1964

Peak heat flux in nucleate boiling heat transfer

Bernard Patrick Breen

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PEAK HEAT FLUX
IN NUCLEATE BOILING HEAT TRANSFER

by

Bernard Patrick Breen

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The use of surface thermocouples in the measurement of boiling heat flux was investigated. Acetone was boiled from a steam heated, polished, horizontal, stainless steel tube. Single wire thermocouples (diameter equal to 0.010 inches) were spot welded at different positions on the tube. Measurements recorded in nucleate and transition boiling showed characteristic differences which were analyzed and are reported. A point of strong discontinuity in the measured boiling surface temperature was evident when the thermocouple site went from nucleate into transition boiling. A method of promoting early transition boiling near the thermocouple site was developed. From the information contained in this thermocouple signal the approach to peak heat flux could be predicted.
INTRODUCTION

Boiling as a means of heat transfer has been known to man almost since his discovery of fire. The complexity of this phenomenon may be realized when one considers that three phases are present: liquid, vapor and solid surface. Heat is transferred from solid to liquid which may or may not be at its saturation temperature. The liquid undergoes a phase change thus forming saturated vapor which may now be superheated by heat transfer from the solid. The liquid and the vapor in contact with the solid surface, where a dynamic flow equilibrium is maintained, are both superheated to some degree. Analysis of the vapor-liquid system presents a problem in two-phase, simultaneous heat, mass and momentum transfer. The addition of the solid phase to this analysis requires, among other things, consideration of the thermal conductivity of the solid material. However, the random distribution of boiling sites on the solid is perhaps the most perplexing of all considerations. This results in a statistical distribution of liquid and vapor flow columns for which a classical hydrodynamic formulation of the problem may not readily be made.

The lack of scientific knowledge concerning boiling becomes evident when one realizes the tremendous range of pertinent variables which have been recently encountered. Within the last few years engineers have succeeded in
achieving heat fluxes to boiling water greater than 20,000,000 BTU per hr. per sq. ft., which is equivalent to the energy flux from the surface of the sun. For many years chemical engineers have used rules of thumb when designing evaporators, boilers, and distillation equipment. Only in recent decades has boiling become the subject of scientific investigation.

The first scientific study of boiling was made by Nukiyama in 1934 (33). He presented the boiling curve shown in Figure 1. The three mechanisms by which liquids boil are nucleate, transition and film boiling. Nucleate boiling, as the name implies, consists of bubbles forming at small imperfections, or nuclei, on the heating surface. A photograph of this type of boiling is shown in Figure 2. This regime of boiling is represented by region A-C of the curve shown in Figure 1. Film boiling is characterized by the presence of a smooth vapor film completely covering the heating surface. This type of boiling occurs at relatively large temperature differences. A photograph of film boiling is shown in Figure 4. This regime is represented by region D-E of Figure 1. Transition boiling occurs during the transition between the other two regimes. A critical condition in two-phase flow occurs at the boiling surface when the shear forces produced by the counter-current flow of liquid and vapor become equal to the bouyant forces which cause vapor removal. When these forces become equal,
Figure 1. Typical heat flux curve
Figure 2. Nucleate boiling, 3/8 inch dia. tube
(methanol, $\Delta T_s = 67^\circ F$) (39)

Figure 3. Transition boiling, 3/8 inch dia. tube
(methanol, $\Delta T_s = 112^\circ F$) (39)

Figure 4. Film boiling, 1/4 inch dia. tube
(isopropanol, $\Delta T_s = 280^\circ F$) (8)
the vapor will tend to remain at the solid surface. Thus a peak heat flux is reached (point C), and transition boiling, as shown in Figure 3 and represented as region C-D in Figure 1, develops.

The physical phenomena pictured in Figures 2, 3 and 4 and represented as a continuous curve in Figure 1 present a problem in the design of boiling heat transfer equipment. Equipment should operate at maximum heat flux but there should be no danger of film boiling developing because of the accompanying decrease in heat flux. The problem of controlling heat flux is complicated by the fact that in the nucleate boiling regime the heat transfer coefficient, \( h \), varies approximately with the square of the temperature difference, \( \Delta T_s \), between the heating surface and the liquid (1). Thus the heat flux, \( Q/A \), varies with the temperature difference according to the relation:

\[
\frac{Q}{A} = h\Delta T_s = C(\Delta T_s)^3,
\]

where \( C \) is a proportionality constant.

Because of the strong dependence of heat flux upon temperature difference it is evident that great savings in heat transfer area may be realized by operating near the peak heat flux. For a temperature input system this would mean as close as possible to the peak difference. For a power input system this would mean the peak heat input. However, when equipment is operating at the highest possible
temperature difference, transition boiling may develop. As a result of the negative slope of the heat flux versus temperature driving-force relationship (Figure 1, section C-D) there exists the further danger that film boiling may develop. As a result of the sudden increase in temperature as film boiling develops, for a constant power source "burnout" is said to occur at point C.

In nuclear reactor technology, where the heat output is the independent variable of the heat transfer system, it is particularly important that the burnout heat flux is never exceeded at any point in a tube bundle. In space applications problems dealing with large heat fluxes during phase change often arise. Bouyant forces resulting from system acceleration become very important in controlling burnout or peak heat flux.

In the general case, operation of boiling equipment near the peak heat flux is difficult because there is no way of accurately predicting the peak heat flux or the corresponding temperature driving force. This is especially true when fouling occurs under service conditions. Transients in fluid flow, temperature, pressure, void fraction and system acceleration further increase the difficulty of operation at maximum heat flux.

The purpose of this work was to determine and analyze measurements which could be made by use of thermocouples welded to the boiling surface. A thermocouple measuring
device distorts the temperature which it is to measure. The wire acts as a cooling fin extending from a point on the boiling surface. This point is therefore cooled and a distorted temperature measurement is recorded.

A mathematical model of this fin effect was developed and used to estimate and minimize the temperature distortion. Experimental data were recorded and analyzed for all regimes of boiling. The useful information resulting from these measurements is discussed. A method for the prediction of peak heat flux was developed and tested.
REVIEW OF LITERATURE

A large amount of research has been directed toward nucleate boiling and the determination of peak heat flux. Safe limits of operation have been defined as is evidenced by operation of boiling water nuclear reactors and ordinary industrial boiling heat exchangers. Studies have been concerned with both the gathering of experimental data and the theoretical prediction of the peak nucleate boiling heat flux.

Nucleate Boiling

Equations which have been derived to describe nucleate boiling vary in their manner of derivation. Hughmark (24) considered thirty-two variables as effecting nucleate boiling. By fitting data with a computer he reduced these to eight variables obtaining an equation with proper exponents.

Foster and Zuber (16), Foster and Greif (15), Gilmore (19), Rohsenow (36), and others have considered nucleate boiling as being similar to single-phase forced convection. They made the supposition that most of the heat is transferred to the liquid and that characteristic lengths and velocities may be determined from bubble dimensions. Their correlations describing nucleate boiling were based upon a relationship between the Nusselt number, Nu, Reynolds number, Re, and Prandtl number, Pr, such that: \( \text{Nu} = \Phi (\text{Re}, \text{Pr}) \).
Ellion (13) has shown that in pool boiling the bubble radius and radial growth velocity, which he determined experimentally, are suitable for use in evaluating a Reynolds number for flow adjacent to the heating surface.

Other investigators have assumed physical models from which they were able to derive equations describing nucleate boiling. These models are of a necessity simple in nature and do not adequately describe the statistical nature of nucleate boiling. Based upon such simplifying assumptions Levy (28) presented an equation describing nucleate boiling heat transfer.

**Peak Nucleate Boiling Heat Flux**

Equations which have been derived to predict the maximum heat flux generally give better results. These equations are derived from analyses similar to those described above. Rohsenow and Griffith (37) have presented a correlation based upon the similarity between the peak heat flux and the flooding of a distillation column. Zuber, Tribus, and Westwater (42) have presented an equation which regards a vapor jet in a liquid as a physical model. They applied Helmholtz and Taylor instability criteria to determine the maximum vapor removal rate. Berenson and Moissis (4), Chang (9), and others (7, 14) have considered various possible critical conditions in obtaining equations which predict the peak heat flux.
Nucleate boiling correlations generally do not take into account the physical properties of the boiling surface. Griffith and Wallis (20), Hsu (23) and others have studied surface affects. Vapor-solid contact angles have been studied in relation to surface roughness and wetting properties. It is generally accepted that surface roughness has a strong effect in nucleate boiling, but the value of the peak heat flux is independent of surface conditions. Thermal conductivity of the solid is not usually considered in boiling models.

Emmerson (14) presents fifteen empirical and semi-empirical correlations for calculation of the peak heat flux for various geometry, flow, and subcooling conditions. However, in the same article, he states that there is an unexplained difference of a factor of two in absolute value of burnout flux between U. S. and U. S. S. R. values. It is evident then that in order to design equipment which will operate near the peak heat flux it is still necessary to determine the stability of operation by experimentation (2, 3, 6, 10, 25, 29, 30).

An alteration of the boiling curve has been attempted by mixing chemical additives with the boiling liquid. For organic additives it has been found that film boiling heat fluxes may be higher, but a substantial peak heat flux still exists (12). There is evidence that by use of ionic additives the temperature at which peak heat flux occurs may be
changed within certain limits (27).

Zuber and Tribus (41) state that the temperature at which peak heat flux occurs is relatively unimportant in the operation of boiling equipment. The peak heat flux is a hydrodynamic phenomenon and its absolute value is independent of the temperature at which it occurs. However, no method of making the heat flux independent of source temperature has been devised. A mechanism could be designed to give a variable temperature drop in the material separating the heat source from the boiling liquid in order to maintain a surface temperature corresponding to the peak heat flux. This would make the attainment of peak heat flux independent of source temperature for temperature-input systems and transient upsets in heat-input systems. A recent demonstration of this principle (insulation of the heating surface in order to increase the boiling heat transfer coefficient and thus the total heat flux) involved coating the boiling surface with such heat insulators as varnish, asbestos, and vaseline (11). A series of unsteady-state quenching experiments were made using liquid nitrogen as the cooling fluid. Increases in the quenching rate of up to 600% were reported. It is significant to note that peak heat flux occurs at a low value of approximately $\Delta T_s$ equal to $7^\circ F$ for liquid nitrogen at atmospheric pressure.

A means of controlling a variable temperature drop would depend upon an indication of the approach to peak heat
flux. An effective indication signal would have to be independent of surface conditions, fouling, system geometry, orientation, acceleration and other system variables. An indication signal predicting the approach of peak heat flux is not discussed in the literature. An understanding of the nature of peak heat flux would prove helpful in the development of such an indicating signal.

Significant advances in the theoretical analysis of peak nucleate boiling heat flux involve study of the change in the vapor removal mechanism from an intermittent to a continuous process (4, 42). The subsequent analysis of the continuous vapor columns (flowing upward) and liquid columns (flowing downward) involves Taylor-Helmholtz instability considerations. It appears that the ultimate analytical solution of the process of hydrodynamic transition at peak heat flux will depend upon the determination of the effect of these counterflow columns upon each other. These columns of liquid and vapor are not distributed over the surface in a homogeneous manner. It has been shown that the population of active sites in nucleate boiling fit a Poisson distribution quite well (18). When developed, the statistical relationship between the nearness of boiling sites (which follow a completely random spatial distribution) and the effective column diameters for flow of vapor and liquid will aid greatly in the analytical solution of the hydrodynamic problem of peak heat flux.

The recent work of Kirby (26), done under the supervision of Westwater, sheds significant light on the flow
situation at peak heat flux. Photographs and motion pictures were taken from below a glass boiling surface. These show that at high heat fluxes there exists large vapor regions above the heating surface and that a thin liquid film is present between the vapor and solid while nucleate boiling exists. They found that only 9% of the heat flux could be attributed to bubble formation at the surface. It is implied that the departure from nucleate boiling occurs at the point where the liquid film disappears. Whether this point corresponds to the beginning of transition boiling or film boiling is not stated.

Transition Boiling

The existence of a transition boiling mechanism has long been a matter of discussion. Santangelo and Westwater (39, p. 1608) gave the following description of transition boiling: "Most prior workers have failed to realize that this boiling is entirely different from both nucleate boiling and film boiling. No active nuclei exist. In fact, no liquid-solid contact exists either. The tube is completely blanketed by a film of vapor, but the film is not smooth nor stable. The film is irregular and is in violent motion." Ellion (13) photographed transition boiling of a liquid flowing axially along a vertical tube. As a result of these photographs he concluded that liquid-solid contact did exist. Berenson (5) studied transition boiling from a horizontal surface. He concluded that transition boiling is a combination of unstable nucleate and unstable film boiling alternating at a given location on the heating surface.
In the present investigation it has been observed that transition boiling appears to take the form described by Santangelo and Westwater (39) when a high conductivity solid, such as copper, is used. The combination model described by Berenson appears to be valid when transition boiling occurs from a lower conductivity solid such as stainless steel. The correspondence of the peak heat flux to the departure from nucleate boiling is thus obscured. This is especially true when the heating surface is a tube for which different radial flow situations exist.

Thermocouple Technology

The study of surface temperature in nucleate boiling has been attempted in several investigations. Hsu and Schmidt (22) have used a No. 17 (0.045 in. dia.) stainless steel hypodermic needle as a thermocouple probe. This probe consisted of a constantan wire insulated by a piece of drawn glass inside the needle. They boiled water at heat fluxes from five thousand to sixty thousand BTU per sq. ft.-hr. They reported average temperature fluctuations of $1^\circ F$ amplitude and 3 to 30 cps frequency over this heat flux range. Average maximum uninterrupted temperature variations ranged from $2^\circ$ to $4^\circ F$ in amplitude.

Moore and Mesler (32) used a specially designed thermocouple which measured the temperature of a small area and had an extremely rapid response time. The thermocouple
junction covered an area having a diameter of 0.015 inches. A unique feature of this thermocouple was that it did not protrude from the boiling surface. The two wires entered the solid from below the boiling surface and made contact at the surface. They found that the surface temperature occasionally dropped 20° to 30°F in about two milliseconds during the boiling of water. From this observation they hypothesized that a microlayer of liquid is exposed to the interior of a vapor bubble and that this microlayer vaporizes removing heat rapidly from the surface until complete vaporization has occurred. Kirby (26) did not observe that the liquid film ever completely vaporized in nucleate boiling.

The heat flowing out of the solid during one of the measured temperature fluctuations was calculated. Multiplying this amount of heat by the measured frequency of these fluctuations gave a heat flux of approximately eighty percent of the measured total heat flux. Kirby (26) reports that only nine percent of the heat flux could be attributed to bubble formation at the boiling surface. This would indicate that there is a microlayer evaporation to the interior of the bubble. The area and the distribution of these areas used in the calculation of the flux were not experimentally determined. The location of the nucleation site relative to the thermocouple and the assumption that it is only one site are subject to question. Kirby and Westwater found that certain nucleation sites exhibit wide
variations in nucleation period. The hypotheses by Moore and Mesler (32), and Hendricks and Sharp (21) of a liquid microlayer and the observations of Kirby (26) are in close agreement.

A simple signal device which would predict the approach to peak heat flux might best be based upon the use of thermocouples. Stock (40) presented surface temperature data for boiling at the peak heat flux and in transition boiling. He used a recording instrument limited to 0.1 mv per cm (approximately 5°F per cm) sensitivity and approximately 30 cps frequency response. The nucleate boiling oscillations reported by Hsu and Schmidt (22) or the ones reported by Moore and Mesler (32) could not be resolved by Stock's recording instrument.

Using 0.010 inch diameter two wire iron-constantan thermocouples, Stock noted a sharp change in the signal oscillations as transition boiling began. Stock did not fully analyze the fluctuations in transition boiling but noted maximum variations of 50°F and average variations of 15° to 20°F depending upon the radial position of the thermocouple. The temperature variations decreased in amplitude as the film boiling became stable. This observation was taken to mean that liquid-solid contact existed in transition boiling and that the beginning of stable film boiling corresponded to the time when surface temperature variations decreased in amplitude. At high film boiling
heat fluxes, bubble departure from the vapor-liquid interface was of considerable disorder. Breen and Westwater (8) observed that bubble departure in this case followed patterns predicted by Taylor instability wave analysis rather closely. The tube diameter rather than the heat flux caused a situation which appeared to be in disorder.

Stock (40) did not discuss the use of information contained in thermocouple signals obtained near the peak heat flux and in transition boiling. An analysis of noise patterns and temperature variations, even from a rather crude thermocouple, could lead to the development of a means by which the operation of boiling equipment can be stabilized.

Pool boiling of saturated liquids at atmospheric pressure is the simplest experimental case. However, the use of empirical correlations such as presented in textbooks by Foust et al. (17), and Rohsenow and Choi (38) may vary one hundred percent from published experimental measurements (34, 35). It has not yet been possible to present a general correlation for data obtained from various geometries, flow conditions, surface roughness, subcooling conditions and fouling.

The problem of two-phase flow occurs often in chemical engineering practice. The problem of peak heat flux and the problem of flooding in a sieve plate column are similar. In the process of bubbling, the effect of pressure drop due
to surface tension is analogous to the effect of the superheat temperature difference in boiling. Indeed, the two parameters can be related by the Clausius-Clapeyron equation. The future understanding of two-phase flow will aid in such applications as extraction, combustion, and underwater propulsion systems.
EXPERIMENTAL APPARATUS

The equipment necessary to carry out this experimental study is shown in Figure 5. A schematic representation of the boiling equipment is presented in Figure 6. The entire apparatus consists of a steam heating system, a boiling cabinet and condensing system, the experimental boiling tubes, the thermocouple and recording systems and the experimental liquid.

The experimental boiling tube was installed inside an insulated stainless steel cabinet. This tube was heated from the inside by the condensation of saturated, high pressure steam. The supply pressure of the steam was 56 psig (310°F). Condensate was removed from the supply steam by impinging it against a pipe tee. The lower outlet led to a steam trap and the upper outlet led to the experimental equipment. The steam pressure in the experimental heating tube was controlled to 0.25 psig by a Fisher Governor diaphragm type pressure regulator. The steam line was constantly drained by gravity. A bleed valve prevented the accumulation of inert gases. The steam feed line was three-eighth inch copper tubing. One-quarter inch copper tubing was used for condensate removal. An iron-constantan thermocouple and a pressure gage were connected to the outlet end of the tube. The S. S. Crosby stainless steel pressure gage was calibrated to one-eighth of a pound.
Figure 5. Photograph of experimental equipment
Figure 6. Schematic representation of equipment
accuracy with a testing gage.

The stainless steel boiling cabinet was eight inches long and eight inches in diameter. It had a five inch diameter window opening located in front to allow observation and photographing and access to the inside of the cabinet. There were two one-inch utility outlets to the cabinet. The tube-to-cabinet seal was made by teflon stoppers which were held secure by a special flange arrangement. The cabinet was completely insulated with a two-inch thickness of fiber glass. The heat loss to the room was determined for cabinet temperatures from 100°F to 212°F.

A multiple-tube, single-pass heat exchanger with 2.4 square feet of cooling area was connected to the top of the boiling cabinet. This exchanger was used as a vapor condenser and returned the liquid to the cabinet by gravity drain. To insure that the liquid was returned in a saturated condition, a sieve plate through which the exit vapor bubbled was placed in the return line. The temperature of the returning liquid was experimentally determined and it was verified that the liquid reached its saturation temperature on the sieve plate. The vapor condenser was insulated with a two-inch thickness of fiber glass. Thermocouples were placed in the cooling water lines and the cooling water flow rate was measured by a calibrated rotometer. A heat balance made on the cooling water, along
with the known heat loss from the cabinet, gave a measurement of the heat flux from the heating tube to the boiling liquid.

Stainless steel boiling tubes were used throughout the experimentation. The tubes were standard one-quarter inch Type 316 stainless steel pipe (0.540 in. O. D., 0.088 in. wall thickness). These tubes were polished to a mirror-like finish with emery cloth of up to grade 600 and then crocus cloth. Standard pipe-to-tube connections were used in completing the steam supply system.

Thermocouples were spot welded to the inside and outside surfaces of the boiling tubes. An Eisler spot welder which had an adjustable output voltage of up to 0.04 V was used. The thermocouple wire was held against the tube surface by a specially machined welding probe having contact area of one-sixteenth inch diameter. The circuit was then completed and a flat spot weld resulted. The inside thermocouples were attached by cutting the tube at a 60° angle and spot welding the thermocouple three-quarters of an inch from the cut. The cut was sealed by Heliarc welding. The inside thermocouple wires were withdrawn through a tee and epoxy resin used to make the pressure seal.

Iron-constantan and stainless steel-constantan thermocouples were used in this experimentation. Several other thermocouple combinations were tested and their signals compared in nucleate boiling and at the peak heat flux.
Thermocouples of 0.020 inch diameter down to 0.010 inch diameter were used in the experimentation. A one-wire thermocouple, using the boiling surface as the second wire to complete the circuit, was found to give the best signals and was used when possible.

Temperatures at various points in the experimental system were monitored during experimental runs. The twenty-four point Bristol automatic recording potentiometer shown in Figure 5 was used for this purpose. This recorder had variable span and zero adjustments. Zero was set to correspond to 32°F. The span adjustment was set at 8.35°F/cm, thus giving a full scale reading of 280°F (30-310°F).

Thermocouples connected to the boiling surface were read on the four channels of the Offner Dynographs also shown in Figure 5. The two continuous recording Dynographs had paper speeds of 1, 5, 25, and 125 mm. per second. They had 300 cm. zero suppression with sensitivity to 10 microvolts per cm (approximately 0.5°F per cm). The frequency response of the recorders was within ten percent at frequencies up to 150 cps.

Experiments were run using Freon-113, isopropanol and acetone as the boiling liquids. These liquids analyzed 99.5 percent minimum purity and were discarded after a maximum of three hours usage.

Photographs of the boiling tube were taken with a Linhof Super Technika IV camera with a 270 mm Tele-Arton
lens at an f stop of eight. Light was supplied by a Heiland Strobanor 72-A unit with one-thousandth of a second flash duration. Kodak Royal Pan film was used.
EXPERIMENTAL PROCEDURE

Experimental studies investigating the relative accuracy of thermocouple measurements and their use in controlling boiling heat transfer were carried out. Information contained in the thermocouple measurements was compared to data calculated from heat balances.

A liquid of known physical properties was boiled from a heating tube. The amount of heat transferred from tube to liquid was calculated from a heat balance. This heat balance involved the measurement of the amount of heat required to condense the boil-up vapor by recording the temperature change and flow rate of cooling water supplied to the vapor condenser. A heat flux measurement, representing the macroscopic heat transfer from the tube for each run, thus exists for comparison with thermocouple measurements made at specific points on the tube.

In order to carry out these experiments a general experimental procedure was outlined. The boiling cabinet, represented in Figure 6, was cleaned and flushed with the liquid to be boiled. The glass face plate with "0" ring seal was installed and the cabinet was charged with experimental liquid. A two-inch thickness of insulation was secured to the outside of the cabinet. The liquid was heated to its boiling point by a three hundred watt heater consisting of heating tape wound around the outside of the
cabinet. When the saturation temperature of the liquid had been reached, steam was supplied to the heating tube and five minutes were allowed for the system to reach steady state temperature. The flow rate of condenser cooling water was recorded and an experimental run was begun. Experimental points on the boiling heat flux curve were recorded with the steam temperature at steady state or with the steam temperature being increased in a linear manner.

Pertinent temperatures, as represented in Figure 6, which were continuously monitored and recorded during all experimental runs were the room (T-4), cabinet (T-5), condenser cooling water in and out (T-2, 3), saturated steam at the exit of the heating tube (T-8), and reference ice (T-1) temperatures. These thermocouples along with others for specific runs were connected to the twenty-four point automatic recording potentiometer shown in Figure 5. Thermocouples at the boiling surface were connected to the four continuous recording channels and all systems were connected to a common ground.

Thermocouples on the boiling surface were calibrated at the boiling points of Freon-113, acetone, and water. This calibration was carried out by filling the cabinet with the reference liquid and maintaining the liquid at its boiling point by using the cabinet heating tape shown in Figure 6. Thus the tube, cabinet and tube surface thermocouples were maintained at the reference liquid boiling
point temperature. The thermocouple voltages, boiling point temperature and ambient temperature were recorded. From these data, calibration curves of temperature versus voltage, with room temperature as a parameter, were constructed for each surface thermocouple.

Photographs were taken at heat fluxes of specific interest. These photographs were taken after the system had operated at steady state conditions for more than five minutes.
PRELIMINARY STUDIES

Boiling studies were made from a polished stainless steel tube using three different experimental liquids. The purposes of these studies were to investigate the operation and reliability of the experimental equipment, to determine the most suitable liquid for experimental purposes, and to develop a reliable thermocouple system. Operating temperatures were limited by the available steam pressure which was 0 to 60 psig (212° to 307°F). This restriction necessitated the use of liquids which exhibited a nucleate boiling peak heat flux in the available steam temperature range.

Heat Loss

The heat loss from the insulated cabinet was measured for temperatures between 90° and 212°F. This was determined by recording the temperature decay curve for the cabinet filled with water. The heat loss was found to be relatively small (approximately one-half percent for acetone at peak heat flux). The overall heat transfer coefficient multiplied by the outside area was calculated and plotted versus cabinet temperature.

Liquids Investigated

Experiments measuring the heat flux and overall temperature difference were next conducted. These consisted
of determining individual heat fluxes at steady state steam temperature.

The first liquid experimented with was Freon-113 (b.p. 118°F). The data obtained in this study are presented in Figure 7. The heat flux was calculated from the vapor condenser heat balance. This heat balance represented five minutes operation at a constant steam pressure (± 1/4 psi) after the equipment had been operated at steady-state for five minutes. The measured overall temperature difference was determined by subtracting the temperature of the liquid at its boiling point from the temperature of the condensing steam inside the tube. Samples of these calculations are shown in the appendix. A peak heat flux for Freon-113 of 47,300 BTU per sq. ft.-hr. occurred at an overall temperature difference of 107°F. The peak heat flux for Freon-113 was calculated using equations presented in the literature. The value of peak heat flux determined from the equation presented by Berenson and Moissis (4) was 82,000 BTU per sq. ft.-hr. Using the equation of Rohsenow and Griffith (37) a value of 102,000 BTU per sq. ft.-hr. was calculated. The value determined from the equation of Zuber, Tribus and Westwater (42) was 68,000 BTU per sq. ft.-hr. Deviations from the experimentally determined value of peak heat flux ranged from 44 to 118%.

Using the measured heat flux and the known physical properties and dimensions of the tube, the tube wall
Figure 7. Steady state heat flux measurements for boiling Freon-113
temperature drop at peak heat flux was calculated to be 44°F. The temperature drop through the inside steam condensate film was calculated from the measured heat flux using a heat transfer coefficient determined by use of the Nusselt equation for filmwise condensation. Experiments conducted by Perkins and Westwater (34) showed that this equation gave good results for a drained tube (slanted 2° from horizontal). The calculated condensate temperature drop at this peak heat flux was 23°F. The temperature difference between the outside tube surface and the saturated liquid, $\Delta T_g$, at peak heat flux was then calculated by difference and found to be 40°F. The boiling heat transfer coefficient at peak heat flux was calculated as 1,200 BTU per sq. ft.-hr.°F. It can be seen from Figure 7 that for this steam heated tube the peak heat flux occurred within 12°F of the lowest steam temperature used. It was decided that a larger nucleate boiling temperature range was desirable.

Heat flux versus overall temperature difference curves were next obtained for isopropanol (b.p. 180°F). These data are presented in Figure 8. With the available steam pressure (60 psig or 307°F) it was impossible to attain peak heat flux with the experimental tube. The highest flux attained was 67,000 BTU per sq. ft.-hr. at an overall temperature difference of 122°F. The heating surface to saturated liquid temperature difference, $\Delta T_g$, at the
Figure 8. Steady state heat flux measurements for boiling isopropanol
highest flux attained was calculated as $26^\circ F$. The peak heat flux determined from equations in the literature was variously: 164,000 (4); 180,000 (37); and 132,000 BTU per sq. ft.-hr. (42).

Heat flux versus overall temperature difference curves were then obtained for acetone (b.p. $133^\circ F$). Typical data are presented in Figure 9. From these data a peak heat flux of 82,000 BTU per sq. ft.-hr. was observed to occur at an overall temperature difference of $152^\circ F$. The tube temperature drop was calculated as $77^\circ F$ and the heating surface to saturated liquid temperature difference, $\Delta T_s$, at this peak heat flux was calculated as $34^\circ F$. The boiling heat transfer coefficient for acetone at peak heat flux was calculated as 2,410 BTU per sq. ft.-hr.$^\circ F$. The peak heat flux determined from equations in the literature was variously: 97,500 (4); 77,300 (37); and 84,500 BTU per sq. ft.-hr. (42). These were respectively 18.9% high, 5.7% low and 3.0% high.

Acetone exhibited nucleate boiling, peak heat flux, and transition boiling in the experimental steam temperature range as may be observed in Figure 9. Because acetone is relatively safe, is readily available, has its physical properties published in the literature, and exhibited the necessary boiling phenomena in the available steam temperature range, it was decided that it would make a suitable
Figure 9. Steady state heat flux measurements for boiling acetone
Thermocouple Studies

In other preliminary studies various surface thermocouples were experimented with to determine their suitability. The information contained in the output signal was of primary interest. Physical limitations were corrosion, fabrication, and strength. The thermocouples were welded to the boiling surface by use of a low voltage (0.04 V) spot welding unit. The weld was made flat and nearly flush with the surface. A photograph of a typical thermocouple weld may be seen in Figure 25a.

Two-wire, 24 gage (0.020 inch dia.) iron-constantan thermocouples gave good qualitative results, but had a large time constant relative to expected boiling oscillation frequencies. Other wire sizes and materials were experimented with. Electrical noise problems were encountered, but it was found that the noise could be minimized by grounding all equipment with two-inch ground belts. Since the noise which was now present in the ground would reach the recording instrument, it was found that the grounded boiling tube could serve as one wire of a thermocouple junction. A lead from this stainless steel tube to a copper lead was extruded from a piece of the tube material. The stainless steel to copper junction was at ambient temperature and the system was calibrated with ambient temperature
as a parameter.

The above modification is important because to obtain accurate thermocouple data the thermocouple probe must cause as little temperature distortion as possible. To realize this, it is common practice to use a small diameter, low conductivity wire in the thermocouple probe. The use of a one-wire thermocouple lead instead of two wires reduces the distortion effect by a factor of two.

The most suitable one-wire thermocouple lead was found to be 30 gage (0.010 inch dia.) constantan. The stainless steel-constantan junction gave a strong voltage versus temperature relationship similar to an iron-constantan junction. The thermal conductivity of constantan is relatively low (15.6 BTU per ft. °F hr.) so that it will not conduct large amounts of heat away from the surface. The use of 30 gage wire provided sufficient physical strength for practical application and gave suitable time response.
RESULTS AND DISCUSSION

Acetone was pool-boiled from the outside surface of steam heated stainless steel tubes which had various thermocouple installations on their inside and outside surfaces. The purpose of these experiments was to determine the amount and usefulness of information contained in the signal from a thermocouple attached to the boiling surface.

The temperature of a single wire extending from a boiling surface may be described (neglecting radial temperature gradient) by the differential equation:

\[ \frac{d^2T}{dx^2} - \frac{2}{r k} \frac{h}{r} (T - T_1) = 0 \]

with boundary conditions: \( T(0) = T_w \)
\( T(\infty) = T_1(\infty) \)

where: \( T \) = temperature of wire at point \( x \), \( T(x) \)
\( x \) = distance from heating surface, units of ft.
\( h \) = boiling heat transfer coefficient, \( h(T) = c T^m \)
\( k \) = thermal conductivity of wire
\( r \) = radius of wire
\( T_1 \) = temperature of liquid at point \( x \), \( T_1(x) \)
\( T_1(\infty) \) = temperature at boiling point of liquid
\( T_w \) = temperature of heating surface

This equation may be rewritten as:

\[ \frac{d^2T}{dx^2} - B T^{n+1} = -B T_1^n \]

where: \( B = \frac{2c}{rk} \)

This equation is non-linear for \( n \) greater than zero and the form of \( T_1 \) is not known. The non-linear equation could
readily be solved on an analog computer. Using data for liquid temperature profiles presented in McAdams (31) a temperature profile of: \[ T_l = 40 e^{-350x} + 133 \] was assumed to exist. It was determined that the wire temperature is always higher than the liquid temperature but as \( B \) increases the wire temperature approaches the liquid temperature. For \( B \) to be large it is required that \( k \) and \( r \) be as small as possible.

**Steady State Experiments**

Experiments were run at individual steady-state steam temperatures with 24 gage (0.020 inch dia.), two-wire, iron-constantan thermocouples spot welded to the inside and outside surfaces of the boiling tube. The thermocouple on the outside (boiling) surface was on top of the tube (90° from horizontal). The inside thermocouple was also on top of the tube. The tube wall temperature drop calculated by subtracting the output voltages of the two thermocouples is represented by the upper curve in Figure 10. The lower curve represents the tube wall temperature drop calculated from the measured vapor boil-up. An example of this calculation is presented in the Appendix.

The temperature drop through the tube wall is directly proportional to the heat flux through the wall. The vapor boil-up heat flux measurement used in calculating the lower curve was taken as the correct value since all assumptions
Figure 10. Steady state tube wall temperature drop measurements for boiling acetone
in its calculation were experimentally verified. From Figure 10 it can be seen that the two curves are parallel in nucleate boiling. This shows that the thermocouple measurement was directly proportional to the actual heat flux through the tube. The thermocouple signals indicated a tube wall temperature drop approximately 20°F higher than that calculated from the vapor boil-up. The thermocouple wire at the boiling surface cools the surface at the point of contact lowering the temperature which it is to measure. Since the outside thermocouple measures a temperature which is lower than actual and the inside thermocouple measures a temperature higher than actual, the distortion effects are additive when the tube temperature drop is calculated. This explains the discrepancy in Figure 10. This effect may be minimized by using low conductivity, small diameter wire. Although the absolute value of the heat flux may not be calculated from the measured tube wall temperature drop, it is important to note that the relative value may be calculated since the curves are parallel.

In Figure 10 it can be seen that the thermocouple indication of peak heat flux occurred at approximately 10°F higher steam temperature than the average peak heat flux actually occurred. This may again be attributed to the cooling effect of the thermocouple on the point of contact at the boiling surface. Because this point is cooled,
nucleate boiling actually existed at the thermocouple site while the rest of the tube was in transition boiling.

Experiments were run with two 24 gage, iron-constantan thermocouples welded to the tube and separated 45° in the radial direction. The thermocouples were positioned at 45° and 90° from the horizontal and a series of experiments were run. The tube was then turned clockwise 135° and a second series of experiments run. Steady-state points were recorded and curves obtained from these data are presented in Figure 11. The vapor boil-up measurements for both series of experimental runs were essentially identical. The tube temperature drop curve calculated from the vapor boil-up is the average obtained from the two series of experiments. The curves are again approximately parallel for all radial positions. Indication of the peak by the thermocouples occurred 10°, 13°, 23° and 25°F after the measured average peak going around the radial positions from top to bottom. The bottom thermocouple remained in nucleate boiling the longest. This would be expected since vapor flowing around the tube tends to surround the upper thermocouples, and film boiling first occurred on the top half of a horizontal tube.

Continuous Experiments

Using the four continuous recording channels it was possible to vary the steam temperature in a linear manner
Figure 11. Steady state tube wall temperature drop measurements for boiling acetone
and record thermocouple measurements. The steam was varied at a constant rate of 4 psi per minute (6°F per min.) while a continuous heat flux curve was being recorded.

A one-wire, constantan-stainless steel thermocouple on the outside surface was connected in series with a one-wire stainless steel-constantan thermocouple on the inside surface. The thermocouple leads were 30 gage (0.010 inch dia.) wire and both thermocouples measured the temperature at the top of the tube. Specific readings from the continuous tube wall temperature drop curve are presented in Figure 12. The tube wall temperature drop calculated from the vapor boil-up is shown for comparison.

The one-wire thermocouple measured the temperature at a single point on the boiling surface. The boil-up measurement is the average for the entire tube. The measurement of the temperature on top of the tube indicates that at low heat fluxes the top of the tube transfers less heat than the bottom of the tube. For nucleate boiling the liquid near the top of the tube has a higher superheat due to vapor flow. However, as peak heat flux is approached, the thermocouple measurement indicates that the top of the tube transfers more heat than the lower part of the tube. This may be due in part to the cooling effect which the thermocouple has upon the boiling surface at the point of measurement and in part to the fact that the peak heat flux is higher than the heat flux at any other point on the tube.
Figure 12. Tube wall temperature drop measurements for boiling acetone
It is apparent from a study of Figure 12 that a complex relationship exists between the heat flux at a single point and the average heat flux for the entire boiling surface. This is particularly true for boiling from a horizontal tube since different vapor flow patterns exist at each radial point. The point heat flux on a flat horizontal surface would be more closely related to the average surface heat flux.

In Figure 12 the one-wire thermocouple curve exhibits a strong discontinuity at its highest value of heat flux. This discontinuity occurred as the junction point went from nucleate into transition boiling and was reproducible within 1°F overall temperature drop. As transition boiling develops and the heat flux decreases, the corresponding decreases in condensate and wall temperature drops cause the outside surface temperature to increase sharply. For a low conductivity material such as stainless steel \((k = 9.4 \text{ BTU per sq. ft.-hr.})\), the average wall temperature drop at peak heat flux is 70°F. Since the outside boiling surface temperature rises rapidly, a large discontinuity occurs in the heat flux. For this reason "patchwise" boiling is often encountered from stainless steel. The data for the thermocouple curve of Figure 12 was taken from the tube temperature drop recording shown in Figure 15.

The boiling surface temperature was measured as it varied with linearly increasing steam temperature in order
to study the occurrence of the point of peak heat flux indication. A 30 gage, constantan wire was spot welded to the top of the outside surface of a stainless steel tube. A reproduction of the continuous curve obtained from this experimental run is presented in Figure 13. The upper curve is the recording of the temperature of cooling water out of the vapor condenser. From this curve it was determined that a peak heat flux of 78,000 BTU per sq. ft.-hr. occurred at an overall temperature drop of 144°F. The lower curve of Figure 13 represents the temperature of the boiling surface. The thermocouple signal was connected to a resistance capacitance noise filter which had a time constant of one second. Thus all high frequency boiling oscillations have been filtered out. The indication that the thermocouple site went into transition boiling occurred 4°F after the average peak heat flux. In a similar experiment the thermocouple indicated peak heat flux 6.9°F after the average peak heat flux had been reached. Three similar experiments with a new constantan wire accurately spot welded to the top of the cleaned and polished tube gave indications 1.5°F, 1.5°F and 2.4°F after the average peak heat flux. The accurate placement of the thermocouple site on top of the tube had a strong effect upon reproducibility. For radial positions other than the top of the tube the indication of transition boiling occurred much later than the average peak heat flux.
Figure 13. Surface temperature discontinuity at peak heat flux
Indication of Peak Heat Flux

The point of discontinuity of the surface temperature, if it occurs before the average peak heat flux, may be used to predict the approach of peak heat flux. This is physically possible by measuring the temperature of a higher conductivity material implanted in the tube wall. This signal could be of great value in the control of nucleate boiling heat transfer equipment especially where such variable conditions as acceleration, orientation, or fouling are important.

Brass Slugs

Stainless steel boiling tubes were fabricated which had high conductivity metals implanted in their walls. Fabrication problems arose because the installation had to withstand large temperature variations and 60 psig steam pressure. A tube with two brass slugs (k = 60 BTU per °F. ft.-hr.) the same thickness as the tube wall was fabricated by threading the slugs and tapping a hole in the tube. "Resiweld" epoxy resin was used as a sealant. The two implanted slugs were one-eighth and one-quarter inch in diameter respectively. Two-wire, 30 gage, iron-constantan thermocouples were used on the brass surface because the slug was electrically insulated from the tube by the resin. The tube had to be filled with mercury in order to complete
a spot welding circuit.

Continuous experimental runs were made with this boiling tube. Heat flux and surface temperature measurements were recorded on the four continuous channels while other system temperatures were monitored by the twenty-four point recorder. A typical experimental run is presented in Figure 14. The lower four curves were obtained from the continuous recording of surface thermocouple signals. The wall temperature drop was measured with one-wire constantan leads. The outside tube temperature was measured with a one-wire constantan-stainless steel thermocouple. The upper curves represent temperatures at monitored points in the experimental system. An average peak heat flux of 74,000 BTU per sq. ft.-hr. occurred at 135°F overall temperature difference while the tube wall temperature drop indicated a peak heat flux at 138°F. The one-quarter inch diameter brass slug showed a slight discontinuity and a large change in amplitude of fluctuation caused by transition boiling. This point was within 10% of the average peak heat flux and occurred 21°F before the peak. The one-eighth inch diameter brass slug did not show a significant discontinuity, but the amplitude of temperature fluctuation changed sharply with the beginning of transition boiling. The indication of transition boiling from this site was within 5% of the average peak and 12°F before it. These brass slugs did not show a strong temperature discontinuity at the inception of
Run M-1

Steam temperature

250°F reference

inside wall temperature
peak heat flux

133°F reference

cooling water out

cooling water in

\[ \Delta T \text{ overall (°F)} \]

1.0 mv

\[ T(\frac{1}{8}'' \text{ brass slug}) \]

\[ \Delta T \text{ through tube} \]

\[ T(\frac{1}{8}'' \text{ brass slug}) \]

\[ T \text{ (outside surface stainless steel)} \]

Figure 14. Continuous heat flux experiment, initial surface temperature 133°F
transition boiling because the temperature drop across them at peak heat flux is smaller than that of stainless steel.

The thermocouples were polished down flush with the slug surfaces and four similar runs were made. Figure 15 shows curves recorded during a typical run. The thermocouple connected to the one-quarter inch brass slug gave a reproducible indication of the start of transition boiling. Since this indication anticipated the occurrence of peak heat on the rest of the tube it may be used as a control signal. The one-eighth inch diameter brass slug was influenced by the type of boiling which was prevalent on the stainless steel tube as can be determined from Figure 15. Since this effect may be attributed to flow phenomena at the surface, it is necessary to have a slug of sufficient diameter to establish an independent flow pattern. A one-quarter inch slug was sufficient in this study.

Nickel Cylinder

A stainless steel tube with a one-inch nickel cylinder welded in its mid-section was fabricated and its behavior studied. The two cylinders had bases slanted at 60°. The thermal conductivity of the nickel cylinder was 34 and that of the stainless steel tube was 9.4 BTU per °F. ft.-hr. Constantan leads (30 gage) were spot welded to the polished tube and the nickel cylinder at top, side, and bottom radial locations. Another constantan lead was spot welded
Figure 15. Surface temperature measurements, initial surface temperature 133°F
3/8 inch from the nickel cylinder on top of the tube and a two-wire iron-constantan thermocouple was spot welded three inches from the nickel cylinder.

The data recorded during a typical experimental run are presented in Figure 16. The steam temperature is shown increasing at approximately 6°F per min. The average peak heat flux calculated from the condenser cooling water duty was 80,800 BTU per sq. ft.-hr. and occurred at a value of 151°F overall temperature difference.

The one-wire thermocouple on top of the nickel cylinder showed an increase in amplitude of oscillation at a value of 115°F overall temperature drop when the average heat flux was 80% of the peak. There was no significant jump in surface temperature at the inception of transition boiling. The one-wire thermocouple on the side of the nickel cylinder showed a 23°F temperature jump and a small increase in amplitude of temperature oscillation at a value of 126°F overall temperature drop when the average heat flux was 87% of the peak. The one-wire thermocouple on the bottom of the nickel cylinder was monitored and showed a 24°F temperature jump at a value of 127°F overall temperature drop while the average heat flux was 88% of the peak. These signals gave a reproducible prediction of the occurrence of peak heat flux but the indication was given at a lower value of heat flux than might be desired for control purposes.
Run Q-1

T (steam)

250°F reference

T (bottom T.C. on nickel surface)

peak heat flux

133°F reference

cooling water out

cooling water in

32°F ice reference

1.0 mv T (top T.C. on nickel surface)

T (side T.C. on nickel surface)

T (one-wire T.C. near nickel cylinder)

T (outside surface stainless steel tube)

Figure 16. Heat flux experiment, initial surface temperature 133°F
The one-wire thermocouple connected to the top of the stainless steel tube indicated transition boiling $5^\circ F$ after the average peak. The one-wire thermocouple, connected to the top of the stainless steel tube but three-eighths inch from the nickel cylinder, showed a discontinuity of $82^\circ F$ at $3^\circ F$ before the peak heat flux. The discontinuity occurred when the heat flux was within 1% of the peak. This signal could be used to control heat transfer equipment at an optimum level, under widely varying conditions.

The thermocouples on the nickel surface gave reproducible indications of relative points on the heat flux curve. The thermocouple on the stainless steel tube indicated the peak after the average peak heat flux had been reached. The thermocouple three-eighths of an inch from the nickel surface was influenced by the nickel cylinder. This thermocouple site was the first on the stainless steel surface to go into transition boiling and gave a reproducible indication of the approach to peak heat flux. By use of the signals from the nickel surface and the one near this surface a control signal was obtained. This signal could be used to bracket the heat flux between 90 and 98% of the peak flux.

**Surface Temperature**

A detailed study was made of the surface thermocouple signals. The steam pressure was varied at the rate of four psi per minute and surface thermocouple signals were
continuously recorded on an expanded scale. Data recorded for nucleate boiling are presented in Figure 17.

The constantan lead welded to the top of the nickel cylinder indicated $\Delta T_s$ equal to $47^\circ F$ for $80^\circ F$ overall temperature drop. This thermocouple site began to indicate peak heat flux at $\Delta T_s$ equal to $58^\circ F$ with $106^\circ F$ overall temperature drop. At $115^\circ F$ overall $\Delta T$ with the start of transition boiling there was a large discontinuity and the signal caused the recording pen to go off scale. The one-wire, 30 gage, constantan-stainless steel thermocouple indicated that $\Delta T_s$ varied from $20^\circ$ to $39^\circ F$ while the heat flux varied from 34,000 to a peak of 82,000 BTU per sq. ft.-hr.

The one-wire, 30 gage, constantan-stainless steel thermocouple which was welded three-eighths of an inch from the nickel cylinder measured $\Delta T_s$ equal to $34^\circ F$ at a heat flux of 34,000 BTU per sq. ft.-hr. At the start of transition boiling $\Delta T_s$ was equal to $55^\circ F$ while the overall temperature drop was $161^\circ F$. The two-wire, 30 gage, iron-constantan thermocouple indicated that $\Delta T_s$ varied from $22^\circ$ to $28^\circ F$ while the heat flux varied from 34,000 BTU per sq. ft.-hr. to the peak.

The one-wire thermocouple gave a good indication of the actual surface temperature. There are many problems both in research and application for which a signal of this
Figure 17. Surface temperatures during nucleate boiling, amplified scale, initial surface temperature 133°F
nature would provide a practical solution. The one-wire thermocouple near the nickel surface was influenced by vapor flow and temperature gradients from the nickel cylinder. The two-wire thermocouple remained nearly constant during nucleate boiling and indicated a surface temperature which was below the actual.

Temperature Fluctuations

A photographic study was made of the stainless steel tube with the inserted nickel cylinder. Photographs at significant points are presented here. At the same time as the photographs were taken, the signals from the one-wire thermocouple near the nickel cylinder and the two-wire thermocouple were recorded. The sensitivity was increased to 0.01 mv per cm to obtain full scale amplification of the fluctuating signals. At this sensitivity the random noise in the signal was less than 0.004 mv amplitude, as shown in Figure 27. Temperature increases in the negative direction for these recordings. A time scale of 12.5 cm per second was used to fully resolve the signal. These temperature fluctuation patterns are presented beneath the corresponding photographs. The amplitude of the temperature oscillation was recorded for these signals and other steady-state points. Curves showing the relationships between the amplitude of oscillation and the overall temperature difference are presented in Figure 26.
Nucleate boiling from the experimental tube is shown in Figure 18a. Portions of the stainless steel tube are clearly visible at this low heat flux. The one-inch long nickel cylinder, with a 60° base slanting to the left, is located approximately one inch from the left border of the photograph. The nucleate boiling heat flux from the nickel cylinder is high and the nickel surface is completely covered with vapor bubbles.

The one-wire thermocouples on the nickel tube at top and side locations are shown. The one-wire constantan lead which is welded three-eighths of an inch from the nickel surface on top of the tube is shown in the middle of the photograph. The signal from the one-wire constantan-stainless steel thermocouple near the nickel surface shown in Figure 18b indicated average temperature fluctuations of $0.47^{\circ}F$ amplitude at a frequency of 20.5 cps.

Nucleate boiling from the stainless steel tube is shown in Figure 19a. Portions of the stainless steel surface are visible. Peak nucleate boiling exists on the nickel tube. The one-wire thermocouple near the nickel cylinder measured average surface temperature oscillations of $0.88^{\circ}F$ at 16.9 cps. In Figure 20a nucleate boiling exists on the stainless steel surface while transition boiling exists on the nickel cylinder. The one-wire thermocouple indicated average temperature oscillations of $1.25^{\circ}F$ at 19.4 cps. In Figure 21a
18a. Nucleate boiling from stainless steel and nickel cylinders

18b. Thermocouple signals
   upper curve: two-wire, 30 gage, iron-constantan thermocouple
   lower curve: one-wire, 30 gage, stainless steel-constantan thermocouple

Figure 18. Boiling at $\Delta T$ overall equal to $82^\circ F$, $Q/A$ equal to 34,000 BTU per sq. ft. -hr.
19a. Nucleate boiling from stainless steel and nickel cylinders

19b. Thermocouple signals
   upper curve: two-wire, 30 gage, iron-constantan thermocouple
   lower curve: one-wire, 30 gage, stainless steel-constantan thermocouple

Figure 19. Boiling at ΔT overall equal to 115°F, Q/A equal to 58,000 BTU per sq. ft.-hr.
20a. Nucleate boiling from stainless steel cylinder transition
boiling from nickel cylinder

20b. Thermocouple signals
upper curve: two-wire, 30 gage, iron-constantan thermocouple
lower curve: one-wire, 30 gage, stainless steel-constantan
thermocouple

Figure 20. Boiling at $\Delta T$ overall equal to 141°F, $Q/A$ equal to 70,000
BTU per sq. ft.-hr.
21a. Nucleate boiling from stainless steel cylinder film boiling from nickel cylinder

21b. Thermocouple signals
   upper curve: two wire, 30 gage, iron-constantan thermocouple
   lower curve: one-wire, 30 gage, stainless steel-constantan thermocouple

Figure 21. Boiling at ΔT overall equal to 154°F, Q/A equal to 80,000 BTU per sq. ft.-hr.
nucleate boiling exists on the stainless steel tube while stable film boiling exists on the nickel cylinder. Average temperature oscillations of 1.20°F at 22.0 cps were recorded for the one-wire thermocouple.

Figure 22a shows nucleate boiling at peak heat flux on the stainless steel tube. Film boiling exists on the nickel surface. The one-wire thermocouple near the nickel cylinder is still in nucleate boiling. It measured average temperature fluctuations of 2.03°F at 22 cps.

Figure 23a shows temperature oscillations when the one-wire constantan-stainless steel thermocouple site was going into transition boiling. Temperature jumps of 60°F are common with some jumps as high as 110°F within 0.6 second being recorded. Increasing temperature was in the negative direction so that there would be no pen interference. Figure 23b is a recording of oscillations at the same temperature with the time scale reduced by a factor of 25.

In Figure 24a transition boiling has begun at the one-wire thermocouple site. The thermocouple trace for this site, shown in Figure 24b, has become smooth with large amplitude oscillations of 9.99°F at 21.3 cps. The thermocouple trace for the two-wire site indicates that it is in nucleate boiling.

In Figure 25a the entire tube is shown in film boiling. The vapor flow pattern is orderly while the volume of vapor
22a. Nucleate boiling from stainless steel cylinder film boiling from nickel cylinder

22b. Thermocouple signals
   upper curve: two-wire, 30 gage, iron-constantan thermocouple
   lower curve: one-wire, 30 gage, stainless steel-constantan thermocouple

Figure 22. Boiling at $\Delta T$ overall equal to $161^\circ$F, $Q/A$ equal to 82,000 BTU per sq. ft. -hr.
23a. Thermocouple signal at peak heat flux, 125 mm per sec

23b. Thermocouple signal at peak heat flux, 5 mm per sec

Figure 23. Thermocouple signals
upper curve: two-wire, 30 gage, iron-constantan thermocouple
lower curve: one-wire, 30 gage, stainless steel-constantan thermocouple
24a. Transition boiling from stainless steel cylinder film boiling from nickel cylinder.

24b. Thermocouple signals
- upper curve: two-wire, 30 gage, iron-constantan thermocouple
- lower curve: one-wire, 30 gage, stainless steel-constantan thermocouple

Figure 24. Boiling at $\Delta T$ overall equal to 166°F, $Q/A$ equal to 77,000 BTU per sq. ft. -hr.
25a. Film boiling from stainless steel and nickel cylinders

25b. Thermocouple signals
upper curve: two-wire, 30 gage, iron-constantan thermocouple
lower curve: one-wire, 30 gage, stainless steel-constantan thermocouple

Figure 25. Boiling at ΔT overall equal to 171°F, Q/A equal to 45,000 BTU per sq. ft.-hr.
generated is much less than shown in Figure 22a where peak nucleate boiling exists. The thermocouple traces shown in Figure 25b for both the one-wire and two-wire thermocouples are smooth and of large amplitude. The one-wire thermocouple indicated temperature oscillations of $10.01^\circ\text{F}$ at 18.2 cps.

The amplitude of temperature fluctuations at various overall temperature drops are shown in Figure 26. The maximum temperature change during a five second period increased from $2.6^\circ\text{F}$ at a heat flux of 34,000 BTU per sq. ft.-hr. to $7.5^\circ\text{F}$ as the nucleate boiling heat flux increased. At the peak heat flux it was $15.6^\circ\text{F}$ and then jumped to $41^\circ\text{F}$ in transition boiling. This signal contains information about the heat flux and also the location of the peak heat flux. This information can be used in control system applications. The maximum continuous fluctuation during a five second period is also shown in Figure 26. The average fluctuation increased slightly during nucleate boiling and showed a jump when transition boiling occurred. The information contained in the temperature oscillations could be used to determine the relative heat flux. The frequency of oscillation increased from 16 to 24 cps during nucleate boiling and showed a slight discontinuity at peak heat flux. The magnitude of the temperature oscillations changed radically as transition boiling began.
Figure 26. Amplitude of boiling oscillations
The fluctuating signals showed that the 30 gage, one-wire thermocouple had a fast enough time response to provide information about the heat flux. The oscillations were of lower frequency and amplitude than those observed by Moore and Mesler (32). They were similar to those observed by Hsu and Schmidt (22) and Stock (40). This is due to the influence of the liquid and vapor temperature oscillations upon the wire. The observed oscillations were due to flow patterns rather than nucleation phenomena at the surface. The information contained in these flow patterns can be used in a control system for which the primary dependent variable, the heat flux, is measured. The direct measurement of the important dependent variable is superior, for control purposes, to relating it to other dependent variables such as steam temperature.
CONCLUSIONS

1. Pool boiling at atmospheric pressure is the least complicated type of boiling. Although numerous peak heat flux correlations exist, large discrepancies between predicted and measured values of peak heat flux are common.

2. Single wire thermocouples of the type used in this experimental study contain useful information concerning the regime of boiling at the heating surface. The regimes of nucleate and transition boiling are clearly distinguishable in the thermocouple signal. The value of the heat flux in relation to the peak heat flux may be ascertained from the nucleate boiling fluctuations. The start of transition boiling is defined by a discontinuous rise in surface temperature and a large increase in temperature fluctuation amplitude.

3. The thermocouple signal contains information about the boiling surface temperature fluctuations. This information is more closely related to liquid and vapor flow than to bubble formation at the surface. The oscillation patterns are complex. The amplitude of the temperature fluctuations increases as the nucleate boiling heat flux increases. The average amplitude of fluctuation does not change as radically as the maximum fluctuations. The average frequency of the fluctuations increases during nucleate boiling and decreases when transition boiling starts.
4. The prediction of peak nucleate boiling heat flux for control purposes is possible by use of surface thermocouples. The prediction signal may be obtained by promoting transition boiling at a specific point on the surface. This may be done by a high conductivity plug or tube section or by artificial surface roughness. The detecting thermocouple is placed where it will be influenced by this surface abnormality. The large discontinuity in surface temperature at the start of transition boiling can be used as a prediction signal.

5. The size, fabrication, and strength of the thermocouples used in this study make possible a technique of boiling surface temperature measurement having numerous practical applications.
RECOMMENDATIONS

1. The thermocouples used in this work gave reproducible signals of surface temperature and fluctuations. Similar thermocouples should be used in research and in practical applications of boiling heat transfer.

2. The use of thermocouples which monitor the value of the heat flux for control purposes has definite advantages. The value of the primary dependent variable (in this case heat flux), when available, should be used as a control signal.

3. Further studies which might be recommended are:
a. Measurement of $T_1$ near the boiling surface, which would lead to a solution for the heat flow through the wire and in general a better understanding of the boiling phenomena.
b. The use of a single wire thermocouple gave good surface temperature measurements. A single wire which could be introduced from the inside of the tube through a small hole, making contact with the tube at the outside surface, would more closely measure the boiling surface temperature. This should be investigated.
c. Due to the complexity of the temperature fluctuation patterns, an analysis of their correlation coefficient or their spectral density should be undertaken and might lead to a strong relationship between the heat flux and the oscillation frequency and amplitude.
d. Data for the boiling of liquid metals are limited. Since the boiling of metals is becoming prominent in fields of direct energy conversion, surface temperature measurements obtained in a manner similar to that used in this experimental work would be of great value and should be investigated.
NOMENCLATURE

A area, sq. ft.

h heat transfer coefficient, BTU per sq. ft.-hr. °F

k thermal conductivity, BTU per ft. hr. °F

Q heat flow rate, BTU per hr.

r radius of tube, ft.

T temperature, °F

T_l temperature of liquid, °F

T_s temperature of steam, °F

T_w temperature of heating surface, °F

\( \Delta T_C \) temperature drop across condensate film, °F

\( \Delta T_o \) overall temperature difference, °F

\( \Delta T_s \) temperature difference between heating surface and saturated liquid, °F

\( \Delta T_t \) temperature drop across tube, °F

x distance, ft.
LITERATURE CITED


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APPENDIX A

Thermocouple Calibrations

Iron-constantan thermocouples used in Figures 10, 11, 14 and 15: $0.0296 \text{ mV/}^{\circ}\text{F}$

Iron-constantan thermocouples used in Figures 16 through 25: $0.0218 \text{ mV/}^{\circ}\text{F}$

Stainless steel-constantan single wire thermocouples used in Figures 12, 13, 16 through 27: $0.0180 \text{ mV/}^{\circ}\text{F}$

Random noise patterns of typical grounded thermocouples are shown in Figure 27.
Figure 27. Random noise pattern
Sample Calculations

1. Calculation of the heat flux from the condenser duty

Typical measurements:
- Cooling water flow rate, \( w = 22.3 \text{ ml/sec} \)
- Cooling water temperature change, \( T = 35.6^\circ \text{F} \)
- Heat capacity of water, \( C_p = 1 \text{ BTU/lb}^\circ \text{F} \)
- Area of tube, \( A = 0.0899 \text{ sq ft} \)
- Outside radius of tube, \( r_o = 0.540 \text{ inches} \)
- Steam temperature \( T_s = 258^\circ \text{F} \)

\[
Q_c = w \cdot C_p \cdot AT
\]
\[
= 22.3 \times 7.93 \times 35.6
\]
\[
Q_c = 6,290 \text{ BTU/hr}
\]

Heat loss from cabinet at boiling point of acetone, \( Q_1 = 39 \) BTU/hr

Total heat flow: \( Q = Q_c + Q_1 \)
\[
= 6,290 + 39
\]
\[
Q = 6,329 \text{ BTU/hr}
\]

Heat flux: \( \frac{Q}{A} = 71,100 \text{ BTU/hr ft}^2 \)

2. Calculation of tube temperature drop

\[
\Delta T_t = \frac{Q}{A} \frac{r_o}{k} \ln \frac{r_o}{r_i}
\]
\[
= \frac{71,100 \times 0.270}{12 \times 9.4} \ln \frac{0.540}{0.364}
\]
\[
\Delta T_t = 68.1^\circ \text{F}
\]
3. Calculation of condensate temperature drop

\[ \Delta T_c = \frac{Q}{h_c} \]

\[ h_c = 3,000 \text{ BTU/hr sq ft } \]

\[ \Delta T_c = \frac{71.100}{3,000} \]

\[ \Delta T_c = 23.7^\circ F \]

4. Temperature difference between heating surface and saturated liquid, \( \Delta T_s \)

overall temperature difference: \( \Delta T_0 = \Delta T_s - \Delta T_1(\infty) \)

\[ = 258 - 133 \]

\[ \Delta T_0 = 125^\circ F \]

\[ \Delta T_s = \Delta T_0 - (\Delta T_c + \Delta T_t) \]

\[ = 125 - (23.7 + 68.1) \]

\[ \Delta T_s = 33^\circ F \]