Measurements of Bubbles Formed in Boiling Methanol

A. S. PERKINS and J. W. WESTWATER

University of Illinois, Urbana, Illinois

The photographic method was used to measure bubble sizes and frequencies for methanol boiling at atmospheric pressure outside a 3/8-in. O.D., steam-heated, horizontal copper tube. The average temperature of the tube was measured by use of the tube as a resistance thermometer. For nucleate boiling at heat fluxes up to 80% of the maximum, the product of bubble diameter and frequency was constant at 4 in./sec. In this region both the Rohsenow equation and the Forster-Zuber equation gave good predictions of the heat transfer. At higher fluxes the product $f \times D$ increased and the equations were much less suitable. The critical temperature difference for copper to methanol was not a single value but was a region extending from 52° to 62°F. The heat flux was nearly constant throughout this range at a maximum of 115,000 B.t.u./(hr.)(sq. ft.). For film boiling, $f \times D$ was nearly constant at 11 sec.$^{-1}$ Bromley's equation was unsuitable for ΔT values less than 180°F., but it became applicable at this ΔT. The use of Nusselt's equation for steam condensing inside the tube was found to be satisfactory, proof that the slight slope of the tube was sufficient to permit adequate condensate drainage.

Boiling liquids represent the least understood form of heat transfer. No single expression has been proposed to describe a complete boiling curve of h vs. ΔT. To obtain an equation which fits any reasonable range of data, it is necessary to choose one of the specific regions of boiling. Bromley (*3*) published a theoretical equation for film boiling outside a horizontal tube. Rohsenow (*14*) and later Forster and Zuber (*6*) published expressions for nucleate boiling, presumably on a hot solid of any shape. These nucleate-boiling equations are partly theoretical and partly empirical.

The equation of Rohsenow is based on the photographic evidence of Jakob (*9*), who discovered that the product of bubble diameter and bubble frequency seemed to be a constant for nucleate boiling. Jakob's observations were valid for both water and carbon tetrachloride; however, Jakob was careful to point out that his data were for small heat fluxes only. The greatest flux studied was about one order of magnitude below the maximum possible flux for nucleate boiling. There was no reason to believe that high and low heat fluxes would result in equivalent bubble sizes or frequencies.

The object of this research was to determine the diameters and frequencies of bubbles formed during nucleate boiling at large heat fluxes. With the equipment used it was possible to investigate the transition region and the film boiling region as well and also to check the correctness of applying Nusselt's equation for condensation to steam inside a horizontal tube.

PHOTOGRAPHIC METHOD USED

Bubble frequencies and diameters were determined by the photographic method. In brief, motion pictures were taken at 4,000 frames/sec. and were projected at 16 frames/sec. Measurements were taken from the projected slow-motion images. The details of the camera, film, and lighting are described in an earlier paper (*17*), which also contained a selection of still photographs and information for viewing samples of the motion pictures.

Methyl alcohol was used as the boiling liquid. It was boiled at atmospheric pressure at 148°F. outside a horizontal, $\frac{3}{8}$-in. O.D. copper tube. Figure 1 is a sketch of the boiler. The boiler dimensions were approximately 8½ by 8½ by 5 in. Flat Pyrex-glass windows were located front and back; the remainder of the boiler was stainless steel. Studs used for a flange to secure the windows against a neoprene gasket are visible in the sketch. Approximately 1 gal. of liquid was contained in the boiler.

The source of heat was steam condensing inside the tube, which passed completely through the boiler, parallel to the windows, the immersed length being 8.4 in. The heat flux was varied by adjustment of the steam pressure between 0 and 100 lb./sq. in. gauge. The resulting values of the methanol film ΔT were between 38° and 181°F.

The over-all piping arrangement was described previously (*17*). The new arrangement included three modifications: the straight-through tube was used in place of the earlier bayonet heater; an automatic, pneumatic controller was installed to regulate the steam pressure; and electrical connections were added to permit using the tube as a resistance thermometer.

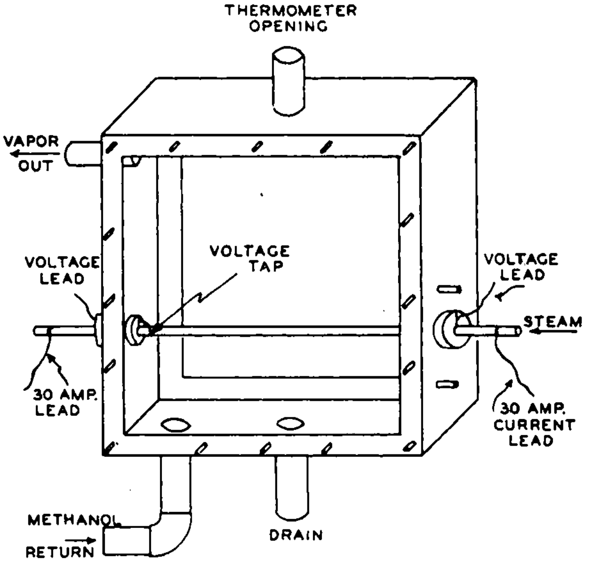

Fig. 1. Details of boiler construction.

A. S. Perkins is with Linde Air Products Company, Tonawanda, New York.

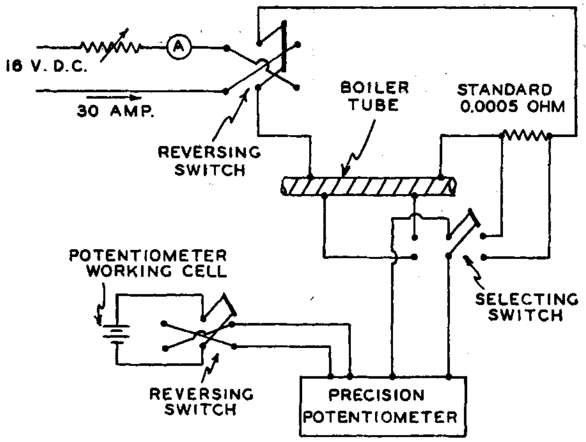

Fig. 2. Steam tube used as resistance thermometer.

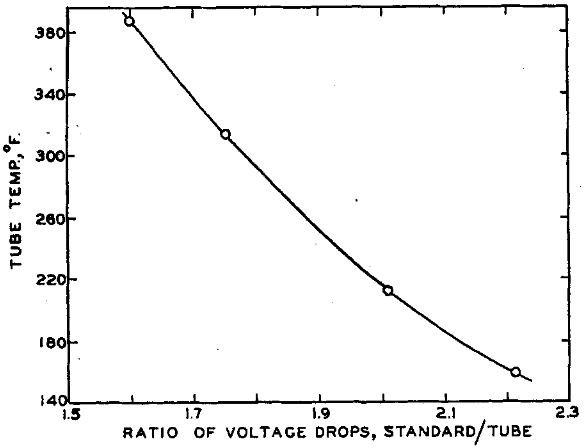

Fig. 3. Calibration of heater tube as a resistance thermometer.

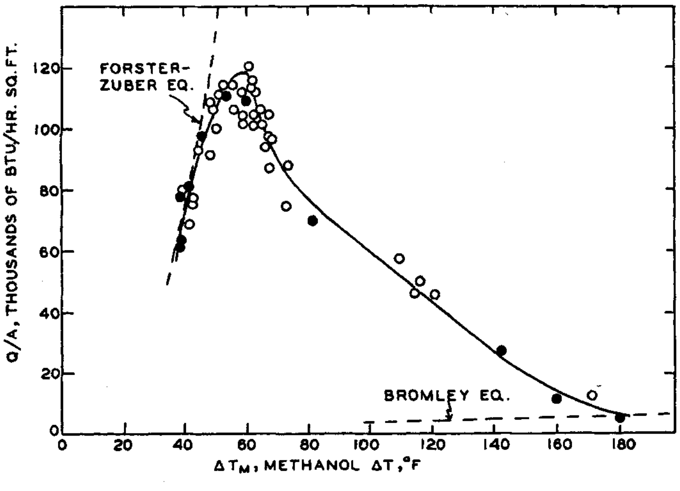

Fig. 4. Experimental data for methanol boiling on a copper tube. The solid symbols indicate runs for which motion pictures were made.

STEAM TUBE AS RESISTANCE THERMOMETER

Use of thermocouples to measure the temperature of the tube was rejected on several grounds. A surface-mounted couple would alter the nature of the boiling at the site of the couple, for it is known that nucleate boiling is dependent on the type of hot metal. In addition, such a couple would have wires extending into the boiling liquid or into the condensing steam. In either case the wires would conduct heat to or away from the junction and result in erroneous readings. Even if the wires were embedded in a groove or a longitudinal hole in the tube wall, the pattern of heat flow would be modified, perhaps seriously.

All these difficulties were avoided by use of the steam tube as a resistance thermometer. This scheme was suggested by Jeffrey in 1936 as a method of measuring the temperature of a condenser tube (*11*); his calculations show that the temperature so obtained is very close to the true value averaged both radially and longitudinally.

Jeffrey's method was modified somewhat for the boiling tests. The present setup is shown in Figure 2. A direct current of about 30 amp. was passed through the steam tube and through a 0.0005-ohm manganin standard resistance in series. The potential drop through the tube was about 0.007 volt. This was read to within 10^{-6} volt by means of a Leeds and Northrup type K-2 potentiometer in conjunction with a galvanometer which responded 1 mm. to 0.5×10^{-6} volt. The electrical generation of heat amounted to only 0.2 watt, which is insignificant compared with the heat supplied by the condensing steam. The maximum uncertainty in the measured metal temperature, because of electrical sources of error and also the other sources, is estimated to be about 4°F.

The voltage drop across the standard resistance was measured also. The ratio of the two voltage drops was sufficient information to allow one to read the average tube temperature from a calibration curve. The calibration data were obtained by immersing the tube in four boiling liquids (methanol, water, bromobenzene, and ethylene glycol). No steam was passed through the tube during calibration. The calibration curve is reproduced in Figure 3.

After thirty experimental runs the calibration was repeated, and a third calibration was carried out after an additional nineteen runs. These recalibrations showed that the resistance of the tube increased slightly with each run, as was to be expected, because the tube was polished before every run and each polishing removed a trace amount of metal. The calibration shift amounted to 0.111°F. per cleaning. This shift was taken into account in the calculation of test results.

Figure 1 shows that the tube was sealed in the boiler by means of two neoprene stoppers. Pressure plates were tightened on steel studs to give the necessary tightness of the stoppers. Voltage leads passed through slits in the stoppers. The ends were soldered to the tube inside the boiler about ¼ in. from each stopper. The current leads were attached to the tube outside the boiler, each end being about 1.2 in. from the stoppers. Thus current passed through a 12.0-in. length of the tube, and the voltage drop was measured for an 8.0-in. section of the immersed portion. The heater tube and the accessories connected downstream (steam trap and the condensate flow line) were electrically insulated from their supports. Thus no current could by-pass the heater tube.

PROCEDURE

The copper tube was polished before every run. A commercial powder for copper cleaning, Cameo, was rubbed over the surface gently with a damp cloth. The tube was then rinsed with water and dried with a clean cloth. The final surface was smooth and lustrous. The inside of the tube was cleaned mechanically several times during the investigation by means of a cloth swab on a metal rod. The inside appeared to be free of fouling.

The cleaned apparatus was assembled, liquid was put in the boiler, and steam was passed through the tube. After steady state was reached, electric current was passed through the tube so that its temperature could be determined. After one set of readings was taken, the current flow was reversed and a second set was taken. The pairs of readings agreed, proving that thermoelectric voltage generation was not a source of error. The temperature calculated was the average metal temperature. From this and from a knowledge of the heat flux it was simple to calculate the temperature of the inside and outside surfaces of the tube. These temperatures were used to compute the individual film-temperature drops.

Heat transfer data consisted of the flow rate of the steam condensate (during continuous operation) and also a final check of the methanol condensate flow rate (during a final batch operation). Blank heat losses determined with an empty boiler were measured separately. The final heat balances closed within 8.9% on the average; the worst deviation was 16%. The heat transfer values reported herein are based on the methanol boil-up.

A 100-ft. reel of 16-mm. motion picture film was exposed during each of eleven selected runs. The exposure time was about 1 sec. for a reel.

RESULTS

The heat transfer values are summarized in Figure 4. The temperature difference between the metal surface and the bulk methanol varied from 38° to 181°F. The maximum heat flux on the smooth curve is 115,000 B.t.u./(hr.)(sq. ft.) and occurs at a ΔT of about 58°F. Prior workers (*13*) in the same laboratory reported a maximum of 139,000 B.t.u./(hr.)(sq. ft.) at an estimated critical ΔT of 51°F. Other workers in this laboratory (*17*) obtained a maximum of 172,000 B.t.u./(hr.)(sq. ft.) at an *over-all* ΔT of 99.5°F. In all three cases the heaters were ⅜-in. O.D. copper tubes, although the tubes were not identical. The two earlier results (*13, 17*) were obtained with bayonet-type heaters cleaned with dry emery cloth. Presumably some difference between the earlier test results and the present ones can be attributed to end effects and to differences in surface texture. The maximum heat fluxes for the three series of tests give a proportion of 1.5 to 1.2 to 1.0. This is much smaller than the ±50% variability (a 3 to 1 proportion) which McNelly (*12*) states is common for boiling tests.

NUCLEATE BOILING AND THE CRITICAL ΔT

Motion pictures were taken at seven heat fluxes during nucleate boiling, varying from 52 to 96% of the maximum flux. In each reel from six to twelve nucleating points were scrutinized closely. The rate of bubble emission for each point was determined, and the bubble diameters at the instant of break off were measured.

Figure 5 shows the locations on the boiling curve for the photographic runs. Figure 6 shows that the average bubble diameter as well as the average frequency of emission is constant for heat fluxes up to about 80% of the maximum flux. At higher fluxes the diameters and frequencies increase.

In the range of constant diameter and constant frequency, the product of diameter and frequency is constant at 4.0 in./sec. A previous set of measurements (*17*) using methanol on a bayonet heater at a heat flux of 78,000 B.t.u./(hr.)(sq. ft.) gave a $f \times D$ product of 3.3. These values are not greatly different from the values of 3.0 for carbon tetrachloride and 3.1 for water which were reported by Jakob and Linke (*9*) for small heat fluxes. Jakob and Linke noted an appreciable dead time after the break off of one bubble before a new bubble began to grow in its place. In the present tests the dead time was so short as to be negligible.

A photographic study of boiling in subcooled water with forced convection has been carried out by Gunther and Kreith (*7, 8*). These conditions are radically different from those for the present case, in which a saturated liquid and no forced convection were used. The subcooled boiling data give an estimated $f \times D$ product of about 80 in./sec. The bubble diameters were smaller for the cold liquid, but the bubble frequencies were greatly increased. Data for total bubble-emission rate are given also by Gunther. If it is assumed that the heat transfer was accounted for entirely by bubble generation, then the maximum bubble generation rate of 16 million bubbles/(sq. in.)(sec.) would account for a heat flux of 249,000 B.t.u./(hr.)(sq. ft.). The measured flux was 3,360,000 B.t.u./(hr.)(sq. ft.). The obvious conclusion is that bubble generation accounts for only a fraction of the heat transfer during subcooled boiling. Of course for a boiling saturated liquid, all the heat transfer appears as bubble generation.

The constancy of bubble sizes and frequencies (at least up to the 80% heat-flux limit) means that increases in heat flux with increases in ΔT must be caused entirely by corresponding increases in the number of nucleating sites. The heat released at a nucleating site is therefore independent of the ΔT. However, starting at about 80% of the maximum heat flux, the number of nucleating sites must increase less and less with each temperature increment.

Attempts were made to obtain motion pictures exactly at the critical ΔT. Although prior workers treat the critical ΔT as being a precise value, in practice it is not a quantity which can be reproduced with exactness. Figure 5 shows the data for temperature differences smaller than 65°F. plotted with an enlarged abscissa. The critical ΔT for methanol on this copper tube is actually a region extending from 52° to 62°F. Of course if an electric heater had been used, burnout would have occurred as soon as one measurement of the critical ΔT was made and duplicate runs with the same heater would have been impossible. Two photographic runs were made in the 10° critical range at 108,000 and 110,000 B.t.u./(hr.)(sq. ft.). In these films both runs were typical cases (visually) of nucleate boiling. Routine bubble counts were made.

One photographic run was made with a ΔT value of 81°F. Visually this case was typical of transition-type boiling; that is vapor formation was explosive, as described earlier (*17*). Bubble counts were not made from this film.

COMPARISON WITH EQUATIONS

In Figure 5 the experimental results for nucleate boiling are compared with the equation of Rohsenow and the equation of Forster and Zuber. The Forster-Zuber equation is plotted also in Figure 4. Rohsenow's expression was developed (*14*) as a relationship between three dimensionless groups, a Nusselt number, a Reynolds number, and a Prandtl number. The Prandtl group refers to the properties of the liquid only. The other groups involve vapor properties. The Reynolds group in particular was taken to be the Reynolds number of a bubble at the instant of break off. The bubble diameter and velocity at the instant of break off are therefore of great importance and are included in the expression.

The Rohsenow equation may be rearranged to show the dependence of h on ΔT and the other variables as shown in Equation (1).

$$h = \frac{C'(\Delta T)^2 {k_L}^{5.1} g^{0.5} (\rho_L - \rho_v)^{0.5}}{\sigma^{0.5} {C_L}^{2.1} \lambda^2 {\mu_L}^{4.1}} \qquad (1)$$

The dimensionless coefficient C′ was not specified; rather it is a value which gives a good fit to the particular system being considered. If the physical properties of the methanol are taken at the saturation temperature of the liquid, as recommended by Rohsenow, the coefficient for the present data becomes 13.1 × 10^6. This corresponds to a coefficient C_{SF} of 0.0042 in Rohsenow's terminology. He reports a range of C_{SF} values of 0.0027 to 0.015 for other systems.

The Rohsenow equation states that for a given system at a given pressure, h is independent of the properties of the superheated liquid film. However, the ΔT across this film is taken as the correct driving force. A possible way to resolve this inconsistency is to take the physical properties of the liquid at the mean temperature of the superheated liquid film. If this is done with the present data, the coefficient in Equation (1) becomes 8.5 × 10^6, corresponding to C_{SF} =

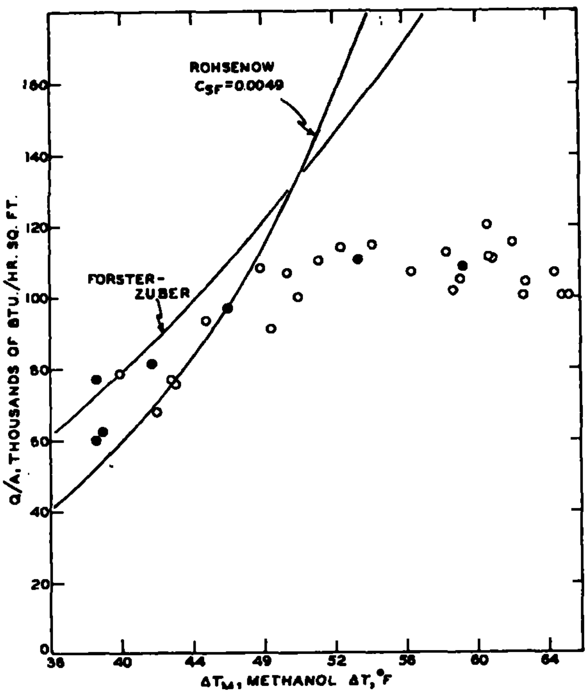

Fig. 5. Test of nucleate-boiling equations for methanol boiling at large heat fluxes. The solid symbols indicate runs for which motion pictures were made.

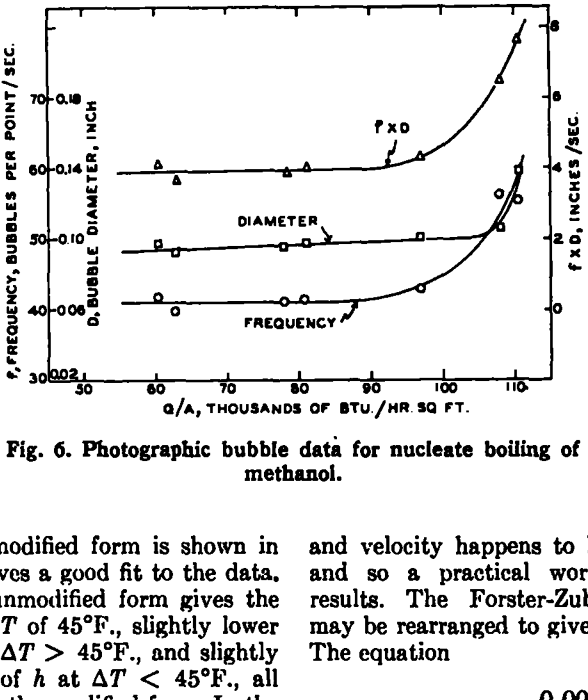

Fig. 6. Photographic bubble data for nucleate boiling of methanol.

0.0049, This modified form is shown in Figure 5; it gives a good fit to the data. The original unmodified form gives the same h at a ΔT of 45°F., slightly lower values of h at $\Delta T > 45$°F., and slightly higher values of h at $\Delta T < 45$°F., all compared with the modified form. In the range of ΔT studied herein, no choice can be made between the two forms.

Forster and Zuber also developed an equation containing Nusselt, Prandtl, and Reynolds groups. The prime difference between this equation and the Rohsenow equation is in the Reynolds number. Forster and Zuber consider the Reynolds number for a bubble which is microscopic and is growing. The diameter is a variable with time. The velocity used is the rate of radial movement of the bubble wall and is variable with time. The theoretical product of the diameter and velocity happens to be a constant, and so a practical working equation results. The Forster-Zuber expression may be rearranged to give Equation (2). The equation

$$h = \frac{0.0012(\Delta T)^{0.24}(p_s - p_L)^{0.75}C_L^{\ 0.45}\rho_L^{\ 0.49}k_L^{\ 0.79}}{\sigma^{0.5}\lambda^{0.24}\mu_L^{\ 0.29}\rho_v^{\ 0.24}} \tag{2}$$

is plotted in Figure 5. The authors evaluate the physical properties of the liquid at the temperature of the solid surface and those of the vapor at the saturation temperature. The dimensionless coefficient 0.0012 is supposed to be the same for all systems. It gives predictions equal to those from the original Forster-Zuber equation, which, because of its different algebraic form, contains a coefficient of 0.0015.

The Forster-Zuber equation gives a fair fit with the methanol data. For fluxes less than 100,000 B.t.u./(hr.)(sq. ft.) the predicted heat fluxes are about 14% greater than the observed values. This accuracy is adequate for many applications. The Rohsenow equation gives a closer fit, but it requires knowledge of experimental boiling data to give the arbitrary constant.

It is possible to manipulate Equations (1) and (2) in an interesting way. Granted that the properties of the superheated liquid film are important and that these properties may be taken at the mean temperature of this film, then it is seen that Equation (1) contains ΔT and viscosity in a sensitive manner. All the other variables in Equation (1) are affected but weakly by changes in the solid-surface temperature (with a constant ambient pressure assumed). Viscosity may be related to temperature by the Eyring type of expression, which shows ln μ_L linear with $1/T$. This substitution in Equation (1), in combination with the constant properties of the liquid at 1 atm. plus the coefficient 8.5 × 10^6 leads to Equation (3):

$$h = 0.50(\Delta T)^2 \cdot e^{9.6\Delta T/T_L} \tag{3}$$

The symbol T_L refers to the mean temperature of the superheated liquid. The coefficient 0.50 is dimensional, B.t.u./(hr.)(sq. ft./°F.^{3}), and T_L is °R.

Equation (2) contains Δp, which is very sensitive to temperature. The other variables have but a weak effect as temperature changes. If vapor pressure is related to temperature by the Clausius-Clapeyron equation. Equation (2) becomes Equation (4):

$$h = 570(\Delta T)^{0.24}(e^{13.8\Delta T/T_s} - 1)^{0.75} \tag{4}$$

The constants 570 and 13.8 were selected to give a good fit to the data obtained at atmospheric pressure. Theoretically the coefficient may be found by using the physical properties of methanol, and at 1 atm. it should be 720. Similarly the exponent 13.8 should be $\lambda/(RT_w)$, or 11.9. The exponent 13.8 is dimensionless, but the coefficient 570 has the dimensions B.t.u./(hr.)(sq. ft./°F.$^{1.24}$, and T_s is the solid-surface temperature in °R.

Equations (3) and (4) suggest that boiling involves an activation energy, an idea which occurs sporadically in the literature (*2, 5, 16*). However, the two expressions deal with different kinds of activation. The exponent on e in Equation (3) contains an activation energy for viscosity, and Equation (4) contains λ, an activation energy for vaporization, in the equivalent exponent. According to Eyring these two values have a constant ratio. Thus Equations (3) and (4) should be identical, but they are not. Future studies will be needed to show which, if either, is correct. Tests showing the effect of pressure are of particular value. In any case, Equations (3) and (4) indicate that empirical equations in the form of $h = a(\Delta T)^n$ may be grossly oversimplified and that an additional factor involving $e^{\Delta T}$ or $e^{1/T}$ is desirable.

Several empirical correlations have been proposed for estimating the maximum heat flux. The expression of Rohsenow and Griffith (*15*), which is a modification of an earlier correlation by Addoms (*1*), predicts a maximum flux of 227,000 B.t.u./(hr.)(sq. ft.) for the present conditions; Cichelli and Bonilla (*4*) predict 197,000. The first figure is too high by over 90%, the second by 70%. Cichelli and Bonilla also give a correlation for the critical ΔT. Their prediction gives about 83°F., which is not very close to the actual value of between 52° and 62°F.

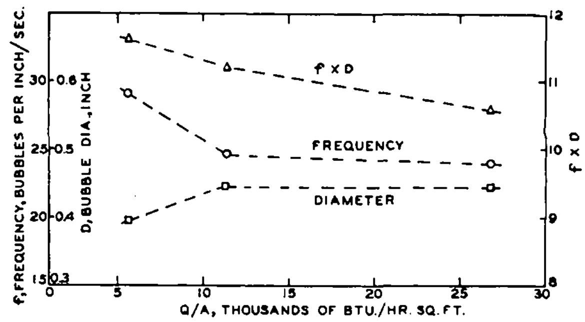

Fig. 7. Photographic bubble data for film-boiling region for methanol.

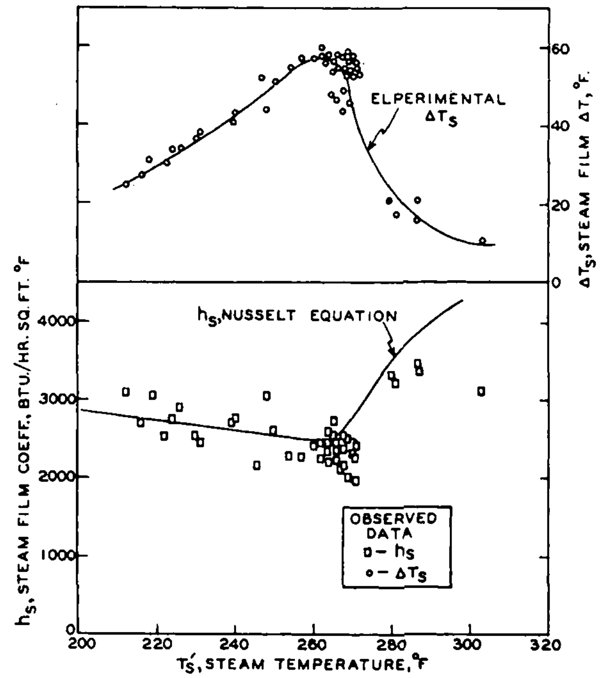

Fig. 8. Test of Nusselt equation for steam condensing inside a horizontal tube. The experimental tube was 20-gauge copper, ⅜-in. O.D., slanted at 1.8° with the horizontal. The heat transfer length was 8.4 in. The inside area was used as a basis for h_s. The theoretical h_s is based on the smoothed values of ΔT_s.

TRANSITION BOILING

One advantage of a steam-heated surface, as opposed to an electrically heated one, is that the former permits tests in the transition region where h decreases as ΔT increases. Photography in this region yielded no information not reported previously (*17*); however, tube-temperature measurements did yield new information. For one thing the actual dependence of the methanol h on the methanol ΔT was found to be less steep than one might deduce from plots of h or U vs. the over-all ΔT.

A second fact was discovered. For each experimental run a series of three replicate heat balances and ΔT measurements were obtained. For the nucleate and film boiling tests, the replicates agreed within a few per cent. But for transition boiling, the methanol-side ΔT often changed slowly during the course of a run. Inasmuch as the steam temperature was controlled, the over-all ΔT remained constant. Thus the steam-side ΔT was changing also, in the opposite direction to the methanol ΔT. The transition-boiling points plotted in Figure 4 are the results of single determinations taken within a few minutes. Typical of the drifting were three successive readings at an over-all ΔT constant at 118.5°F. The heat flux shifted slowly from 87,800 to 100,700 B.t.u./(hr.)(sq. ft.) as the methanol ΔT changed from 73° to 62°F. and the steam ΔT changed from 44° to 55°F. The reason for the drifting is not known. A guess may be based on the fact that this region gives a steam film ΔT which is strongly—and a steam h which is somewhat—dependent on the steam temperature, as shown in Figure 8. Thus a slight shift in the steam temperature could cause a significant shift in the steam h and a resulting shift in the metal temperature. This would alter the methanol ΔT and the methanol h. The new coefficients would cause a change in the heat flux. The new flux would alter the various values further, and the process might continue until a random fluctuation of the steam temperature in the reverse direction occurred. If this explanation is correct, transition boiling is "unstable" to temperature shifts even less than 1°F., because the steam temperature was controlled within 1°F.

FILM BOILING

Three reels of motion pictures were taken during film boiling. These covered the range of ΔT values for the methanol film 143° to 181°F., corresponding to heat fluxes of 27,000 down to 5,590 B.t.u./(hr.)(sq. ft.). Visually, well-developed film boiling existed. The bubble release was in the form of orderly rows as previously discussed (*17*). The diameter at break off was measured for eleven or twelve bubbles in each film. The frequency of formation of the rows was measured.

Averaged results are shown in Figure 7. The product of frequency and diameter does not change with increasing heat flux, as would be predicted from observations of the uniformity of the bubble sizes plus considerations that (*a*) all the bubbles formed can be seen and measured and (*b*) the volume of vapor formed must account for the heat transferred. Two explanations are possible for the discrepancy. The bubbles grow considerably after break off, and the amount of growth probably varies with the heat flux. Also, a small error in the measured diameter causes a large error in the calculated bubble volume. The heat fluxes calculated from bubble measurements (assuming no growth after break off) give but fair agreement with the measured heat fluxes. The table shows that an error of 41% in the measured diameter would explain the worst discrepancy in the data. Some adjustment should be made because the bubbles are egg-shaped at the instant of break off. The following calculations are for idealized spheres.

Actual heat flux, B.t.u./(hr.)(sq. ft.)	Heat flux estimated from bubble data, B.t.u./(hr.)(sq. ft.)	Theoretical error in diameter, %
5,590	11,500	+27
11,300	10,400	−3
27,000	9,600	−41

Bromley's equation for stable film boiling, Equation (5), is plotted in Figure 4.

$$h = 0.62\left[\frac{k_v^3 \rho_v(\rho_L - \rho_v)\lambda g}{\mu_v D_0 \Delta T}\right]^{0.25} \quad (5)$$

The equation does not give a good fit for the first stages of film boiling. For example, photography shows that a methanol ΔT of 140°F. results in clear-cut film boiling. The Bromley equation predicts a heat flux which is only one sixth the observed flux. However, at a ΔT of 180°F. Equation (5) gives excellent agreement with the data.

NUSSELT EQUATION OF CONDENSATION

Nusselt's theoretical equation for film-type condensation, Equation (6), was derived for a vapor outside a horizontal tube.

$$h_S = 0.725\left[\frac{k_L^3 \rho_L^2 \lambda g}{\mu_L D_i \Delta T'_S}\right]^{0.25} \quad (6)$$

Jakob (*10*) states that the expression should apply for condensation inside a horizontal tube provided the inside diameter is used. However, the two cases have one distinct difference: during outside condensation, liquid drips from the entire tube length; during inside condensation the liquid must collect in the bottom of the tube and flow toward the exit. In the second case liquid may blanket the tube bottom and lead to poor heat transfer there.

Inasmuch as the tube temperature, steam temperature, and heat transfer rate were all measured, the actual heat transfer coefficient for steam condensing inside the copper tube was determined. In Figure 8 the data are compared with those predicted from the Nusselt equation. The physical properties were taken at the average temperature of the liquid film. The observed values are seen to agree well with the theoretical ones for steam temperatures up to about 280°F. At higher temperatures the observed values are less than the theoretical, and the equation is not conservative. The observed results hold probably only for the particular tube geometry used in these tests: an I.D. of 0.305 in., a heat transfer length of 8.4 in., and an inclination of 1.8° with the horizontal. A longer tube or a smaller angle could cause deviations.

The unusual shape of the curve of h in Figure 8 is a result of the change in the steam ΔT coincident with the changes in the steam temperature and pressure. The steam ΔT is shown in the graph. The peak occurs when the methanol is at its maximum heat flux.

CONCLUSIONS

For methanol boiling at atmospheric pressure on a ⅜-in. copper tube:

1. The nucleate boiling region is described satisfactorily by either the Rohsenow equation or the Forster-Zuber equation for heat fluxes between 50,000 and 100,000 B.t.u./(hr.)(sq. ft.)
2. The critical point for boiling is not a point but is rather a region extending from 52° to 62°F.
3. For nucleate boiling the product of bubble diameter and frequency of emission is constant at 4 in./sec. up to about 80% of the maximum heat flux, thus extending the observations of Jakob for small fluxes.
4. Between 80 and 100% of the maximum flux the $f \times D$ product is greater than 4 and is not constant.
5. For film boiling, the product $f \times D$ is nearly constant at about 11 sec.$^{-1}$
6. For film boiling at the lower values of ΔT, the Bromley equation is not applicable; at values of ΔT near the maximum ΔT used, 180°F., the equation is satisfactory.
7. Nusselt's equation for condensation outside a horizontal tube is applicable to condensation inside a horizontal tube provided that liquid accumulation at the bottom of the tube is prevented.
8. An excellent method of measuring the average temperature of a steam tube in a boiling liquid consists of the use of the tube as a resistance thermometer.

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NOTATION

a = arbitrary constant
C_L = heat capacity of liquid, B.t.u./(lb.)(°F.)
D = bubble diameter, in.
D_i, D_0 = inside and outside diameters of a tube, ft.
e = base of Naperian logarithms, 2.718
f = frequency of bubble release, bubbles/sec./point (nucleate boiling) or bubbles/sec./in. (film boiling)
g = gravity constant, ft./hr.^{2}
h = heat transfer coefficient for methanol, B.t.u./(hr.)(sq. ft./°F.)
h_s = heat transfer coefficient for steam, B.t.u./(hr.)(sq. ft./°F.)
k_L, k_v = thermal conductivity of liquid, vapor, B.t.u./(hr.)(ft./°F.)
n = arbitrary constant
p_L = vapor pressure at saturation (at T_∞), lb./sq. ft.
p_v = vapor pressure at maximum superheat (at T_s), lb./sq. ft.
Q/A = heat flux, B.t.u./(hr.)(sq. ft.)
R = gas constant, B.t.u./(lb.)(°F.)
T = temperature, °F. or °R.
T_L = liquid temperature at mean of T_s and T_∞, °R.
T_s = surface temperature of hot solid, °R.
T_s' = steam temperature, °F.
T_∞ = liquid temperature at saturation, °F. or °R.
ΔT = temperature difference, °F.
ΔT_M = temperature driving force across methanol, °F.
ΔT_s = temperature driving force across steam, °F.
U = over-all heat transfer coefficient, B.t.u./(hr.)(sq. ft./°F.)
λ = latent heat of vaporization, B.t.u./lb.
μ_L, μ_v = viscosity of liquid, vapor, lb./(ft.)(hr.)
ρ_L, ρ_v = density of liquid, vapor, lb./cu. ft.
σ = surface tension, lb./ft.

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