr>
<td>A</td>
<td>296</td>
<td>1.04</td>
<td>5350</td>
<td>21.7</td>
<td>16.0</td>
</tr>
<tr>
<td>B</td>
<td>295</td>
<td>0.69</td>
<td>8010</td>
<td>26</td>
<td>28.0</td>
</tr>
<tr>
<td>C</td>
<td>296</td>
<td>0.93</td>
<td>6200</td>
<td>41.6</td>
<td>35.0</td>
</tr>
<tr>
<td>D</td>
<td>298</td>
<td>0.85</td>
<td>6590</td>
<td>30.3</td>
<td>26.8</td>
</tr>
<tr>
<td>A</td>
<td>309</td>
<td>1.03</td>
<td>5670</td>
<td>15.6</td>
<td>13.6</td>
</tr>
<tr>
<td>B</td>
<td>307</td>
<td>0.76</td>
<td>7640</td>
<td>23.4</td>
<td>26.4</td>
</tr>
<tr>
<td>C</td>
<td>306</td>
<td>0.79</td>
<td>7310</td>
<td>31.4</td>
<td>33.6</td>
</tr>
<tr>
<td>D</td>
<td>310</td>
<td>0.93</td>
<td>6260</td>
<td>24.4</td>
<td>22.7</td>
</tr>
<tr>
<td>A</td>
<td>316*</td>
<td>0.66</td>
<td>9010</td>
<td>7.5</td>
<td>7.27</td>
</tr>
<tr>
<td>B</td>
<td>314</td>
<td>0.66</td>
<td>8700</td>
<td>14.8</td>
<td>20.2</td>
</tr>
<tr>
<td>C</td>
<td>316</td>
<td>0.60</td>
<td>9950</td>
<td>23.6</td>
<td>32.4</td>
</tr>
<tr>
<td>D</td>
<td>318</td>
<td>0.58</td>
<td>10320</td>
<td>12.8</td>
<td>21.1</td>
</tr>
</tbody>
</table>

* This group of velocities represents the acoustic condition for the existing conditions of pressure and temperature.
increased, reaching a minimum value of 7.5 microns at acoustic velocity or 316 m. per sec. On the other hand, the atomization number $A_N$ increases with increasing air velocity to a maximum value of $16 \times 10^3$ at a velocity of 296 m. per sec. and then decreases rapidly as the acoustic velocity is approached.

When the liquid is injected normal to the surrounding air stream, for given values of $Q_w$, $Q_a/Q_w$, and $v_a$, the degree of atomization is decidedly poorer. This is especially true at low air velocities and $Q_a/Q_w$ less than 5000. For similar conditions, water injection by method C consistently gives the larger mean diameter $d_o$ as well as the larger atomization number, $A_N$. For this method of injection the mean-diameter varies from $123.7 > d_o > 23.6$ microns for a respective range of air velocities $107 < v_a < 316$ m. per sec. At the same time $A_N$ increases rapidly to a maximum value of $40.6 \times 10^3$ at a velocity of 239 m. per sec. and then decreases as the acoustic velocity is approached. Thus this method of injection appears the poorest of all tried.

Of the other two methods tested, method D appears to give the more satisfactory atomization. Although for air velocities in excess of 190 m. per sec. there isn't any remarkable difference. The atomization number is similar in order of magnitude at similar conditions. A maximum $A_N$ of $28 \times 10^3$ for method B occurs at a velocity of 295 m. per sec. A maximum of $26.8 \times 10^3$ for method D occurs at a
velocity of 298 m. per sec. In each case, a decrease of $A_N$ follows to acoustic velocity. The minimum mean-diameters found for methods B, C, and D are 14.8, 23.6, and 12.8 microns, respectively.

For similar liquid rates a graphical plot of the variation of the atomization number with air velocity is contained in Figure 11 for the various methods of water injection. This should be compared to Figure 12 which illustrates the variation of the mean-diameter $d_o$ with the air velocity under similar conditions.

In Table 4 the results are included for higher liquid rates and for air to water volume ratios less than 4500. Otherwise the arrangement of Table 4 is similar to Table 3. For similar conditions, again method A gave consistently more satisfactory atomization from the standpoint of a lower mean-diameter, $d_o$, and a lower atomization number than the other three methods tested. As the air velocity was increased the mean-diameter steadily decreased while the atomization number reached a maximum value of $11.45 \times 10^3$ at approximately 292 m. per sec. and then decreased to $9.4 \times 10^3$ at acoustic velocity.

Of the methods of injection which utilized water injection normal to the surrounding air flow, again method D appears to provide the more satisfactory atomization from the standpoint of a consistently lower mean-diameter and lower atomization number. In addition, method B is superior
Figure 11. Variation of the Atomization Number, $A_{nw}$, with Air Velocity, for Various Methods of water injection, and at similar flow rates.
Figure 12. Variation of the Droplet Mean-Diameter, $d_p$, with Air Velocity, for Various Methods of Water Injection, and at Similar Flow Rate.
(continued on next page)

<table>
<thead>
<tr>
<th>V, cm/sec</th>
<th>W, cm/sec</th>
<th>V/W ratio</th>
<th>Atom. Drop mean</th>
<th>Water Rate</th>
<th>Air Vel.</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55</td>
<td>0.50</td>
<td>1.11</td>
<td>1.034</td>
<td>1.08</td>
<td>0.96</td>
<td>a</td>
</tr>
<tr>
<td>0.30</td>
<td>0.25</td>
<td>1.20</td>
<td>0.97</td>
<td>1.146</td>
<td>0.84</td>
<td>b</td>
</tr>
<tr>
<td>0.45</td>
<td>0.40</td>
<td>1.12</td>
<td>0.98</td>
<td>1.064</td>
<td>0.87</td>
<td>c</td>
</tr>
<tr>
<td>0.60</td>
<td>0.50</td>
<td>1.20</td>
<td>1.06</td>
<td>1.025</td>
<td>0.74</td>
<td>d</td>
</tr>
<tr>
<td>0.75</td>
<td>0.60</td>
<td>1.25</td>
<td>1.09</td>
<td>1.012</td>
<td>0.78</td>
<td>e</td>
</tr>
<tr>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.000</td>
<td>1.00</td>
<td>f</td>
</tr>
</tbody>
</table>

The Air-Spray Atomization of Water

The Air-to-Water Flow Rate of Suspension of Fine Particles

Table 4.4

-67-
Table 4. (Continued)

<table>
<thead>
<tr>
<th>Method of water injection</th>
<th>Air vel. ( (v_a) ) m./sec.</th>
<th>Water rate ( (q_w) ) cm.(^3)/sec.</th>
<th>Air-water ratio ( (c_v/c_w) )</th>
<th>Drop mean-dia. ( (d_0) ) microns</th>
<th>Atom. number ( (A_N \times 10^{-3}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>175</td>
<td>1.28</td>
<td>2570</td>
<td>36.1</td>
<td>3.93</td>
</tr>
<tr>
<td>B</td>
<td>180</td>
<td>1.48</td>
<td>2305</td>
<td>69.3</td>
<td>7.14</td>
</tr>
<tr>
<td>C</td>
<td>181</td>
<td>1.35</td>
<td>2520</td>
<td>87.2</td>
<td>10.15</td>
</tr>
<tr>
<td>D</td>
<td>178</td>
<td>1.57</td>
<td>2145</td>
<td>63.6</td>
<td>6.19</td>
</tr>
<tr>
<td>A</td>
<td>189</td>
<td>1.65</td>
<td>2155</td>
<td>36.4</td>
<td>4.00</td>
</tr>
<tr>
<td>B</td>
<td>191</td>
<td>1.40</td>
<td>2580</td>
<td>67.4</td>
<td>8.89</td>
</tr>
<tr>
<td>C</td>
<td>193</td>
<td>1.05</td>
<td>3465</td>
<td>83.5</td>
<td>15.35</td>
</tr>
<tr>
<td>D</td>
<td>189</td>
<td>1.55</td>
<td>2300</td>
<td>62.2</td>
<td>7.29</td>
</tr>
<tr>
<td>A</td>
<td>234</td>
<td>1.94</td>
<td>2270</td>
<td>32.4</td>
<td>5.91</td>
</tr>
<tr>
<td>B</td>
<td>235</td>
<td>1.26</td>
<td>3510</td>
<td>62.3</td>
<td>17.65</td>
</tr>
<tr>
<td>C</td>
<td>240</td>
<td>1.25</td>
<td>3610</td>
<td>72.4</td>
<td>22.5</td>
</tr>
<tr>
<td>D</td>
<td>235</td>
<td>1.45</td>
<td>3050</td>
<td>57</td>
<td>14.2</td>
</tr>
<tr>
<td>A</td>
<td>274</td>
<td>1.66</td>
<td>3110</td>
<td>28.0</td>
<td>9.96</td>
</tr>
<tr>
<td>B</td>
<td>274</td>
<td>1.35</td>
<td>3820</td>
<td>52.5</td>
<td>23.2</td>
</tr>
<tr>
<td>C</td>
<td>268</td>
<td>1.56</td>
<td>3250</td>
<td>70</td>
<td>25.0</td>
</tr>
<tr>
<td>D</td>
<td>277</td>
<td>1.26</td>
<td>4150</td>
<td>50</td>
<td>23.7</td>
</tr>
<tr>
<td>A</td>
<td>292</td>
<td>1.65</td>
<td>3330</td>
<td>26.1</td>
<td>11.45</td>
</tr>
<tr>
<td>B</td>
<td>292</td>
<td>1.14</td>
<td>4850</td>
<td>40.7</td>
<td>26</td>
</tr>
<tr>
<td>C</td>
<td>294</td>
<td>1.37</td>
<td>4060</td>
<td>56</td>
<td>30.5</td>
</tr>
<tr>
<td>D</td>
<td>296</td>
<td>1.45</td>
<td>3860</td>
<td>42.1</td>
<td>21.6</td>
</tr>
<tr>
<td>A</td>
<td>311</td>
<td>1.94</td>
<td>3020</td>
<td>21.8</td>
<td>9.95</td>
</tr>
<tr>
<td>B</td>
<td>307</td>
<td>1.34</td>
<td>4330</td>
<td>35.5</td>
<td>22.7</td>
</tr>
<tr>
<td>C</td>
<td>308</td>
<td>1.44</td>
<td>4030</td>
<td>40.1</td>
<td>24.0</td>
</tr>
<tr>
<td>D</td>
<td>312</td>
<td>1.43</td>
<td>4100</td>
<td>27</td>
<td>23.0</td>
</tr>
<tr>
<td>A</td>
<td>316(^{f})</td>
<td>1.51</td>
<td>3950</td>
<td>14.9</td>
<td>9.4</td>
</tr>
<tr>
<td>B</td>
<td>316</td>
<td>1.33</td>
<td>4460</td>
<td>26.4</td>
<td>18.4</td>
</tr>
<tr>
<td>C</td>
<td>316</td>
<td>1.34</td>
<td>4460</td>
<td>28.2</td>
<td>20.0</td>
</tr>
<tr>
<td>D</td>
<td>318</td>
<td>1.40</td>
<td>4300</td>
<td>23.8</td>
<td>16.6</td>
</tr>
</tbody>
</table>

\(^{f}\) This group of velocities represents the acoustic condition for the existing conditions of pressure and temperature.
Figure 13. Variation of the Atomization Number, $A_n$, with Air Velocity, for Various Methods of Water Injection, and at Similar Flow Rates.
LEGEND

METHOD

WATER VOLUME<br>(GALLONS)

A  O  0  1.6
B  w  1  1.7
C  a  A  1.9
D  v  V  1.6

AIR VELOCITY IN METERS PER SEC.
Figure 14. Variation of the Droplet Mean-Diameter, \( d_\mu \), with Air Velocity, for Various Methods of Water Injection, and at Similar Flow Rate.
to method C. For increasing air velocities and at similar liquid rates a graphical plot illustrating the variation of the atomization number and mean-diameter is contained in Figure 13 and Figure 14, respectively.

An attempt was made to measure the angle of spray dispersion although this data was not included in Tables 3 or 4. However, it was found that for similar liquid rates as indicated in Table 3, the angle of spray dispersion was directly related to the air velocity if the liquid rate was relatively small and constant. With liquid injection parallel to the ambient air flow, as the air velocity increased from 107 m. per sec. to 316 m. per sec., the total angle of spray dispersion varied from 128 degrees to 56 degrees, respectively. At higher liquid rates, similar to those in Table 4, and consequently higher liquid velocities and for a similar air velocity range as above, the total angle of spray dispersion varied from 130 degrees to 86 degrees. The values for the angles given include the outer surface extremities of the spray. The major portion of the spray is concentrated near the center-line of the air and certain smaller droplets than the surface extremities. The values given are not necessarily a measure of the angle of the highest concentration.
VII. DISCUSSION AND INTERPRETATION OF RESULTS

A. Comparison with Previous Investigations

The portion of the present experimental investigation that may be directly compared to previous investigations is the one pertaining to a similar manner of liquid injection and ambient air flow. This similarity exists in the case where the liquid is injected in a direction parallel to the ambient air flow. For this type of flow an empirical formula relating the volume-surface mean diameter $d_o$ to all the pertinent variables was given by Nukiyama and Tanasawa (48) as

$$d_o = \frac{583 \sqrt{\sigma}}{v \sqrt{\rho}} + 597 \left( \frac{\mu}{\sqrt{\sigma \rho}} \right)^{0.45} \left( \frac{1000 \frac{Q}{Q_a}}{1.5} \right)$$. (1)

For the liquid utilized in the present investigation, distilled water at $20^\circ C$ ($\rho = 1$ gm. per cm.$^3$, $\sigma = 72.75$ dynes per cm., and $\mu = 0.01$ dyne-sec. per cm.$^2$), the formula reduces to

$$d_o = \frac{5000}{v} + 28.6 \left( 1000 \frac{Q}{Q_a} \right)^{1.5}$$. (2)

1 Taken from the International Critical Tables. See reference no. 26.
The water rates in the tests conducted were controlled to give small velocities at exit from the liquid tube. At no time did the liquid velocity exceed 0.95 m per sec., and the usual range was between 0.4 and 0.6 m. per sec. Consequently, for all practical purposes the relative velocity between the air and water, \( v \), is approximately equal to the air velocity, \( v_a \). The air velocities ranged from 106 m. per sec. to 316 m. per sec. The latter is the acoustic velocity for present conditions of pressure and temperature at the nozzle entry.

In Table 5 a comparison is made of the volume-surface mean diameter \( d_o \) between the results of the present experiments and those as calculated from equation 2 for given conditions of \( \frac{Q_a}{Q_w} \) and \( v_a \). In general, the agreement is good. This is especially true for \( 2,000 < \frac{Q_a}{Q_w} < 9,000 \) with concomitant air velocities up to acoustic. As expected, for a constant air velocity, \( v_a \), and for increasing \( \frac{Q_a}{Q_w} \) the mean-diameter, \( d_o \), decreases, as it again does for a constant \( \frac{Q_a}{Q_w} \) and increasing air velocities. In addition, the results indicate for the data obtained that for \( \frac{Q_a}{Q_w} > 5000 \), the principal controlling factor of the atomization process is the velocity, as previously shown by Nukiyama and Tanasawa. An inverse relationship exists between the mean-diameter and the air velocity for the conditions noted above.
Table 5.
Droplet Mean Diameter Comparison Between Experimental Tests and Nukiyama-Tanasawa Equation

<table>
<thead>
<tr>
<th>Air vel. (v&lt;sub&gt;a&lt;/sub&gt;) m./sec.</th>
<th>Water rate (Q&lt;sub&gt;w&lt;/sub&gt;) cm.&lt;sup&gt;3&lt;/sup&gt;/sec.</th>
<th>Air-water ratio Q&lt;sub&gt;a&lt;/sub&gt;/Q&lt;sub&gt;w&lt;/sub&gt;</th>
<th>Droplet mean dia. by exp. d&lt;sub&gt;o&lt;/sub&gt;(microns)</th>
<th>Droplet mean dia. by Tan.-Nuk. eq. d&lt;sub&gt;o&lt;/sub&gt;(microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>0.14</td>
<td>18,700</td>
<td>21.6</td>
<td>36.1</td>
</tr>
<tr>
<td>192</td>
<td>0.34</td>
<td>14,600</td>
<td>25.4</td>
<td>26.1</td>
</tr>
<tr>
<td>228</td>
<td>0.26</td>
<td>13,580</td>
<td>17.5</td>
<td>22.5</td>
</tr>
<tr>
<td>250</td>
<td>0.23</td>
<td>22,700</td>
<td>8.6</td>
<td>18.1</td>
</tr>
<tr>
<td>316</td>
<td>0.56</td>
<td>10,630</td>
<td>7.3</td>
<td>16.6</td>
</tr>
<tr>
<td>107</td>
<td>0.79</td>
<td>2,560</td>
<td>46.1</td>
<td>53.8</td>
</tr>
<tr>
<td>132</td>
<td>0.90</td>
<td>2,780</td>
<td>42.5</td>
<td>44.1</td>
</tr>
<tr>
<td>140</td>
<td>0.71</td>
<td>3,740</td>
<td>38.2</td>
<td>39.8</td>
</tr>
<tr>
<td>183</td>
<td>0.64</td>
<td>5,370</td>
<td>25.8</td>
<td>29.7</td>
</tr>
<tr>
<td>190</td>
<td>0.71</td>
<td>5,910</td>
<td>26.1</td>
<td>28.8</td>
</tr>
<tr>
<td>235</td>
<td>0.86</td>
<td>5,170</td>
<td>23.6</td>
<td>23.7</td>
</tr>
<tr>
<td>274</td>
<td>0.90</td>
<td>5,735</td>
<td>20.4</td>
<td>20.4</td>
</tr>
<tr>
<td>296</td>
<td>1.04</td>
<td>5,350</td>
<td>21.7</td>
<td>19.2</td>
</tr>
<tr>
<td>309</td>
<td>1.03</td>
<td>5,670</td>
<td>15.6</td>
<td>18.3</td>
</tr>
<tr>
<td>316</td>
<td>0.66</td>
<td>9,020</td>
<td>7.5</td>
<td>16.9</td>
</tr>
<tr>
<td>107</td>
<td>1.46</td>
<td>1,390</td>
<td>71.3</td>
<td>64.3</td>
</tr>
<tr>
<td>130</td>
<td>1.53</td>
<td>1,605</td>
<td>56.4</td>
<td>52.6</td>
</tr>
<tr>
<td>150</td>
<td>1.44</td>
<td>1,970</td>
<td>59.5</td>
<td>43.5</td>
</tr>
<tr>
<td>175</td>
<td>1.28</td>
<td>2,570</td>
<td>36.1</td>
<td>35.6</td>
</tr>
<tr>
<td>189</td>
<td>1.65</td>
<td>2,155</td>
<td>36.4</td>
<td>35.6</td>
</tr>
<tr>
<td>234</td>
<td>1.94</td>
<td>2,270</td>
<td>32.4</td>
<td>29.8</td>
</tr>
<tr>
<td>274</td>
<td>1.66</td>
<td>3,110</td>
<td>28.0</td>
<td>23.8</td>
</tr>
<tr>
<td>292</td>
<td>1.65</td>
<td>3,330</td>
<td>26.1</td>
<td>21.8</td>
</tr>
<tr>
<td>311</td>
<td>1.94</td>
<td>3,020</td>
<td>21.8</td>
<td>21.6</td>
</tr>
<tr>
<td>316</td>
<td>1.51</td>
<td>3,950</td>
<td>14.9</td>
<td>19.5</td>
</tr>
</tbody>
</table>
The principal ranges of disagreement are: 1. At \( \frac{Q_a}{Q_w} \) less than 2000 with concomitant air velocities less than 130 m. per sec. 2. At velocities greater than 280 m. per sec. with \( \frac{Q_a}{Q_w} \) greater than 10,000. 3. In the proximate region of acoustic velocity.

As the ratio \( \frac{Q_a}{Q_w} \) is progressively reduced along with the air velocity, there is an increasing tendency for several large drops to appear among a myriad of smaller drops and offset the effect upon \( d_o \) of the latter. This effect was particularly noticeable for air velocities less than 100 m. per sec. with concomitant ratios of \( \frac{Q_a}{Q_w} \) less than 1000. In this region the degree of uniformity of atomization rapidly decreases. Consequently, an accurate evaluation of the droplet mean-diameter is difficult. This may in part explain the discrepancy between comparative values at \( v_a = 107 \) m. per sec. and \( \frac{Q_a}{Q_w} = 1390 \), in that an altogether truly representative count of the sample was not made, or on the other hand the contribution in magnitude of the second term in equation 2 may not fully describe the tendency mentioned above.

The second and third discrepancies may in part be accounted for in the respective designs of the atomization apparatus, the precautions taken against the possible evaporation of the very small liquid drops, or in the manner in
which the liquid approaches the point of maximum air velocity. However, first considering equation 2 it is apparent that a lower limit of \( d_o \) exists. This lower limit is accentuated when operating with a convergent nozzle since the maximum possible velocity obtainable is acoustic. For air and assuming perfect gas behaviour with a reversible adiabatic expansion through the nozzle this velocity is dependent upon the average temperature at the nozzle entry and takes the form,

\[
v_c = 13.62 \sqrt{T_1} \text{ m. per sec.}
\]

where \( T_1 \) = average temperature at nozzle entry, °F. abs. For values of \( \frac{Q_a}{Q_w} > 10,000 \) the effect of the second term of equation 2 is negligible. Assuming \( T_1 = 560^\circ \text{F.} \) abs. then \( v_c = 323 \text{ m. per sec.} \) which places a lower limit upon the mean-diameter \( d_o \) of 15.5 microns. At no time during the present tests was the nozzle entry temperature greater than 560° F. abs. A repetition of tests at acoustic velocity \( \frac{Q_a}{Q_w} > 10,000 \), and \( T_1 < 560^\circ \text{F.} \) abs., indicated a lower limit of \( d_o \) to be between 6 and 7 microns.

As previously mentioned, for \( \frac{Q_a}{Q_w} > 5,000 \) and increasing air velocities, \( d_o \) becomes smaller and tends toward a lower limit. However, in the proximate vicinity of acoustic velocity a sudden drop of \( d_o \) occurred, as much as 3 to 4
result in temperature that some water droplets greater than
drops were sprayed to which vectorat air phases. The
this view. In these experiments various sizes of water
maximum vectorat some experiments of lane (74) (Is)
subsequently at all of the samples were evenly distributed the section of
these experiments with resultant. This appears to be true even though
the protonation at the corresponding some protonation or the
maximum vectorat if it is interested in the point of maximum vectorat or the
moment, subsequent tests interested that it not all of the
condensation imposed on the desert. In these experiments the
the maximum vectorat. This is necessary as before the latter at time
contact with the surrounding air before the latter comes in
the some of the which comes in
In the maximum: range, (74, 75, 76) experiments these
mean-diameter d o vary from 7 to 7.5 microns.
the platitude was found when these patents occurred, the
number of duplicate tests were made no consistent drop of
a rather unprecedented droplet dispersibility. Although a
distributions occurred in the exact speck pattern resulting in
was reduced below the artificial pressure rateo, patenting
mena. As the ratio of nozzle discharge to initial pressure
consequent increased turbulence may account for this phase-
aerosol condensation. A possible turbulent shock condensation and
microns, even though the vectorat changed slightly to attain
5 microns in diameter will remain intact in air moving at sonic velocity relative to the drops. Thus some fairly large drops may be simply accelerated through the region of high velocity without undergoing a further breakup.

B. Effect of Liquid Tube Position on Atomization

For a given liquid, the results indicate that with liquid injection parallel to the ambient air flow, the finer atomization occurs in the region of maximum velocity. Also, for sufficiently large $\frac{Q_a}{Q_w}$ the principal controlling factor of the degree of atomization is the air velocity if the liquid velocity is small, or the relative velocity between the air and liquid, if the latter is substantial. For a given liquid and $\frac{Q_a}{Q_w}$ greater than 5000, the droplet mean-diameter is primarily inversely related to the air velocity. For values of $\frac{Q_a}{Q_w}$ less than 5000, in addition to the air velocity, the mean-diameter is also affected by the magnitude of $\frac{Q_a}{Q_w}$. As expected, for a given air velocity, the mean-diameter is inversely related to $\frac{Q_a}{Q_w}$.

In a convergent nozzle the maximum attainable velocity is the acoustic velocity. The magnitude of this velocity is principally affected by the average temperature at the entry section of the nozzle. Consequently, preheating the air entering the nozzle would proportionately raise this velocity. However, the added advantage of preheating the air may
be offset by the possible evaporation of the smaller drops. If air at normal atmospheric temperature is utilized in a practical installation there appears to be a limit as to the fineness of droplet size attainable for a given design. For the particular unit used and using distilled water under normal atmospheric conditions, the limiting mean-diameter, \( d_0 \), is found to be approximately 7 microns. Increasing the magnitude of \( Q_a/Q_w \) does not appear to affect this size by any appreciable amount.

As the results indicate for values of \( Q_a/Q_w \) less than 5000 and air velocities less than 150 m. per sec., appreciable differences in the droplet mean-diameters may be found depending upon where the liquid is injected into the air stream. For the size of nozzle used and under the above circumstances, there is the possibility of a sizeable portion of the atomized spray striking the inner walls of the straight section of the nozzle when the liquid is injected at section e-e. This of course could be appreciably obviated by an increased size ratio of nozzle diameter to tube diameter. However, this condition is entirely obviated at air velocities higher than those mentioned as well as \( Q_a/Q_w \) greater than 5000. In excess of the above values, there is very little difference between the mean-diameters at section t-t and section e-e. The principal factor for this difference is the somewhat lower velocity at section e-e. This
illustrates the fact that liquid injection should occur at the section of maximum velocity. Injection upstream of the aforementioned section, although satisfactory atomization may occur for sufficiently high values of $v_a$ and $Q_a/Q_w$, results in a lesser degree of atomization even though the atomized particles may subsequently pass through the region of maximum velocity. Thus some degree of incompleteness of atomization occurs. The droplets are accelerated through this section without undergoing a substantial further breakup. On the other hand, if a small range of drop sizes is desired, and since the atomized spray has a tendency to follow the air flow lines an additional advantage may be had in injection a short distance up or downstream of the section of maximum velocity. Thus in a design where the position of liquid injection may be varied, a relatively larger angle of spray dispersion may be obtained for injection upstream rather than injection at the exit of the nozzle. This is possible without an appreciable concomitant sacrifice in droplet size. In addition, injection a short distance downstream produces a smaller angle of dispersion than that occurs at the exit of the nozzle. The results further suggest that if the velocity is constant throughout the straight section of the nozzle, the length of this straight section does not sensibly affect the droplet sizes obtained. Of course, this is valid only if there is no extensive spray impingement upon the nozzle walls.
C. Effect of Method of Liquid Injection Upon Atomization

If liquid is injected through a tube in a direction parallel to the ambient air flow at a constant liquid rate for a given air velocity, one observes a node of liquid shaped somewhat like an arrowhead projecting some distance out of the end of the tube. This node is liquid throughout and at its apex there occurs a rapid disruption resulting in the spray formation. As the air velocity is increased at a constant liquid rate, the length of this node decreases until it almost disappears from view at extremely high air velocities. This gives the impression that the liquid is atomized immediately upon leaving the liquid tube. This phenomenon is seen also to occur for the other methods of injection tested.

As the results indicate, for similar conditions of $Q_w$, $Q_a/Q_w$, and $v_a$, method A of liquid injection gives more satisfactory atomization than in the other methods tested. Thus it appears that the normal process of attenuation of the liquid node, followed by ligament formation, and finally drop formation is impaired to some extent in the latter methods tested. Two principal physical factors may contribute to this. One of these is the sealed end of the liquid tube. As the liquid flows over the outer surface and sealed end of the tube a partial static air space occurs immediately after the sealed end. Thus for a given $Q_w$, $Q_a/Q_w$, and $v_a$,
this causes the liquid node to be projected farther down-
stream of the exit of the nozzle than in the case of parallel
flow. This results, for identical conditions, in a longer
node length than that obtainable for parallel flow. Conse-
quently, the node stretches over a larger range where the
air velocity is rapidly decreasing. This is particularly
noticeable at low air-velocities and low values of $\frac{Q_a}{Q_w}$.

Another factor, which may contribute to poorer atomiza-
tion in normal injection to the ambient air flow, is the
projection of a liquid layer over the liquid tube into the
air stream. As Figure 8 indicates the distance through
which the air flows before reaching the nozzle exit is rela-
tively long, and the initial disturbances caused by the
small liquid tube along the length of air flow will be sub-
stantially obviated by the time the air reaches the exit of
the nozzle. In addition, the precaution of using low liquid
velocities was taken, thereby mitigating the effect of the
liquid velocity upon the average horizontal component of
relative velocity between the air and liquid. However, the
presence of a liquid projection may have resulted in a dis-
ruption of the air flow at the surface of contact between the
air and liquid. Consequently, a partial condition of impact
may occur within this region, and impair the normal process
of "drawing out" and "peeling away" of the liquid surface as
is normal in parallel liquid injection. Further evidence of
the above view was found in that no consistent angle of
spray dispersion existed for liquid injection normal to the air flow.

As the results indicate, differences in the quality of atomization occurs in that category of experiments where the liquid is injected normal to the ambient air flow. These differences are due principally to the manner and amount of surface presented to the passing air stream. Method D of liquid injection, where a thin liquid sheet extending over a large peripheral arc exposed to the region of maximum air velocity is used, gives a larger liquid surface contact than in methods B and C. However, remarkable differences between methods D and C did not occur. Although upon ejection through the peripherally located circular orifices the liquid had a tendency to spread over the outer surface of the liquid tube, this amount of spread was incomplete as compared to method D. This in addition to the partial liquid buildup at the orifices may be the reasons for a somewhat inferior quality of atomization for method B than for method D. In method C where rectangular orifices are used with the longer side collinear with the axis of the tube, gives the poorest quality of atomization. This may be expected due to the liquid buildup along the length of the orifice, resulting in an inadequate spread of the liquid surface.

In light of the foregoing statements, an improved quality of air-stream atomization (for a given $Q_w$, $Q_a/Q_w$, and $v_a$) may possibly result if a double annular air stream
is used. That is to say, with liquid fed in an annular manner such that its inner annular surface comes in contact with a high velocity air stream as well as its outer surface. This may result in improved attenuation of the liquid surface and ligament formation culminating in smaller drop sizes.

Values of the atomization number, $A_N$, indicate that considerable kinetic energy of the air is needed to accomplish a fine degree of atomization. Thus the major portion of the energy upon the completion of the atomization is within the kinetic energy of the water droplets and in leaving kinetic energy of the air.

The inverse of the atomization number indicates the relative inefficiency of the atomization process in forming small drops having a combined large surface area. Of course, the smaller the number, the more efficient is the process. However, to obtain atomization such that the drops are at least less than 100 microns, this number must necessarily be large.

As the results indicate, for a certain liquid rate and for increasing air velocities, the magnitude of $A_N$ increases to a maximum and then decreases rapidly. Thus at a given liquid rate to reach a certain small drop size, a considerable amount of kinetic energy of the air is needed. However, a comparison of Figures 11 and 13 with Figures 12 and 14 indicates that passing beyond the maximum $A_N$ in Figures 11 and 13 results in comparatively smaller increasing
changes of air kinetic energy to obtain proportionately smaller drop sizes. Thus if fine atomization is desired it would be preferable to use air velocities to the right of this maximum $A_N$.

For a given practical application utilizing water atomization, for example, usually a given rate of liquid is necessary as well as a certain range of drop sizes. Therefore, the atomization number for a given application would reduce to

$$A_N = C_1 Q_a v_a^2 \rho_a$$

where $C_1$ is a constant based on the value of $Q_w$ and $d_o$ desired. Consequently, the atomizing unit giving the lowest value of $A_N$ is preferable. Furthermore, the experimental results indicate certain optimum limits in regard to airstream atomization. This allows the postulation of an optimum value of $A_N$. For a given liquid and $Q_a/Q_w$ less than 1000 and $v_a$ less than 100 m./per sec. the degree of fineness and uniformity of atomization diminishes rapidly. On the other hand, for a given liquid with $Q_a/Q_w$ greater than 5000 the mean-diameter, $d_o$, is primarily dependent upon the air velocity. That is, for a given air velocity and a liquid at a certain temperature an increase in the value of $Q_a/Q_w$ greater than 5000 will not perceptibly change the size of the drops obtained. Thus $A_N$ would be unnecessarily increased for the degree of atomization obtained. This allows one to
postulate a certain optimum $A_N$.

In general

$$A_N = \frac{\rho_a d_o}{12\sigma} \frac{Q_a}{Q_w} v_a^2$$

$$A_N(\text{optimum}) = \frac{417}{\sigma} \rho_a d_o v_a^2$$

for water

$$A_N(\text{optimum}) = 5.75 d_o v_a^2 \rho_a$$

The change in magnitude of the air density, $\rho_a$, will not contribute substantially to a change in $A_N$. Thus an ideal condition for very fine atomization and lowest value of $A_N$ for this design (air temperature of 78° F. at entry of nozzle and a standard pressure atmosphere) would be at $v_a = 316$ m. per sec. where $d_o = 7.5$ microns, approximately.

$$A_N(\text{fine atomization}) = 5900$$
VIII. CONCLUSIONS

In the present experimental investigation, the atomizing unit consisted of a glass convergent air nozzle with a short straight section and a concentric hypodermic tube for the purpose of water injection. In this arrangement it is possible to vary the point of water injection along the axis of air flow as well as the manner and amount of liquid surface presented to the ambient air flow. In light of this investigation, the following conclusions can be made.

1. Among the various methods of liquid injection tested, liquid injection parallel to the ambient air flow gives a better degree of atomization than liquid injection normal to the ambient air flow.

2. Differences in the degree of atomization with liquid injection normal to the air flow depend principally upon the amount of liquid surface that comes in contact with the high velocity air.

3. In light of the above two conclusions, the most important factor governing the degree of atomization of a given liquid at certain values of $v_a$, $Q_a/Q_w$, and $Q_w$ is the manner in which liquid injection is used so as not to impair the normal process of attenuation of the liquid surface, ligament formation, and finally drop formation. This
condition appears to be best satisfied when the liquid is
injected parallel to the ambient air flow and the air flow
lines approach the position of liquid injection uniformly
and undisturbed.

4. With liquid injection parallel to the ambient air
flow for best degree of atomization the mass of liquid should
enter the region of maximum velocity.

5. Since a convergent air nozzle is used, the maximum
velocity attainable is acoustic. At this velocity (without
the use of preheated air) and for $Q_a/Q_w$ greater than 5000 the
mean-diameter tends towards a lower limit. This lower limit
may range between 5 and 7 microns for the atomizing unit
used.

6. For air velocities less than 100 m. per sec. and
$Q_a/Q_w$ less than 1000 the degree of uniformity of drops de-
creases rapidly. For $Q_a/Q_w$ greater than 5000, the droplet
mean-diameter is independent of the liquid rate and depends
on the air velocity (for low liquid velocities), decreasing
as the air velocity increases.

7. The angle of spray dispersion increases as the
point of liquid injection is varied from upstream of the
exit of the nozzle and on through the straight section of the
nozzle. For air velocities greater than 150 m. per sec.,
the droplet mean-diameter does not appreciably vary over an
interval which with respect to the nozzle exit extends
through the straight and one-half an inch downstream.
Consequently, the spray angle may be varied by manual adjustment.

8. At a particular liquid rate and as the air velocity is increased, the kinetic energy of the air needed to form progressively smaller drops increases rapidly. This rate of energy increase is much higher than the rate of decrease in size of the droplets formed. A certain maximum is reached after which any further increase in the air velocity results in a decrease of the kinetic energy of air needed to perform a progressively higher degree of atomization.

9. For a certain liquid injected at a given rate, the atomization number, $A_N$, or the ratio of the kinetic energy of the air to the actual superficial surface potential energy of the droplets formed can serve as an adequate index of the quality of air-stream atomization for various atomizing units. Furthermore, for droplet formation whose mean-diameter, $d_o$, is less than 50 microns the above ratio is very large. This indicates the relative inefficiency of the air-stream atomization process. For example, an ideal condition of very fine atomization for the unit used would be for $v_a = 316$ m. per sec., $d_o = 7.5$ microns, and $Q_a/Q_w = 5000$. This gives a value for $A_N$ or the energy ratio of 5900. Thus the major portion by far of the energy, upon completion of the atomization, is within the kinetic energy of the liquid droplets and the kinetic energy of the leaving air.
IX. ACKNOWLEDGMENTS

The author wishes to express his appreciation to Professor Henry M. Black, Head of the Department of Mechanical Engineering, for his encouragement and suggestions during the course of this study and for his critical proof-reading of the manuscript. The author is also indebted to Dr. Ernest W. Anderson, Professor of Mathematics and Aeronautical Engineering, for his criticisms and suggestions.
X. LITERATURE CITED


46. and 138. 1938. 2nd Rpt. Ibid. 4 (No. 15):

47. and 63. 1939. 3rd Rpt. Ibid. 5 (No. 18):

48. and 68. 1939. 4th Rpt. Ibid. 5 (No. 18):

49. and 6th Rpt. Ibid. 6 (No. 22): Feb., 1940.

50. and 6th Rpt. Ibid. 6 (No. 23): Feb., 1940.


XI. APPENDICES
Appendix A. Nomenclature

\( m_a \) = mass rate of flow of air, gm. per sec.
\( m_w \) = mass rate of flow of water, gm. per sec.
\( v_a \) = air velocity, m. per sec.
\( v_w \) = water velocity, m. per sec.
\( E_s \) = actual superficial surface potential energy of the droplets formed by the atomization of one gm. per sec. of liquid sprayed.
\( E_k \) = total kinetic energy of the water droplets, dyne-cm. per sec.
\( i-i \) = section of flow immediately preceding the region of contact between air and water.
\( f-f \) = section of flow where atomization is completed.
\( S_o \) = actual superficial surface area produced by the atomization per cm.\(^3\) of liquid sprayed.
\( \bar{\sigma}_w \) = mean surface tension of the water, dynes per cm.
\( Q_w \) = volume rate of water flow, cm.\(^3\) per sec.
\( \rho_a \) = air density at the exit of the nozzle, gm. per cm.\(^3\).
\( Q_a \) = volume rate of air flow, cm.\(^3\) per sec.
\( d_o \) = volume-surface mean diameter or the Sauter mean diameter, where \( d_o = \frac{\Delta x^3}{\Delta x} \frac{\Delta n}{\Delta x} \) and \( x-\Delta x < x < \) \( x+\Delta x \) and \( \Delta n \) is the fractional count of the total number of drops whose diameter is \( x \).

\(^1\) Symbols arranged in order of occurrence in the subsequent development of the atomization number.
Appendix B. Development of the Atomization Number

In the air-stream atomization phenomenon the principal source of energy in converting the bulk liquid into a larger surface consisting of many droplets is the kinetic energy of the air. As previous investigations indicate the atomization occurs rapidly, and is completed in the proximate vicinity of the point of liquid injection. Furthermore, the work of Maxwell and Rayleigh (40,54,55) assumes the phenomenon to be principally a dynamic one. This view was substantiated by Castleman (6) with the use of experimental data as well as by Merrington and Richardson (43) and Schweitzer (64).

In the event the temperature of the liquid and the air at the point of contact are very nearly the same, and since the process occurs so rapidly the atomization will be very nearly adiabatic in nature. However, a slight rise in temperature may be expected due to the frictional contact between the high velocity air and the liquid. If during the atomization process the temperature change of the high velocity air and the liquid is negligible and, consequently, the enthalpy change of the air and water is negligible, a dynamic energy balance may be made. This is tantamount to saying the process is principally governed by dynamic rather than thermodynamic factors.
Assume an energy balance is made between a section i-i immediately preceding the region of contact between the air and the liquid, and a section f-f where the atomization is completed. That is,

\[
\frac{10^4}{2} m_a v_a^2 + \frac{10^4}{2} m_w v_w^2 \quad i-i = \begin{bmatrix}\ \end{bmatrix}^{f-f}
\]

where each term has the units of dyne-cm. per sec. \( E_s \) is the actual superficial potential energy of the droplets formed by the atomization of one gm. per sec. of liquid sprayed. If the velocity of the water leaving the liquid tube or nozzle is small compared to the velocity of the air, a useful relation may be determined. This relation is the ratio of the kinetic energy of the air to the actual superficial surface potential energy of the droplets formed by the atomization. This dimensionless energy ratio is termed the atomization number, \( A_N \). Therefore, omitting the subscript i-i it follows that

\[
A_N = \frac{10^4 m_a v_a^2}{2E_s} = \frac{10^4 \rho_a v_a^2}{2S_o \sigma_w v_w}
\]

and

\[
E_s = S_o \sigma_w v_w \text{ dyne-cm. per sec.}
\]

where \( S_o \) is the actual superficial surface area produced by
the atomization per one cm.\(^3\) of liquid sprayed, where \(\sigma_w\) is the mean surface tension of the water, \(Q_w\) is the volume rate of flow of the water in cm.\(^3\) per sec., \(\rho_a\) is the air density at the exit of the nozzle in gm. per cm.\(^3\), \(Q_a\) is the volume rate of flow of the air in cm.\(^3\) per sec., and \(v_a\) is the air velocity in m. per sec.

Since

\[ S_o = \frac{6 \times 10^4}{d_o} \quad \text{cm.}^2 \text{ per cm.}^3, \]

where \(d_o\) in microns is the volume-surface droplet mean diameter or the Sauter (60,61) mean diameter.

Then

\[ A_N = \frac{\rho_a d_o Q_a v_a^2}{12 \sigma_w Q_w}. \]

If the liquid sprayed is water and at an average temperature of 20\(^\circ\) C., we may assume \(\sigma_w = 72.75\) dyne per cm.

\[ A_N = \frac{\rho_a}{870} \frac{Q_a}{Q_w} d_o v_a^2. \]

It may be seen that the atomization number or the energy ratio is directly proportional to the cube of the air velocity, since \(Q_a = \frac{\pi}{4} x 10^2 D^2 v_a\), where \(D\) is the exit diameter of the air nozzle in cm.\(^2\). For purposes of analysis it is best to leave the above in the present form.