BOILING OF LIQUIDS

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This chapter concludes the review on "Boiling of Liquids," the first part of which, published in Volume I of *Advances in Chemical Engineering*, 1956, included: I. Introduction; II. Nucleate Boiling and the Critical Temperature Difference.

I. Transition Boiling

Rarely has the transition type of boiling received attention. It cannot be studied by researchers using electric heaters because of the inherent instability of electric heaters in this region. As recently as ten years ago one writer, familiar with tests with electric heaters, argued that the transition region does not exist.

To study the transition region, one must employ a hot fluid or a condensing vapor as the source of heat. Drew and Mueller (D3) obtained transition boiling data for six liquids boiling on a steam-heated copper tube. The heat transfer coefficients and ΔT values measured were overall values. McAdams (M2) reports individual values for h and ΔT in the transition region for two liquids, but he does not describe in detail the method of determining the wall temperature. Some studies of the transition region are now under way at the University of Illinois. Certain of the observations are included below.

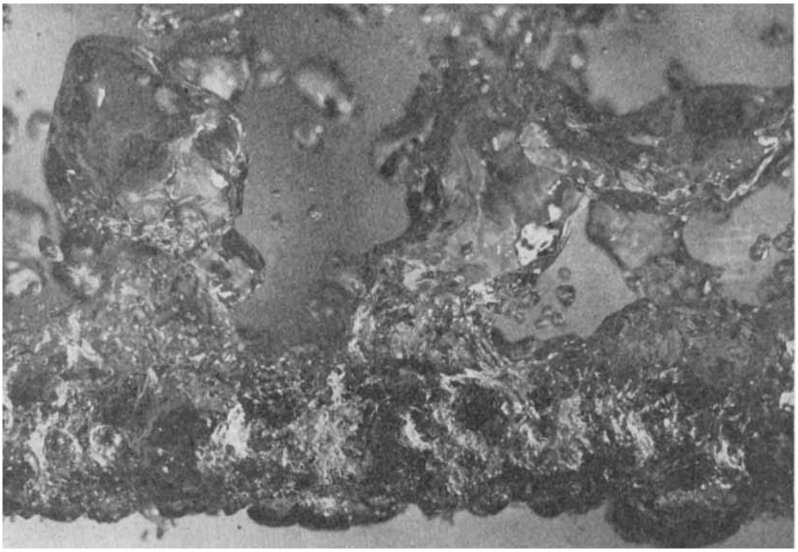

FIG. 1. Transition boiling of methanol. Point C on the boiling curve, Fig. 15. Overall ΔT = 112°F. Heat flux = 69,000 B.t.u./hr. sq. ft. (W2).

A. DESCRIPTION FROM PHOTOGRAPHIC STUDIES

The only photographs of transition boiling are those of Westwater and Santangelo (W1, W2, W3). The photographs prove that transition boiling is entirely different from both nucleate boiling and film boiling. Figures 1 and 2, for methanol on a $\frac{3}{8}$-in. copper tube, show that no active points exist on the metal surface. In fact none of the photographs obtained so far shows a clear-cut contact between the liquid and solid. The photographic evidence demonstrates that the tube is completely blanketed with vapor. However the vapor blanket is not a smooth, stable film. It is irregular and in violent motion.

The high-speed motion pictures show that vapor is formed by explosive bursts which occur at random locations on the tube. Apparently the vapor film becomes very thin at some location, the liquid moves in toward the tube, and then a miniature blast occurs. The blast creates a slug of vapor which forces the liquid back. The vapor slug eventually ruptures and leaves the tube. Two explosions are evident in Fig. 1. One is in profile below the tube at the right end; the other is a fourth of the way from the left end, a "plan" view of a circular slug moving toward the eye of an observer.

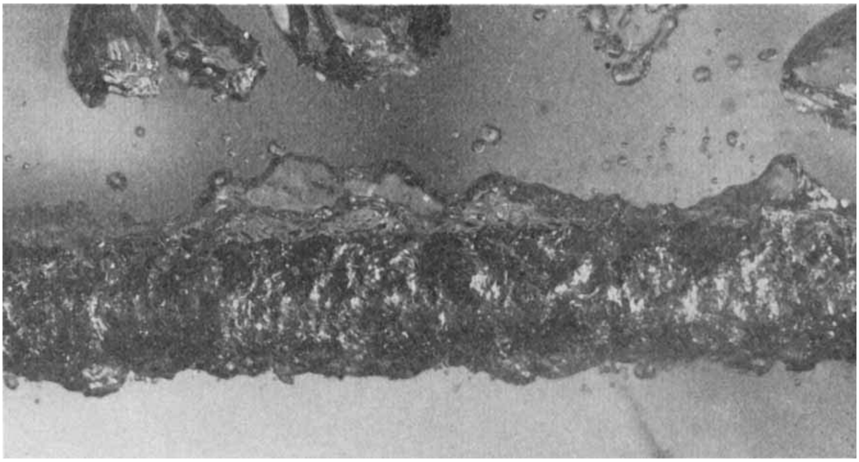

FIG. 2. Transition boiling of methanol. Point D on the boiling curve. Overall ΔT = 124°F. Heat flux = 27,200 B.t.u./hr. sq. ft. (W2).

The frequency of the vapor bursts is very high. For an over-all ΔT of 133°F., each inch of the photographed side of the tube exhibited 84 bursts per sec. A typical burst has a vigorous life of about 0.003 sec. A burst in profile shows that the surrounding liquid is shoved back about 0.16 in. in this time, or the average velocity of the interface is about 4.5 ft./sec.

B. EXPERIMENTAL VALUES

The boiling data of Drew and Mueller were exploratory in nature, and the authors did not claim high accuracy for the values. However, the general shape of the transition boiling curve was well illustrated. Figure 3 shows some of the data. Note that the ΔT includes the temperature drop across the steam film.

The data of Braunlich and of Kaulakis and Sherman, reported by McAdams, are shown in Figs. 4 and 5. These show the effect of modest changes in pressure. The important fact is that the individual curves remain apart. That is, increasing pressure (at least by small amounts) improves the heat transfer in the transition region just as it does in the nucleate region.

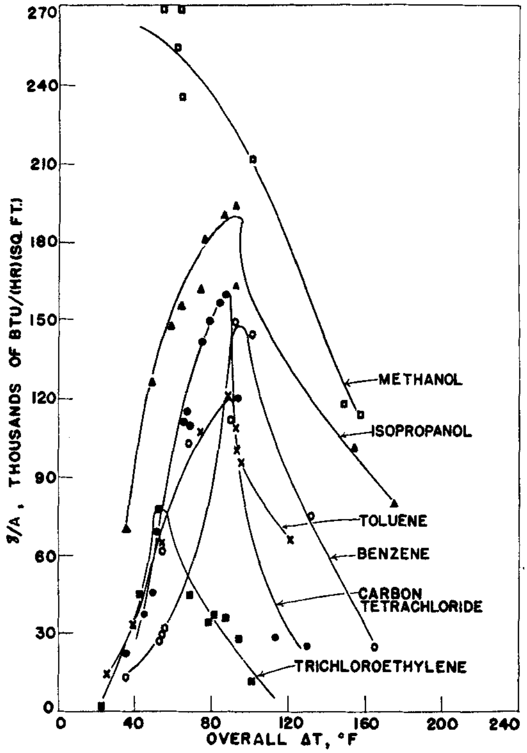

FIG. 3. Nucleate and transition boiling. Six liquids were boiled on a ¼-inch steam-heated, copper coil, at one atmosphere (D3).

In addition to pressure, certain other variables which are important during nucleate boiling are important during transition boiling. Figure 6 shows the results obtained when small amounts of a material which is known to be surface active with water was added to methanol. The change in the boiling curve is very real, although no proof exists that surface tension effects are the correct explanation. In fact, the liquid-vapor interfacial tension of methanol is not affected by the agent. Figure 7 shows the effect of surface texture on boiling methanol. The results are very similar to those obtained in nucleate boiling. Figure 8 shows that agitation improves the heat transfer in the transition region as well as in the nucleate region.

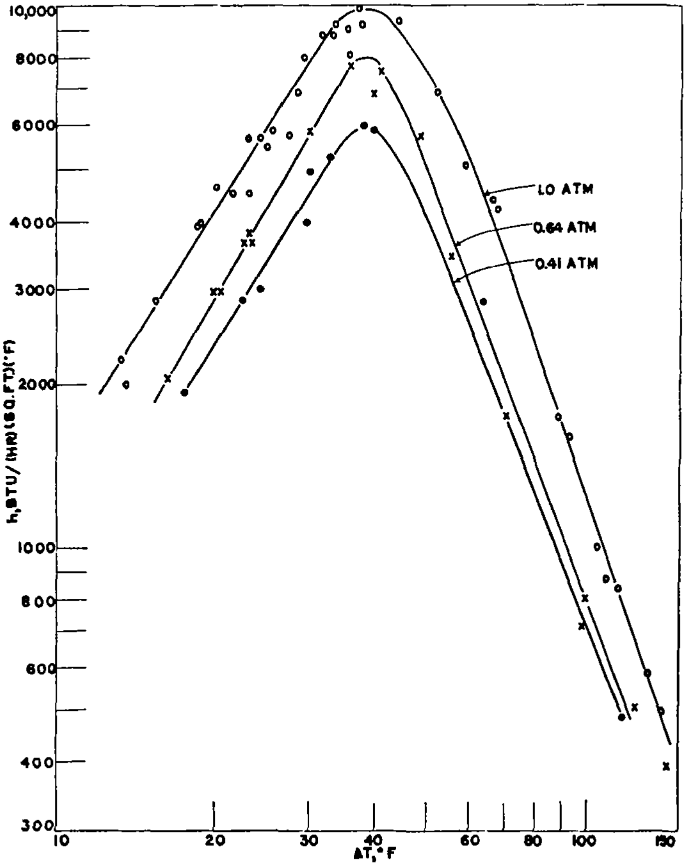

FIG. 4. Nucleate and transition boiling for water on a horizontal tube (M2).

To summarize the small quantity of data: the variables for transition-type boiling seem to be the same as those for nucleate boiling. The magnitude of each effect is not necessarily the same. As the film boiling region is approached, agitation remains an important variable, whereas surface texture becomes of negligible importance. The addition of surface active agents seems to result in an improvement in heat flux, even as the film boiling region is approached closely.

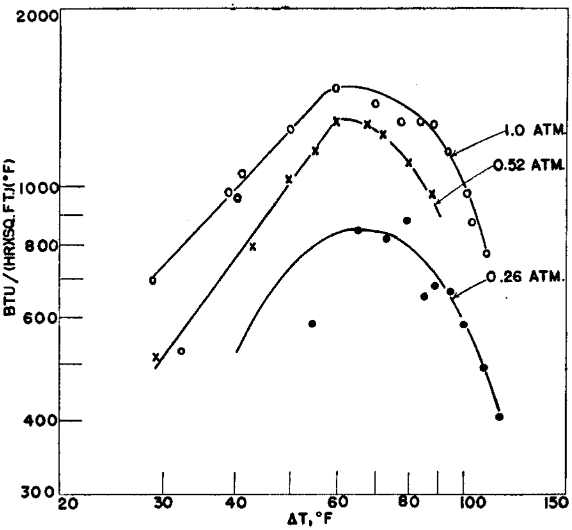

FIG. 5. Nucleate and transition boiling for isopropanol (M2).

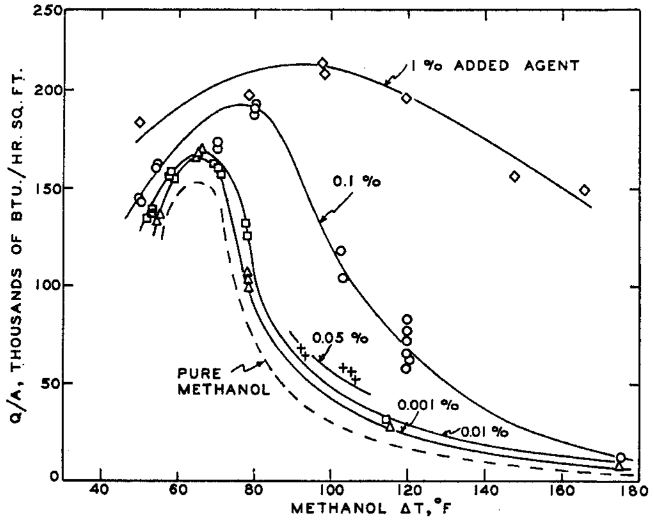

FIG. 6. Effect of surface-active agent on transition boiling. Rohm and Haas Hyamine 1622 (benzyldimethyl {2-[2(*p*-1,1,3,3-tetramethylbutylphenoxy)ethoxy]-ethyl} ammonium chloride: mol. wgt. = 466) was added to methanol boiling on a ¼-inch, horizontal steam-heated, copper tube at one atmosphere (L1).

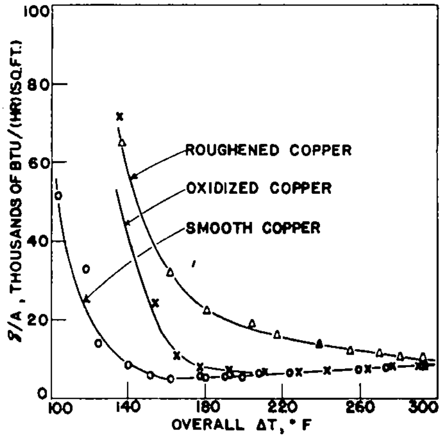

FIG. 7. Effect of surface texture on transition boiling. Methanol was boiled at one atmosphere on a ⅜-inch, horizontal, steam-heated, copper tube (D2).

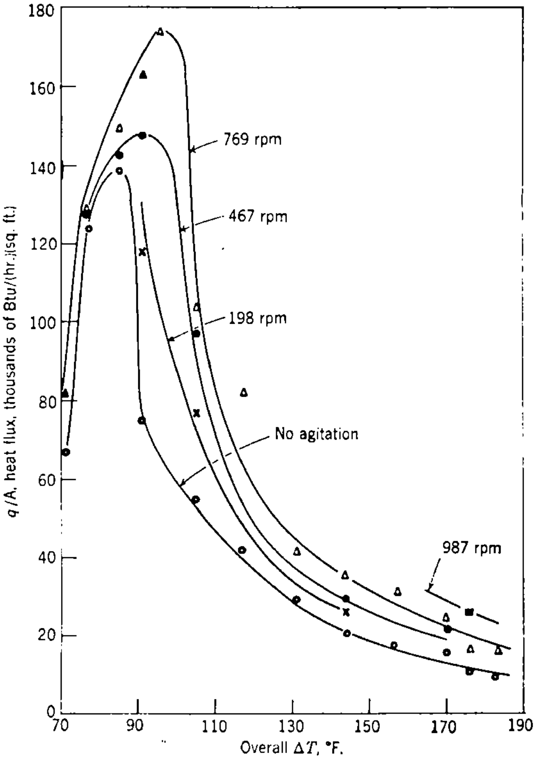

FIG. 8. Effect of agitation. Methanol was agitated with a 3-blade propeller while boiling at one atmosphere on a ⅜-inch horizontal, steam-heated, copper tube. The shaft speed is indicated (P1).

It is obvious that much more experimental work is needed. No theoretical treatment of transition boiling has ever been given. A convincing explanation of why there should be a smooth decrease in h with an increase in ΔT has never appeared. It is possible to "explain" the effect in terms of film thickness, but this is a superficial explanation based on the false assumption of a stable film. It is also possible to "explain" that transition boiling is a mixture of nucleate and film boiling, but this is contrary to photographic evidence.

At present it is impossible to design commercial equipment to operate in the transition region. From a practical standpoint, equipment should not be operated in this region anyhow. The performance would be superior at the critical ΔT.

II. Film Boiling

Film boiling has received more attention than the transition type, but still only a fraction of the attention given to nucleate boiling. The reasons are clear. Film boiling results in very low heat fluxes if conveniently small temperature differences are used; therefore the region of "easy" study is commercially unimportant. The region of high heat fluxes (and of practical interest) requires high-temperature techniques if ordinary liquids are used. Film boiling may be the convenient operating region when liquefied permanent gases are boiled, but this demands a knowledge of low-temperature techniques.

A. Description from Photographic Studies

Film boiling is characterized by action which is the slowest, most orderly, and best defined of the three main types of boiling. It is significant that film boiling is the first type to be attacked, with success, from a theoretical standpoint. Boiling heat transfer in most of the film region is described fairly well by the equations of Bromley (B3, B4, B5).

During film boiling no active centers exist. No explosive bursts occur. The hot solid is encased completely in a slowly moving film of vapor. No vapor is generated at the solid surface; it is all generated at the liquid-vapor interface. If a horizontal hot tube is used, the vapor flows up the tube in a series of ripples. In Fig. 9, the ripples are quite evident. For the conditions of Fig. 10, the ripples move up the tube at a rate of 74 each sec. on each side of the tube.

As vapor accumulates at the top of the tube a wavy, rodlike mass forms. At first the mass is fairly smooth and uniform, as shown in Fig. 10, although some movement occurs constantly. Eventually the vapor-rod becomes unstable and changes into a series of nodes, as shown in Fig. 9. Then the entire rod ruptures, between all the nodes at about the same instant. A horizontal row of bubbles, side by side, rises. After the rupture, the whole procedure is repeated. For Fig. 10, one complete cycle required 0.06 sec.

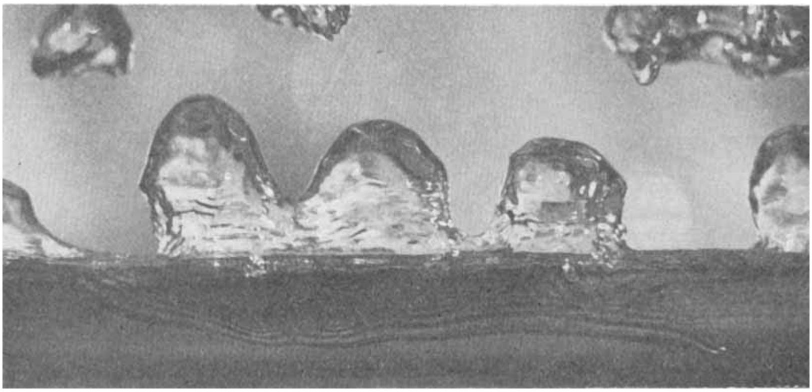

FIG. 9. Film boiling of methanol. Point *E* on the boiling curve. Overall ΔT = 148°F. Heat flux = 12,970 B.t.u./hr. sq. ft. (W2).

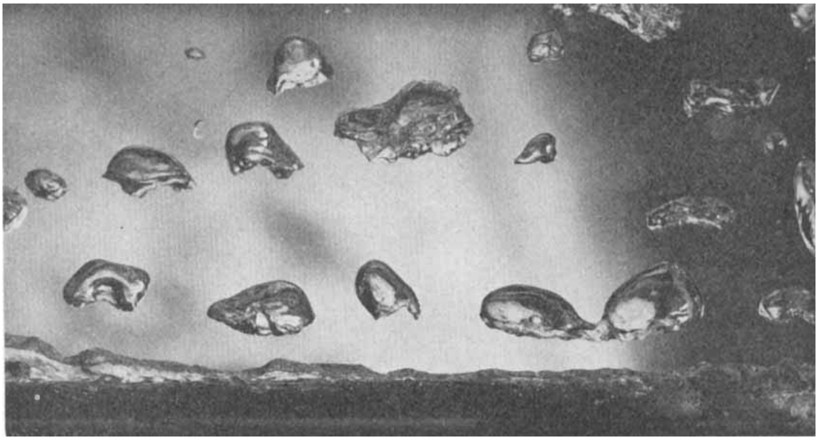

FIG. 10. Film boiling of methanol. Point *F* on the boiling curve. Overall ΔT = 181°F. Heat flux = 5,470 B.t.u./hr. sq. ft. (W2).

The second vapor-rod usually ruptures at points between the preceding break-points. Thus even-numbered rows of bubbles are displaced sideways by a half-space from the odd-numbered rows. This is clear in

Fig. 9. The fact has been observed for film boiling on wires (C1) as well as tubes. No information is available for film boiling on plates.

Bubbles formed during film boiling are much larger than those from nucleate boiling. For the instant of release in Fig. 10, the diameters range from 0.20 to 0.36 in., averaging 0.30 in. The horizontal spacing, center to center, is about 0.5 in., with an occasional value as great as 0.75 in. Bubbles are released from the top only, never from the bottom or sides of the tube as in nucleate and transition boiling.

The history of these large bubbles after release is interesting. A "stretched" vapor filament is the last part of a bubble to break from the hot solid. The filament contracts rapidly, because of surface tension, and rams into the main body of the bubble. The bubble shape is distorted by the impact, becoming umbrellalike. The deformed surface then snaps back down, and the bubble vibrates as it rises. The true shape of rising, large bubbles is evident in Fig. 10.

B. THEORETICAL TREATMENT

Two types of condensation, drop-wise and film-wise, have been known for many years. As soon as the two types of boiling, nucleate and film, were described, certain similarities to condensation became evident. Nucleate boiling and drop-wise condensation were seen to be analogous. This is of little practical value, because no good theory of drop-wise condensation exists. However the analogy between film boiling and film condensation is fruitful, because a good theory of film condensation exists.

Colburn (C2), and probably other writers, suggested that Nusselt's excellent equation for film condensation could be modified for use with film boiling. Colburn gave as a guess that the proper form of the equation for boiling outside a horizontal tube would be the same as Nusselt's, except for certain changes from the physical properties of the liquid to those of the vapor and an adjustment in the dimensionless coefficient. Colburn suggested a coefficient of $\frac{1}{2}$ for a liquid boiling outside a horizontal tube and $\frac{2}{3}$ for a vertical tube.

In 1950, Bromley (B3) presented a complete derivation for film boiling outside a horizontal tube. The derivation is based on the fact that liquid is separated from the tube continuously. Important assumptions are involved: (1) The vapor film is smooth, and vapor escapes from the top of the tube as if issuing from a narrow slot. (Figures 9 and 10 show that this is not truly the case.) (2) The rise of vapor due to buoyancy is a viscous flow. (3) The kinetic energy of the vapor is negligible. (4) The liquid-vapor interface is at the liquid boiling point. (5) The temperature drop across the vapor film is assumed to be constant. (6) Heat transfer across the vapor film is by conduction and radiation, but not by convection. (7) Sensible heat transfer to the vapor is negligible.

The principal features of the derivation consist of a force balance and a heat balance for an element of vapor volume. These are also the principal features of Nusselt's derivation for film condensation. The forces acting on a tiny volume are those due to buoyancy and viscosity. The equation for the heat balance states that the increase in the flow rate of vapor which occurs along an increment of tube circumference corresponds to the heat flow rate in that region. Inasmuch as Nusselt's derivation is available in numerous books, Bromley's equivalent derivation will not be given here. The final equation is

$$h' = 0.62 \left[\frac{k_v{}^3 \rho_v (\rho_L - \rho_v) \lambda g}{D \mu_v \, \Delta T} \right]^{1/4} \tag{1}$$

(Bromley equation, horizontal tube)

The coefficient 0.62 is empirical. The theoretical value is either 0.512 (stagnant liquid around the vapor) or 0.724 (liquid moving with same velocity as the vapor). The average of these two numbers is 0.62.

Equation (1) omits the effect of radiation. Radiation is accounted for by use of the familiar expression for parallel plates,

$$h_R = \frac{\sigma' F_\epsilon (T_s{}^4 - T_L{}^4)}{\Delta T} \tag{2}$$

The combined film coefficient becomes $h = h' + h_R$.

Verification of Eq. (1) is shown in Figs. 11 to 13. The value of h_R has been subtracted from the observed h. Figure 13 shows the comparable magnitudes of h' and h_R and the agreement between the observed sum and the predicted sum.

For a vertical tube, Bromley predicts the equation,

$$h' = (\text{Const.}) \left[\frac{k_v{}^3 \rho_v (\rho_L - \rho_v) \lambda g}{L \mu_v \, \Delta T} \right]^{1/4} \tag{3}$$

No data are available to test this expression.

If the sensible heat content of the vapor is important, it can be shown (B4) that a correction factor $(1 + 0.4 C_v \, \Delta T / \lambda)^{1/2}$, should be included on the right side of Eq. (1).

Bromley's equations are consistent with reality in that they predict a minimum value of h'. As the solid temperature is increased, two counteracting effects occur. The values of k_v and ΔT both increase. At first the

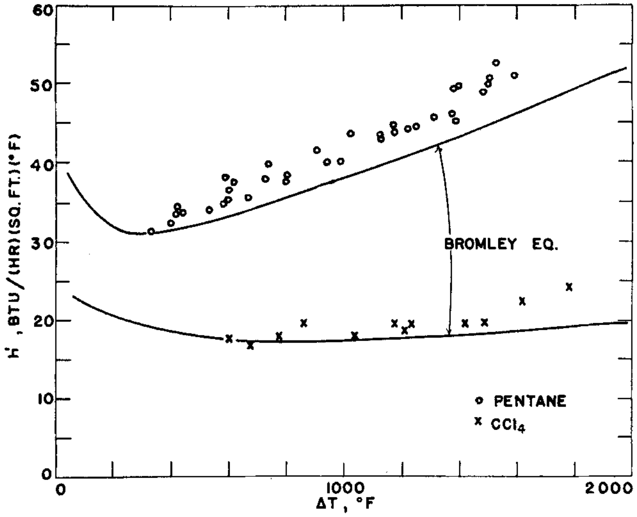

FIG. 11. Film boiling. The boiling heat transfer coefficients, corrected for radiation, are shown for two liquids, at one atmosphere, on a 0.352-inch carbon tube (B3).

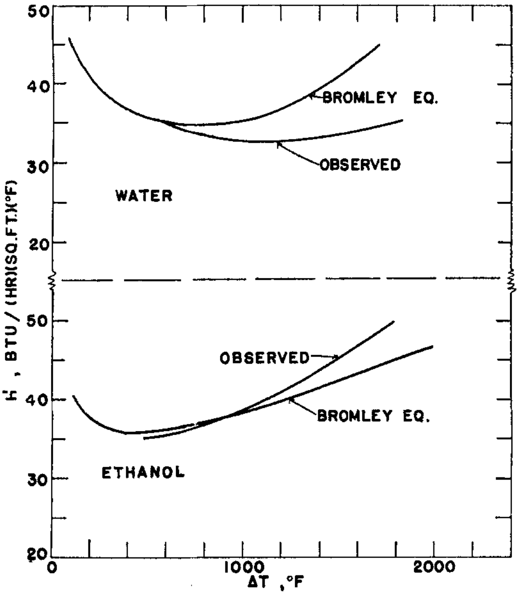

FIG. 12. Film boiling. The conditions were the same as for Fig. 11. The actual data scatter was similar to that in Fig. 11 (B3).

change in ΔT is predominant, but as the temperature level becomes greater, the change in k_v becomes more important. The other physical properties are temperature-sensitive, but their effects are not so great. Of course at very high temperatures, radiation is sufficient to account for increases in h.

Marx and Davis (M1) present the interesting thought that the film thickness during film boiling is some value greater than the mean free path of a vapor molecule. This idea leads to reasonable qualitative predictions as to the effects of pressure and temperature. These authors suggest also that transition boiling occurs if the film thickness becomes equal to the mean free path, but proof is not available.

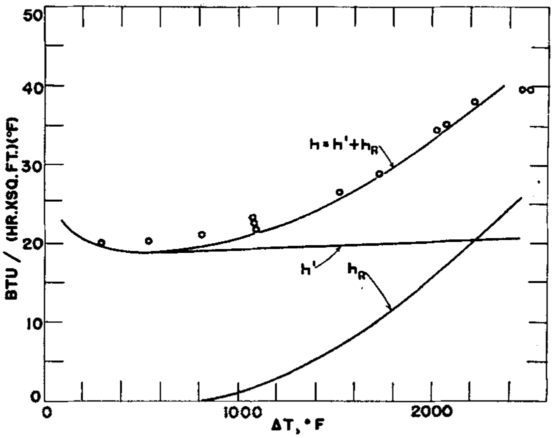

FIG. 13. Importance of radiation during film boiling. Nitrogen was boiled at the same conditions as for Fig. 11 (B3).

C. EXPERIMENTAL VALUES

1. *Type of Liquid*

a. Water. Data for water in film boiling are available for horizontal wires and a tube. Bromley's results are shown in Fig. 12. The data of Rinaldo (M3) and Nukiyama (N1) are compared with Bromley's in Fig. 14. The agreement, for the wires, is good if consideration is given to the effect of diameter. Platinum was used by both Rinaldo and Nukiyama; Bromley used a carbon tube. All these tests were at atmospheric pressure.

Water in film boiling is normal in that it does not give unusual test values. The physical properties for which water is most different from common liquids are the latent heat of vaporization, heat capacity, and surface tension. According to Eq. (1), surface tension and heat capacity are not variables, and the other factor appears to a low exponent. Thus on theoretical grounds, water should be rather ordinary.

b. Other Common Liquids. Data are available for six organic liquids (benzene, methanol, ethanol, carbon tetrachloride, *n*-pentane, and diphenyl ether) and two permanent gases (nitrogen and oxygen). Data for some of these are shown in Figs. 11, 12, 13, 15, 16, and 17.

A striking fact is that at atmospheric pressure all these materials have roughly the same value of h', namely about 20 to 50 B.t.u./(hr.)(ft.^{2})(°F.).

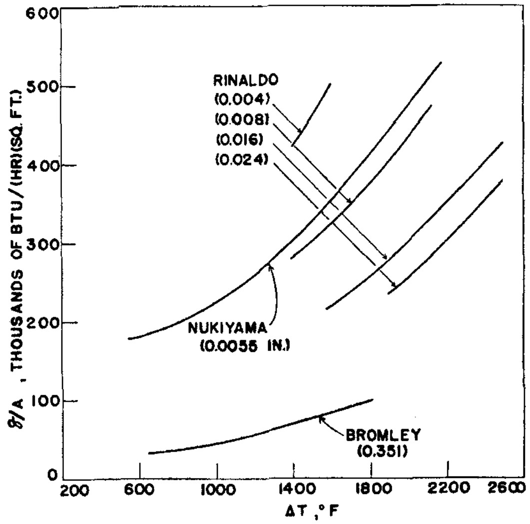

FIG. 14. Observed film boiling values for water at one atmosphere on horizontal tubes and wires.

If one were to use $h' = 35$, the error would be no worse than 50% for nearly every point in the graphs shown. One reason for this interesting occurrence is that h' is a weak function of all the variables except k_v, at atmospheric pressure. The thermal conductivities of different gases are not highly variable. At high pressures, the vapor density will become a relatively strong function, and the "uniformity" of different boiling liquids should no longer exist.

c. Liquid Metals. A major problem with boiling metals is the decision as to which type of boiling is occurring. Transparent vessels are not convenient, because of the high temperatures; thus rarely is the boiling visually observed.

Farmer (F1) obtained data for mercury boiling on a horizontal chromium plate at an absolute pressure of 0.25 in. mercury (340°F.).

Lyon and co-workers (L2) have published data for sodium, sodium-potassium alloy, cadmium, and mercury, at 1 atmos. The values of q/A vs. ΔT are shown in Fig. 18. In this graph the results all appear to be for nucleate boiling.

However, if the results are plotted as h vs. ΔT, the issue is confused. Figure 19 suggests that pure mercury boils in the film-fashion, even at the surprisingly low ΔT of 15°F. The cadmium data may be for film boiling. Obviously, much more information is needed concerning boiling metals.

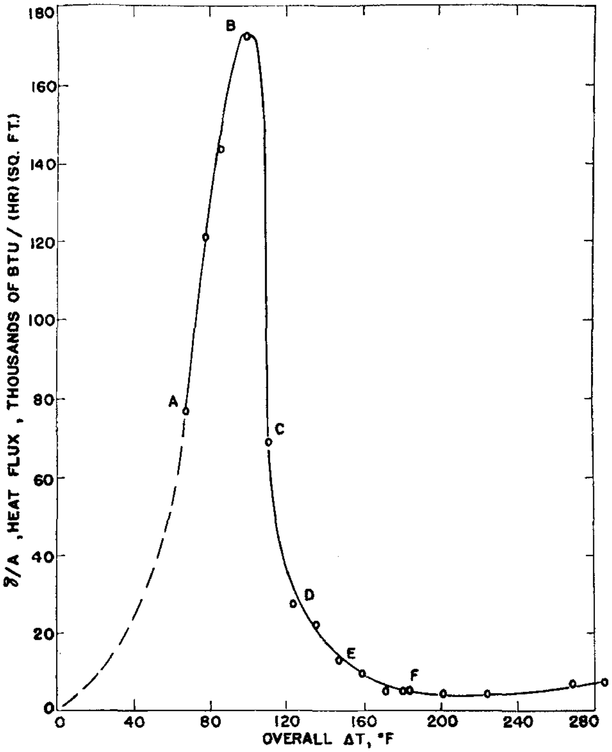

FIG. 15. Boiling curve for methanol. The liquid was outside a $\frac{3}{8}$-inch, steam-heated, horizontal copper tube, at one atmosphere. The letters represent the conditions for the photographs, Figs. 1, 2, 9, and 10 (W2).

At temperature differences of 500 to 1000°F., pure mercury gives values of h of from 30 to 50. This is about the same as for water and other non-metals. The advantage of using boiling mercury in the film region therefore is not in a superiority in h at a stated ΔT, but rather in superiority from other standpoints such as discussed in Sec. II, E, 1 of Part I.

2. *Type of Hot Solid and Surface Texture*

Because the hot solid is covered completely with vapor during film boiling, the type of solid and its surface texture should be of little importance. Nucleation occurs at the vapor-liquid interface, and the process should not be influenced by conditions remote from that location.

Bromley's data for *n*-pentane boiling on carbon and stainless steel (Fig. 20) show no effects attributable to the surface. Banchero's data for oxygen boiling on platinum, copper, aluminum, and stainless steel (Fig. 16) show no surface effects. Both fresh and oxidized surfaces were used.

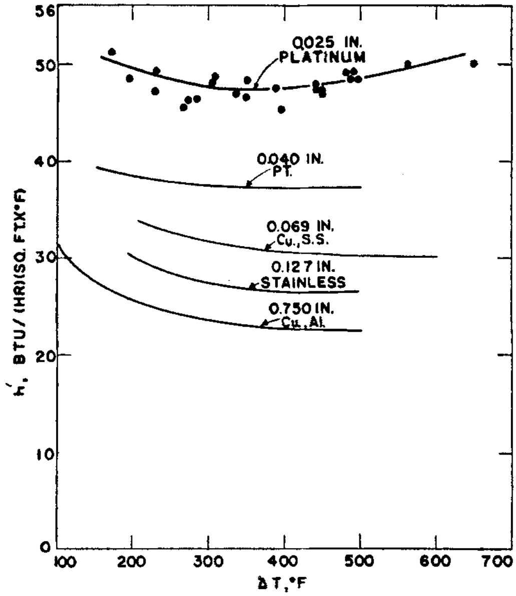

FIG. 16. Film boiling of oxygen. The effect of diameter of horizontal tubes and wires is demonstrated at one atmosphere. The type of metal has no effect. Data are shown for one line only (B1).

Two imagined conditions for which the solid surface could become important are: (1) At very high temperatures radiation is important, and the emissivity of the solid should be significant. (2) For very coarse surfaces the flow of vapor on the solid could be disturbed, and a change in h could result. These conditions have not been studied experimentally.

3. *Geometric Arrangement*

The data for film boiling permit a discussion of the effect of diameter for horizontal tubes. Equation (1) predicts that h' is proportional to $D^{-1/4}$.

Figure 20, based on diameters from 0.188 to 0.468 in., shows good agreement with this prediction for *n*-pentane at one atmosphere. However for smaller diameters, 0.004 to 0.024 in., a better correlation for water at 1 atmos. is $q/A = (\text{const.})\ D^{1/2}$, as shown by McAdams (M3). Note that the McAdams expression includes radiation. The Bromley expression excludes it. On the other hand for oxygen at one atmosphere, on diameters ranging from 0.025 to 0.750 in., Banchero (B1) states the best correlation

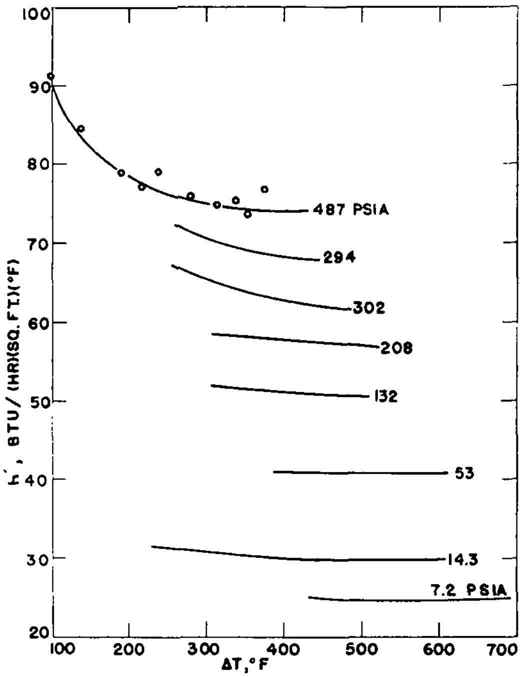

FIG. 17. Effect of pressure on film boiling. Oxygen was boiled on a 0.069-inch stainless-steel, horizontal tube. Data are shown for one line only (B1).

is $h' = (\text{const.})\ (D^{-1} + C)$, where C is a "constant" which is slightly temperature dependent.

The theoretical expression, Eq. (1), should be expected to fail for very small and very large diameters. For small diameters, the diameter and film thickness become comparable in size, a condition not allowed for in the derivation. For very large diameters, the equation predicts $h' = 0$. This prediction cannot be correct.

No data are available for demonstrating other geometric factors.

4. *Pressure*

According to Eq. (1), a change in pressure should affect h', because of changes in k_v, ρ_v, λ, and μ_v. Of these, ρ_v is the most sensitive. Figure 17 illustrates experimental results for the effect of pressure on boiling oxygen. The authors state that these results agree with predictions from Eq. (1).

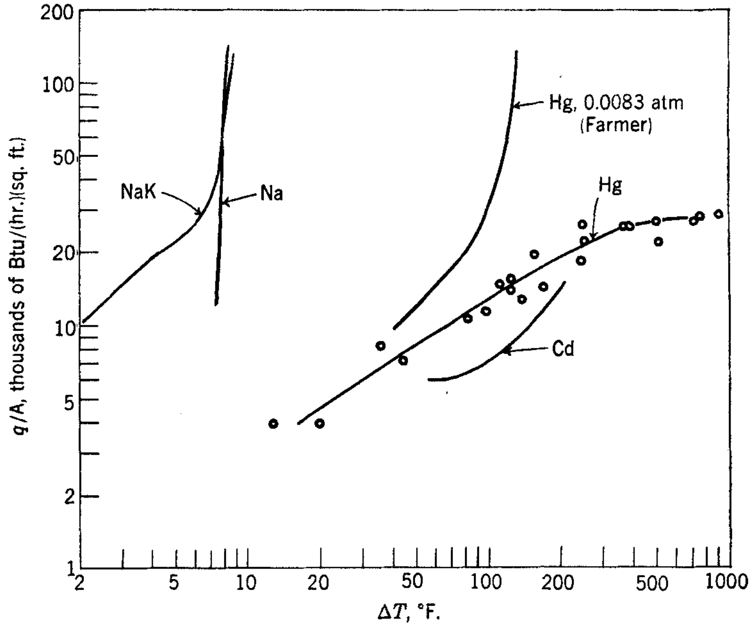

FIG. 18. Liquid metals boiling on a horizontal stainless-steel tube at one atmosphere. Data points are shown for mercury only (L2).

5. *Surface Tension*

Surface tension is not a variable in Eq. (1). The fact that water fits the expression as well as other liquids which have much lower surface tensions indicates that omission of σ in Eq. (1) is defensible.

Inasmuch as surface tension is an important factor for nucleation, one may conclude that nucleation is not rate-controlling during film boiling. The controlling mechanism must be the transfer of heat across the vapor film.

A theoretical treatment of the formation of bubbles from the gas rod that appears on the top of a tube is still in the future. Intuition suggests that surface tension should enter such a theory. If so, this bubble forma-

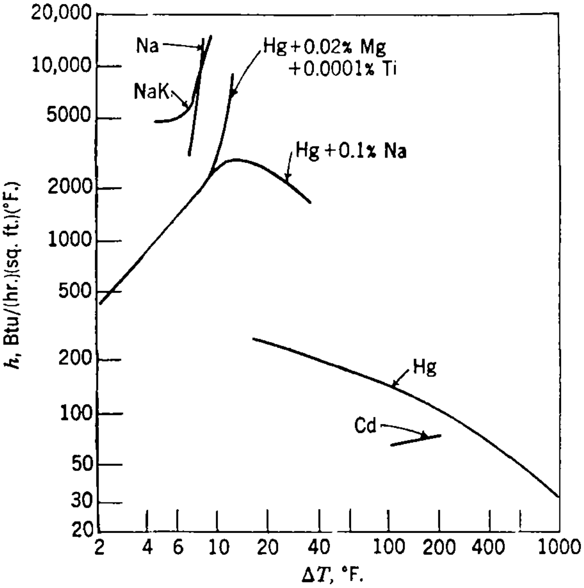

FIG. 19. Individual heat transfer coefficients for boiling metals. Data from Fig. 18 are included (L2).

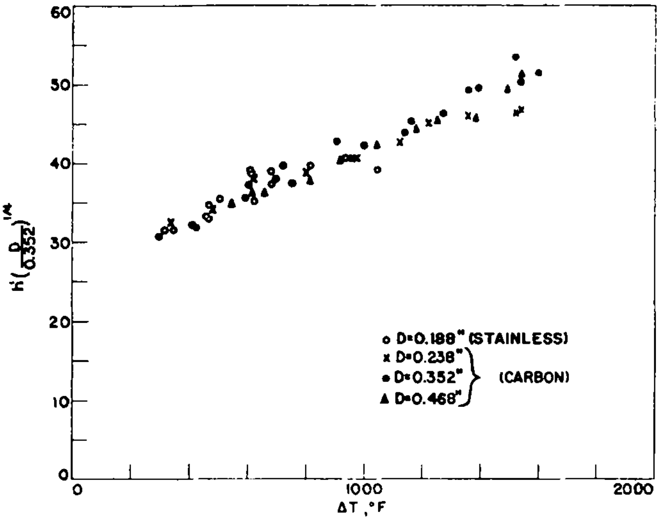

FIG. 20. Effect of diameter for film boiling of *n*-pentane on a horizontal tube at atmospheric pressure. The type of solid has no effect (B3).

tion may be the source of disagreement between Bromley's equation and observations for very small and very large tubes.

6. *Agitation*

Figure 8 includes data for methanol extending partly into the film-boiling region. It is clear that mechanical agitation increases the value of h in the film region as well as in the nucleate and transition regions.

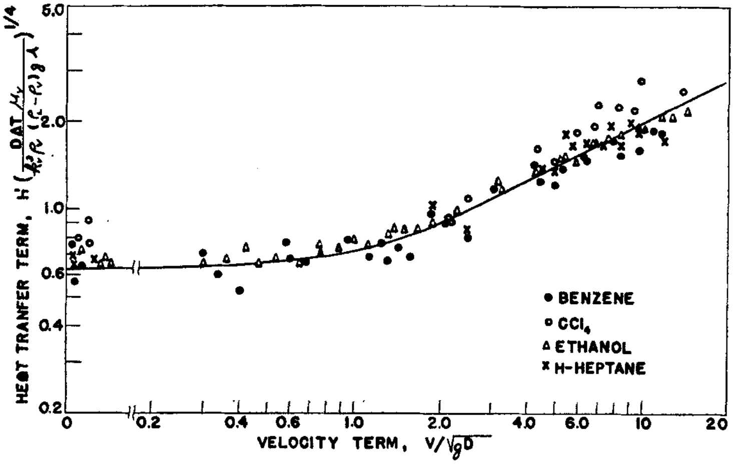

FIG. 21. Film boiling with forced convection. The liquid flow was normal to a horizontal tube at one atmosphere. Velocity = 0 to 14 ft./sec. Diameter = 0.387 to 0.637 inch (B5).

Bromley and co-workers (B5) derived an expression for film boiling with inclusion of the effect of forced flow upward normal to a horizontal tube. The main effects of the liquid flow are to produce changes in the velocity profile for the vapor film and in the thickness of the vapor film. The theoretical differential equation is too complex for a direct solution, but it does show that the variables occur in three groups. By use of experimental observations, it was possible to obtain a correlation of the groups,

$$h'\left[\frac{D^2\mu_v\,\Delta T}{v^2k_v{}^3\rho_v\rho_L\lambda}\right] = 0.88\left[\frac{gD(\rho_L-\rho_v)}{4v^2\rho_L} + \frac{3D\mu_v}{vk_v{}^2\rho_L}\left(\frac{\pi h'}{\theta'}\right)^2\right]^{1/4} \tag{4}$$

where v is the liquid velocity of approach and θ' is the working angle for heat transfer around the tube. For natural convection θ' is taken to be 180 degrees, for high velocities it is taken as 90 degrees.

A modified form of Eq. (4) is given in Fig. 21. The correlation covers four liquids, three tube diameters (0.387, 0.496, and 0.637 in.), and a velocity range of zero to 14 ft./sec. A single, horizontal, carbon tube was used in each test at atmospheric pressure. The correlation is satisfactory.

Figure 21 can be represented fairly well by two straight lines. In this case, simplified equations result. If $v/(gD)^{1/2} < 1$, the liquid flow is negligible and the usual film-boiling equation results, Eq. (1). If $v/(gD)^{1/2} > 2$, then

$$h' = 2.7 \left[\frac{v k_v \rho_v \lambda}{D \, \Delta T} \right]^{1/2} \tag{5}$$

In this case, h' varies directly as the square root of the velocity, and the vapor viscosity has ceased to be a variable.

7. *Impurities*

The role of impurities in a liquid during film boiling is not known. Because surface tension appears to be unimportant, at least for tubes of intermediate size, a first guess is that impurities should be of small importance also. Experimental study is indicated.

III. Boiling of Subcooled Liquids

The usual water-cooled, internal-combustion engine is designed for non-boiling in the heat-transfer sections. Engineers have realized for many years that the heat transfer rates occurring in such equipment sometimes become much greater than can be explained by the usual forced-convection equations. It is known now that a localized boiling on the hot solid can occur if the solid is sufficiently hot, even if the liquid bulk temperature is below the boiling point.

A. DESCRIPTION FROM PHOTOGRAPHIC STUDIES

Gunther and Kreith (G2) have photographed water during subcooled boiling at 1 atmosphere in the absence of forced convection. The liquid was kept cold by cooling coils in the upper portion of the boiling vessel. The important characteristics of the bubbles formed were their small size, large numbers, and rapid collapse. Some of the bubbles grew and collapsed at one location on the hot solid, while some succeeded in breaking away from the solid, only to collapse in the surrounding cold liquid.

Figure 22 is typical for the bubble behavior with no forced convection. The sizes of the bubbles decrease rapidly as the liquid temperature is decreased. For water at 60°F., the bubbles are about 12% of the size at 195°F. The lifetime of a bubble in water at 60°F. is only 2 or 3% of that in water at 195°F. There is good visual evidence that the rapid growth and collapse of tiny bubbles in greatly subcooled water causes strong convection near the hot solid.

If forced convection, the common practice, is used during subcooled boiling, some bubbles slide along the solid surface as they grow and collapse. Gunther (G1) found photographically that increases in the flow velocity result in a decrease in the average bubble size, bubble lifetime, and bubble population (at constant heat flux and liquid temperature). Decreases in the liquid temperature (or an increase in the degree of subcooling), cause a decrease in bubble size and life and an increase in their population. The motion pictures of Dew (D1) confirm all these observations except one. Dew found that increased subcooling causes a decrease in the bubble population. Increases in the heat flux give results such as shown in Fig. 23. Note the tremendous increase in bubble population as the maximum heat flux is approached.

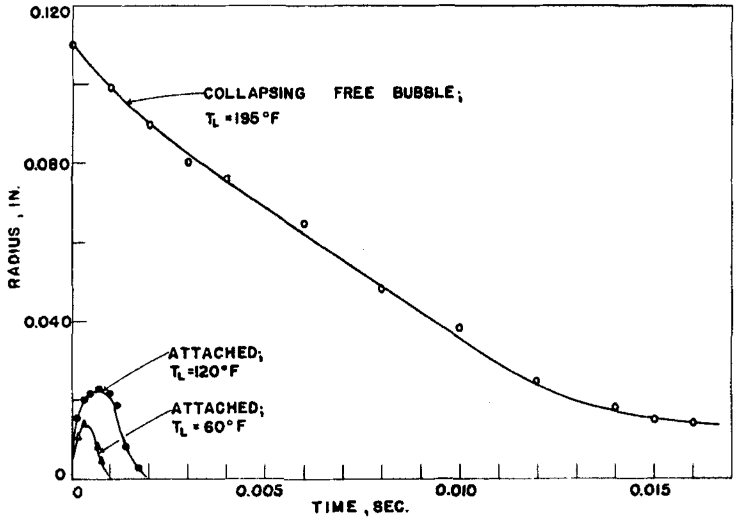

FIG. 22. Behavior of steam bubbles during subcooled boiling. No forced convection was used. The heat flux from the stainless-steel heating surface was 518,000 B.t.u./hr. sq. ft. (G2).

B. DATA AND CORRELATIONS

For subcooled boiling with no forced convection, Gunther and Kreith found that h vs. ΔT data were different from data obtained for ordinary nucleate boiling in at least three respects. The slope of the curve was steeper; the burnout heat flux was increased greatly, as demonstrated in Fig. 24; and lastly, it was necessary to use $T_s - T_{BP}$ for ΔT (rather than $T_s - T_L$) to get good correlations of the data for burnout. The amount of subcooling is not as significant as the temperature excess of

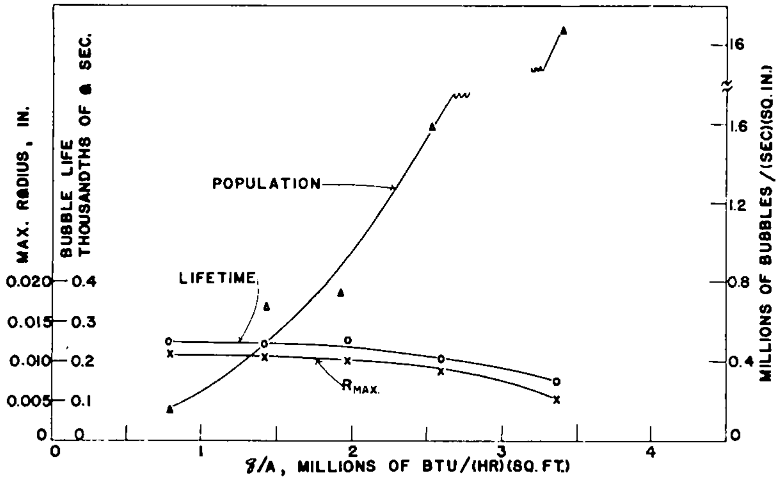

FIG. 23. Bubble histories for forced-convection, subcooled boiling. Water was boiled at 25 psi. on a stainless-steel strip. Velocity = 10 ft./sec. Subcooling = 155°F. (G1).

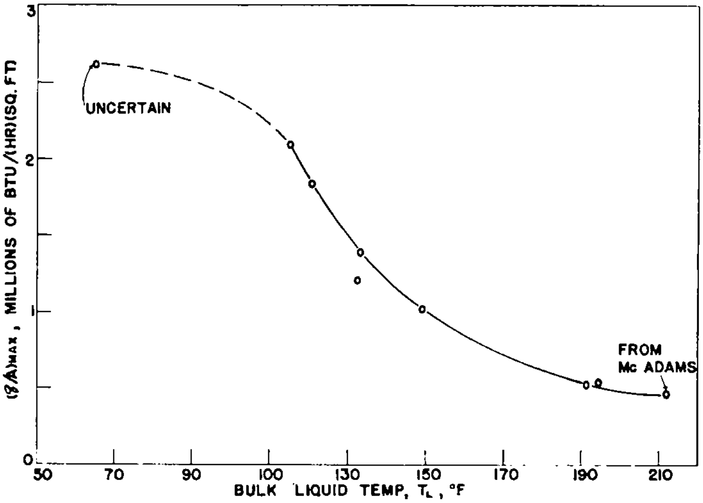

FIG. 24. Effect of subcooling on burnout point. Water was boiled on stainless-steel at one atmosphere with no forced convection (G2).

the solid above the saturation temperature of the liquid, if one wishes to express the critical ΔT. In fact for a given system at a fixed pressure, the critical $T_s - T_{BP}$ is practically constant, regardless of subcooling.

When forced convection is superimposed on subcooled boiling, the resulting heat transfer rate is some sum of the rates due to boiling and to forced convection. Figure 25 shows forced-convection, subcooled boiling observations for water under pressure (K2). Other workers report similar data. The lower portion of the graph indicates that no boiling at all occurs when ΔT is very small. This portion of the graph can be represented accurately by the usual forced-convection, heat transfer

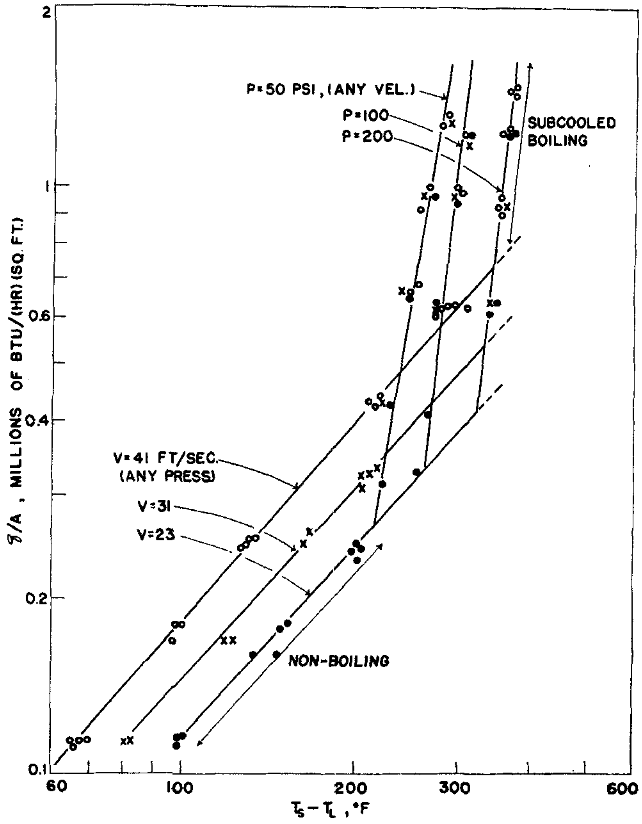

FIG. 25. Effect of pressure and velocity on subcooled boiling. Normal butanol was boiled inside a 0.587-inch stainless tube (K2).

correction such as used by Sieder and Tate or Colburn. In this region, the flow velocity is very important, and the pressure is not significant.

When the ΔT is large enough, subcooled boiling begins. After the boiling is well established, corresponding to the upper portion of Fig. 25, the pressure becomes very important and velocity is less significant. The reason pressure becomes important is that a vapor is created and vapor properties (such as density) are affected by pressure. The reason velocity becomes less important is that the agitation caused by the growth and collapse of bubbles is so great that it overshadows additional convection caused by forced fluid flow. At least this is true for liquid velocities up to about 40 ft./sec.

As the burnout point is approached, velocity again becomes important. It was pointed out (Part I, Sec. II, E, 7) that for ordinary nucleate boiling, agitation causes but a slight change in h until the critical ΔT is reached. The value of h at the critical ΔT is increased significantly by agitation. The same is true for subcooled boiling. Data from McAdams and coworkers (M4) show the effect of velocity and subcooling on the burnout heat flux for water at 60 lb./sq. in., abs. outside a vertical 0.25-inch, stainless tube.

Velocity ft./sec.	Subcooling °F.	Max. q/A B.t.u./(hr.)(ft.^{2})(°F.)
1	50	651,000
4	50	1,030,000
12	50	1,390,000
1	100	854,000
12	100	2,010,000

An examination of Fig. 25 reveals an interesting point concerning pressure. Consider a forced convection, non-boiling system at a reasonable high temperature driving force, $T_s - T_L$, and a high pressure (for example: $\Delta T = 300°\text{F.}$, $v = 23$ ft./sec., $p_L = 200$ lb./sq. in., abs. in Fig. 25). An improvement in heat transfer can be achieved by *decreasing* the pressure. If the pressure is dropped to 100 lb./sq. in., abs., boiling occurs and the heat flux increases to about 2.5 times the original value.

No theoretical description in mathematical form is available for forced-convection, subcooled boiling. A number of correlations have been presented. McAdams (M4) gives

$$q/A = 0.378(T_s - T_{BP})^{3.86} \tag{6}$$

for water on a ¼-in. stainless tube, at pressures below 100 lb./sq. in., abs., for velocities up to 12 ft./sec. Jens and Lottes (J2) give

$$q/A = 0.45 \cdot e^{p_L/225} \cdot (T_s - T_{BP})^4 \tag{7}$$

for water in a tube at velocities up to 45 ft./sec., showing that pressure definitely influences the heat transfer. Neither expression can be general, since both omit the fluid velocity, tube dimensions, and other factors. The expressions show that the heat flux is very sensitive to the temperature difference between the solid and the boiling point (saturation temperature) of the liquid. In fact many writers have commented that

q/A seems to be independent of the solid temperature T_s. This cannot be true, strictly speaking. Rather it means that a modest change of q/A can occur with almost no observable change in T_s. At high pressures this becomes particularly noticeable, because the critical ΔT becomes very small. For example, with water at different amounts of subcooling, at 2000 lb./sq. in., abs., and $v = 10$ ft./sec., Rohsenow and Clark (R1) found that a change in $T_s - T_{BP}$ from 4.3°F. to 8.6°F. was sufficient to change the heat flux from 1,000,000 to 2,000,000 B.t.u./(hr.)(ft.^{2}).

Bernath (B2) has presented a correlation which is shown to fit the burnout points for water at various pressures and velocities, in systems of various geometries.

$$\text{Max. } h = 5710\left(\frac{D_e}{D'}\right)^{0.6} + 48\left(\frac{v}{D_e^{0.6}}\right) \tag{8}$$

Here D_e is the equivalent diameter of the flow passage in ft., D' is the heated perimeter divided by π, and v is the liquid velocity in ft./sec. The equation fits the data from six observers for pressures up to 3000 lb./sq. in., abs., velocities up to 54 ft./sec., and for tubes, annuli, and duct shapes. In spite of the good fit, the equation is not general. It predicts no effects for the type of metal or the pressure of the system.

Bernath also presents a correlation (for water) for the temperature of the solid at the burnout point.

$$\text{Burnout } T_s = 57 \ln p_L - 54\left(\frac{p_L}{p_L + 15}\right) - \frac{v}{4(D_e/D')^{0.6}} \tag{9}$$

Here p_L is in lb./sq. in., abs., and T_s is °C. This predicts that pressure, velocity, and geometry are the only variables of significance.

The interesting case of a "chopped-cosine" heat flux distribution to a tube is discussed by Bernath. Expressions are developed for the burnout heat flux and the burnout location. An atomic reactor can have a heat flux of this type, so the problem is not trivial.

In addition to the recent Bernath correlation, a number of prior correlations for burnout have been published. Whereas Eq. (8) contains no temperatures, the older equations do. Jens (J1) reviews these equations and comments that they are not particularly reliable. It is obvious that theoretical work is needed badly. These expressions are for water only.

(1) McAdams (M4)

$$(q/A)_{\text{max.}} = v^{1/3}[400{,}000 + 4800(T_{BP} - T_L)] \tag{10}$$

(2) Gunther (G1)

$$(q/A)_{\text{max.}} = 7000v^{1/2}(T_{BP} - T_L) \tag{11}$$

(3) Buchberg (B6)

$$(q/A)_{\text{max.}} = 520G^{1/2}(T_{\text{BP}} - T_{\text{L}})^{1/5} \tag{12}$$

(4) Jens-Lottes (J2)

$$(q/A)_{\text{max.}} = C\left(\frac{G}{10^6}\right)^m (T_{\text{BP}} - T_{\text{L}})^{0.22} \tag{13}$$

$$C = \text{f (Pressure)}, \qquad m = \text{f (Pressure)}$$

Here q/A is in B.t.u./(hr.)(ft.^{2}), v in ft./sec., G in lb./hr. sq. ft., and ΔT in °F.

For a subcooled liquid in forced convection, boiling inside a tube, pressure drop considerations are important. As the burnout condition is approached, the volume of vapor formed becomes great and causes a back pressure. This back pressure can decrease the liquid flow rate so that the tube condition becomes serious. Burnout may occur because of this "choking." Kreith and Foust (K1) discuss this problem and present a graph for predicting choking for boiling water.

No data are available for subcooled boiling at temperature differences beyond the critical ΔT.

IV. Bumping during Boiling

Bumping during boiling has long been a scientific oddity and a laboratory nuisance. Scientific studies of the subject could throw light on an understanding of boiling. Unfortunately there is no practical incentive, for bumping is practically nonexistent in equipment of industrial size.

Bumping is a mode of boiling during which the liquid erupts suddenly, and a portion is ejected into the vapor space with considerable force. Bumping in a laboratory beaker can be severe enough to splatter the ceiling of a room.

The literature on bumping is curious. By the year 1919, the published methods for preventing bumping included the addition of chips or bits of glass beads, porcelain plates, bricks, granite, coal, talc, and pumice. One author noted that powdered coal was very effective, while solid chunks were valueless. Another author claimed the exact reverse.

Since 1919, progress in the prevention of bumping has not been great. Capillary glass tubes, hydrogen peroxide, platinum tetrahedrons, and other items have joined the list of additives. Air bubblers are claimed to prevent bumping; so are bare-wire electric heaters immersed in the liquid. The introduction of electrodes is a patented idea for prevention of bumping. The explanations of why these devices sometimes work are plentiful, but none has been proved. Adsorbed gas is suggested for things such as glass beads. Contact with trapped vapor is given as the explanation for capillary tubes. Local convection currents are claimed for the platinum, glass beads, and chips by one author. He states that these local currents give good mixing, intimating that bumping is caused by lack of mixing. Air bubbles and bubbles from peroxide or from electrolysis are supposed to furnish nuclei for vapor generation. No bibliography is included for this early work, since the tests were not designed carefully. Not one author "measured" bumping; it was "observed" only.

A. Torpidity Theory

Several papers discussing torpidity have been presented recently by Hickman (H1, H2, H3). A bumping liquid is stated to be one with a torpid surface. A torpid surface is one with an extremely thin layer of a surface-seeking impurity. Hickman reports, for example, that pure water at a high vacuum was boiled normally from an immersed nichrome heating wire. However, if the water was allowed to stand in glass for 16 hours, normal boiling was impossible. Violent bumping, breaking a flask on one occasion, was the result.

Hickman suggests that a tiny amount of something was leached from the glass. This material then formed a membrane-like layer on the surface. The membrane suppressed normal boiling and resulted in bumping.

These observations could be dismissed were it not for the plentiful evidence that boiling liquids sometimes exhibit a split surface. One part will be working, with a steady discharge of vapor. The other part will be torpid with no vapor discharge. Hickman has published numerous photographs of these schizoid surfaces. He has demonstrated also that it is possible to mechanically remove a torpid surface. However the torpid material has never been concentrated or chemically analyzed.

If this view of bumping is correct, agitation can decrease or prevent bumping. Sources of inert bubbles could also break the surface and be effective. Inert material such as clean chips of insoluble solids should have no effect.

B. Nucleation Theory

If a liquid is pure and its container is clean, considerable superheating is possible as discussed earlier. Under these conditions boiling could occur in a cyclic manner: first a quiet, non-boiling period as the liquid superheats; then an explosion when the nucleation rate becomes large; and finally a sudden drop in the liquid temperature after the superheat has disappeared as heat of vaporization. The process would then repeat.

If this view is correct, cleanliness and purity are necessary for bumping. Addition of most impurities would catalyze nucleation and decrease bumping. After bubbles are created, it is difficult to concede that a thin layer of molecules could prevent their escape.

Glaser's observations, Part I, Sec. II, C, 1b, that superheat (of particular liquids) is destroyed by particles of high energy radiation, are pertinent to bumping. Glaser calculated that hard cosmic ray particles struck his small laboratory apparatus at a rate of about one per half-hour. This would mean that a large-scale industrial boiler would be struck by cosmic particles continuously. Thus nucleation should be continuous, and bumping should be absent in industrial equipment. Of course an alternate explanation for the lack of bumping in large equipment is the great difficulty in obtaining sufficient purity and cleanliness.

C. Measurement of Bumping

Before bumping can be studied, it must be measured. A suggested method has been tried at the University of Illinois. Bumping in a flask creates sudden pressure fluctuations. These are used to vibrate a flexible diaphragm. An electrical scheme is used to measure the amplitude and frequency of the resulting deflections. Preliminary measurements with methyl alcohol show quantitatively that a decrease in pressure increases the severity of bumps, use of a smooth glass surface causes stronger bumps than an etched glass surface, and emanations from radium do not affect the course of bumping. The first two observations are consistent with nucleation theory. The later observation may mean that methyl alcohol does not ionize readily. Additional quantitative tests are needed.

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Nomenclature

A	Surface area, sq. ft.
C	Constant
C_v	Heat capacity of vapor, B.t.u./lb. (°F.)
D	Diameter of tube or wire, ft.
D'	Heated perimeter divided by π, ft.
D_e	Equivalent diameter of flow passage, ft.
F_ϵ	Radiation emissivity factor, dimensionless
g	Acceleration of gravity, ft./hr.^{2}
G	Mass velocity, lb./hr. sq. ft.
h	Individual heat transfer coefficient, B.t.u./(hr.)(sq. ft.)(°F.)
h'	Heat transfer coefficient, neglecting radiation, B.t.u./(hr.)(sq. ft.)(°F.)
h_R	Heat transfer coefficient for radiation, B.t.u./(hr.)(sq. ft.)(°F.)
k_v	Thermal conductivity of vapor, B.t.u./(hr.)(ft.)(°F.)

L	Length of tube, ft.
p_L	Pressure imposed on a liquid, lb./sq. ft.
q	Heat transfer rate, B.t.u./hr.
ΔT	Temperature driving force, $T_L - T_v$ for homogeneous case; $T_s - T_\infty$ for heterogeneous case, °F.
T_{BP}	Boiling point of the bulk liquid at the existing pressure; T_∞, °F.
T_L	Temperature of the bulk liquid, °F, or °R.
T_s	Temperature of a solid surface, °F, or °R.
T_v	Temperature inside a bubble, °F.
T_∞	Saturation temperature of a liquid flat surface at the existing pressure, °F.
v	Velocity, usually ft./hr.
θ'	Working angle around a tube, radians
λ	Latent heat of vaporization, B.t.u./lb.
μ_v	Viscosity of vapor, lb./(ft.)(hr.)
ρ_L, ρ_v	Density of liquid, vapor, lb./cu. ft.
σ	Surface tension, liquid-vapor interface, lb./ft.
σ'	Stefan-Boltzmann radiation constant, B.t.u./(hr.)(sq. ft.) $(°R)^4$

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