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Heat Transfer in Stable Film Boiling

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Heat Transfer in Stable Film Boiling.

by

LeRoy Alton Bromley

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University of Rochester	81-82
Chicago Directed Operations	83
Declassification Procedure	
Declassification Officer	84-87
Publication Officer	88
Patent Department	89-90
E. O. Lawrence	91
Area Manager	92
Information Division	93
Total	93

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TABLE OF CONTENTS

Page

Theory

LIST OF TABLES

(LIST OF TABLES CONTINUED)

Table Page

(LIST OF TABLES CONTINUED)

LIST OF ILLUSTRATIONS

ABSTRACT

By the use of equations, which are derived from a few simple premises and well verified by extensive experimental data, it is possible to calculate coefficients of heat transfer to be expected in natural convection stable film boiling from a horizontal tube.

The method employed for the derivation may be applied to derive equations for heat transfer coefficients to be expected in film boiling from any other shape. Equations are derived for the case of film boiling from a vertical tube or a vertical plane surface.

Introduction

The name, film boiling, has been given to that type of boiling which occurs when a complete vapor film exists between the heated surface and the boiling liquid. Nucleate boiling, in which the vapor originates from individual points on the hot surface, is the type of boiling most generally encountered (McAdams)[13] and usually is to be preferred because of the large heat transfer coefficients that can be obtained.

The basic equation for heat transfer is written:

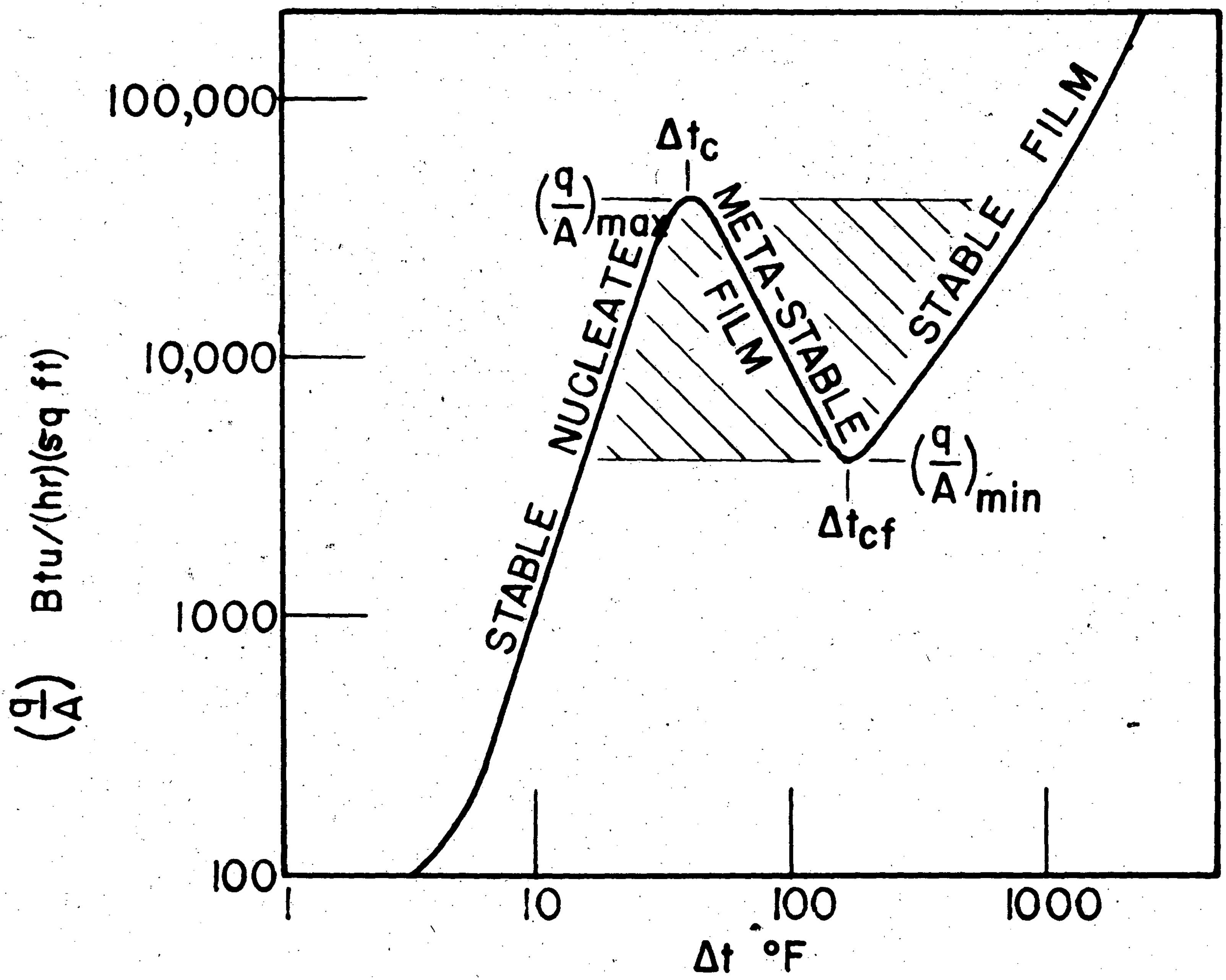
$$q = hA\,\Delta t. \tag{1}$$

q represents the heat transferred per unit time; h is the coefficient of heat transfer; A represents the area; Δt is the temperature difference between the hot surface and the boiling liquid.

All authors agree that the coefficients of heat transfer in film boiling are much smaller than those in nucleate boiling. Because of the difference in the stability of the boiling within the film boiling range, the latter may be subdivided into a stable and a metastable film boiling region. As can be seen from Figure 1 I have termed the intermediate temperature region the metastable film boiling region, as it is usually impossible to operate here unless the temperature is the controlled variable. By careful manuvering Farber and Scorah[7a] were able to operate in this metastable region using an electrically heated wire.

The more usual case encountered with slow cooling of a very hot object immersed in a boiling liquid is slow cooling to what I will term the minimum critical heat flux (Δt_{cf} in Figure 1). Then abruptly the boiling will become nucleate on one or more points on the surface and rapidly spread over the entire surface. If the solid has a rather large heat capacity, there will be a large amount of vapor evolved in this collapse of the sphereoidal state (film boiling). This latter phenomenon has been given as an explanation of the exploding of some boilers in the early part of the last century.[2, 18]

It is the purpose of this work to develop a sound theory which will predict the coefficients of heat transfer to be expected when there is stable film boiling. The experimental work was all carried out on the boiling of liquids from the outside of horizontal tubes, although the equations are also developed for the case of free convection stable film boiling from a vertical tube.



TYPICAL BOILING CURVE

FIG. 1

Importance of Film Boiling

The operation of jets or rockets frequently involves the contact of a boiling liquid with quite hot surfaces; this is the condition for film boiling.

Film boiling usually occurs in the boiling of mercury, especially at high heat fluxes. Attempts to use the mercury-steam cycle to obtain better thermodynamic efficiency in the use of heat have been hampered by a lack of knowledge of this phenomenon.

In any boiler operation in the nucleate range where the heat input is the controlled variable, as in an electrically heated boiler or an atomic power plant, there is always danger that the temperature of the heated object will rise abruptly if the heat input is above the minimum critical heat flux. (See Figure 1). The danger is even greater if the heat input is near the maximum critical heat flux and since the temperature rise would be quite large, it probably would have a very pronounced effect on the system, such as expansion and weakening of the parts to cause breakage. It is therefore most important that in the design of any such boiler that consideration be given to the possibility of the occurrence of film boiling. In some cases it may be desireable to operate in the film boiling range because of the predictable (as a result of this paper) and smooth variation of the heat transfer coefficients with this type of boiling.

In the selection of quenching agents for the heat treating of steel or other metals, it is usually film boiling combined with natural convection in the liquid (important if the liquid is below the boiling point) that produces the temperature drop in the metal where most of the desirable effects are noted.

In thermal cracking operations it may be sometimes desirable to use high temperatures and short contact times. It would appear that film boiling might be the answer and since the heat transfer coefficients are rather low, it might also be economically feasible.

It is thus apparent that the phenomenon of film boiling is very real and that a sound theory by which to predict heat transfer coefficients is needed.

Previous Work on Film Boiling

Up to the present time only Farber and Scorah[79] have made a clear distinction between stable and metastable film boiling; each was previously termed film boiling.

Drew and Mueller[2] have published an extensive survey of the known facts about film boiling up to 1937. Recent data (1937 - 1948) have been reviewed and discussed by this author[3]. From this the following qualitative facts may be listed.

Metastable Film Boiling

1. All high-speed photographs of metastable film boiling indicate definite waves or ripples in the vapor-liquid boundary[13,6,22,23]. The film sometimes appears to alternately build up and collapse[7a].

2. The heat transfer coefficients are higher than would be predicted if the film were perfectly smooth. This is at least partially due to the ripples[3].

3. The nature of the hot solid surface is important but decreasingly so as the stable film boiling region is approached[3,21,20,23].

4. An increase in pressure, while boiling is maintained, especially when the pressure approaches the critical value, lowers the critical Δt and the $(q/A)_{max}$ thus making it increasingly easy to get film boiling[5].

5. A decrease in the liquid vapor interfacial tension causes a lowering and shifting to the left of the metastable portion of the curve in Figure 1[6,15,13]. Such a decrease

also shifts the critical temperature difference Δt_c quite appreciably to the left and downward. This effect is completely ignored by certain authors[11,12].

Stable Film Boiling

1. The liquid-vapor interface is substantially smooth[3] except at very high heat fluxes. It is of course always uneven at its top surface due to bubble formation.

2. The heat transfer coefficient for natural convection stable film boiling from a horizontal tube may be calculated from the theory presented in this paper[3]. One need only know the physical properties of the liquid, its vapor and the tube. The method is restricted to tubes which are large compared to the vapor film thickness and thus do not apply for film boiling from small wires[16,12a], but is fair for moderate sized wires[7a].

3. The heat transfer coefficients are independent of the tube material except for the radiation contribution[3].

4. The effect of any variable such as pressure may be calculated from its effect on the physical properties of the liquid and its vapor.

5. A decrease in vapor-liquid interfacial surface tension produces no change in the calculated coefficients but such a decrease in interfacial tension does reduce the minimum critical heat flux and the temperature corresponding to it[19,6].

6. If the liquid is below the boiling point it is possible to still have a complete vapor blanket around the hot

object but the coefficients of heat transfer are higher than those to a liquid at the boiling point[19]. This phenomena occurs in the quenching of steel etc.

7. This type of boiling is usually encountered in mercury boilers[14,8,9,7]. The heat transfer coefficients to boiling mercury are usually smaller than to non-boiling mercury[24,25,3]. Addition of potassium to the mercury which should tend to wet the solid surface does not help prevent vapor binding (film boiling)[10].

8. Vigerous agitation of the boiling liquid and its vapor (such as rapid two-phase flow through tubes) increases the heat transfer coefficients over those for natural convection film boiling.[24]

THEORY

Horizontal Tube

I will develop a simple theory which will enable one to calculate the coefficients of heat transfer to be expected in stable film boiling (for natural convection) from the outside of a horizontal tube. The vapor film is in dynamic equilibrium for as it rises under the action of buoyant forces, vapor is added to it from the boiling liquid. The necessary heat is supplied by conduction or radiation across the film. This mechanism appears from visual observations to be the situation on about the lower two-thirds of a tube; here there appears to be a smooth continuous film. On the upper third of the tube, however, the situation is very complicated for in this part the bubbles form before rising. Since most of the heat will be transferred on the bottom two-thirds of the tube it would seem most important to have the theory fit the situation in this part of the tube.

The assumptions in the simple theory and a short discussion of their validity follows.

1. The liquid is separated from the hot tube by a continuous vapor blanket. There can be little question that this is the situation as there is both visual and photographic evidence of it.

2. Heat travels through the vapor film by conduction and radiation. This implys that there is viscous flow within the vapor film. Some of the heat will be used in the heating of the film and hence will not have to travel completely

through the film. The best evidence against appreciable mixing or turbulence in the film are rough calculations of the Reynolds' Number in the film[3], which indicate that the flow is viscous even at the highest flow rates. The effect of radiation will be considered near the end of this section on theory.

3. The vapor rises under the action of buoyant forces. Since these forces act in any liquid, they must be present here.

4. The vapor-liquid interface is smooth in that section of the tube where most of the heat is transferred.

5. The rise of the vapor is retarded by the viscous drag on the tube and on the liquid. Since the flow is viscous, this must be the situation. The per cent of the frictional drag contributed by the liquid is not easy to determine. For purposes of integration it will be assumed that the drag of the liquid is constant around the tube. This factor will be incorporated into a constant which will be determined experimentally and hence, the error in the integration will be at least partially corrected.

6. The latent heat of vaporization is the major item in the heat supplied to the vapor film. This is equivalent to assuming that the film has thermal conductivity but little or no heat capacity. This is only a fair approximation even at the lowest temperature. Even though the assumption is not good, it is apparently satisfactory to use the difference in heat content of the vapor and liquid, which of course is a measure of the true heat load, as a latent heat item.

7. The kinetic energy of the vapor in the film is negligible. Calculations[3] indicate that this may possibly be a poor assumption.

8. The vapor-liquid interface is smooth and continuous and is not effected by a variation in the vapor-liquid interfacial tension. The surface tension of the liquid produces large bubbles at the top of the tube rather than a continuous upsweep of vapor but this is not serious since not much heat is transferred in this region. It is assumed also that no capillary waves are produced when operating in the stable film boiling region. It is further assumed that the uneveness in the bottom of the film produced at very high heat fluxes does not effect the heat transfer.

9. It is permissible to use an average value for the temperature difference between the hot tube and the boiling liquid and treat it as a constant value around the tube in the integrations. This approach to the problem is essentially that used by Nusselt[17] for condenser problems and has been shown by this author[4] to be justified in the case of condensers to within the accuracy required for engineering calculations.

10. The boiling liquid is at its boiling point at the vapor liquid interface. Since it is normally impossible to superheat a liquid more than a very few degrees, the temperature of the liquid in the vicinity of the tube is given to within a few degrees by equating the equilibrium vapor pressure to the pressure existing in the vicinity of the tube.

11. For engineering calculations it will be satisfactory

to evaluate all physical properties of the vapor at the arithmetic average temperature of the hot surface and the boiling liquid. This is perhaps the simplest procedure and any consistent error it may tend to introduce will be corrected if the experimental data (using physical properties evaluated at the arithmetic mean temperature) are made to fit the theory by the use of a constant factor.

12. The combined effect of most of the errors in the foregoing assumptions may be corrected by evaluating a suitable factor to be determined from the experimental data.

The theory is represented diagrammatically in Figure 2.

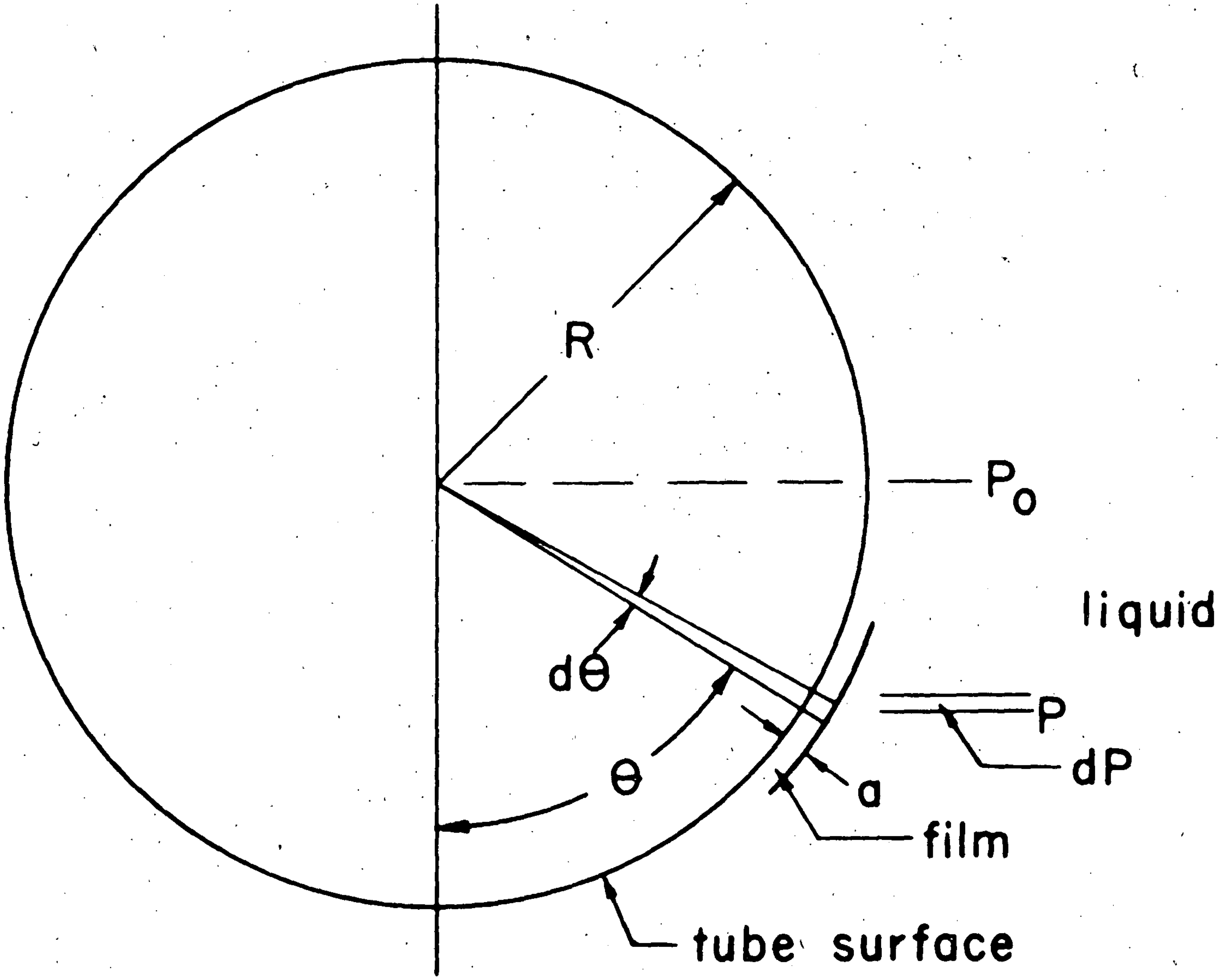


FIG. 2

If P represents the pressure at point P, and P_o represents the pressure at θ equals 90°, then

$$P = P_o + \frac{g}{g_c} R \rho_l \cos \theta, * \tag{2}$$

and

$$dP = \frac{-g}{g_c} R \rho_l \sin \theta \, d\theta. \tag{3}$$

Let us consider a heat balance on the element of vapor in the film enclosed by dθ. Consider length of tube, L.

$$dq = h'_{co} \, dA \, \Delta t = h'_{co} \, RL \, \Delta t \, d\theta = \lambda' \, dw, \tag{4}$$

where λ' is the average difference in heat content between the vapor and the liquid.

$$\lambda' = \lambda + \int_{t_b}^{t_b + \frac{\Delta t}{2}} cp \, dt. \tag{5}$$

We will consider that heat travels through the vapor film by conduction only. Let a be the thickness of vapor film at any angle θ. Then

$$h'_{co} = \frac{k}{a}. \tag{6}$$

Here h'_{co} represents the local value at a point on the tube of the convection coefficient of heat transfer when h_r is equal to zero, that is, there is no radiation. Since all the heat does not travel clear through the vapor film for some is used to heat it, the above expression can not be exact but should give a fairly good result if the latent heat is the major item in λ'.

$$\lambda' \, dw = \frac{k}{a} \, RL \, \Delta t \, d\theta. \tag{7}$$

---

*A complete list of symbols will be found in the nomenclature at the end of this paper.

Let us apply Bernoulli's theorem to the element $d\theta$. Consider a unit mass of material entering this differential section in viscous flow. Let us neglect the kinetic energy of the vapor in the film. Then

$$-\frac{dP}{\rho} = dx\,\frac{g}{g_c} + dF. \qquad (8)$$

By use of a material balance,

$$w = \rho V a L. \qquad (9)$$

From the geometry of the system we obtain:

$$dx = R \sin\theta\, d\theta. \qquad (10)$$

Let us restrict ourselves to a tube large enough so that the vapor film may be considered between two parallel plates. One of these plates is more or less movable. Where there is viscous flow between two parallel plates both of which are fixed,[26]

$$\frac{dF}{R\,d\theta} = \frac{12\mu V}{\rho g_c\, a^2}. \qquad (11)$$

This would be the case when the liquid is very viscous or possibly quite dense. If the liquid moves with the gas film, because it is fluid and because of the convection currents set up in the boiling liquid, then equation (11) must be modified. If a situation exists such that the liquid exerts no retarding action on the gas film, then only the tube contributes to the frictional drag. In this case,

$$\frac{dF}{R\,d\theta} = \frac{3\mu V}{\rho g_c\, a^2}. \qquad (12)$$

In general we may write,

$$\frac{dF}{R\,d\theta} = \frac{\beta\mu V}{\rho g_c\, a^2}, \qquad (13)$$

where for natural convection,

$$3 < \beta < 12$$

If there is forced convection of the liquid across the tube surface, it would be possible to reduce β below 3.

Let us substitute into equation (8) the value of dP from equation (3), the value of dF from equation (13), and the value of dx from equation (10). The following equation is the result after rearrangement.

$$\frac{g}{g_c}\left(\frac{\rho_l}{\rho} - 1\right) \sin\theta \, d\theta = \frac{\beta \mu V \, d\theta}{g_c \rho a^2} \qquad (14)$$

We shall replace V by its value from equation (9) and for, a, substitute its value from equation (7). Then

$$\frac{g \rho L^4 k^3 R^3 \Delta t^3 (\rho_l - \rho)}{\mu (\lambda')^3} \sin\theta = \beta \, w \left(\frac{dw}{d\theta}\right)^3. \qquad (15)$$

Let us take the cube root of this equation and separate the variables. Then

$$\left[\frac{g \rho L^4 k^3 R^3 \Delta t^3 (\rho_l - \rho)}{\mu (\lambda')^3}\right]^{1/3} \sin^{1/3}\theta \, d\theta = \beta^{1/3} w^{1/3} dw. \qquad (16)$$

By integration of the right hand side of equation (16) between zero and W, we obtain:

$$\beta^{1/3} \int_0^W w^{1/3} \, dw = \beta^{1/3} \, 3/4 \, W^{4/3}. \qquad (17)$$

$$\frac{4}{3} \int_0^\pi \sin^{1/3}\theta \, d\theta = 3.428. \qquad (18)$$

Since we have only integrated around one side, the total mass flow, W, for both sides will be twice that given by integration of equation (16).

$$W = \frac{3.428^{3/4} \times 2L}{\beta^{1/4}} \left[\frac{k^3 \rho(\rho_l - \rho) g R^3 \Delta t^3}{\mu (\lambda')^3}\right]^{1/4}. \qquad (19)$$

If no radiation is present,

$$W = \frac{h_{co} \, 2\pi R L \Delta t}{\lambda'} . \qquad (20)$$

Replacing R by half of the diameter, D/2, and solving for h_{co}, we obtain:

$$h_{co} = \frac{3.428^{3/4} \, 2^{1/4}}{\pi \quad \beta^{1/4}} \left[\frac{k^3 \rho(\rho_l - \rho) g \lambda'}{D\mu \Delta t}\right]^{1/4}, \qquad (21)$$

or

$$h_{co} = \frac{0.9536}{\beta^{1/4}} \left[\frac{k^3 \rho(\rho_l - \rho) g \lambda'}{D\mu \Delta t}\right]^{1/4}. \qquad (22)$$

It is of interest at this point to compare this equation with that for the coefficient of heat transfer in the condensation of vapors on a horizontal tube.

$$h = 0.724 \sqrt[4]{\frac{k^3 \rho^2 g \lambda}{D\mu \Delta t}} , \qquad (23)$$

where the quantities are for those of the liquid film. The resemblence between equations (22) and (23) is striking but it should have been expected.

Since for natural convection

$$3 < \beta < 12$$

then

$$.512 \sqrt[4]{\frac{k^3 \rho(\rho_l - \rho) g \lambda'}{D\mu \Delta t}} < h_{co} < 0.724 \sqrt[4]{\frac{k^3 \rho(\rho_l - \rho) g \lambda'}{D\mu \Delta t}} \qquad (24)$$

Since the numerical values of these constants are limits, let us write the numerical constant simply as "constant".

It is convenient when dealing with a gas to lump certain quantities together into the Prandtl Number, (Pr), which is nearly independent of temperature and pressure.

$$Pr = \frac{\mu c_p}{k} \quad . \qquad (25)$$

Hence equation (24) becomes:

$$h_{co} = (\text{const}) \; {\frac{k^2 \rho(\rho_l - \rho)\, g \lambda' \, c_p}{D \;\; \Delta t \;\; Pr}}^{1/4} . \qquad (26)$$

h_{co} = film coefficient of heat transfer if there were no radiation.

k = thermal conductivity of the vapor.

ρ = density of the vapor.

ρ_l = density of the liquid.

g = local acceleration of gravity.

λ' = difference in heat content between the vapor at its average temperature and the liquid at its boiling point. See equation (5).

c_p = heat capacity of the vapor at constant pressure.

D = outside diameter of the tube.

Δt = temperature difference between the hot surface and the liquid at its boiling point.

Pr = Prandtl number of the vapor. See equation (25).

All of the physical properties of the vapor are evaluated at the average temperature of the film. This average has been arbitrarily taken as the arithmetic average of the tube surface temperature and the boiling liquid temperature.

Most of the experimental work will be concerned with the evaluation of this "constant" and will be shown in the sections on data and results to have a value of about 0.62.

$$(\text{const}) = 0.62 \pm 0.04 \tag{27}$$

This "constant" is dimensionless and therefore its equivalent in equation (26) is a dimensionless group.

Our assumption 6, page 18, (that the latent heat is so large that the heat required to heat the film is negligible) may be seriously in error. We would thus expect the dimensionless group in equation (26) to be a function of the ratio of the heat required for vaporization to the heat used in raising the temperature of the film. That is to say,

$$(\text{const}) = f\left(\frac{\lambda 2}{\Delta t\ c_p}\right) = f'\left(\frac{\Delta t\ c_p}{\lambda'}\right). \tag{28}$$

If the kinetic energy of the vapor in the film is not negligible (assumption 7, page 18) then the derivation should be changed to include this kinetic energy term in Bernoulli's equation. For weight, w, in the section at $d\theta$ we have:

$$-w\,\frac{dP}{\rho} = \frac{2V\ dV\ w}{g_c} + w\ dF + w\ dx\frac{g}{g_c} \tag{29}$$

Consider a differential weight dw entering the film. Then

$$-dw\,\frac{dP}{\rho} = \frac{bV^2}{g_c}dw + dw\ dF + dx\ dw\,\frac{g}{g_c}\ . \tag{30}$$

It is realized that this new entering material will not leave with the average velocity of the stream; also it will not enter with zero velocity as the liquid may also move along with the gas as the latter moves. For these reasons a corrective term, b, is put into the V^2 term in equation (30).

This term, b, is between zero and one and much closer to zero. By adding the foregoing two equations, dividing by w and multiplying by ρ, we obtain:

$$-dP = \frac{2\rho V dV}{g_c} + b\rho \frac{V^2}{w}\frac{dw}{g_c} + \rho dF + \rho dx \frac{g}{g_c}, \tag{31}$$

Double differentials have been neglected.

Let us combine the equations (3), (7), (9), (10), (13), and (31) as before to eliminate P,V,F,x, and a. The resulting equation after combining terms is:

$$\frac{g\rho L^4 k^2 R^3 \Delta t^2 (\rho_l - \rho)}{(\lambda')^2} \sin \theta = 2w^2 \frac{d^2w}{d\theta^2}\frac{dw}{d\theta} + w(\frac{dw}{d\theta})^3$$

$$\left[2 + b + \beta \frac{\mu\lambda'}{k\,\Delta t}\right]. \tag{32}$$

This differential equation is as yet unsolved. It would be impossible to get an exact solution as neither β nor b is a true constant. However, by inspection of the dimensions of the various terms of this equation (32) and by use of equation (4) we may write dimensionless groups which must be functions of each other. Let us use the diameter instead of the radius of the tube.

$$h_{co}(\frac{D\ \Delta t\ \mu}{k^3\ \rho(\rho_l - \rho)g\ \lambda'})^{1/4} = f''(2 + b + \frac{\beta\mu\lambda'}{k\ \Delta t} = f'''(\frac{\mu\ \lambda'}{k\ \Delta t}), \tag{33}$$

or

$$h_{co}(\frac{D\ \Delta t\ Pr}{k^2\ \rho(\rho_l - \rho)\ g\ \lambda'\ c_p})^{1/4} = (\text{const}) = f''''(\frac{\Delta t\ c_p}{\lambda'\ Pr}), \tag{34}$$

where the "constant" is only a true constant in the simple theory, equation (26). Thus we see that by plotting experimental values of the "constant" against the group $\Delta t\ c_p/\lambda'$ Pr we should show the comined effect of kinetic energy in the vapor film equation (34), and the heat capacity of the vapor in the film, equation (28). Errors in other assumptions in the simple theory should also show up on this plot. The amount of flow of the liquid at the vapor boundary affects β and thus must also affect the "constant".

From all of this, it is apparent that nearly all of the assumptions which might be considered poor in the simple theory should show their effect when the "constant" is plotted against $\Delta t\, c_p/\lambda'$ Pr. It will be shown in the section on results that within the limit of experimental error there is no trend of the "constant" with the group $\Delta t\, c_p/\lambda'$ Pr and hence the errors in the simple theory either tend to cancel or are of small magnitude.

Vertical Tube or Plate

No experimental work is reported on natural convection film boiling from a vertical tube or plate but by applying the same simple theory as for the horizontal tube, we arrive at the following equation:

$$h_{co} = \left(\frac{4}{3}\right)^{3/4} \frac{1}{\beta^{1/4}} \left[\frac{k^3 \rho(\rho_l - \rho)\, g\, \lambda'}{L \mu\, \Delta t}\right]^{1/4} ; \qquad (35)$$

which may be written:

$$h_{co} = (\text{const}') \left[\frac{k^2 \rho(\rho_l - \rho)\, g\, \lambda'\, c_p}{L\ \Delta t\ Pr}\right]^{1/4} . \qquad (36)$$

L is the distance along the tube or plate in the direction of vapor flow.

Effect of Radiation

Since we are really interested in the combined effect of radiation and convection, let us study the effect of radiation on the convection coefficient. An attempt was made to put the effect of radiation directly into the differential equation for convection which was not readily soluble. It was therefore thought that a less rigorous but at least qualitatively correct approach was in order. Let us postulate that the radiation from the tube will be largely absorbed in a very small thickness of the liquid and hence will produce vapor which will contribute to the vapor film thickness. This is equivalent to saying that the transmissivity of the liquid is low for thermal radiation. Since the total coefficient is merely the sum of the convection and radiation coefficients, we may write:

$$h = h_c + h_r \, . \tag{37}$$

For any given value of h_{co} (the convection coefficient if there were no radiation) the pressure drop from the top to the bottom of the film, the viscosity of the vapor, the diameter of the tube and the density of the vapor may be taken as constant. Hence, from equations 9 and 13 the weight flow at any angle θ is proportional to the cube of the thickness of the film.

$$w \propto a^3 . \tag{38}$$

If the contribution of the radiation to w is small, then, since the rate of increase of w with angle always decreases, w increases with W to somewhat greater than the first power. If the radiation is already large, however, then w is more nearly proportional to W and in any case the relation between w and W is not far from a direct proportion. For a given h_{co}, the thermal conductivity of the film will be approximately constant and hence, the convection coefficient, h_c, will vary nearly inversely as the thickness of the film. Since the temperature difference and the enthalpy difference of the vapor and liquid will also remain nearly constant, the total weight of material evaporated will be proportional to the heat transfer coefficient. Thus,

$$h_c \propto \frac{1}{a} \propto \frac{1}{w^{1/3}} \propto \frac{1}{W^{1/3}} \propto \frac{1}{h^{1/3}} \quad . \tag{39}$$

Combining this with equation (37), we obtain:

$$h = \frac{K}{h^{1/3}} + h_r \quad . \tag{40}$$

When h_r is equal to zero there is no heat transferred by radiation and hence, h is equal to h_{co}. Therefore, K is equal to $h_{co}{}^{4/3}$ and

$$h = h_{co}\left(\frac{h_{co}}{h}\right)^{1/3} + h_r \quad . \tag{41}$$

Equation (41) gives us the approximate relationship between h, h_{co} and h_r. This equation is difficult to use because h occurs implicitly in it.

As long as h_r is smaller than h_{co},

$$h = h_{co} + \frac{3}{4} \ h_r \tag{42}$$

to within five per cent of the h from equation (41). If h_r is very large, one may use the following equation which gives the same relationship as equation (41) between h, h_{co} and h_r to within three-tenths of one per cent, as long as hr/h_{co} is between zero and ten. This is certainly within any practical operating range.

$$h = h_{co} + h_r \left[\frac{3}{4} + \frac{1}{4}\frac{h_r}{h_{co}}\left(\frac{1}{2.62 + \frac{h_r}{h_{co}}}\right)\right]. \qquad (43)$$

The term h_r may be calculated by the following equation for parallel plates.

$$h_r = \frac{\sigma}{\frac{1}{\epsilon} + \frac{1}{\alpha} - 1}\left(\frac{T_H^4 - T_C^4}{\Delta t}\right). \qquad (44)$$

T_H is the temperature of the hot tube in degrees R.

T_C is the temperature of the cold liquid in degrees R.

ϵ is the emissivity of the hot tube.

α is the absorptivity of the cold liquid. (usually near unity).

σ is the Stefan-Boltzman constant, 0.1713×10^{-8} Btu/(hr)(ft^2)($^\circ$R^4).

The graph in McAdams(13) Figure 27, page 63 may be used to get h_r for black surfaces. This value may then be multiplied by the emissivity factor $\left[\frac{1}{\frac{1}{\epsilon} + \frac{1}{\alpha} - 1}\right]$ to get the true h_r.

In all of the above it is assumed that the transmissivity of the liquid for thermal radiation is small (as it is for most liquids).

APPARATUS

Figure 3 is a diagram of the apparatus used in these experiments on film boiling. Figure 4 is a photograph of the same apparatus.

The apparatus essentially consists of a carbon tube heating element, from which the boiling occurs, contained between holders in a four-inch pyrex pipe tee. This apparatus is described in detail in the author's thesis[3].

The carbon tubes used were nominally 1/4, 3/8 and 1/2 inches. One run was made with a 3/16 inch stainless steel tube. The hole in the tube was used to accommodate a thermocouple. From the reading of this thermocouple it was possible[3] to calculate the tube surface temperature. The difference between the tube surface temperature and the observed inside temperature of the tube was at most ten percent of the temperature difference between the tube surface and the boiling liquid temperature. The thermocouple was also used to check the temperature uniformity along the tube[3]. The heating was obtained as the product of the current through the tube by the voltage drop along a given section, usually five inches in the center of the tube.

EXPERIMENTAL PROCEDURE

The various parts of the apparatus, Figures 3 and 4, were cleaned thoroughly. The tube to be used was polished. The copper inserts and the stainless steel holders were cleaned with emery cloth to give good electrical contacts. The tube was put in place between the stainless steel holders and the packing glands at the sides of the apparatus were tightened to give a liquid seal. After assembly, the apparatus was filled with liquid to the desired level. Unless otherwise stated the level was between one and one and one quarter inches above the center of the tube. The external heater was turned on and current was passed through the tube until the liquid was boiling at the prevailing atmospheric pressure.

The heat input to the tube was increased to a high value for a few minutes to insure stable film boiling over the entire surface. Film boiling is evidenced by a smooth film on the bottom and sides of the tube. The current was then set at the desired value. Of the liquids which were run only water was difficult to get into the fim boiling range with-out burning out the tube. All data were taken with stable film boiling of the various liquids except for a few data taken with nucleate boiling of water for the purpose of evaluating roughly the thermal conductivity of the carbon[3].

The current was held constant and the potentiometer, which was connected to the thermocouple in the tube through the rotary thermocouple switch, was observed until steady conditions were established. This usually required only a few minutes. The reading of the potentiometer was recorded and

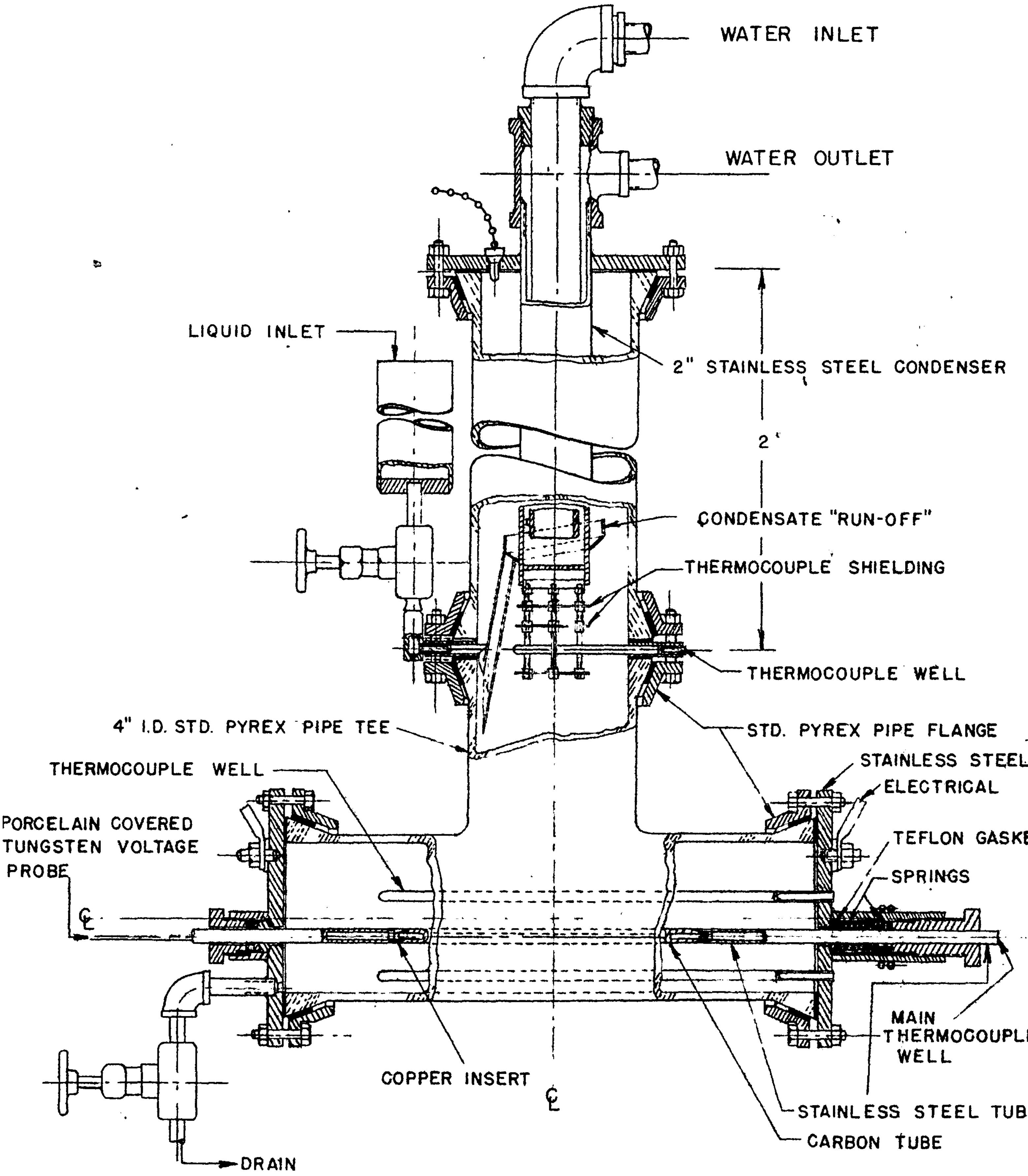

WATER INLET
WATER OUTLET
LIQUID INLET
2" STAINLESS STEEL CONDENSER
2'
CONDENSATE "RUN-OFF"
THERMOCOUPLE SHIELDING
THERMOCOUPLE WELL
4" I.D. STD. PYREX PIPE TEE
STD. PYREX PIPE FLANGE
STAINLESS STEEL
ELECTRICAL
THERMOCOUPLE WELL
PORCELAIN COVERED
TUNGSTEN VOLTAGE
PROBE
℄
TEFLON GASKE
SPRINGS
MAIN
THERMOCOUPL
WELL
COPPER INSERT
℄
STAINLESS STEEL TUB
CARBON TUBE
DRAIN

FIG. 3

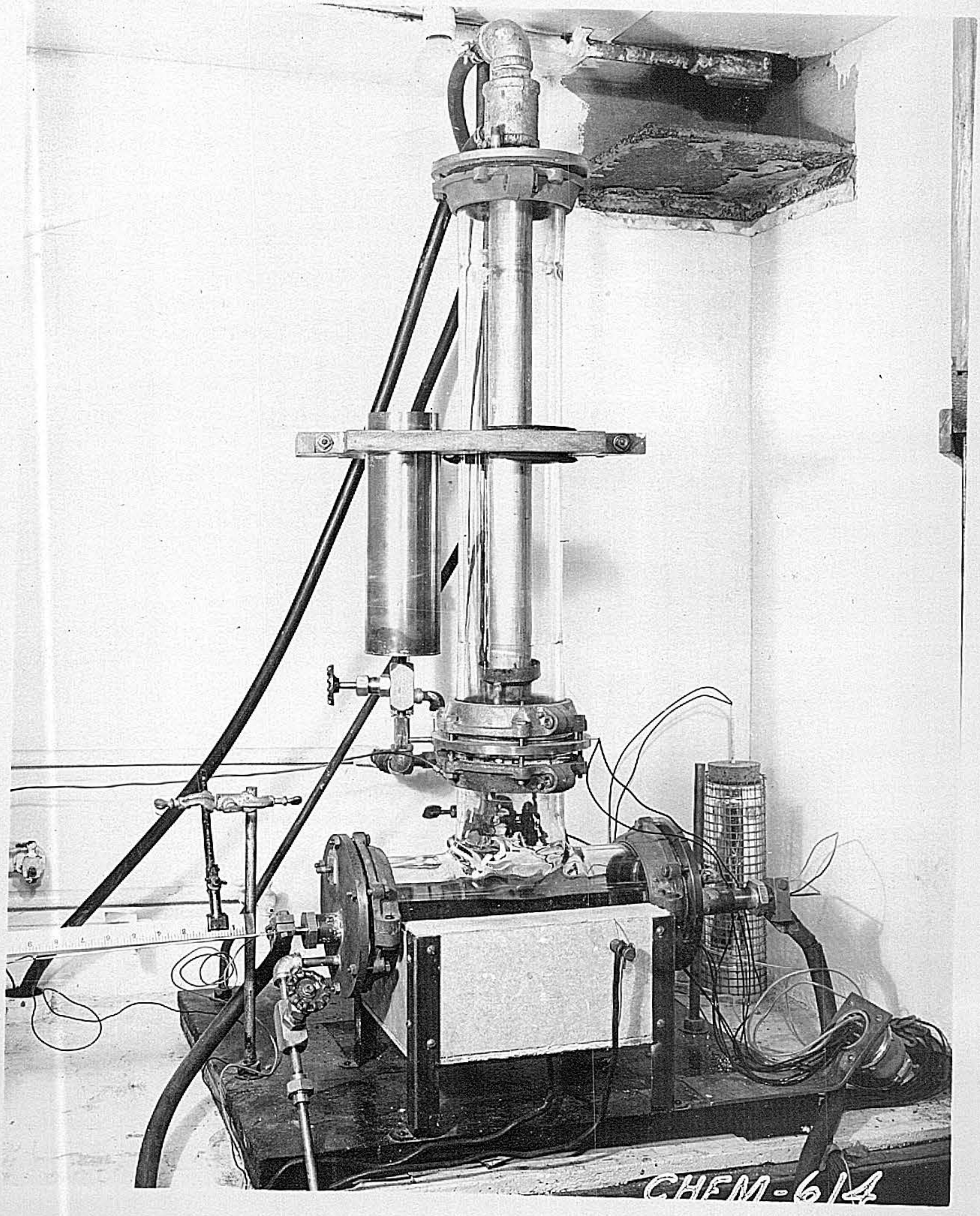


FIG. 4

the reading on the voltmeter which was connected to the voltage probe (which was usually two and one-half inches to the left of the center) was recorded. The thermocouple was removed and the voltage probe was moved to the same distance on the other side of the center and the voltage was then again recorded. The other voltage terminal was fastened to one terminal of the apparatus. The voltage probe was then moved back to its former position and the thermocouple replaced to its center point position. This reading was usually compared to the first reading of the thermocouple and if no check was obtained the readings were repeated. At some point during the run readings were taken of all the other thermocouples. These readings were hardly necessary as the observed liquid temperatures vary at most a degree or two from the reported boiling points for one atmosphere and this is a relatively unimportant item in the theory. The external heater temperature has essentially no effect on the observed coeffecients[3].

The thermocouple used in the tube temperature measurements was calibrated[3] at the boiling point of water, the melting point of tin and at the melting point of copper.

DATA

The important experimental and calculated data are summarized in Tables 1-21. Data were taken on the following liquids: water (Table 1-2), nitrogen (Table 3), carbon tetrachloride (Table 4), absolute ethyl alcohol (Tables 5-7), benzene (Table 8), diphenyl oxide (Table 9) and n-pentane (Tables 10-16). Calculated data are also presented on mercury (Table 17). Tables 18 and 19 summarize the data of Pilling and Lynch[19] on the quenching of a hot nickel rod in boiling water and in soap solution.

To check the effect of tube diameter on heat transfer coefficients, data were taken on pentane with carbon tubes of diameters: 0.352, o.238 and 0.469 inches (Tables 10-15), and with a stainless steel tube of diameter of 0.188 inches (Table 16).

The physical constants which were used in the calculations were obtained from the literature which was carefully searched up to 1948 and are summarized in graphical form in the author's thesis[3].

Included in the tables are the following quantities:

1. The run number refers to the page number in the laboratory notebook. The other numbers next to these are the dates when the run was performed.
2. The liquid and the size and kind of tube used are also included in the heading.
3. The point numbers represent the order in which the data were taken in each run.
4. The "amps" refers to the current flowing through the tube.
5. The "volts" refers to the voltage drop across the section

of the tube or apparatus indicated. This is actually the difference of two readings in most cases.

6. The "t_i mv" refers to the temperature at or near the center point of the tube and is the value in millivolts observed on the potentiometer. It is not corrected as written but since chromel vs. alumel thermocouples were used its reading can be converted to temperature by reference to any standard table of e.m.f. for these thermocouples.

It was necessary to apply a small correction (not over 0.2 mv). It has been shown[3] that this center point temperature is representative of the temperature over a section at least five inches long.

7. The "Δt" is the calculated value of the difference in temperature between the tube surface and the boiling liquid. Here it is necessary to convert the measured inside temperatures to outside temperatures. This involves a rough estimate of the thermal conductivity of the tube[3].

8. The "h" is the calculated coefficient of heat transfer in English Engineering Units and is obtained from the basic equation:

$$h = \frac{q}{A \Delta t} .$$

A is the surface area of the tube in the section which has a heat input, q.

9. The "h_{co}" is the calculated value, from equation (41), of the coefficient of heat transfer to be expected if there were no radiative heat transfer.

10. The "const" is the value which appears in equation (26). This value was calculated from the value of h_{co}, Δt, the tube

diameter and the physical constants[3] of the liquid and its vapor.

11. The quantity, $\Delta t\ c_p/\lambda'\ Pr$, is important in that the extended theory, equation (34), indicates that the "const" should be some function of this dimensionless group.

The external heater temperature and the observed liquid and vapor temperatures are not included. It has been shown[3] that the results are not effected by changes in heater temperature. The liquid and vapor temperatures were in all cases very close to the published values for the normal boiling point at one atmosphere.

All of the data in the tables were taken with the entire tube in stable film boiling.

The water that was used in these experiments was distilled water from Gilman Hall. The nitrogen was distilled in the liquid air plant in Gilman Hall, University of California; it was better than 99.9 percent pure. The carbon tetrachloride was analytical reagent grade from Mallinckrodt. The ethyl alcohol was 200 proof commercial grade absolute alcohol from the University storehouse. They purchased it from concerns such as Commercial Solvents Inc. The benzene was reagent grade from Baker and Adamson. The diphenyl oxide was laboratory grade from Eimer and Amend. The n-pentane was 99 percent pure and was obtained from Phillips Petroleum Co.

At the highest tube temperatures there was appreciable decomposition of the various liquids. Although no attempt was made to correct for this in the physical properties used to evaluate the "constant", the residual alcohol in one run was analyzed by fractional distillation and found to be better than 99.9% absolute alcohol.

TABLE 1

Run Number 55 - 8/20/47

Experimental and Calculated Data on the Film Boiling of Water from a 0.351-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t mv	Δt °F	h Btu/(hr)(sq ft)(°F)	h_{co} Btu/(hr)(sq ft)(°F)	Const	$\frac{\Delta t\ c_p}{\lambda'\ Pr}$
1	100	11.5	35.5	1296	46.8	34.3	0.56	0.61
2	90	10.6	32.4	1166	43.2	32.8	0.56	0.52
3	79	9.7	27.9	980	41.4	33.5	0.59	0.43
4	75	9.2	25.9	896	40.8	33.9	0.60	0.40
5	70	8.6	23.9	816	39.1	33.0	0.59	0.36
6	65	8.1	21.2	703	39.7	34.6	0.61	0.32
7	100	11.7	35.8	1310	47.2	34.6	0.57	0.62
8	110	12.9	39.5	1469	51.0	35.5	0.54	0.74
9	120	13.9	43.4	1644	53.5	34.3	0.49	0.90

The voltage across the apparatus with the carbon tube replaced by a solid copper rod was 1.3 volts at 200 amperes.

The inside diameter of the carbon tube is 0.125 inches.

The effective length of the carbon tube for heat transfer was estimated to be eight inches.

* The voltage was measured across the entire apparatus.

TABLE 2

Run Number 94A - 2/17/48

Experimental and Calculated Data on the Film Boiling of Water from a 0.352-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_i mv	Δt °F	h Btu/(hr)(sq ft)(°F)	h_{co} Btu/(hr)(sq ft)(°F)	Const	$\frac{\Delta t\, c_p}{\lambda' \, Pr}$
1	100	6.81	36.35	1296	46.7	33.2	0.55	0.61
2	90	6.3	32.50	1174	43.0	32.6	0.55	0.53
3	80	5.87	28.35	1002	41.7	33.4	0.59	0.45
4	70	5.33	23.75	815	40.8	34.7	0.62	0.36
5	110	7.63	40.15	1495	50.0	34.2	0.52	0.77

The inside diameter of the carbon tube is 0.125 inches.

* The voltage was measured across the center five inches of the carbon tube.

TABLE 3

Runs Number 57 and 58 - 8/20/47 and 8/21/47

Experimental and Calculated Data on the Film Boiling of Nitrogen from a 0.350-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_1 mv	Δt ^oF	h	h_{co}	Const	$\frac{\Delta t\ c_p}{\lambda'\ Pr}$
					$\frac{Btu}{(hr)(sq\ ft)(^oF)}$			
1	50	6.5	10.43	795	21.8	20.8	0.67	1.44
2	61	7.7	17.60	1099	22.8	20.6	0.66	1.67
3	71	8.6	23.26	1333	24.4	20.7	0.66	1.83
4	38	5.3	4.35	530	20.3	19.9	0.64	1.18
5	30	4.1	-0.70	323	20.3	20.1	0.63	0.87
6	60	7.6	17.13	1079	22.4	20.3	0.65	1.66
7	71	8.8	24.3	1377	24.1	20.0	0.63	1.84
8	81	9.7	29.1	1576	26.6	20.5	0.65	1.96
9	89	10.5	32.8	1732	28.5	20.9	0.65	2.01
10	107.5	12.1	39.73	2031	34.6	22.2	0.68	2.12
11	80	9.5	27.7	1506	26.7	21.5	0.68	1.91
12	113	12.6	41.26	2098	35.8	21.7	0.66	2.13
13	121	13.25	43.9	2216	38.0	22.5	0.68	2.17
14	130	14.5	50.2	2520	39.4	15.7	0.47	2.24
15	129	14.5	49.2	2470	39.9	18.3	0.54	2.24
16	58.5	8.0	17.7	1104	21.1	18.8	0.61	1.67

The voltage across the apparatus with the carbon tube replaced by a solid copper rod was 1.3 volts when the current through the rod was 200 amperes.

*The voltage was measured across the entire apparatus.

The inside diameter of the carbon tube is 0.125". The effective length of the carbon tube for heat transfer was estimated to be eight inches.

TABLE 4

Run Number 77 - 10/29/47

Experimental and Calculated Data on the Film Boiling of Carbon Tetrachloride from a 0.352-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_1 mV	Δt °F	h	h_{co}	Const	$\frac{\Delta t\, c_p}{\lambda' Pr}$
					$\frac{Btu}{(hr)(sq\ ft)(°F)}$			
1	77	5.22	32.25	1220	29.3	18.9	0.64	1.38
2	68	4.70	28.24	1054	27.0	18.7	0.64	1.27
3	60	4.30	24.05	882	26.1	19.8	0.68	1.14
4	76.5	5.22	31.80	1201	29.6	19.4	0.65	1.37
5	54.5	3.88	21.77	789	23.9	18.6	0.64	1.07
6	50	3.54	19.58	701	22.5	17.9	0.62	0.99
7	45	3.22	17.00	594	21.7	18.0	0.62	0.88
8	80	5.26	32.86	1245	30.2	19.4	0.65	1.39
9	90	5.80	36.75	1411	33.0	19.4	0.65	1.48
10	100	6.26	39.60	1528	36.5	20.4	0.68	1.53
11	110	6.78	42.05	1635	40.6	22.3	0.72	1.57
12	120.5	7.48	44.80	1757	45.6	23.9	0.77	1.61

The inside diameter of the carbon tube is 0.125 inches.

*The voltage was measured across the center five inches of the carbon tube.

TABLE 5

Run Number 84 - 12/26/47

Experimental and Calculated Data on the Film Boiling of Absolute Ethyl Alcohol from a 0.239-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_i mv	Δt °F	h	h_{co}	Const	$\frac{\Delta t \, c_p}{\lambda' \, Pr}$
					$\frac{Btu}{(hr)(sq\ ft)(°F)}$			
1	50	11.35	34.8	1329	56.7	44.9	0.61	1.39
2	55	12.0	37.5	1445	60.7	48.1	0.64	1.46
3	60	12.8	40.2	1563	65.4	49.7	0.65	1.54
4	65	13.3	42.4	1658	69.4	51.3	0.66	1.59
5	70	13.8	44.3	1742	73.6	54.9	0.69	1.63
6	75	14.05	45.5	1794	78.0	57.0	0.71	1.66
7	50	9.85	31.7	1181	55.4	45.8	0.64	1.28

The inside diameter of the carbon tube is 0.125 inches.

*The voltage was measured across the center five inches of the carbon tube.

TABLE 6

Run Number 89 - 2/7/48

Experimental and Calculated Data on the Film Boiling of Absolute Ethyl Alcohol from a 0.468-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_i mV	Δt °F	h	h_{co}	Const	$\frac{\Delta t\ c_p}{\lambda'\ Pr}$
					$\frac{Btu}{(hr)(sq\ ft)(^oF)}$			
1	110	6.87	30.96	1113	45.4	36.7	0.62	1.23
2	100	6.37	27.65	982	43.4	36.1	0.62	1.11
3	90	5.89	24.30	851	42.3	36.5	0.63	0.99
4	110	6.92	30.8	1105	46.1	37.5	0.64	1.22
5	120	7.46	33.7	1219	49.1	39.0	0.65	1.31
6	130	7.95	36.7	1341	51.4	39.4	0.64	1.40
7	140	8.43	39.5	1454	54.1	40.5	0.64	1.47
8	100	6.15	27.0	958	42.9	35.9	0.62	1.09

The inside diameter of the carbon tube is 0.128 inches.

*The voltage was measured across the center five inches of the carbon tube.

TABLE 7

Run Number 90 - 2/7/48

Experimental and Calculated Data on the Film Boiling of Absolute Ethyl Alcohol from a 0.352-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_i mv	Δt °F	h	h_{co}	Const	$\frac{\Delta t}{\lambda'} \frac{c_p}{Pr}$
					$\frac{Btu}{(hr)(sq\ ft)(^oF)}$			
1	80	5.62	24.82	891	44.8	38.5	0.63	1.03
2	80	5.58	24.36	871	45.6	39.6	0.65	1.01
3	70	4.95	20.73	726	42.4	37.7	0.64	0.86
4	65	4.62	18.70	645	41.5	37.4	0.64	0.77
5	60	4.30	16.75	566	40.6	37.2	0.64	0.69
6	55	4.03	15.10	501	39.3	36.3	0.63	0.61
7	50	3.65	13.32	428	37.9	35.1	0.61	0.53
8	45	3.30	11.75	364	36.2	33.8	0.58	0.46
9	80	5.58	24.35	871	45.6	39.5	0.65	1.01
10	90	6.10	27.83	1011	48.3	40.8	0.66	1.14
11	100	6.60	31.05	1144	51.3	42.3	0.66	1.25
12	110	7.08	34.10	1262	54.8	44.1	0.68	1.34
13	120	7.72	36.83	1371	60.1	47.7	0.72	1.41
14	130	8.20	39.60	1486	63.9	49.6	0.73	1.44
15	80	5.48	23.90	853	45.6	39.9	0.66	0.99

The inside diameter of the carbon tube was 0.125 inches.

*The voltage was measured across the center five inches of the carbon tube.

TABLE 8

Run Number 87A - 2/6/48

Experimental and Calculated Data on the Film Boiling of Benzene from a 0.352-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_i mv	Δt °F	h $\frac{\text{Btu}}{(\text{hr})(\text{sq ft})(^\circ\text{F})}$	h_{co} $\frac{\text{Btu}}{(\text{hr})(\text{sq ft})(^\circ\text{F})}$	Const	$\frac{\Delta t\ c_p}{\lambda'\ \text{Pr}}$
1	60	4.2	17.35	590	38.11	34.4	0.62	1.31
2	55	3.88	15.85	530	35.9	32.6	0.60	1.21
3	50	3.48	14.0	455	34.1	31.3	0.58	1.06
4	60	4.25	17.55	598	37.9	34.1	0.62	1.33
5	70	4.68	21.23	750	39.1	34.1	0.58	1.57
6	80	5.29	24.73	886	42.4	36.2	0.58	1.78
7	90	5.86	28.0	1015	46.2	38.7	0.60	1.94

The inside diameter of the carbon tube is 0.125 inches.

*The voltage was measured across the center five inches of the carbon tube.

TABLE 9

Run Number 91 - 2/9/48

Experimental and Calculated Data on the Film Boiling of Diphenyl Oxide from a 0.352-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_i mv	Δt °F	h	h_{co}	Const	$\frac{\Delta t\, c_p}{\lambda'}P_r$
					Btu / (hr)(sq ft)(°F)			
1	70	4.8	24.7	572	52.4	43.7		
2	60	4.16	21.4	438	50.7	43.7		
3	55	3.78	19.7	371	50.0	43.1		
4	70	4.88	24.6	566	53.7	45.1		
5	80	5.4	27.8	695	55.5	45.3		
6	90	5.9	30.6	810	58.5	46.6		
7	100	6.35	33.5	930	61.8	48.0		

The inside diameter of the carbon tube is 0.125 inches.

*The voltage was measured across the center five inches of the carbon tube.

TABLE 10

Run Number 85 - 12/30/47

Experimental and Calculated Data on the Film Boiling of n-Pentane from a 0.352-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_i mv	Δt °F	h	h_{co}	Const	$\frac{\Delta t\, c_p}{\lambda' \mathrm{Pr}}$
					$\frac{\text{Btu}}{(\text{hr})(\text{sq ft})(^\circ\text{F})}$			
1	60	4.6	15.8	598	41.1	38.2	0.70	1.45
2	50	3.87	12.57	468	36.8	34.6	0.66	1.21
3	45	3.55	11.14	411	34.6	32.6	0.63	1.11
4	40	3.15	9.3	334	33.6	32.0	0.62	0.94
5	60	4.6	15.9	602	41.0	38.0	0.70	1.44
6	70	5.28	19.6	751	43.9	39.9	0.70	1.67
7	80	5.93	23.15	890	47.5	42.4	0.70	1.84
8	90	6.42	26.5	1024	50.2	43.0	0.68	2.00
9	100	7.0	30.1	1168	53.4	45.4	0.70	2.13
10	110	7.5	33.4	1300	56.5	46.8	0.68	2.24
11	120	8.0	36.0	1405	60.7	49.7	0.70	2.31
12	130	8.3	38.7	1518	63.4	50.3	0.69	2.38

The inside diameter of the carbon tube is 0.125 inches.

*The voltage was measured across the center five inches of the carbon tube.

TABLE 11

Run Number 86 - 2/5/48

Experimental and Calculated Data on the Film Boiling of n-Pentane from a 0.352-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t, mv	Δt °F	h $\frac{\text{Btu}}{(\text{hr})(\text{sq ft})(°\text{F})}$	h_{co} $\frac{\text{Btu}}{(\text{hr})(\text{sq ft})(°\text{F})}$	Const	$\frac{\Delta t \, c_p}{\lambda'' \, Pr}$
1	70	4.98	19.10	733	42.4	38.5	0.68	1.65
2	60	4.27	15.57	592	38.5	35.6	0.65	1.44
3	50	3.7	12.30	458	36.0	33.8	0.65	1.20
4	100	6.53	29.2	1138	51.3	43.8	0.68	2.10
5	120	7.8	35.4	1380	60.4	49.7	0.71	2.30
6	130	8.58	38.5	1505	65.9	53.2	0.73	2.38
7	140	8.62	40.9	1608	66.7	52.1	0.69	2.44

The inside diameter of the carbon tube is 0.125 inches.

*The voltage was measured across the center five inches of the carbon tube.

TABLE 12

Run Number 87 - 2/6/48

Experimental and Calculated Data on the Film Boiling of n-Pentane from a 0.238-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_i mv	Δt °F	h $\frac{\text{Btu}}{(\text{hr})(\text{sq ft})(^\circ\text{F})}$	h_{co}	Const	$\frac{\Delta t\, c_p}{\lambda' \Pr}$
1	40	9.24	24.6	975	50.5	44.7	0.66	1.94
2	35	8.03	20.45	807	46.3	42.0	0.65	1.74
3	30	6.85	15.85	617	44.2	41.2	0.68	1.48
4	25	5.75	12.55	480	39.8	37.5	0.65	1.23
5	20	4.7	9.20	336	37.2	35.5	0.63	0.94
6	40	9.3	24.7	979	50.7	44.8	0.66	1.94
7	45	10.2	28.0	1115	54.7	47.5	0.67	2.08
8	50	11.12	31.5	1258	58.9	49.8	0.68	2.22
9	55	11.68	34.3	1376	62.1	51.5	0.66	2.29
10	60	12.1	37.2	1501	64.5	51.8	0.65	2.38

The inside diameter of the carbon tube is 0.125 inches.

The voltage was measured across the center five inches of the carbon tube.

TABLE 13

Run Number 86 - 2/7/48

Experimental and Calculated Data on the Film Boiling of n-Pentane from a 0.468-Inch Outside Diameter Carbon Tube

Point No	Amps	Volts*	t_i mv	Δt °F	h Btu/(hr)(sq ft)(°F)	h_{co} Btu/(hr)(sq ft)(°F)	Const	$\frac{\Delta t\ c_p}{\lambda'\ Pr}$
1	70	5.45	18.02	676	37.7	34.2	0.66	1.57
2	60	4.72	14.6	540	35.1	32.5	0.66	1.34
3	80	6.0	21.5	812	39.5	35.1	0.67	1.74
4	90	6.68	24.45	924	43.5	38.1	0.67	1.89
5	100	7.42	27.85	1055	46.9	40.2	0.68	2.03
6	110	7.88	31.10	1181	49.1	41.1	0.67	2.14
7	120	8.33	33.85	1290	51.8	42.3	0.66	2.23
8	130	8.77	36.6	1400	54.4	43.3	0.66	2.31
9	140	9.15	38.7	1481	57.9	46.1	0.68	2.37
10	150	9.34	40.1	1536	61.0	47.6	0.69	2.40
11	70	4.83	16.37	610	37.0	34.1	0.67	1.46

The inside diameter of the carbon tube is 0.128 inches.

*The voltage was measured across the center five inches of the carbon tube.

TABLE 14

Run Number 92 - 2/13/48

Experimental and Calculated Data on the Film Boiling of n-Pentane from a 0.352-Inch Outside Diameter Carbon Tube*

Point No	Amps	Volts**	t_i mv	Δt °F	h Btu/(hr)(sq ft)(°F)	h_{co} Btu/(hr)(sq ft)(°F)	Const	$\frac{\Delta t\ c_p}{\lambda'\ Pr}$
1	70	5.2	19.85	764	42.5	37.2	0.65	1.68
2	60	4.58	16.10	612	39.9	36.9	0.68	1.46
3	50	3.85	12.75	477	35.9	33.6	0.64	1.24
4	45	3.55	11.22	415	34.3	32.3	0.62	1.11
5	40	3.21	9.45	339	33.8	32.1	0.63	0.95
6	37.5	3.00	8.55	301	33.2	31.7	0.62	0.86

The inside diameter of the carbon tube is 0.125 inches. The minimum critical heat flux occurs when there is about 36 amperes through the tube.

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*The tube used here was of special design[3] such as to allow investigation of the stable film boiling range down to the minimum critical heat flux.

**The voltage was measured across the center five inches of the carbon tube.

TABLE 15

Run Number 93A - 2/15/48

Experimental and Calculated Data on the Film Boiling of n-Pentane from a 0.352-Inch Outside Diameter Carbon Tube*

Point No	Amps	Volts	t_i mV	Δt °F	h Btu/(hr)(sq ft)(°F)	h_{co} Btu/(hr)(sq ft)(°F)	Const	$\frac{\Delta t\, c_p}{\lambda'}$ Pr
1	50	3.95	13.10	492	35.7	33.4	0.63	1.26

* This run was the same as run number 92 except that the level of the pentane was lowered until only about 5/6 of the tube was covered with liquid.

** The voltage was measured across the center five inches of the carbon tube.

TABLE 16

Run Number 94 - 3/12/48

Experimental and Calculated Data on the Film Boiling of n-Pentane from a 0.188-Inch Outside Diameter Stainless Steel Tube

Point No	Amps	Volts *	t_i mv	Δt °F	h	h_{co}	Const	$\frac{\Delta t \, c_p}{\lambda' \, Pr}$
					$\frac{\text{Btu}}{(\text{hr})(\text{sq ft})(^\circ\text{F})}$			
1	110	1.9	18.35	730	47.6	45.1	0.68	1.64
2	100	1.6	15.7	618	43.1	41.4	0.64	1.47
3	90	1.4	12.8	494	42.4	41.4	0.67	1.27
4	110	1.8	17.8	707	46.5	44.2	0.67	1.60
5	120	2.05	20.4	815	50.1	46.9	0.69	1.76
6	130	2.35	23.7	952	53.3	48.6	0.68	1.90
7	140	2.50	27.2	1099	52.8	46.0	0.62	2.06

The inside diameter of the carbon tube is 0.143 inches. The tube was highly polished to start with but soon after film boiling set in and the tube held at red heat for a few minutes the surface became quite dark. Its emissivity was estimated therefore to be about 0.7.

*The voltage was measured across the center five inches of the stainless steel tube.

TABLE 17

Calculated Data on the Film Boiling of Mercury at a Pressure of One Atmosphere from a 0.352-Inch Outside Diameter Tube

Δt °F	h_{co} $\frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
100	28.3
200	24.0
300	22.0
500	20.0
1000	17.9
1500	16.9
2000	16.5

In the calculation of h_{co}, a value of 0.62 was used as the constant in equation (26).

TABLE 18

Data of Pilling and Lynch[19] on the Quenching of a Hot 0.25-Inch Outside Diameter Nicket Alloy Rod in Water at 98°C

Point No	ti °C	$\frac{dt}{d\theta}$ $\frac{°C}{sec}$	c_p rod $\frac{Btu}{lb\ °F}$	Δt °F	h $\frac{Btu}{hr\ ft^2\ °F}$	h_{co}	Const	$\frac{\Delta t\ c_p}{\lambda'\ Pr}$
1	500	14.5	0.131	720	40	36	0.59	0.32
2	600	19	0.133	900	43	38	0.61	0.40
3	700	24	0.134	1080	46	39	0.61	0.49

The composition of the rod was 95 per cent nickel and five per cent silicon. The weight of the rod was 11.6 grams. The length of the rod was fifty millimeters. The emissivity was taken to be 0.6. The original temperature of the rod was 830 °C. The water was open to the atmosphere.

TABLE 19

Data of Pilling and Lynch[19] on the Quenching of a Hot 0.25-Inch Outside Diameter Nickel Alloy Rod in a Two Per Cent Soap Solution at 98°C

Point No	t_i °C	$\frac{dt}{d\theta}$ $\frac{°C}{sec}$	c_p rod $\frac{\text{Btu}}{\text{lb °F}}$	Δt °F	h $\frac{\text{Btu}}{\text{hr ft}^2\ °\text{F}}$	h_{co}	Const	$\frac{\Delta t}{\lambda'}\frac{c_p}{\text{Pr}}$
1	700	21	0.134	1080	40	33	0.53	0.49
2	600	19	0.133	900	43	38	0.61	0.40
3	500	14	0.131	720	39	35	0.57	0.32
4	400	10	0.129	540	36	33	0.54	0.25
5	300	10	0.127	360	53	51	0.78	0.17

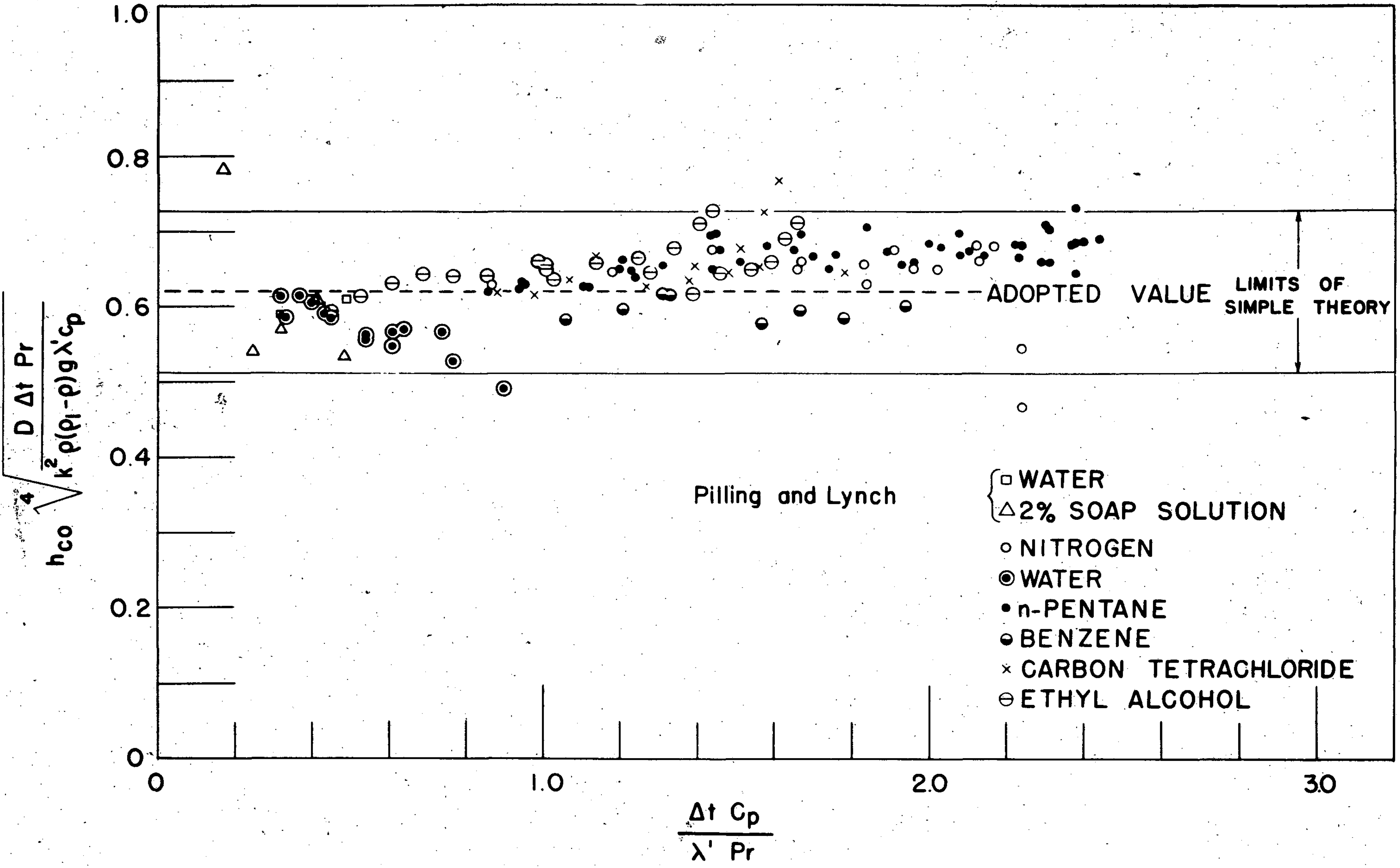
The rod is the same as that described in Table 20. About two per cent of Ivory soap was dissolved in hot water for the soap solution. Its analysis was 1.85 per cent total solids and 1.47 per cent true soap. In the calculation of the "constant" the physical properties used were taken to be the same as those of pure water.

Results

Figure 5 is a plot of the experimental values of the "constant" in equation (26), as given in tables (1) through (21), against the parameter $\Delta t\ c_p/\lambda'\ Pr$. It can be seen that there is perhaps a slight trend of the "constant" with $\Delta t\ c_p/\lambda'\ Pr$ but it is certainly not conclusive and in fact it is to be noted that the data for each liquid which were taken at the smallest temperature differences lie almost on a straight line at the adopted value of the "constant" of 0.62 ± 0.04. This tends to indicate that at least for the range of liquids chosen there is no trend of the "constant" with the physical characteristics of the liquid, other than with density which occurs in equation (26). These liquids do not, however, cover a wide range of viscosity and it is still possible that a very viscous liquid would give a value of the "constant" below 0.62 (but not below 0.52).

These values at the lowest temperature differences are the most accurate because the physical constants are known better here than at high temperatures. The radiation term is also less important at the lower temperature of the tube and since the emissivity of the tubes is only estimated from other workers data, the value of the "constant" will be more accurate at the lower values of the temperature difference. For these several reasons the low temperature data were given the most weight in the determination of the adopted value of the "constant". Equation (26) then becomes:

$$h_{co} = 0.62 \left(\frac{k^2 \rho (\rho_l - \rho)\ g\ \lambda'\ c_p}{D\ \ \Delta t\ Pr}\right)^{1/4}. \qquad (45)$$



EVALUATION OF "CONSTANT" IN CONVECTION EQUATION 26

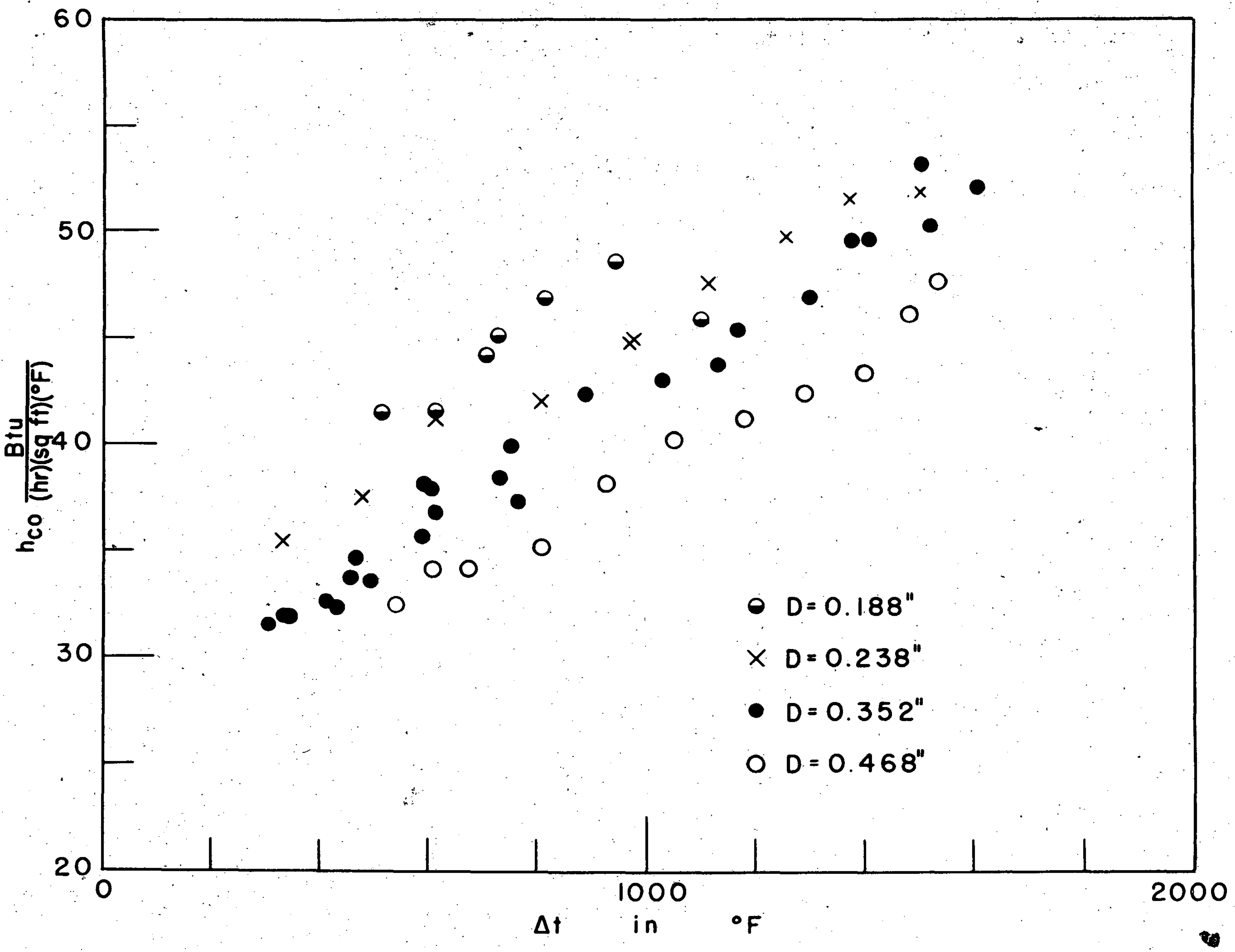
FIG. 5

The effect of the tube diameter on the coefficient of heat transfer is shown clearly in Figure 6. This indicates that a decrease in tube diameter, other things being equal, results in an increase in the coefficient of heat transfer.

Equations (26) or (45) would predict that the coefficient of heat transfer, h_{co}, should vary inversely as the one-fourth power of the diameter. Figure 7 shows that within the limit of experimental error this is certainly the case.

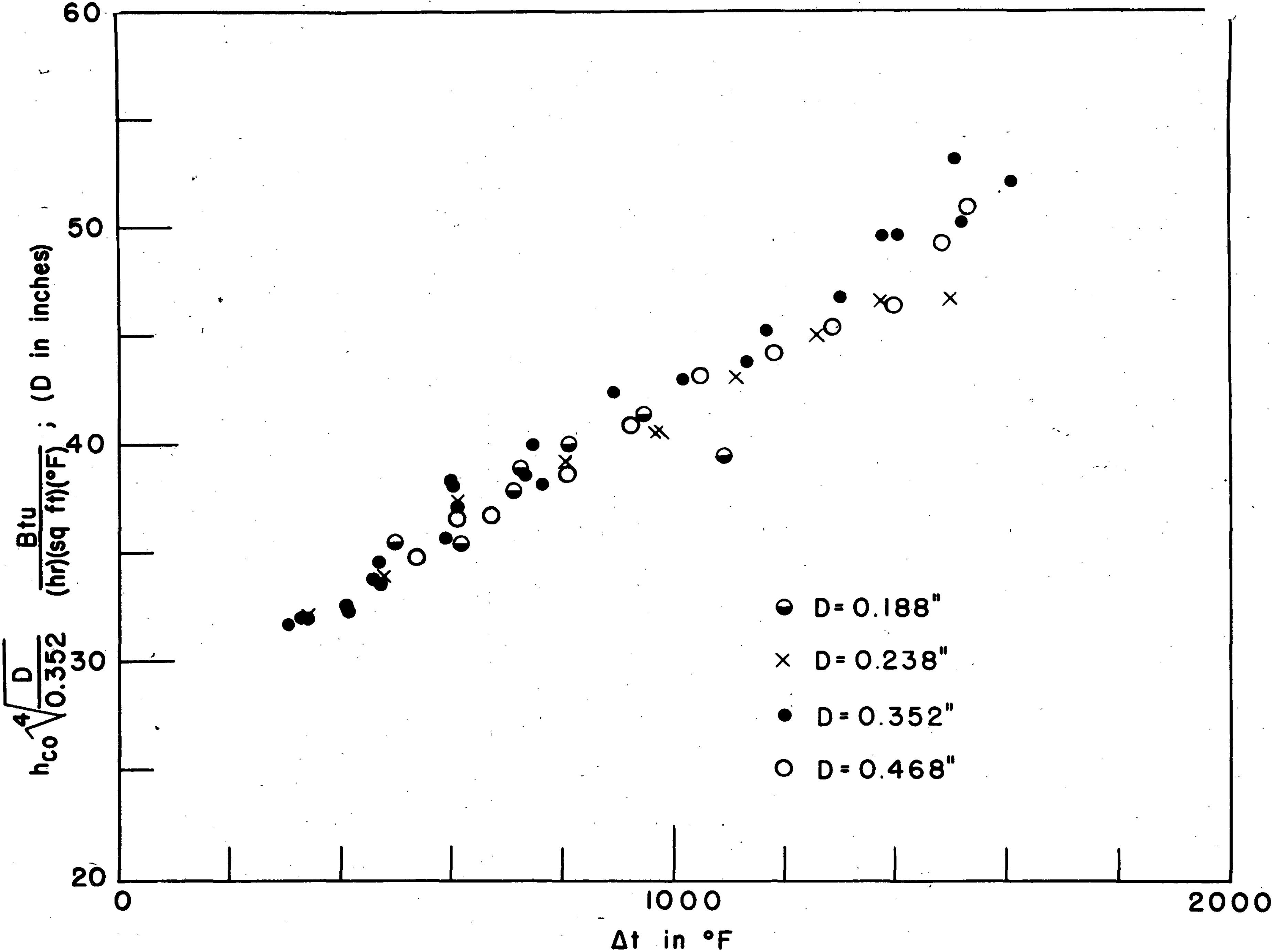
The data for the stainless steel tube fits on the same curve as the carbon tube and also the data of Pilling and Lynch[19] on a nickel rod, Table 18, check equation (45). From this it is apparent that the physical or chemical character of the tube or tube surface has little or no effect as long as it is fairly round and smooth. This is what the theory predicts.

It might be expected that the shape of the containing vessel or the depth of emersion of the tube would be at least somewhat important. The latter effect was checked in run 93A, Table 15, in which the liquid level which was normally at least one inch above the tube was lowered until the tube was about one-sixth exposed. In this case there was no bubble formation but the rising vapor merely escaped directly into the vapor phase. This caused but little disturbance of the liquid. It will be seen that the coefficient for this run is the same as that when the tube is covered. This tends to indicate that convection currents set up in the liquid by the rising bubbles do not substantially increase the heat transfer coefficient. It is realized that the evidence is as yet too meagre to be conclusive on this point and indeed, if



FILM BOILING OF n-PENTANE

FIG. 6



FILM BOILING OF n-PENTANE

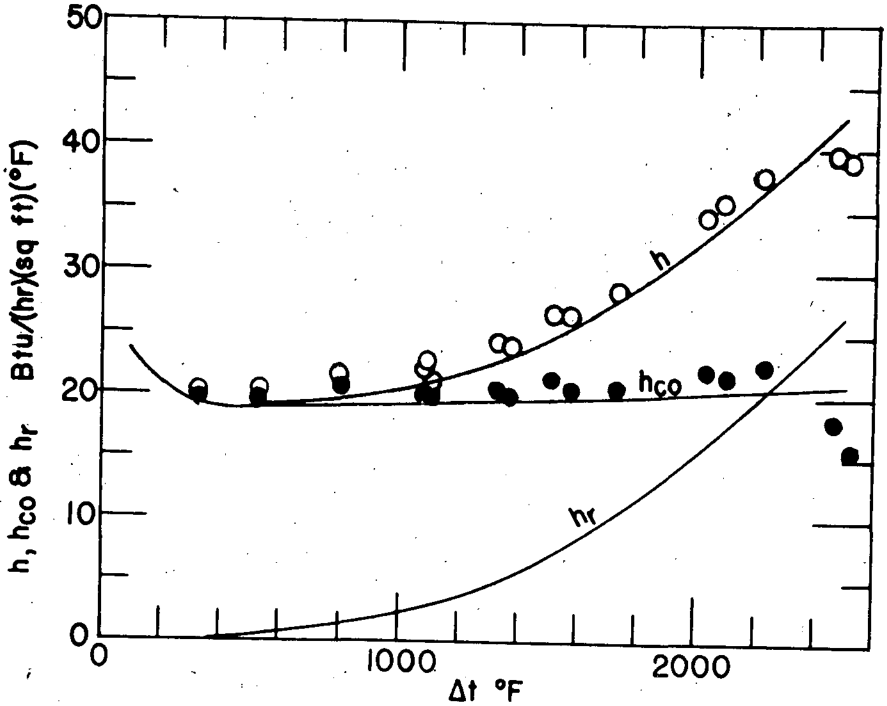
FIG. 7

several tubes were located above or near each other there might be an appreciable effect on the heat transfer.

Figure 8 is a plot of the coefficients of heat transfer in film boiling from a heated 0.350-inch outside diameter horizontal carbon tube to liquid nitrogen. The lowest curve is the calculated coefficient of heat transfer by radiation alone using a value of 0.8 for the emissivity of carbon. The intermediate curve is the calculated coefficient of heat transfer, h_{co}, from equation (45). This is the coefficient of heat transfer which would be expected if there were no radiation. The upper curve is the calculated coefficient of heat transfer using equation (41); this includes both the contribution of radiation and convection. It may be seen that the experimentally measured values of h, represented by the open circles, agree fairly well with the calculated coefficients. The solid points are the experimental values of h_{co} calculated from the measured values of h, using equation (41). Equation (43) might just as well have been used since it is numerically equivalent to equation (41).

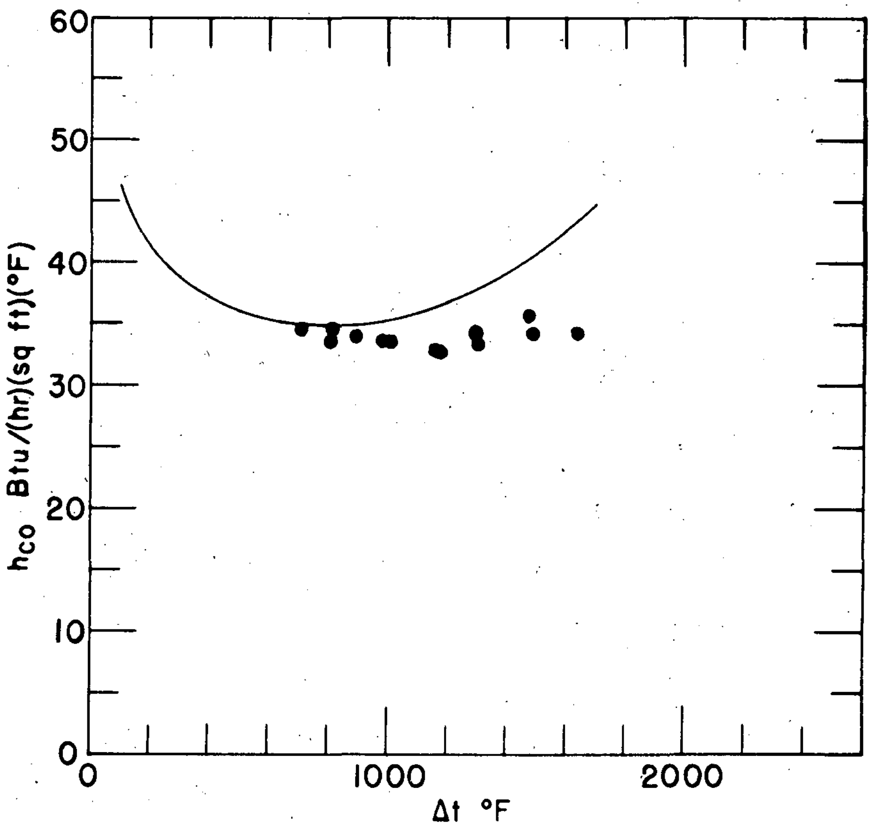
Since a plot of h_{co} against Δt is of perhaps more value than one of h against Δt, figures 9 through 15 include only the former. The curves are the calculated values and the points are the experimented values. It is felt that the measured points are in all cases of higher accuracy than the calculated curves because of the uncertainty in the physical properties of the liquid, its vapor and the tube.

For simplified calculations for the liquids studied the curves in figures 8 through 15 may be used to estimate heat

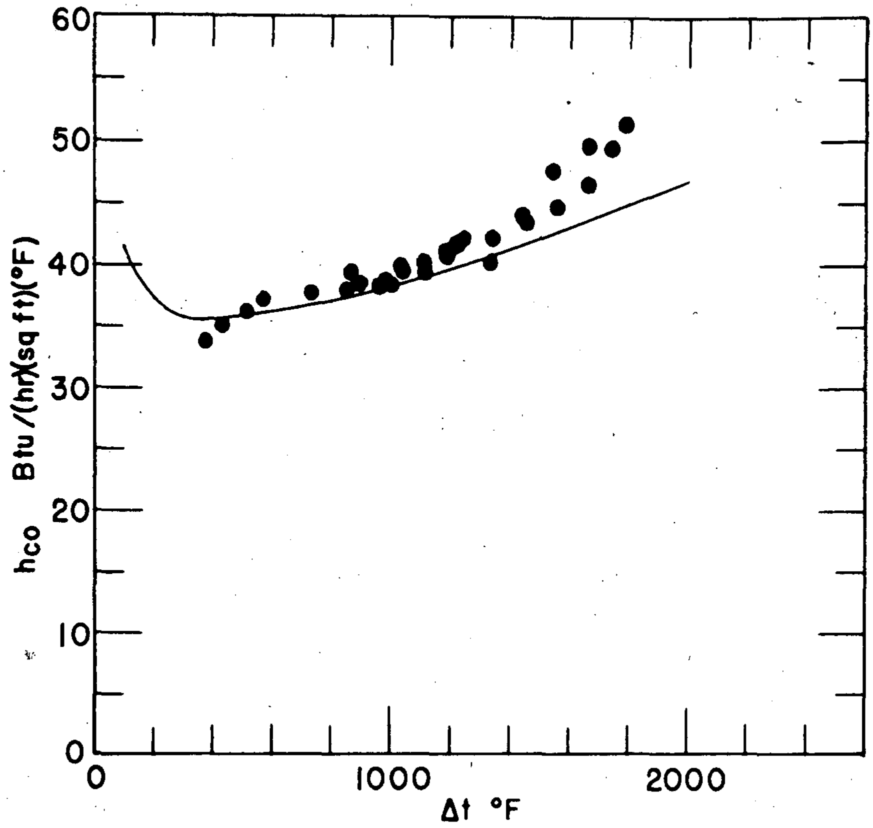


Film Boiling of Nitrogen from 0.350" Carbon Tube

FIG. 8

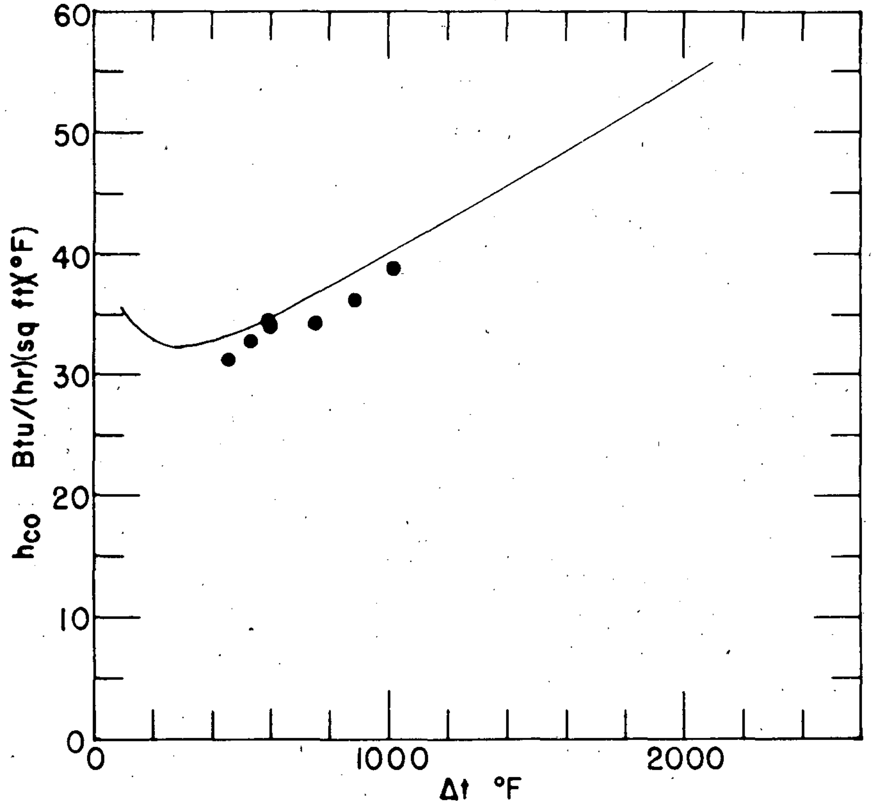


Film Boiling of Water from 0.351" Carbon Tube

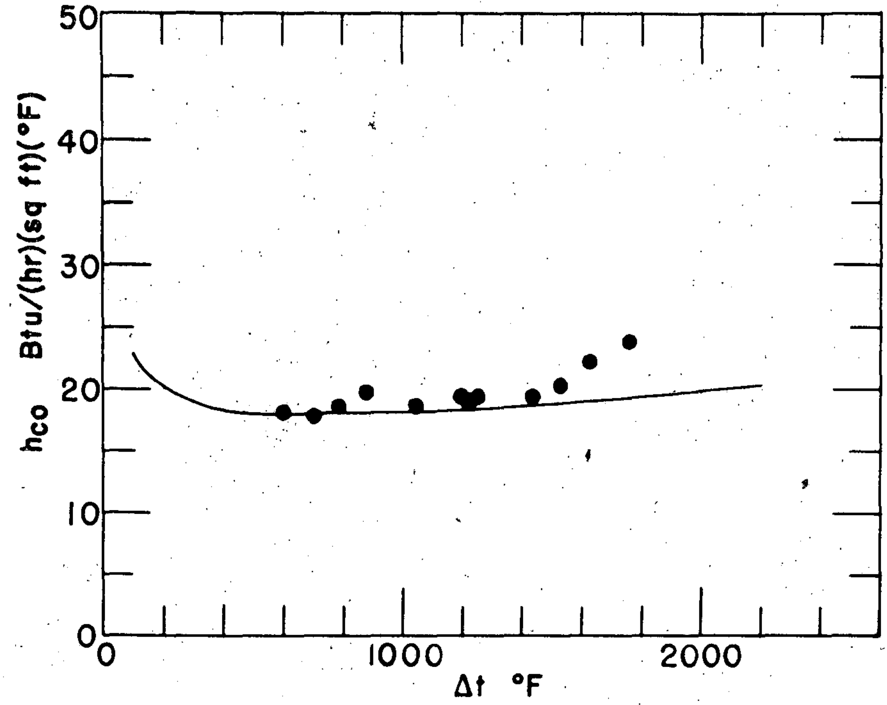


Film Boiling of Ethyl Alcohol from
0.352" Carbon Tube

FIG. 10

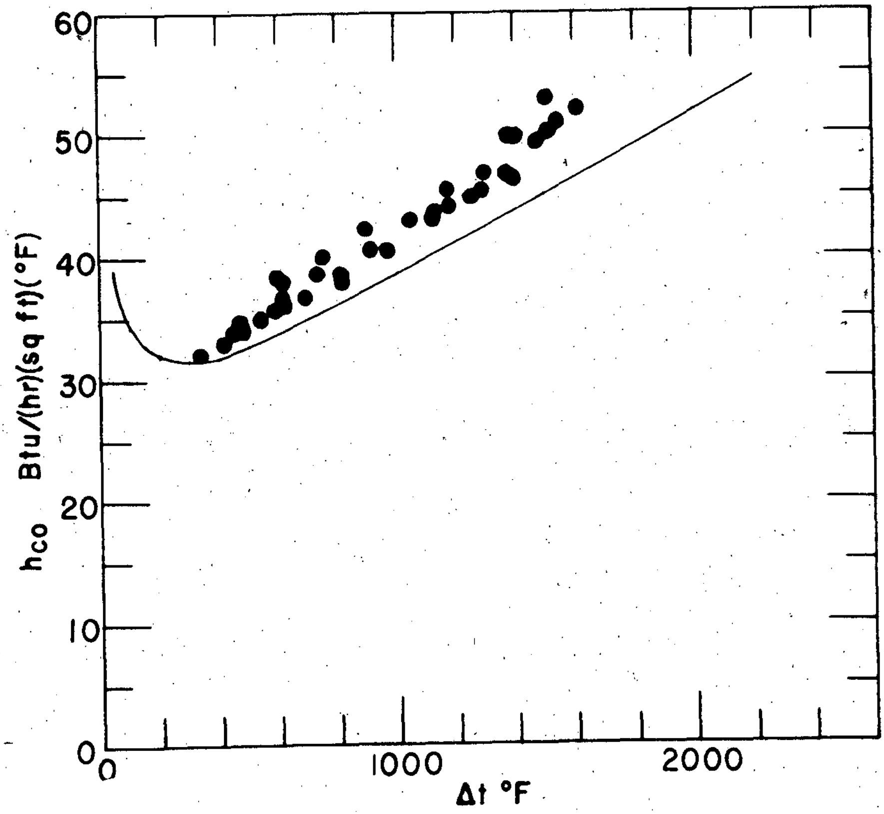


Film Boiling of Benzene from



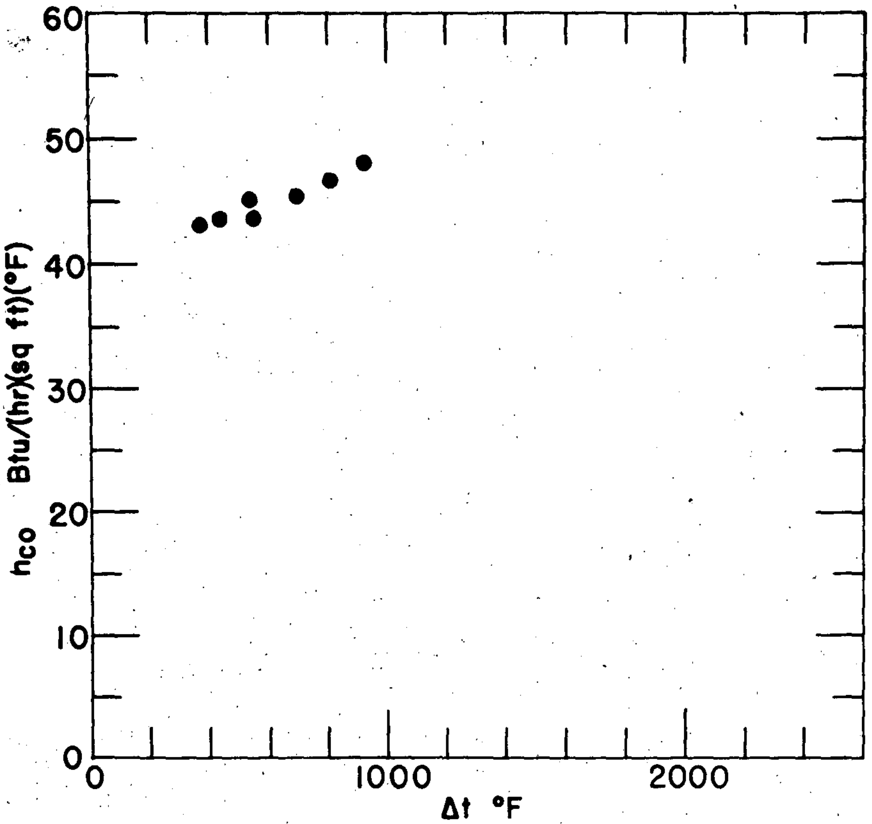
FILM BOILING OF CARBON TETRACHLORIDE FROM
0.352" CARBON TUBE

FIG. 12



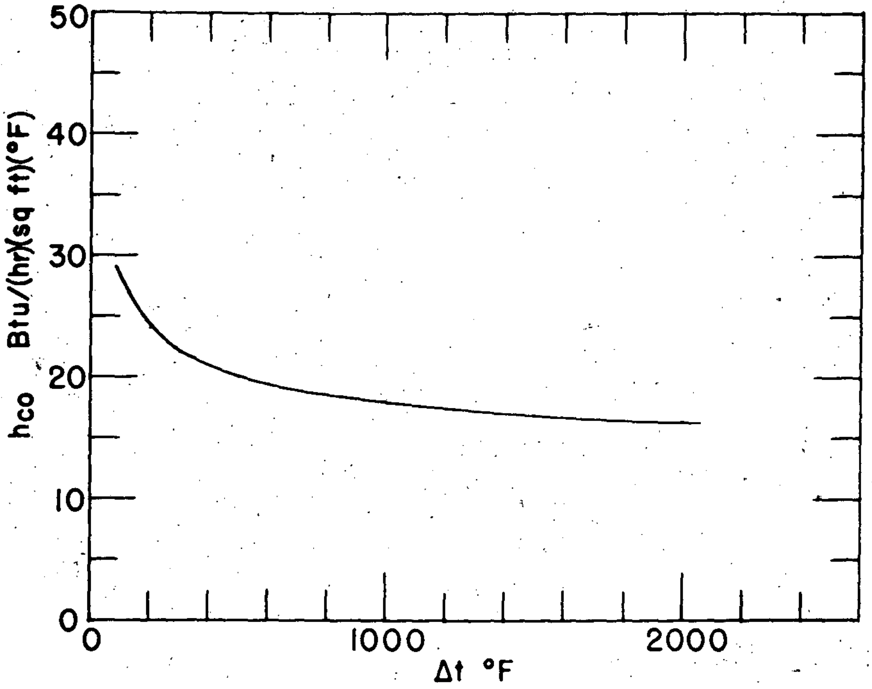
FILM BOILING OF n-PENTANE FROM
0.352" CARBON TUBE

FIG. 13



FILM BOILING OF DIPHENYL ETHER FROM
0.352" CARBON TUBE

FIG. 14



FILM BOILING OF MERCURY FROM
0.352" CARBON TUBE

FIG. 15

transfer coefficients for the same liquid boiling at one atmosphere from tubes of other diameters. The necessary relationship is:

$$h_{co} = h_{co(D = 0.35")} \left(\frac{0.35"}{D_{inch}}\right)^{1/4} \qquad (46)$$

which may be directly derived from equation (45).

h_{co} is the unknown heat transfer coefficient if there were no radiation. This is for stable film boiling from a horizontal tube.

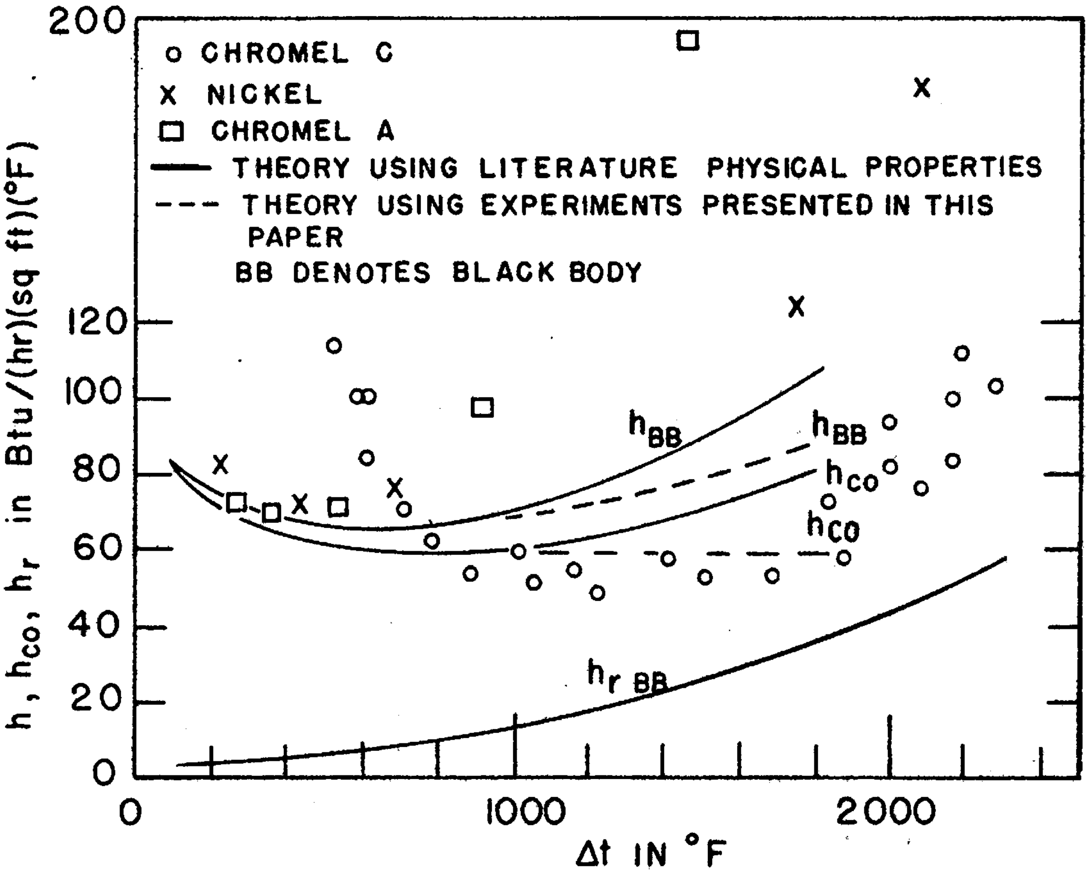
$h_{co(D= 0.35")}$ is the measured or calculated value of the heat transfer coefficient from a 0.35 inch tube.

D_{inch} is the outside diameter of the tube under consideration expressed in inches.

The heat transfer coefficient, h, is calculated from equation (43) or (42) by use of equation (44).

No concerted effort was made to determine the minimum critical heat flux or the critical temperature difference in the film boiling. Run 92, Table 14, was made from a carbon tube designed[3] to operate down to the minimum critical heat flux in film boiling. The data of Pilling and Lynch[19], Tables 18 and 19 indicate clearly that it is possible to go to much lower values of the temperature of the tube in film boiling when soap is dissolved in the water. This indicates that a decrease in surface tension of the liquid lowers the minimum critical heat flux and the temperature corresponding to this heat flux.

Figure 16 is a comparison of the theory presented here with the recent data of Farber and Scorah[7a] on the boiling



COMPARISON OF THE DATA OF FARBER AND SCORAH WITH THE THEORY PRESENTED IN THIS PAPER FOR THE BOILING OF WATER FROM A 0.040" HORIZONTAL WIRE.

Figure 16

of water from a 0.040 inch horizontal wire. The solid curve labelled h_{co} is the calculated heat transfer coefficient if there were no radiation, using the physical properties of water from the literature. The solid curve labelled h_{BB} is the calculated curve assuming that the wire was a black body. The true emissivity of the wires is unknown. The dashed curves were obtained from the data in Figure 9 by use of equation 46 and hence should be of higher order of accuracy. It can be seen that although the agreement is not as good as might be hoped for it is certainly qualitatively correct when there is stable film boiling. As was pointed out in the discussion following the paper of Farber and Scorah there are several chances for rather serious error in their measurements especially in temperature. However they must certainly be of the correct order of magnitude and hence give some additional confirmation to the theory presented here. It is of interest that the theory holds as well as it does at this small a wire size.

Very recent data of McAdams, Addoms, Rinaldo and Day[12a] on film boiling of water from platinum wires of from 0.004 to 0.024 inches diameter indicate that the theory is not accurate within this range of wire size, the error ranging from about 30% to 100% as size of wire is decreased from 0.024 to 0.004 inches. McAdams et al[12a] report that the flux was inversely proportioned to the square root of the diameter of the wire, whereas at larger wire sizes it is proportional to the one quarter power. Qualitatively, this should be expected from the assumptions made in the simple theory. It thus appears that the developed theory is fairly accurate for wire sizes down to 0.040" but not much below this figure.

Conclusions

By the use of equations (45) or (26), (44) and (43), which are derived from a few simple premises and well verified by extensive experimental data, it is possible to calculate coefficients of heat transfer to be expected in natural convection stable film boiling from a horizontal tube. If the amount of heat transferred by radiation is not over half the total heat transferred, i.e. the temperature of the tube is not too high, the simplified equation (42) may be used in place of equation (43). The amount of heat transferred per unit time may then be calculated by equation (1).

For simplified calculations for the liquids studied the experimental points or calculated curves in Figures 11 through 18 may be used together with equation (46) to estimate heat transfer coefficients in film boiling for the given liquid from tubes of other diameters.

It is to be noted that this theory gives the heat transfer coefficients in stable film boiling from the outside of a horizontal tube when the liquid surrounding the hot tube is at its boiling point under the pressure prevailing in the system. As was mentioned in the section "Previous Work on Film Boiling", when there is either metastable film boiling or stable film boiling with the bulk of the liquid below its boiling point, the coefficient of heat transfer is higher than would be calculated by this theory. The theory is restricted to tubes of such a diameter that the thickness of the film is small compared to the diameter of the tube, although it appears to hold fairly well down to tubes of 0.040 inches diameter.

The method employed for the derivation which may be found in the section "Theory" may be applied to derive equations for heat transfer coefficients to be expected in film boiling from any other shape.

Equation (36), page 28, results from the application of the method to the case of film boiling from a vertical tube or vertical plane surface.

Nomenclature and Suggested Units

Symbol	Definition	Units
A	heat transfer area	ft^2
a	thickness of film	ft
b	constant	
c_p	specific heat of vapor at constant pressure	Btu/(lb)(°F)
D	outside diameter of tube	ft
d	differential operator	
F	friction loss	(ft)(lb force)/(lb mass)
f	function	
g	acceleration of gravity	ft/hr^2
g_c	gravitational constant, 4.17 x 10^8	(lb mass)(ft)/(lb force)(hr^2)
h	film coefficient of heat transfer	Btu/(hr)(ft^2)(°F)
h_c	convection coefficient of heat transfer, see equation (37)	Btu/(hr)(ft^2)(°F)
h_{co}	film coefficient of heat transfer if there were no radiation	Btu/(hr)(ft^2)(°F)
h'_{co}	local value of h_{co} at a point on the tube	Btu/(hr)(ft^2)(°F)
h_r	radiation coefficient of heat transfer, see equation (44)	Btu/(hr)(ft^2)(°F)
k	thermal conductivity	Btu/(hr)(ft)(°F)
L	length of tube	ft
ln	logarithm	
ℓ	subscript denoting liquid	
mv	millivolts	

Symbol	Definition	Units
P	Pressure	lb force/ft^2
P_o	pressure at θ equals 90°	
Pr	Prandtl number, see equation (25)	
q	heat flow	Btu/hr
R	outside radius of tube	ft
R_i	inside radius of tube	ft
r	radius of tube between R_i and R	ft
T	temperature	°R
t	temperature	°F
Δt	temperature difference between hot surface and liquid at its boiling point	°F
t_b	temperature at which the liquid boils	°F
t_i	temperature of the inside of the tube	°F
V	velocity	ft/hr
W	weight evaporated on entire tube	lb mass/hr
W	heat generated per unit volume in rod	Btu/(ft^3)(hr)
w	weight evaporated up to any angle θ	lb mass/hr
x	height above datum plane	ft
	denotes proportionality	
	absorptivity of liquid	

Symbol	Definition	Units
β	constant, see equation (13)	
Δ	finite difference	
	emissivity of hot tube	
θ	angle measured from the bottom of the tube	
λ	latent heat of vaporization at boiling point	Btu/lb mass
λ'	difference in heat content between vapor at its average temperature and the liquid at its boiling point, see equation (5)	Btu/lb mass
μ	viscosity of vapor	lb mass/(hr)(ft)
π	3.1416	
ρ	density of vapor	lb mass/ft^3
ρ_l	density of liquid	lb mass/ft^3
σ	Stefan-Boltzman constant, 0.1713 x 10^{-8}	Btu/(hr)(ft^2)(°R)^4

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