Film Boiling from Vertical Tubes

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Heat transfer measurements were made with vertical stainless steel bayonet tubes, 3/8 to 3/4 in. O.D., with lengths from 2.6 to 6.5 in. The heat source was steam. The boiling film ΔT ranged from 154° to 314°F. for three organic liquids and from 547° to 788°F. for nitrogen, all at 1 atm. No forced convection was used. Benzene, carbon tetrachloride, and nitrogen on the longer tubes had h values two or three times greater than predicted by the Bromley equation; however, the Reynolds numbers were found to exceed 2,000. Nitrogen on the 2.6-in. length obeyed the equation; the Reynolds numbers were less than 2,000. Methanol is an anomaly; although the Reynolds numbers were less than 2,000, the flow was proved by photography to be turbulent and the h values were much higher than predicted for viscous flow. A correlation is given which fits all the data except for methanol. It shows that a vertical orientation is superior to the horizontal for liquids boiling outside tubes.

Film boiling is typified by the existence of a vapor film coating the heat transfer surface. The film hinders heat transfer, and the resulting heat flux is usually small compared with the values observed during nucleate boiling. With most industrial processes for vaporizing liquids, film boiling is avoided. However, when large temperature differences are encountered, such as when an ordinary liquid contacts a very hot solid or when steam is used to heat liquids with low boiling points, film boiling may occur.

The object of this investigation was to study film boiling outside vertical tubes. As no prior data for film boiling from vertical surfaces in the absence of forced flow are available, it was desirable to obtain experimental data and to make a comparison with the theoretical equation of Bromley.

THEORETICAL EQUATION OF BROMLEY

Film boiling has received much less attention than nucleate boiling; yet the film-type phenomenon appears to be more susceptible to attack from the theoretical viewpoint. The analogy between film boiling and film condensation was apparent to many of the early writers on boiling, but Bromley (*2*) in 1950 was the first to present a formal derivation of an equation for film boiling. The derivation is similar to Nusselt's derivation (*9*) for film condensation, with the substitution of a vapor film for a liquid film. Fos a horizontal tube the equation for film boiling is

$$h = C_1\left[\frac{k^3\rho_v(\rho_L - \rho_v)g\lambda'}{\mu D\Delta T}\right]^{1/4} \tag{1}$$

The physical properties k, ρ_v, and μ are taken at the mean temperature of the vapos film, $\frac{1}{2}(T_S + T_L)$. The symbol λ' represents the latent heat of vaporization plus the sensible heat of the vapor. Originally this was taken as $\lambda' = \lambda + \frac{1}{2}C_p\ \Delta T$. Later it was shown that a better fit with data occurs if one uses $\lambda' = (\lambda + 0.4C_p\ \Delta T)^2/\lambda$, and the theoretical reason for this was given (*4*). Recently it was shown (*11*) that a more accurate expression for λ' employs 0.34 instead of 0.4. The disagreement here is minor, and 0.4 was used in the present work.

Two values for the coefficient C_1 may be derived. If the liquid is imagined to be stationary, C_1 is 0.512; if the liquid moves with the same velocity as the vapor, C_1 is 0.724. The mean of these values, 0.62, gives the best fit to Bromley's data and is the value he recommends.

Bromley made runs at atmospheric pressure with seven liquids, using horizontal tubes with diameters between $\frac{3}{16}$ and $\frac{1}{2}$ in. His values agreed within about 10% of the predictions of Equation (1) (with $C_1 = 0.62$.) There is no question as to the applicability of this equation to horizontal tubes of intermediate diameter; however, the equation must not be used blindly when the diameter is very small or very large. For very small diameters, the film thickness and the cylinder diameter are comparable, and therefore the data for hot wires, such as given by Nukiyama (*8*), McAdams and coworkers (*6*), and others show greater heat fluxes than predicted. For very large diameters Equation (1) predicts vanishingly small values of h. Banchero and coworkers (*1*) propose a modified form of Equation (1) which was selected empirically so as to give realistic values of h for values of D near $\frac{3}{4}$ in.

For vertical tubes or vertical plates, the theoretical expression for film boiling (*2*) is given by Equation (2):

$$h = C_2\left[\frac{k^3\rho_v(\rho_L - \rho_v)g\lambda'}{\mu L\Delta T}\right]^{1/4} \tag{2}$$

Although the value of C_2 was not stated by Bromley, it can be easily derived. If the liquid is stagnant, C_2 has a theoretical value of 0.667; if the liquid moves with

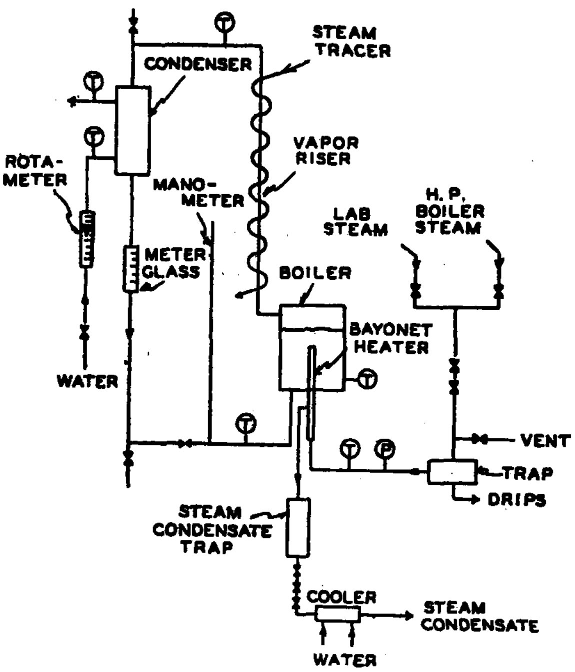

Fig. 1. Sketch of boiling equipment.

the same velocity as the vapor, C_2 is 0.943. No prior data have been published to show whether Equation (2) is valid.

A number of assumptions are necessary in the derivation of Equation (2). Most of these seem reasonable, for example: (*a*) a continuous film of vapor separates the liquid from the solid heat source; (*b*) the vapor motion upward is caused by buoyancy and is opposed by drag at the solid surface and perhaps by additional drag at the liquid; (*c*) kinetic energy of the vapor is not important; (*d*) the liquid is at its boiling point throughout; (*e*) the solid surface is at a uniform temperature; (*f*) radiation heat transfer is negligible or will be accounted for by means of a radiation term, such as shown by Bromley (*2*); (*g*) forced convection in the liquid is negligible or will be handled by means of a correlation like that shown by Bromley and coworkers (*4*); (*h*) the vapor flow is viscous. This last assumption, however, seems questionable for a vertical surface. The length of the flow path for the vapor film is much greater for a vertical tube than for a horizontal one. The largest tube used by Bromley had a diameter of $\frac{1}{2}$-in.; thus the flow path, half the circumference, was 0.8 in. For Banchero et al. the greatest flow path was 1.2 in. For vertical tubes, however, the flow path is the tube length, which is usually much greater than 1.2 in. A long flow path results in a thick film. A thick film could be unstable, turbulence could develop, and Equation (2) could fail.

TEST LIQUIDS

The present tests were conducted with methanol, benzene, carbon tetrachloride, and nitrogen, each boiling at atmospheric pressure, the range in boiling points being from −321° to +176°F. Steam, the source of heat, was available as hot as 475°F. The temperature drop across the vapor film of the test liquids was varied from 154° to 788°F. The choice of liquids offered a wide range in physical properties: latent heat of vaporization from 86 to 474 B.t.u./lb., vapor-heat capacity from 0.09 to 0.46 B.t.u./(lb.)(°F.), vapor density from 0.06 to 0.31 lb./(cu. ft.), liquid density from 49 to 99 lb./(cu. ft.), and vapor thermal conductivity from 0.005 to 0.016 B.t.u./(hr.)(ft./°F.).

Great care was taken to exclude impurities from the test liquids. The organic liquids were reagent grade and before each run were purified by distillation in a column with reflux. When stored, the organic liquids were kept in glass containers with glass stoppers. The stored liquids were in contact with silica gel so as to keep them free from water. The liquid nitrogen was obtained directly from the university liquid-air-fractionation plant, the purity varying from 95 to 99+% nitrogen, with the remainder being oxygen.

VERTICAL HEATING TUBE

The experimental apparatus is illustrated in Figure 1. Each test liquid was boiled outside a single vertical tube, with no forced convection. The effective tube length was 2.60, 4.38, 4.63, 5.0, 5.38, and 6.5 in. Three outside diameters were used, $\frac{3}{8}$, $\frac{1}{2}$, and $\frac{3}{4}$ in. Each tube was made of copper or 18-gauge stainless steel and had at the top a flat plug sealed in place with silver solder. As the tip area did not exceed 5% of the side area for any test, for convenience the tip area was omitted from the heat-flux calculations. Each heater tube was actually the outside tube of a bayonet heater. Steam flowed upward in a $\frac{1}{4}$- or a $\frac{5}{16}$-in. O.D. inner tube and then downward in the annulus.

For pressures less than 100 lb./sq. in. gauge the source of steam was the laboratory supply; for pressures between 100 and 500 lb./sq. in. a special steam generator was used. The steam pressure in the heater tube was adjusted by means of a pressure controller connected to the generator (which was electrically heated with a maximum input of 39,000 B.t.u./hr.) and also by means of two needle valves in series near the heater. During each run the steam pressure was held to within 1 lb./sq. in.

The heating tube was located in a stainless steel, rectangular boiler which measured 11 by 8 by 4 in. Flat Pyrex-glass windows were located front and back during runs with the organic liquids. Approximately 1.5 gal. of liquid was placed in the boiler for each run. The top of the heater was immersed to a depth of several inches at the start and was adjusted so as to be 2.0 in. at the time data were recorded. Prior tests (*7*) had shown that depths of immersion varying from zero (liquid level at the top of the tube) to several inches do not affect the results. Banchero and coworkers (*1*) also had found that liquid levels between 1 and 6 in. gave the same results for tests with a horizontal tube. The vapors which formed during the present tests passed up a 1-in. pipe 5.5 ft. long. In this riser the vapors were superheated by means of a steam tracer located outside the pipe, so that condensation of test vapors in the riser was prevented and a potential source of error eliminated. The vapors subsequently passed downward to a condenser, and the condensate was metered by a graduated glass tube in the vertical liquid line below the condenser. After a valve downstream was closed, the time for 80 ml. of condensate to collect in the glass was measured. Then the valve was opened and the liquid could be either returned to the boiler or removed from the apparatus. The closed- and open-loop arrangements both were used with the organic liquids in film boiling. Either gave good results as shown by heat balances.

The uncertainty in *h*, due to heat unaccounted for, averaged 9.6% for methanol. This was considered satisfactory; so only the heat output was recorded for benzene and carbon tetrachloride. On the other hand, past experience had shown that the closed loop was preferable during nucleate boiling, and with it the heat input (found by metering the steam condensate) was found routinely to be very close to the heat output (found by metering the boil-up rate and measuring heat losses during a dry run).

For liquid nitrogen an open loop was always used. With nitrogen some modifications of the apparatus were employed so as to minimize heat leakage from the surroundings. The boiler, for instance, was fitted with double walls, the outer part being the metal container described above and the inner part a smaller concentric container made of Plexiglas sheeting. Liquid nitrogen was in the inner boiler only. Nitrogen vapors passed through a 2-in. gap between the two boilers and then entered the riser described above. Thus heat which leaked in from the surroundings was absorbed by the leaving vapor instead of by the boiling liquid. Each window on the boiler was also of double-wall construction, consisting of two $\frac{1}{16}$-in. sheets of Plexiglas with dry air sealed in a $\frac{1}{8}$-in. gap between. Nitrogen vapor from the boiler was allowed to flow through sufficient piping until it had warmed to roughly 70°F.; then it was metered with a calibrated rotameter and was discharged to the room. Complete heat balances were made for all runs with nitrogen. The uncertainty in h, due to heat unaccounted for, averaged 23.7%.

The windows, the boiler, and the important flow lines were covered with from 3 to 6 in. of insulation during runs, but before certain runs the windows were uncovered to allow still photographs and motion pictures to be obtained. The photographic techniques have been described previously (*12*).

The gasket material for the windows was neoprene for the organic liquids and paraffin-impregnated yarn for the nitrogen. Replacement was necessary every two or three weeks. In the packing gland which sealed the heating tube in the boiler, a combination of Teflon, asbestos, and neoprene was used. The test liquids contacted the Teflon only.

PROCEDURE

Before each run the heater surface was polished with a commercial polishing agent and the heater was rinsed and dried. Little attention was needed to keep the surface smooth and lustrous, in contrast to past experience with liquids in nucleate boiling, when (*10, 12*) contamination of the tubes was a persistent problem.

When the boiler windows had been closed, the test liquid was added and heating was started. After a warm-up of about 1 hr. the readings became steady and data were recorded. For runs with nitrogen it was important to remove all water and stagnant steam from the heater tube before the test liquid was put into the boiler, to prevent the formation of ice, which would prevent the flow of steam later. In addition, in order to conserve liquid nitrogen, the boiler was cooled with dry ice for about an hour before nitrogen was introduced.

Observations of the steam pressure and the boiling temperature of the boiling liquid provided values of the over-all temperature-difference driving force. The temperature drop through the metal wall was calculated from a knowledge of the heat flux, that through the steam film by the assumption of a steam-film coefficient of 3,000 B.t.u./(hr.)(sq. ft./°F.). When film-type boiling is occurring, these two ΔT corrections are quite small compared with the boiling-side ΔT. Thus a precise value of the steam-film coefficient is of no importance. In no case was the boiling-side ΔT less than 95% of the over-all ΔT. There was no need to use the resistance-thermometer technique (*10*) to measure directly the metal temperature.

RESULTS

The results are shown in Figures 2 to 5, plotted in the form used by Bromley for horizontal tubes.* It is evident that the Bromley type of theoretical equation for vertical tubes has poor accuracy for all tests except that of nitrogen boiling on the shortest length used, 2.6 in. Excluding this case, the heat transfer rates were definitely greater than the predicted values. The h values for benzene average 120% higher than the theoretical ones predicted from the equation based on a moving-liquid boundary; h for carbon tetrachloride is about 150% high, nitrogen on the longer tube is about 40% high, and methanol is about 60% high.

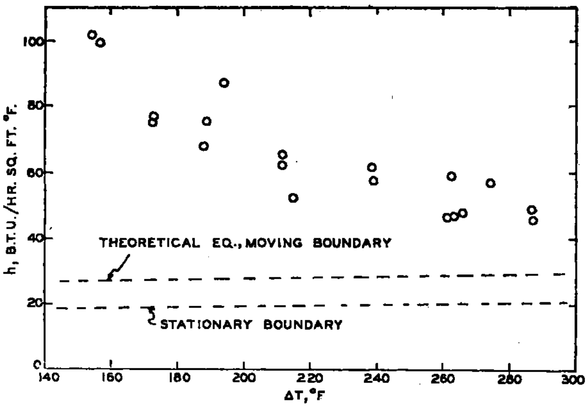

Fig. 2. Film boiling of benzene from a vertical tube, 1/2-in. O.D., 4.63 in. long, at 1 atm.

The test results are shown again in Figure 6, plotted in the manner suggested by Colburn (*5*) for film-type condensation on vertical surfaces. The two lines having negative slopes are exactly equivalent to Equation (2) when its coefficient C_2 is given values of 0.943 and 0.667. The transformation from Equation (2) to the form shown in Figure 6 is straightforward. The abscissa in Figure 6 corresponds to the Reynolds number at the top of the tube, defined as $4W/(\pi D\mu)$. For nitrogen on the shortest tube, the Reynolds number is less than 1,400. Thus the flow was probably viscous and for this reason the results obtained are consistent with Equation (2).

The Reynolds numbers for carbon tetrachloride, benzene, and nitrogen on the longer tube lie between 2,100 and 4,800. Without a doubt in such cases the flow is turbulent, and Equation (2) cannot apply.

The solid curve having a positive slope in Figure 6 corresponds to Equation (3):

$$h\left[\frac{\mu^2}{k^3\rho_v(\rho_L - \rho_v)g}\right]^{1/3} = \frac{\left(\dfrac{4W}{\pi D\mu}\right)}{22\left(\dfrac{C_P\mu}{k}\right)^{-1/3}\left[\left(\dfrac{4W}{\pi D\mu}\right)^{0.8} - 364\right] + 12{,}800} \qquad (3)$$

This equation was derived originally by Colburn (*5*) for condensation on a vertical surface with the liquid flow being viscous for part of the flow path and turbulent for the rest of the way. For the viscous region the expression $Y = 1.47\ Re^{-1/3}$ [exactly equivalent to Equation (2) with $C_2 = 0.943$] was assumed to hold. For the turbulent region the expression $Y = 0.056\ Re^{0.2}\ (C_P\mu/k)^{1/3}$ was assumed to hold. This last expression is Colburn's correlation involving the Reynolds number, Prandtl number, and a modified Stanton number. The dividing point between viscous and turbulent flow was assumed to occur at a Reynolds number of 1,600. The value of h in Equation (3) is a true integrated average over both flow regimes. In Colburn's original equation the physical properties refer to the liquid phase; in Equation (3) they refer to the vapor phase except for the one density factor. The Prandtl number used for graphing Equation (3) in Figure 6 was unity, the true Prandtl numbers for the materials tested being between 0.5 and 1.1.

For all Reynolds numbers greater than about 2,000, Equation (3) gives much better predictions than does the Bromley type of equation. Furthermore, the trend of the data agree with Equation (3) but not with the Bromley equation. The data are still somewhat high, by about 40% on the average.

If the best correlation is desired, theory must be abandoned, and a single straight line may be drawn on Figure 6 which passes through all data except methanol. The equation for this correlation, line

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*Tabular material has been deposited as document 5496 with the American Document Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $2.50 for photoprints or $1.75 for 35-mm. microfilm.

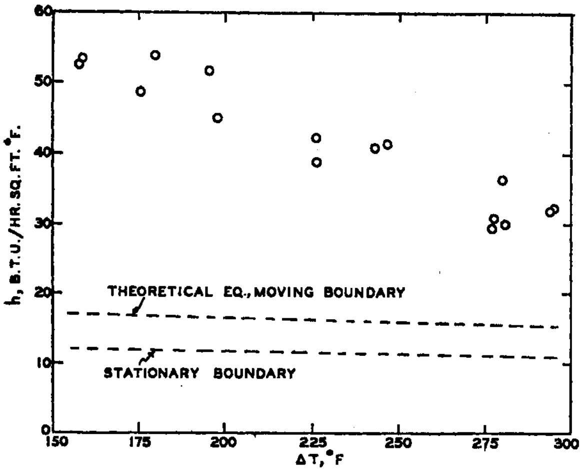

Fig. 3. Film boiling of carbon tetrachloride from a vertical tube, 1/2-in. O.D., 4.63 in. long, at 1 atm.

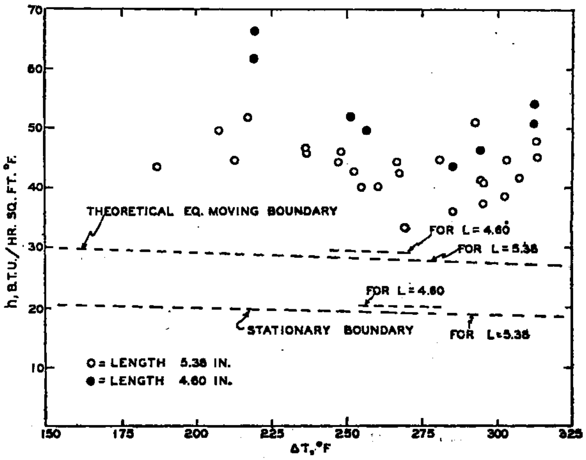

Fig. 4. Film boiling of methanol from vertical tubes, 3/8-in. O.D., 5.38 in. long and 1/2-in. O.D., 4.60 in. long, at 1 atm.

A B, is Equation (4):

$$h\left[\frac{\mu^2}{k^3\rho_v(\rho_L - \rho_v)g}\right]^{1/3} = 0.0020\left[\frac{4W}{\pi D\mu}\right]^{0.60} \qquad (4)$$

This equation applies for Reynolds numbers from 800 to 5,000. The average absolute error in h is but 14%, and the worst error is 36%.

VERTICAL vs. HORIZONTAL TUBES

Comparison of Equation (4) with Equation (1) shows that film boiling outside a vertical tube is superior to boiling outside a horizontal tube for all practical lengths, at least in the range of diameters for which data are available, The expression for the break-even length is complex, involving the physical properties of the fluid as well as the ΔT and the diameter. For ¼-in. tubes, at atmospheric pressure, all lengths greater than about 1.2 in. favor the vertical orientation for the liquids reported here. For larger diameters the break-even length is shorter than this. Therefore, if equipment is designed for film boiling outside tubes, the tubes should be vertical if possible. This rule is contrary to the practice fos film-type condensation, during which horizontal tubes are usually better than vertical ones. There is no assurance that this film-boiling rule will hold if the horizontal tubes have diameters large enough to cause turbulent flow.

ANOMALOUS BEHAVIOR OF METHANOL

Methanol in film boiling outside vertical tubes is an anomaly, the data lying in the range of Reynolds number from 840 to 1,430. In spite of this the actual flows were not viscous. High-speed motion pictures (4,000 frames/sec.) illustrated the flow pattern, which was similar to that shown by other test liquids at high Reynolds numbers. For example, Figure 7 is a high-speed still photograph (10^{-6} sec. exposure) of benzene at a ΔT of 287°F. and a theoretical maximum Reynolds number of 3,000. Methanol in the motion pictures has an appearance just like this. The tube is surrounded by vapor, and no solid-liquid contact exists. The vapor flows in waves, and the liquid-vapor interface is greatly disturbed.

Methanol behaves normally in horizontal tubes. Still photographs and motion pictures (*12*) show a viscous-flow pattern on a horizontal tube during film boiling in which small ripples cause a slight disturbance of the liquid-vapor interface, but the disturbance is not enough to affect the heat transfer. With the vertical tubes, however, the interface is deformed greatly and the heat transfer is definitely affected.

Numerous attempts were made to photograph nitrogen boiling on the short tube to see whether it exhibited a true viscous flow. Unfortunately, this project had to be abandoned before satisfactory pictures had been obtained. The lighting problems resulting from the use of double windows were very troublesome, and the scattering of light, by traces of fog that formed continuously on the outer window, was also a problem which was not overcome.

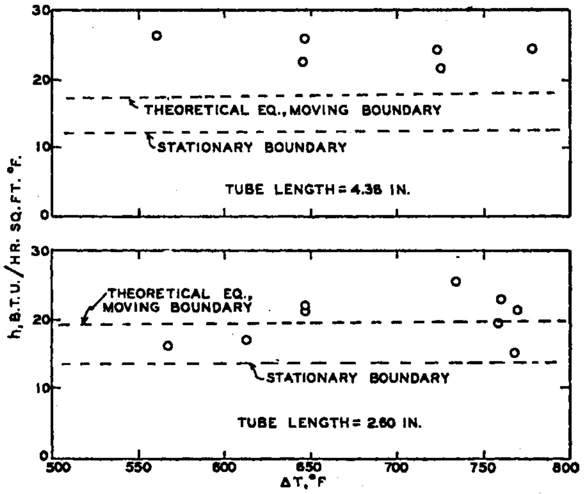

Fig. 5. Film boiling of nitrogen from vertical tubes, 1/2-in. O.D., 2.60 in. and 4.38 in. long, at 1 atm.

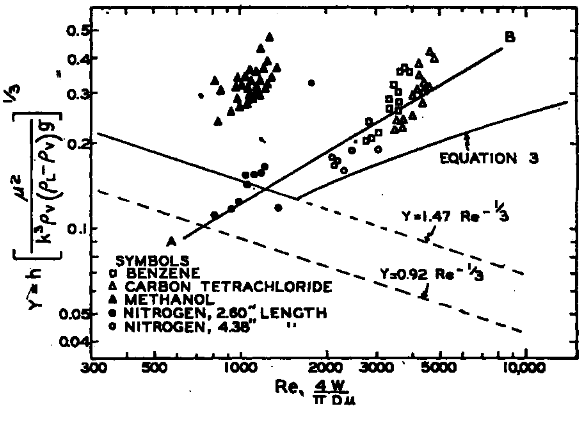

Fig. 6. Film boiling from vertical tubes as affected by Reynolds number.

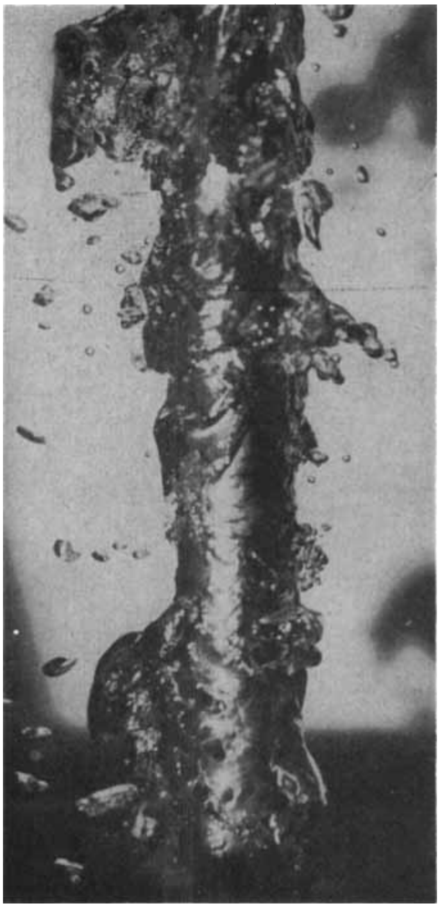

Fig. 7. Film boiling of benzene on a vertical tube, 1/2-in. O.D., ΔT = 287°F.; Reynolds number at top = 3,000.

Film boiling outside horizontal tubes may be represented in terms of a Reynolds number, although other workers have not chosen to do so, Bromley's data are shown in Figure 8. The range of Reynolds number is from 70 to 600, the flow is viscous, and the data fit the line nicely. The equation of the line is exactly equivalent to Equation (1), with C_1 = 0.62.

CRITERIA FOR FILM BOILING

One of two perplexing problems which future scientists must solve concerning the criteria for film boiling is the question: what is the minimum ΔT needed to cause stable film boiling? Here *stable* means that the equations based on the concept of heat conduction across a vapor film will apply. Probably this value is a function of pressure. We do not know whether it should be the same for horizontal and vertical surfaces. Bromley found that his horizontal tubes had stable film boiling at the lowest values of ΔT reported in his paper. These minimum values for 1 atm. are nitrogen = 300°F., pentane = 310°F., ethanol = 350°F., benzene = 415°F., carbon tetrachloride = 600°F., and water = 700°F. The equation for horizontal tubes probably applies at even lower temperature differences. Data for methanol (*10*, *12*) outside horizontal tubes show that the Bromley equation is accurate (within 2%) at a ΔT of 180°F.; however, at a ΔT of 160°F. it is of poor accuracy, and at a ΔT of 147°F. it predicts a value of h which is but one-third the correct value. Banchero and coworkers (*1*) found that film boiling of oxygen at 14.3 lb./sq. in. abs. was stable at a ΔT of 240°F. on a 0.069-in. horizontal tube and also at a ΔT of 100°F. at 487 lb./sq. in. abs.

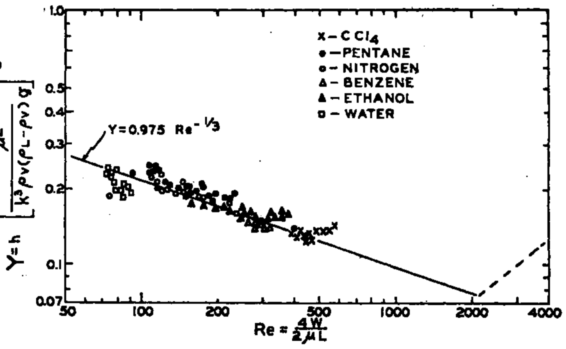

Fig. 8. Bromley's data for film boiling from horizontal tubes, 0.188- to 0.468-in. O.D., at 1 atm.

The second important question is indirectly related to the first: what conditions are required so that the vapor-liquid interface will be smooth during film boiling? This question cannot be answered in simple terms of a limiting Reynolds number, as is illustrated by the data in Figure 6 and by the motion pictures. It is likely that the interfacial tension between the liquid and vapor must be important, but this value does not appear in any equations in this paper. The flow situation is complex: vapor flows upward in an annular space, and the inner boundary is fixed but the outer boundary is liquid at the saturation temperature. Under certain circumstances the liquid-vapor interface will be smooth. Under other conditions the vapor drag will cause the interface to break into waves, just as wind causes waves on the ocean. But the boiling case is more difficult, because the amount of flowing vapor increases steadily along the flow path. At present this flow problem has not been solved.

ACKNOWLEDGMENT

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NOTATION

C_1, C_2 = constants, determined by boundary conditions
C_P = heat capacity of vapor, B.t.u./(lb.)(°F.)
D = outside diameter of tube, ft.
g = gravity constant, ft./hr.^{2}
h = individual heat transfer coefficient averaged over entire tube, B.t.u./(hr.)(sq. ft./°F.)
k = thermal conductivity of vapor, B.t.u./(hr.)(ft./°F.)
L = tube length, ft.
Re = Reynolds number, $4W/(\pi D\mu)$ for vertical tubes, $4W/(2L\mu)$ for horizontal tubes, dimensionless
T_L = boiling point of liquid, °F.
T_S = surface temperature of heat source, °F.
ΔT = temperature difference, $T_S - T_L$
W = maximum vapor flow rate, lb./hr.
Y = dimensionless, group, $h[\mu^2/(k^3\rho_v\{\rho_L - \rho_v\}g)]^{1/3}$
λ = latent heat of vaporization, B.t.u./lb.
λ' = latent heat plus sensible heat content of vapor, B.t.u./lb.
μ = viscosity of vapor, lb./(ft.)(hr.)
ρ_L, ρ_v = density of liquid and vapor, lb./cu. ft.

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