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FILM BOILING OF FLOWING SUBCOOLED LIQUIDS

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FILM BOILING OF FLOWING SUBCOOLED LIQUIDS

Eugene Izoard Motte

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(Thesis)

Master of Science
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FILM BOILING OF FLOWING SUBCOOLED LIQUIDS

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ABSTRACT

Heat transfer coefficients across the vapor film were evaluated from the rates of heat transfer in upward flow forced convection from outside single horizontal tubes to four liquid systems: ethyl alcohol, benzene, hexane and carbon tetrachloride. These heat transfer coefficients were found to be markedly increased by subcooling the liquids.

It has previously been shown that, since the vapor film is in laminar flow in forced convection film boiling, heat is transferred across the vapor film by conduction and radiation. In this study it has been further shown that, if the liquid is subcooled, heat is transferred from the vapor liquid interface into the liquid by eddy conduction and the effect of thermal conduction is negligible.

Correlation of the data for the four liquid systems investigated was found possible by use of the theoretical parameters

$$h_{co}\sqrt{\frac{D\ \Delta t_o}{Uk_v\rho_v\lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{Uk_v\rho_v\lambda'}{D\ \Delta t_o}}$$

and

$$\Delta t_{sc}\ Cp_l\ \rho_l\sqrt{\frac{\varepsilon}{\Delta t_o\ k_v\ \rho_v\lambda'}}$$

where h_{co} is the heat transfer coefficient across the vapor film if there were no radiation. D is the diameter of the tube, Δt_o is the temperature difference across the vapor film, U is the velocity of

the liquid, Δt_{sc} is the amount of subcooling of the liquid, and ε is the eddy conductivity. The physical properties k_v, ρ_v, λ', Cp_l, and ρ_l are respectively the vapor thermal conductivity, the vapor density, the effective heat of vaporization, the liquid heat capacity, and the liquid density.

INTRODUCTION

There are two distinct types of boiling phenomena: nucleate and film boiling. Nucleate boiling, where the vapor originates from individual points on the heated surface, is the type of boiling usually preferred due to the high heat transfer coefficients and low temperature difference between the heated surface and the boiling liquid as compared to film boiling. Film boiling is that type of boiling where the heated surface is separated from the liquid by a continuous vapor film.

It has only been in recent years that there has been a need for information concerning film boiling. Since nucleate boiling is the most common type encountered in practice, considerable work has been done on that problem. However, with the development of new high-temperature processes and high-temperature equipment for power producing units, the interest in film boiling has increased. The selection of suitable quenching agents for the heat treatment of metals also depends somewhat on the rate of heat transfer in film boiling. Perhaps the greatest need for a film boiling theory will come as exploration into industrially applied atomic energy continues.

Previous to 1948, most of the work on film boiling had been done on particular liquids under special conditions. It was at this time that L. A. Bromley[1] presented the first sound theoretical development on film boiling. The equations resulting from this theory enable one to predict heat transfer coefficients for natural convection film boiling of any liquid when it is at its boiling point. Bromley experimentally measured the heat transfer coefficients of several liquids from the outside of horizontal carbon and steel tubes. He also made an extensive survey of previous work on film boiling and verified the theoretical correlation with these data.

J. T. Banchero, G. E. Barker and R. H. Boll[2] have recently investigated film boiling of liquid oxygen outside single tubes and wires over a wide range of temperatures and pressures. This work reported the correlation suggested by Bromley to predict correctly the effects of temperature and pressure.

In 1950, L. A. Bromley, N. R. LeRoy and J. A. Robbers[3] proposed a theory for forced convection film boiling of saturated liquids. The prediction of heat transfer coefficients to any liquid was found possible through the use of two pairs of equations developed from this theory. At values of $U/\sqrt{gD}$ less than one, where U is the velocity, g is the gravitational constant, and D is the outside diameter of the tube, heat transfer coefficients were found to be predicted by the correlation proposed by Bromley[1] for free convection film boiling.

$$h = h_{co} + 3/4\ h_r$$

$$h_{co} = 0.62 \sqrt[4]{\frac{k_v^3\ (\rho_1 - \rho_v)\ \rho_v g \lambda'}{D\ \Delta t_o\ \mu_v}}$$

where h is the heat transfer coefficient for film boiling, h_{co} is the heat transfer coefficient for convection if there were no radiation, h_r is the heat transfer coefficient for radiation, D is the diameter of the tube, Δt_o is the temperature difference across the vapor film, μ_v is the viscosity of the vapor, k_v is the conductivity of the vapor, λ' is the effective difference in heat content between the vapor at its average temperature and the liquid at its boiling point.

At values of $U/\sqrt{gD}$ greater than two, the heat transfer coefficients were predicted by[3]

$$h = h_{co} + 7/8\ h_r$$

$$h_{co} = 2.7 \sqrt{\frac{U k_v \rho_v \lambda'}{D\ \Delta t_o}}$$

This work also includes a description of the vapor film in both natural and forced convection film boiling.

Y. Nakagawa and T. Yoshida[4] have investigated film boiling in quenching steel rods in various liquids. Heat transfer coefficients were determined from the cooling curves and correlated in the empirical dimensionless equation,

$$Nu = 4.07 \times 10^5 \left(\frac{\sigma}{\rho_l r^2}\right)^{1.275} - (Pr)^{-0.33} \left(\frac{\Delta t_o}{\Delta t_{sc}}\right)^{-2.466}$$

where Nu is the Nusselt number for the vapor, σ_l is the surface tension of the liquid, ρ_l is the density of the liquid, r is the radius of the rod, Pr is the Prandtl number of the vapor, Δt_o is the temperature difference between the rod and the boiling liquid, and Δt_{sc} is the temperature difference between the boiling liquid and the subcooled liquid.

Since heat is transferred across the vapor film by conduction in forced convection film boiling, the heat transfer coefficients increase with velocity due to the decrease in the thickness of the vapor film. If the liquid is below its boiling point, some heat will be transferred from the vapor-liquid interface, which is at the boiling point, into the bulk of the liquid. Since this heat will not be available for vaporization of the liquid, the vapor film thickness will be less if the liquid is subcooled, which will result in a larger heat transfer coefficient. It is the purpose of this study to develop a theory to predict the heat transfer coefficients to be expected in forced convection film boiling from a horizontal tube to subcooled liquids, and to verify experimentally the resulting expressions.

FILM BOILING THEORY

Mathematical relationships will be developed which should enable one to calculate the heat transfer coefficients to be expected in upward flow forced convection to subcooled liquids outside a horizontal tube. Heat is transferred through the vapor film by conduction and radiation since it has been shown[2] that the vapor film is in laminar flow. It is assumed that no heat is conducted along the tube. Since most of the heat is transferred across the film on the bottom half of the tube, the theory will be developed to fit the mechanism on this part of the tube.

Figure 1 shows the tube immersed in a body of fluid which is moving upward at a uniform velocity of U. If q_o is the rate of heat transfer from the heated surface by conduction, then

$$q_o = q_v - q_l \qquad (1)$$

where q_v is the heat flow into the vapor stream and q_l is the heat flow into the liquid stream. Heat transferred by radiation will only affect q_v since q_l is constant for any liquid at set values of the velocity and the amount of subcooling of the liquid below the boiling point. The correction of the measured heat transfer coefficient across the vapor film for radiation may be found on Page 116.

$$q_o = h_{co} A \Delta t_o \qquad (2)$$

where h_{co} is the heat transfer coefficient across the vapor film if there were no radiation, A is the area of the horizontal tube over which heat is transferred, and Δt_o is the temperature difference between the heated surface and the boiling liquid, that is, across the vapor film.

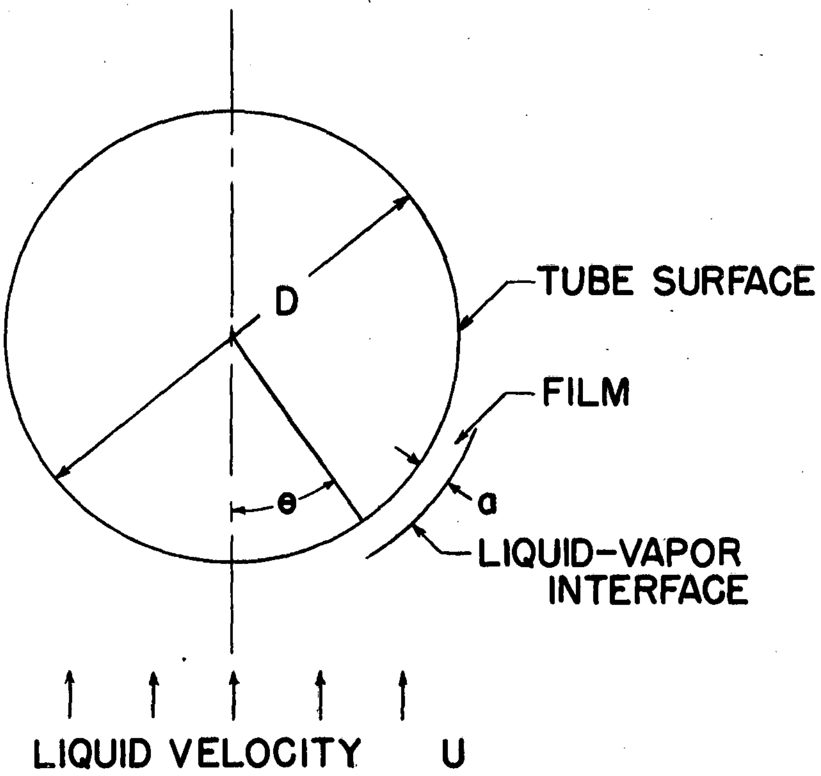

FIG. 1

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Fig. 1

Substituting equation (2) into equation (1) and dividing through by the area, we obtain the following equation:

$$h_{co} \quad \Delta t_o - \frac{q_v}{A} = \frac{q_l}{A} . \tag{3}$$

Multiplying both sides of equation (3) by $\sqrt[4]{\dfrac{D^2\mu_v}{U^2 k_v{}^3 \rho_v \rho_l \lambda' \Delta t_o{}^3}}$, equation (3) becomes

$$h_{co} \sqrt[4]{\frac{D^2 \Delta t_o \mu_v}{U^2 \; k_v{}^3 \rho_v \rho_l \lambda'}} - \frac{q_v}{A} \sqrt[4]{\frac{D^2\mu_v}{U^2 k_v^3 \rho_v \rho_l \lambda' \Delta t_o^3}} = \frac{q_l}{A} \sqrt[4]{\frac{D^2\mu_v}{U^2 k_v^3 \rho_v \rho_l \lambda' \Delta t_o^3}} \tag{4}$$

where D is the diameter of the tube, μ_v is the vapor viscosity, k_v is the vapor thermal conductivity, ρ_v is the vapor density, ρ_l is the liquid density, and λ' is the effective heat content of the vapor film in excess of the heat content of the boiling liquid.

When the liquid is not subcooled below its boiling point, the heat absorbed by the liquid, q_l, is zero. It has been shown[3] for forced convection film boiling to liquids which are not subcooled that

$$h_{co} \sqrt[4]{\frac{D^2 \Delta t_o \mu_v}{U^2 \; k_v^3 \rho_v \rho_l \lambda'}} = 0.88 \left[\frac{gD(\rho_l - \rho_v)}{4 \; U^2 \rho_l} + \frac{3D \; \mu_v \; h_{co}^2}{U \; k_v^2 \; \rho_l} \left(\frac{\pi}{\Theta'}\right)^2 \right]^{1/4} \tag{5}$$

where g is the gravitational constant and Θ' is the value of Θ at the separation point. The separation point is that point at which the thickness of the vapor approaches infinity compared to the normal thickness. Since the heat absorbed by the liquid, q_l, is zero, we may obtain the following equation by substituting equation (5) into equation (4):

$$\frac{q_v}{A}\sqrt[4]{\frac{D^2\mu_v}{U^2k_v^3\rho_v\rho_l\lambda'\Delta t_o^3}} = 0.88\left[\frac{gD(\rho_l-\rho_v)}{4U^2\rho_l} + \frac{3D\mu_v h_{co}^2}{U\,k_v^2\rho_l}\left(\frac{\pi}{\theta'}\right)^2\right]^{1/4} . \tag{6}$$

At the velocities encountered in forced convection film boiling, $\frac{U}{\sqrt{gD}} > 2$, the term $\frac{gD(\rho_l-\rho_v)}{4U^2\rho_l}$ may be neglected.[3]

Equation (6) then reduces to

$$\frac{q_v}{A} = 0.88\left[\frac{3\,h_{co}^2\,U\rho_v\lambda'\,\Delta t_o^3\,k_v}{D}\left(\frac{\pi}{\theta'}\right)^2\right]^{1/4} . \tag{7}$$

Since one of the premises of equation (7) is that q_v is equal to q_o, we may substitute

$$\Delta t_o = \frac{q_v}{A\,h_{co}}$$

into equation (7), which results in

$$\frac{q_v}{A} = 7.29\,\frac{U\rho_v\lambda' k_v}{h_{co}\,D} . \tag{8}$$

Since this equation for q_v can also be developed, though not entirely rigorously, by a simple heat and material balance as shown on Page 117 without implying the restriction that the liquid is not subcooled, this expression may be used for q_v at any degree of subcooling of the liquid.

Substituting equation (8) into equation (3) and multiplying through by $\sqrt{\frac{D}{\Delta t_o U k_v\rho_v\lambda'}}$, we obtain the following equation:

$$h_{co}\sqrt{\frac{D\Delta t_o}{Uk_v\rho_v\lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{D\Delta t_o}{Uk_v\rho_v\lambda'}} = \frac{q_l}{A}\sqrt{\frac{D}{\Delta t_o Uk_v\rho_v\lambda'}} . \tag{9}$$

Equation (9) reduces to the correlation proposed for forced convection film boiling of saturated liquids[3] when q_l is equal to zero.

Only the heat transfer rate from the vapor-liquid interface, q_1, remains to be determined. This heat transfer rate is dependent upon the mechanism by which heat is transferred through the liquid: either by thermal conduction or by eddy conduction.

Three cases involving these mechanisms will be solved to determine q_1.

Case 1. Heat is transferred by thermal conduction.

Case 2. Heat is transferred by eddy conduction.

Case 3. Heat is transferred by eddy conduction, but the time of contact is small compared to the ratio of the scale of turbulence to the intensity of turbulence. In this case the eddy conductivity is independent of the scale of turbulence and proportional to the time of contact multiplied by the square of the intensity of turbulence.

Since neither the surface area of the vapor-liquid interface nor the velocity distribution of the liquid around the top half of the tube can be defined, we will assume that the rate of heat transfer into the liquid from the vapor film around the top half of the tube is equal to that around the bottom half, although it is certainly smaller. The rate of heat transfer into the liquid may then be found by the following equation for conduction:

$$q_1 = 4 \int_0^{\pi/2} -\left(\frac{dT}{dx} \right) \alpha \, Cp_1 \rho_1 \, dA \, , \qquad (10)$$

where $\frac{dT}{dx}$ is the temperature gradient in the x direction, α is the thermal diffusivity, Cp_1 is the liquid heat capacity, and ρ_1 is the liquid density.

From the geometry of the system we obtain,

$$dA = \frac{D}{2} L \, d\theta \, , \qquad (11)$$

where D is the diameter of the tube, θ is the angle from the vertical, and L is the length of the tube over which the heat transfer is desired.

Since the problem is one of unsteady state heat transfer, we must solve the general unsteady state conduction equation in order to determine the temperature gradient in the x direction.

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{12}$$

where T is the temperature, t is the time of contact, and x is the radial distance from the film perpendicular to the lines of flow. This definition for x is equivalent to assuming that the liquid-vapor interface is a flat plate with liquid flowing by it.

Depending upon the mechanism by which heat is transferred,

$$\alpha = \frac{k_l}{Cp_l \rho_l} \tag{13}$$

or

$$\alpha = \varepsilon, \tag{14}$$

where k_l is the thermal conductivity of the liquid and ε is the eddy conductivity.

Case I. Thermal Conduction.

In order to solve equation (12), we must first determine the boundary conditions. At time equal to zero at any distance from the film x, the temperature T is equal to the temperature of the subcooled liquid T_l. At any time t when x equals zero, the temperature T is equal to the temperature of the vapor-liquid interface which is at the boiling point T_b. The limit of the temperature T as x approaches infinity at any time t is equal to the temperature of the subcooled liquid T_l. The boundary conditions may also be expressed as follows, Initial Condition $T_{x,o} = T_1$, (15)

Boundary Conditions $T_{o,t} = T_b$, (16)

$$\lim_{x \to \infty} T_{x,t} = T_1 . \tag{17}$$

By transforming the boundary conditions and the differential equation into the La Place domain, we obtain

Initial Condition $T_{x',o} = T_1$, (15)

Boundary Conditions $T_{o,s} = T_b/s$, (18)

$$\lim_{x' \to \infty} T_{x',s} = T_1/s , \tag{19}$$

$$\frac{\partial^2 T}{\partial x'^2} - \frac{s}{\alpha} = - \frac{T_1}{\alpha} . \tag{20}$$

Solving the reduced equation and for the particular solution, we find

$$T_{x',s} = C_1 e^{\sqrt{\frac{s}{\alpha}}\, x'} + C_2 e^{-\sqrt{\frac{s}{\alpha}}\, x'} + \frac{T_1}{s} . \tag{21}$$

Substituting equation (19) into equation (21) we find that, in order for the temperature to be finite, C_1 must be equal to zero.

Substituting equation (18) into equation (21) results in

$$C_2 = \frac{T_b - T_1}{s} . \tag{22}$$

Substituting the values for C_1 and C_2 into equation (21), the resulting equation is

$$T_{x',s} = \left(\frac{T_b - T_1}{s}\right) e^{-\sqrt{\frac{s}{\alpha}}\, x'} + \frac{T_1}{s} . \tag{23}$$

Transforming equation (23) into the time domain, we find that

$$T_{x,t} = (T_b - T_1) \operatorname{erfc} \frac{x}{2\sqrt{\alpha t}} + T_1 . \qquad (24)$$

Expanding the error function into a series and taking the derivative with respect to x, the desired temperature gradient is obtained.

$$\frac{dT}{dx} = (T_b - T_1) \left[-\frac{2}{\sqrt{\pi}} \left(\frac{1}{2\sqrt{\alpha t}} - \frac{3x^2}{3.1!8\ (\alpha t)^{3/2}} + \text{- - - -} \right) \right] . \qquad (25)$$

Substituting x equal to zero and Δt_{sc} for $T_b - T_1$, we obtain,

$$\frac{dT}{dx} = - \frac{\Delta t_{sc}}{\sqrt{\pi \alpha t}} ; \qquad (26)$$

Δt_{sc} is the amount by which the liquid is subcooled below the boiling point.

Since the velocity[3] around the tube is equal to 2U sin Θ, the time of contact can be shown to be the following:

$$t = \frac{D/2\ \Theta}{2U \sin \Theta} . \qquad (27)$$

By substituting equations (11), (26), and (27) into equation (10), we obtain the following equation:

$$q_1 = 4L \sqrt{\frac{UD}{\pi \alpha}}\ \Delta t_{sc}\ k_1 \int_0^{\pi/2} \left(\frac{\sin\Theta}{\Theta} \right)^{1/2} d\Theta . \qquad (28)$$

Substituting equation (13) into equation (28) and graphically integrating equation (28), we arrive at the following equation:

$$q_1 = \pi D L \frac{4}{\pi} \sqrt{\frac{U C p_1 \rho_1 k_1}{\pi D}}\ \Delta t_{sc}\ (0.1895) . \qquad (29)$$

Substituting A for πDL, equation (29) reduces to

$$\frac{q_1}{A} = 0.1356\ \Delta t_{sc} \sqrt{\frac{U\ C p_1 \rho_1 k_1}{D}} . \qquad (30)$$

Case 2. Eddy Conduction (Long Contact Time)

In this case the eddy conductivity is not a function of time but is dependent only upon the conditions downstream. The eddy conductivity will be assumed constant in the x direction. Since the boundary conditions are the same as for "Case 1", equation (26) will also represent the temperature gradient in this case.

$$\frac{dT}{dx} = - \frac{\Delta t_{sc}}{\sqrt{\pi \alpha t}} \; . \tag{26}$$

Assuming that the eddy conductivity is proportional to the eddy viscosity, it can be shown that for a straight conduit

$$\varepsilon = K_1 \sqrt{\frac{f}{2}} \; U_o l_o \tag{31}$$

where K_1 is a constant of proportionality, f is the Fanning friction factor, and l_o is the diameter of the conduit in which the eddy conductivity exists. The derivation of this relationship for eddy viscosity can be found on Page 130. The eddy viscosity is related to the eddy conductivity by a factor which is dependent upon the Reynold's number and the distance from the conduit wall. It has been shown for air that the eddy conductivity is greater than the eddy viscosity by a factor of 1.35 and 1.05 at the Reynold's numbers of 9,190 and 53,450 respectively in the central portion of a conduit.[5]

The friction factor f is approximately proportional to $\left(\frac{U_o l_o \rho_1}{\mu_1} \right)^{-0.2}$ for smooth pipes;[6] therefore,

$$\varepsilon = K_2 \, U_o l_o \left(\frac{U_o l_o \rho_1}{\mu_1} \right)^{-0.1} \tag{32}$$

where K_2 is now a new constant of proportionality.

By substituting equations (11), (14), (26) and (27) into equation (10), we obtain,

$$q_1 = 4L\ \Delta t_{sc}\ Cp_1 \rho_1 \sqrt{\frac{UD\varepsilon}{\pi}} \int_0^{\pi/2} \left(\frac{\sin\theta}{\theta}\right)^{1/2} d\theta \qquad (33)$$

Substituting equation (32) and graphically integrating, equation (33) becomes

$$q_1 = \pi DL \frac{4}{\pi} \sqrt{\frac{K_2 U_o l_o U}{\pi D}}\ \Delta t_{sc}\ Cp_1 \rho_1 \left(\frac{U_o l_o \rho_1}{\mu_1}\right)^{-0.05} (0.1895) \qquad (34)$$

Substituting A for πDL, equation (34) reduces to

$$\frac{q_1}{A} = 0.1356\ \Delta t_{sc}\ Cp_1 \rho_1 \sqrt{\frac{K_2 U_o l_o U}{D}} \left(\frac{U_o l_o \rho_1}{\mu_1}\right)^{-0.05} \qquad (35)$$

Case 3. Eddy Conduction (Short Contact Time)

In this case, which represents the limiting case of a line source of heat, the eddy conductivity is dependent upon the time of contact as well as the conditions downstream.[7]

$$\varepsilon = K_3\ t\ u'^2 \qquad (36)$$

where u' is the intensity of turbulence and K_3 is a proportionality constant. The eddy conductivity is thus independent of the scale of turbulence.[7]

If we assume that the intensity of turbulence is proportional to the velocity, we have

$$\varepsilon = K_4^2\ U^2 t \qquad (37)$$

where K_4 is a constant of proportionality.

Setting

$$c = K_4^2\ U^2 \qquad (38)$$

equation (38) reduces to

$$\varepsilon = ct. \qquad (39)$$

Substituting equations (14) and (39) into equation (12), we find that

$$\frac{\partial T}{\partial t} = ct\,\frac{\partial^2 T}{\partial x^2}\,. \tag{40}$$

Rearranging and substituting $\frac{\partial t^2}{2}$ for $t\,\partial t$, we obtain

$$\frac{\partial T}{\partial t^2} = 2c\,\frac{\partial^2 T}{\partial x^2}\,. \tag{41}$$

If we replace t^2 by a new variable n, we have an equation of the same form as equation (12) used for the solution of "Case 1",

$$\frac{\partial T}{\partial n} = 2c\,\frac{\partial^2 T}{\partial x^2}\,. \tag{42}$$

Since the boundary conditions are the same as for "Case 1", the solution of equation (42) for the temperature gradient will have the same form as the solution for "Case 1",

$$\frac{dT}{dx} = \frac{\Delta t_{sc}}{\sqrt{\pi 2cn}}\,. \tag{43}$$

Replacing n by t^2 and substituting equations (27) and (38) into equation (43), we find that

$$\frac{dT}{dx} = \frac{4}{K_4}\sqrt{\frac{1}{2\pi}}\;\frac{\Delta t_{sc}}{D\theta}\,\sin\theta\,. \tag{44}$$

Substituting equations (11), (14), (36), and (44) into equation (10), we obtain

$$q_1 = \pi LD\,\frac{K_5}{\pi}\sqrt{\frac{1}{2\pi}}\;\Delta t_{sc}\;Cp_1\rho_1\;U\int_0^{\pi/2} d\,\theta\,. \tag{45}$$

If we integrate equation (45) between the limits of zero and $\pi/2$ and substitute A for πLD, we find that

$$\frac{q_l}{A} = \frac{K_5}{4.02} \quad \Delta t_{sc} \; Cp_l \rho_l \, U . \qquad (46)$$

Summary of Theory

We have developed expressions for heat transfer in forced convection film boiling involving the rate heat is transferred into the liquid. Since this rate is dependent upon the mechanism by which heat is transferred, we have developed expressions for three mechanisms by which heat may be transferred.

For forced convection film boiling in which the heat is transferred into the liquid by thermal conduction, we find by combining equations (9) and (30) that

$$h_{co}\sqrt{\frac{D \, \Delta t_o}{U \, k_v \rho_v \lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{U \, k_v \rho_v \lambda'}{D \, \Delta t_o}} = 0.136 \, \Delta t_{sc}\sqrt{\frac{Cp_l \rho_l \, k_l}{\Delta t_o \, k_v \rho_v \lambda'}} \qquad (47)$$

For forced convection film boiling in which the heat is transferred into the liquid by eddy conduction, we find that:

(1) if the contact time is large compared to the ratio of the scale of turbulence to the intensity of turbulence, then from equations (9) and (35) we have

$$h_{co}\sqrt{\frac{D \, \Delta t_o}{U \, k_v \rho_v \lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{U \, k_v \rho_v \lambda'}{D \, \Delta t_o}} = 0.136 \, \Delta t_{sc} \, Cp_l \rho_l \sqrt{\frac{K_2 \, U_o l_o}{\Delta t_o \, k_v \rho_v \lambda'}} \left(\frac{U_o l_o \rho_l}{\mu_l}\right)^{-0.05} . \qquad (48)$$

(2) If the contact time is small compared to the ratio of the scale of turbulence to the intensity of turbulence, then from equations (9) and (46) we have

$$h_{co}\sqrt{\frac{D\ \Delta t_o}{U\ k_v \rho_v \lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{U\ k_v \rho_v \lambda'}{D\ \Delta t_o}} = K_6\ \Delta t_{sc}\ Cp_l \rho_l \sqrt{\frac{D\ U}{\Delta t_o\ k_v \rho_v \lambda'}}. \quad (49)$$

It will be noted that the only significant difference between equations (48) and (49) for a particular piece of equipment is that equation (49) shows a dependence of the rate of heat transfer into the liquid upon the diameter of the tube in the last term.

Equations (47) and (48) may be expressed by the single equation (50) by substituting equation (13) into equation (47) and/or by substituting equations (14) and (32) into equation (48):

$$h_{co}\sqrt{\frac{D\ \Delta t_o}{U\ k_v \rho_v \lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{U\ k_v \rho_v \lambda'}{D\ \Delta t_o}} = 0.136\ \Delta t_{sc}\ Cp_l \rho_l \sqrt{\frac{\alpha}{\Delta t_o\ k_v \rho_v \lambda'}}. \quad (50)$$

EQUIPMENT

The equipment used to carry out the experimental work is shown in the accompanying diagrams. The circulating liquid was raised to and maintained at a constant temperature by means of two heat exchangers through which either steam or cold water could be run. The larger of these exchangers was located in the surge tank and consisted of an internal copper coil with an area of approximately 3.7 square feet. A small auxiliary coil was located near the suction of the circulating pump. The temperature of the liquid was measured by a chromel-alumel thermocouple. The liquid leaving the surge tank passed down through a straightening section and then through a three -inch square-edged orifice which was calibrated directly from pitot tube measurements at the nozzle opening in the test section. The manometer system consisted of two vertical glass tubes open to the atmosphere.

The circulation of the liquids through the apparatus was provided by a five-horsepower Ingersoll Rand centrifugal pump. The liquid flow rate was controlled by a four-inch gate valve on the discharge side of the pump. Leaving this control valve, the liquid passed through a set of 3/4-inch square honeycomb straightening vanes and then to a nozzle immediately below the graphite heating tube. The nozzle opening was one inch wide and a full five inches in length with a one-half-inch radius of curvature at each end. The liquid velocity issuing from the nozzle was investigated by means of a pitot tube traverse and found to be constant within two percent.

Screens were mounted on the nozzle for some runs to produce a higher intensity of turbulence. Two different screens were used: the small screen had an 0.1033-inch mesh and an 0.0250-inch wire thickness, and the large screen had an 0.2435-inch mesh and an 0.0466-inch wire

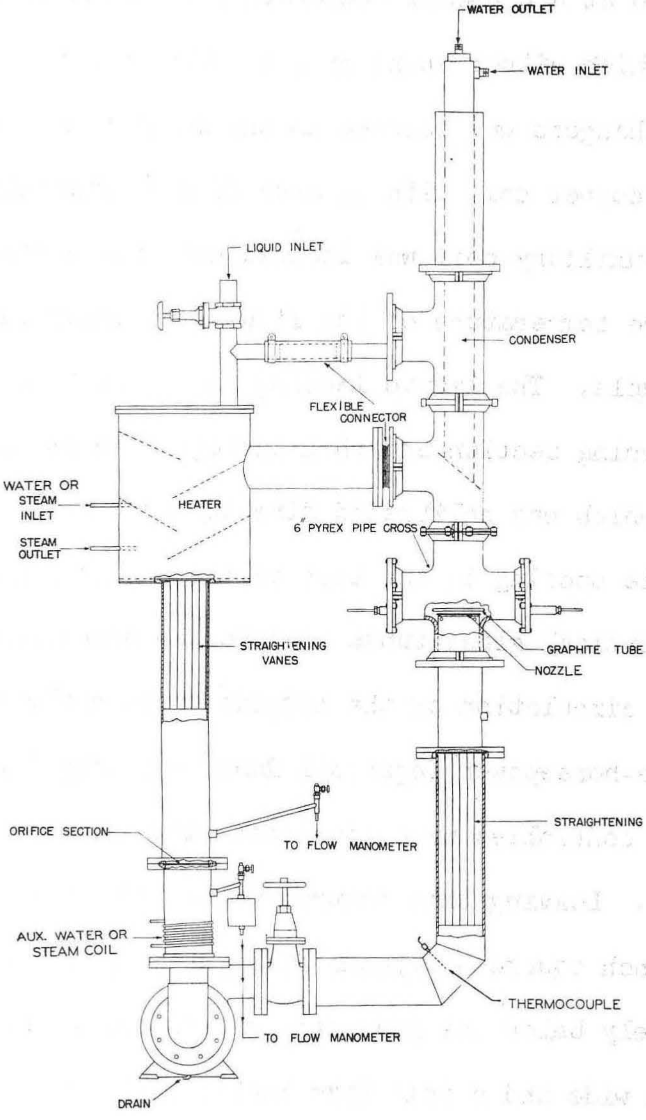
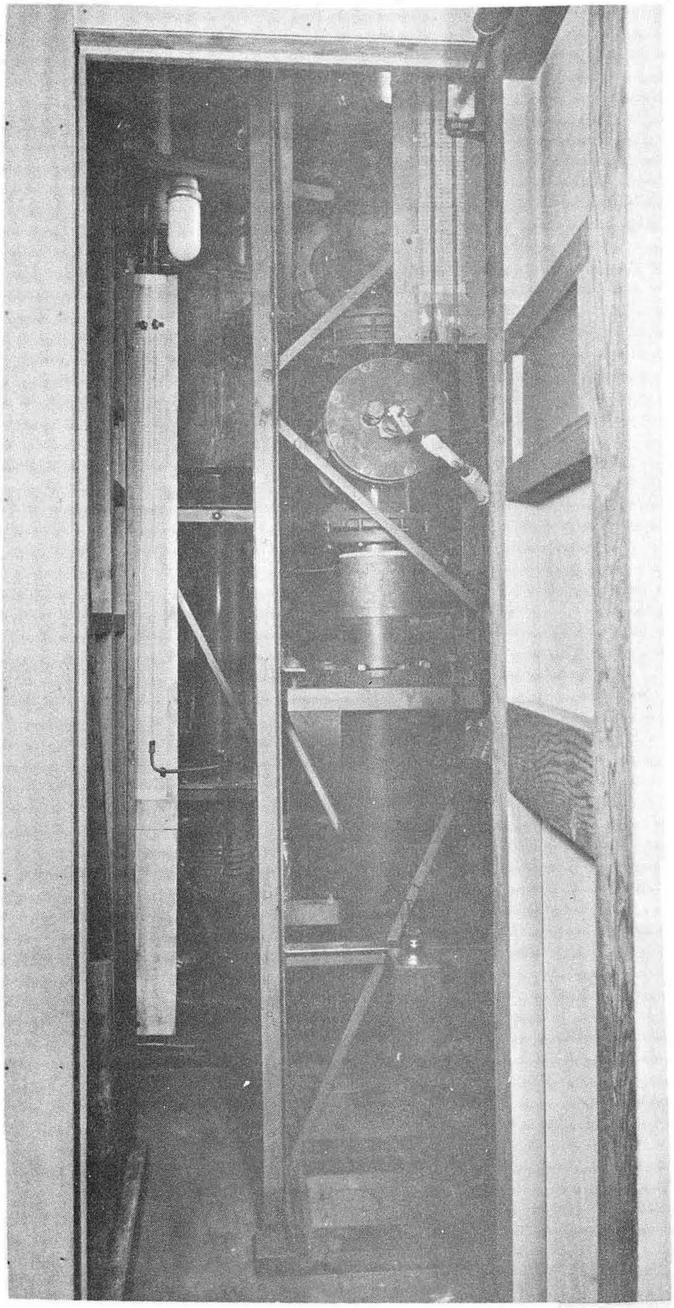


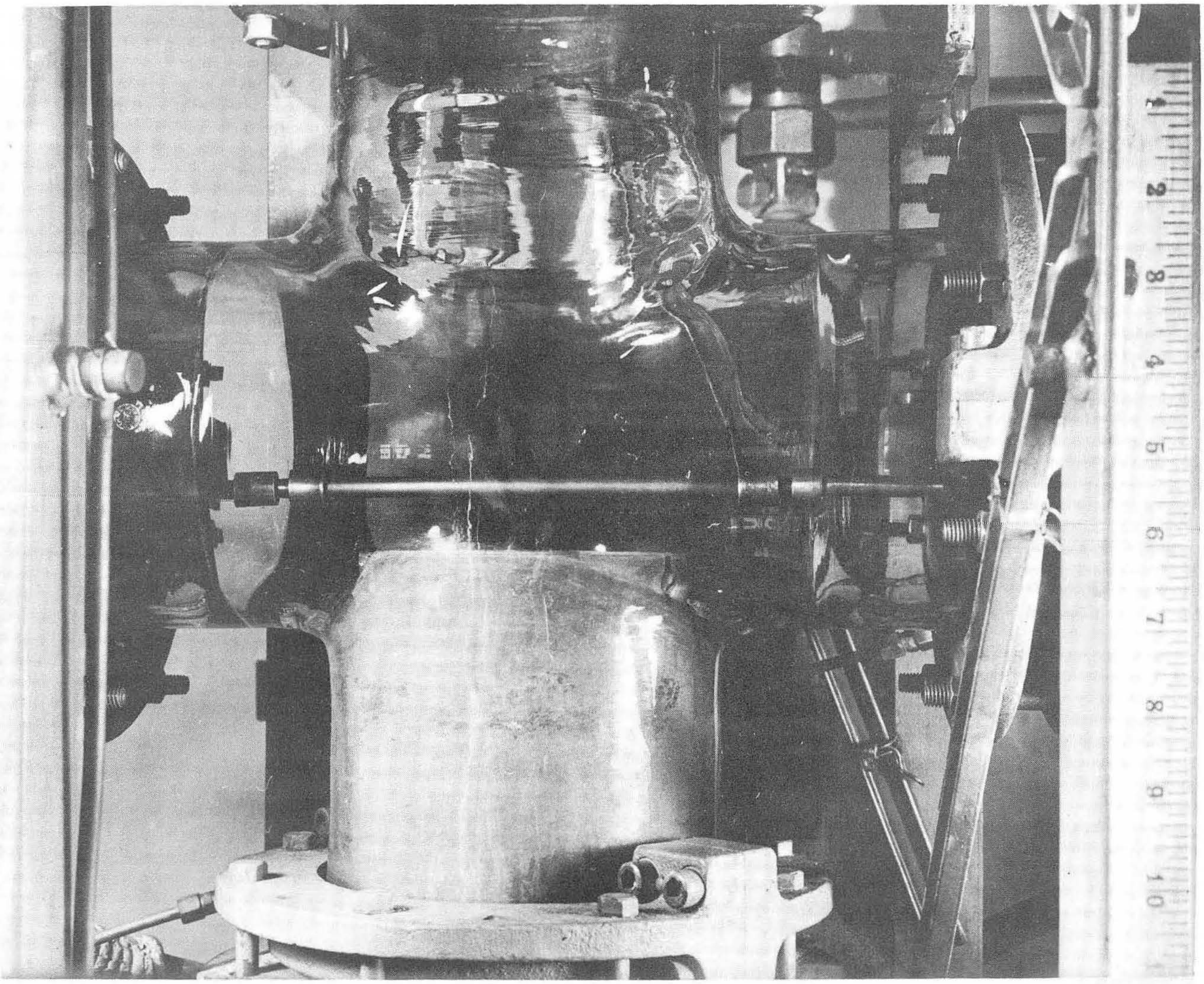
FIG. — FORCED CONVECTION FILM BOILER

Fig. 2



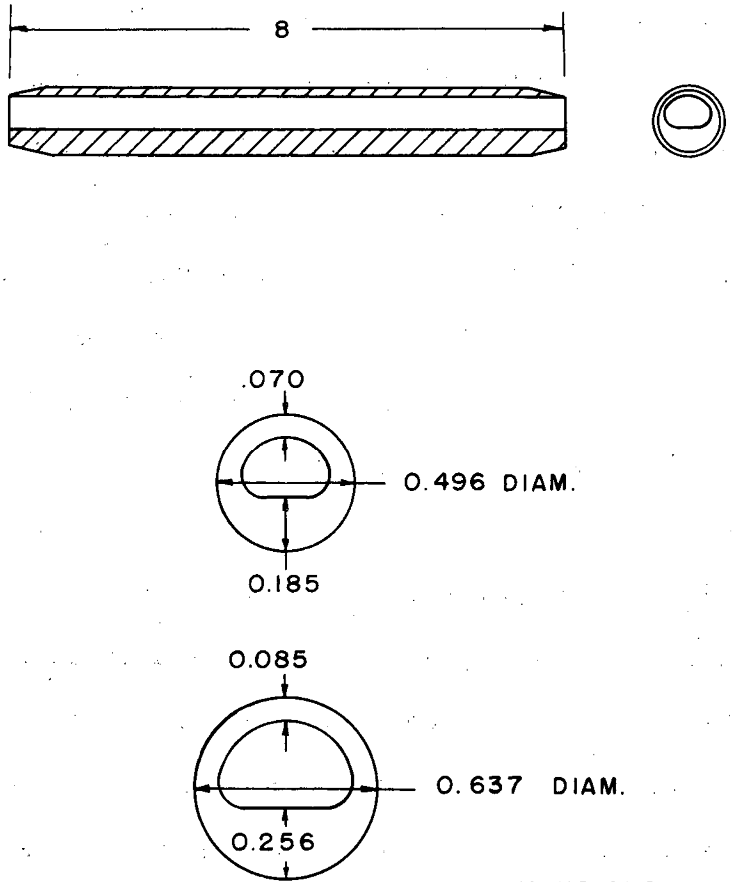
ZN-941

Fig. 3



ZN-942

Fig. 4



DIMENSIONS IN INCHES

GRAPHITE HEATING TUBES

Fig. 5

thickness.

Film boiling was produced by passing an electric current through the graphite heating tube mounted in a six-inch glass cross. Graphite was chosen for its high thermal conductivity and moderate electrical resistance. The tubes were eight inches in length and tapered at both ends to fit supporting steel inserts. Three tube sizes were used of nominal outside diameter of 3/8, 1/2, and 5/8 inches. For the 3/8-inch size, a 3/16-inch-diameter hole was bored at the center the full length of the tube. In the case of the 1/2- and 5/8-inch sizes, special broaches were designed for an oval-shape hole as shown in Figure 5. This shape was adopted to prevent temperature gradients from occuring between the top and bottom half of the tube. Since the heat transfer on the bottom half of the tube is much greater than the top, a larger cross section was provided at the bottom.

The tubes were supported in position over the nozzle by steel inserts tapered to form a seal with the ends of the tube. The inserts, in turn, fitted into copper rods. Two coil springs mounted in the packing unit of one of the brass end plates on the glass cross provided for the thermal expansion of the tube and insured a constant tension on the tube and inserts. Separate copper connectors were fastened firmly to the ends of the rods for electrical connections.

Above the six-inch glass cross in which the heating tube was mounted there were two six-inch glass tees and a stainless steel condenser. The outlet in the first tee allowed liquid to return to the surge tank completing the flow cycle. The second tee permitted any vapor entrained by the liquid to escape from the surge tank to the condenser, from which the condensate was returned to the main body of the liquid. The bottom face of the condenser served as a baffle to change the direction of the main liquid stream, and an opening at the top of the condenser provided a means of venting the system to the atmosphere.

The electrical energy for the apparatus was supplied from equipment adjacent to the main apparatus. A 220-volt main line was connected to a 25-KVA continuous-duty General Electric induction voltage regulator. From the regulator the current passed to an air-cooled transformer for a step-down reduction from 230 volts at 150 amperes to 40 volts at 875 amperes. A current transformer with a rating of 800/5 was mounted on this piece of apparatus to reduce the current to the measuring ammeter.

The voltage was measured by using a porcelain-covered tungsten voltage probe which was bent at one end so as to contact the inside surface of the tube when inserted down the hole of the tube mounting. The voltage drop across a known section was measured by reading the voltage at each end of the section. Two General Electric alternating voltmeters were used in reading the voltage. One voltmeter had a double scale range of 0 to 5.0 volts and 0 to 10 volts, and the other had a scale range of 0 to 40 volts. The amperage was read on a General Electric alternating-current ammeter which had a double scale range of 0 to 2.5 amperes and 0 to 5.0 amperes. A current transformer with the rating of 800/5 was used to reduce the current to the measuring ammeter. These measuring instruments were calibrated to within 0.5 percent of the total scale reading.

When the liquid was not in use it was stored in a stainless steel drum adjacent to the apparatus. The liquid was transferred to and from the equipment by means of a 3/4-horsepower centrifugal pump.

Due to the properties of the liquids investigated, it was necessary to provide safety precautions against fire and toxic vapors. There was a four-inch concrete dike around the system of such an area to confine the liquid in case of breakage. This dike also served as a footing for an eight-foot fire wall surrounding the equipment. Four doors in the partition made the apparatus accessible. A ventilating blower removed toxic vapors and maintained the atmosphere above the upper explosive limit of the vapors. An automatic fire-extinguishing system was arranged so as to spray carbon dioxide from two 100-pound cylinders in the event the temperature inside the partition exceeded a set value.

EXPERIMENTAL PROCEDURE

The graphite tube to be used in a series of runs was polished with crocus cloth before being installed in the test section. The outside diameter of the tube was determined with a micrometer and recorded.

After assembling the test section, the desired liquid was pumped into the apparatus. The flow rate and the temperature of the liquid were adjusted to approximately the desired values. The current through the graphite tube was increased until the boiling around the tube changed from nucleate to film boiling. The flow of cold water through the coils was then set so that the temperature of the liquid remained approximately constant.

A chromel-versus-alumel thermocouple was inserted through the copper supporting tubes and was used to determine the temperature of the graphite tube. At least five minutes were allowed to attain thermal equilibrium on each run. Consecutive temperature readings were used to determine if the stable film boiling had attained steady state. Once a steady state had been attained, the average temperature of the center of the tube and at each end of the central five-inch section was measured. The temperatures at the ends of the central five-inch section were determined in order to calculate the heat conducted longitudinally away from the center of the graphite tube.

The thermocouple was removed and the voltage probe was inserted. The leads of a voltmeter were connected to the voltage probe and to the electrical connector on the right-hand supporting tube. The voltage was determined at points 2.5 inches on either side of the center of the graphite tube and the difference between the two values was recorded as the voltage drop across the central five-inch section of the graphite tube. The current flowing through the graphite tube during each run was measured with the ammeter and recorded.

The temperature of the liquid was determined by means of a chromel-alumel thermocouple before and after the other measurements had been made. The liquid temperature was usually found to vary about one degree Fahrenheit during the run. After each run the flow rate was measured by the pressure drop across the three-inch orifice.

The three-inch orifice was calibrated by means of a movable pitot tube which could be mounted in the left-hand end plate when the graphite tube was removed. A static pressure tap was mounted in the right-hand end plate. The static tap and the pitot tube were connected to two vertical glass tubes which were open to the atmosphere. The difference in the hydrostatic heads developed at each flow rate was used as a basis for calibrating the orifice manometer.

EXPERIMENTAL DATA

Experimental data were taken for four systems: benzene, carbon tetrachloride, ethyl alcohol, and hexane. These four systems were chosen for their physical properties, which vary over a fairly wide range. The values of the physical properties can be found on Page 120.

Three tube sizes of 0.387, 0.496, and 0.638 inches outer diameter were used to study the effect of the tube diameter. Liquid velocities were varied from three feet per second to approximately thirteen feet per second at the nozzle and the amount of subcooling was varied from twenty degrees to approximately eighty degrees Fahrenheit.

The intensity of turbulence was varied by introducing screens directly above the nozzle below the graphite tube. The "small" screen had a 0.1033-inch mesh and a 0.0250-inch wire thickness, and the "large" screen had a 0.2435-inch mesh and a 0.0466-inch wire thickness. Extensive data were taken with ethyl alcohol in order to determine the effect of turbulence on the rate of heat transferred into the liquid.

Included in the tables are the following quantities. A sample calculation of these quantities may be found on Page 87.

1. The run number is taken directly from the laboratory notebook and is used only as a means of listing the data in the correct columns.
2. "Volts" refer to the voltage difference across the five-inch test section at the center portion of the tube. The values represent the difference of two readings from the current flux voltmeter.
3. "Amp" refers to the total current flowing in the graphite tube.

4. The "t_i" is the recorded average inside temperature of the tube at the center point. The values were measured in millivolts with a precision potentiometer and were converted to degrees Fahrenheit.

5. The "Δt_o" is the temperature difference across the film, that is, between the outside tube surface and the boiling liquid. The temperature at the surface of the tube is calculated from the knowledge of "t_i" and the thermal conductivity of graphite.

6. The "h" is the overall coefficient of heat transfer which has been corrected for losses due to conductivity along the tube.

7. The "h_{co}" is the coefficient of heat transfer due to convective heat transfer.

8. The "U" is the velocity of the liquid at the nozzle opening below the graphite tube as measured by the calibrated three-inch square-edged orifice.

9. The "Δt_{sc}" is the amount of subcooling of the liquid, which is the temperature difference between the liquid temperature and its boiling point.

10. The "$h_{co}\sqrt{\frac{D\,\Delta t_o}{Uk_v\,\rho_v\lambda'}}$" is the dimensionless parameter which has been used to correlate data in forced convection film boiling to saturated liquids.

11. The "A" is the dimensionless parameter

$$h_{co}\sqrt{\frac{D\,\Delta t_o}{Uk_v\,\rho_v\lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{Uk_v\,\rho_v\lambda'}{D\,\Delta t_o}}$$

12. The "B" is the dimensionless parameter

$$\Delta t_{sc}\, Cp_l\, \rho_l \sqrt{\frac{U_o l_o}{\Delta t_o\, k_v\, \rho_v \lambda'}} \qquad \left(\frac{U_o l_o \rho_l}{\mu_l}\right)^{-0.05} .$$

13. The "α" is the diffusivity of heat into the liquid as calculated from equation (50).

Table 1 - Part I

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.387-Inch Outside Diameter Tube without a Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{\text{BTU}}{(\text{hr})(\text{ft})^2(°\text{F})}$	h_{co} $\frac{\text{BTU}}{(\text{hr})(\text{ft})^2(°\text{F})}$	U ft/sec
101	3.89	238.2	669	488	153.2	149.7	3.68
102	6.14	362	1828	1631	108.9	89.6	3.68
103	5.25	326.5	1383	1193	115.8	104.7	5.12
104	4.47	280	698	515	197.1	193.4	5.12
105	6.94	398.2	1906	1704	131.3	110.1	5.12
106	5.67	352	777	588	280.0	275.8	8.00
107	6.71	415	1508	1308	172.8	159.9	8.00
108	7.80	450	2001	1791	158.8	135.7	8.00
109	7.76	481	1232	1028	294.0	285.3	10.93
110	6.03	382	751	561	335.0	331.0	10.93
111	9.06	504	2161	1938	190.9	163.9	10.93
112	7.65	476	962	761	389.5	383.7	13.98
113	7.05	422	763	568	424.0	419.9	13.98
114	8.75	546	1335	1121	345.0	335.0	13.98
115	5.17	320	1533	1343	98.9	85.4	3.52
116	4.46	281	846	662	153.2	148.3	3.52
117	6.11	411	1852	1652	122.9	103.1	3.52
118	6.45	388	1760	1561	129.5	111.2	5.20
119	5.52	344	880	692	222.2	217.1	5.20
120	7.77	435	2096	1885	145.2	119.7	5.20
121	7.74	480	1250	1046	284.0	275.7	8.04
122	6.48	399.2	857	664	312.5	307.6	8.04
123	8.99	499	2260	2037	178.9	149.0	8.04
124	8.25	505	1170	963	350.0	342.1	10.85
125	7.55	424	877	680	380.5	375.5	10.85
126	9.41	585	2280	2045	217.6	187.4	10.85
127	8.90	559	1239	1025	392.0	383.3	13.13
128	8.10	486	918	716	446.0	440.7	13.13
129	6.23	342.3	1703	1513	114.1	97.3	3.65
130	5.41	315	962	770	248.5	242.7	3.65
131	7.50	406	2008	1802	136.9	113.2	3.65
132	7.24	400	1818	1615	145.1	126.1	5.02
133	5.78	352	932	742	222.0	216.4	5.02
134	7.65	430	1956	1748	152.1	130.1	5.02
135	8.30	509	1332	1123	304.0	293.9	8.05
136	7.34	426	923	724	350.0	344.6	8.05
137	8.98	496	2245	2021	178.4	168.4	8.05
138	8.23	519	1197	989	349.5	341.3	10.93
139	7.62	476	991	790	372.0	366.0	10.93
140	9.65	544	2400	2168	196.1	162.1	10.93
141	9.21	571	1297	1080	394.5	385.0	13.74
142	5.13	315	922	736	173.1	167.6	3.60
143	8.73	535	1102	891	424.9	417.8	13.67
144	10.70	604	1882	1650	318.0	298.3	13.67
145	4.68	278	1392	1206	86.6	75.2	3.52

Table 1 - Part 1

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\dfrac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda'}}$	A	$\Delta t_{sc}\sqrt{\dfrac{cp_l\rho_l k_l}{\Delta t_o k_v\rho_v\lambda'}}$	B
101	40.2	5.61	4.48	3.13	306
102	41.0	4.48	0.74	0.85	84
103	40.2	3.04	1.19	1.26	144
104	40.3	6.18	5.21	3.00	344
105	40.5	3.04	0.87	0.79	91
106	41.3	6.99	6.31	2.67	460
107	39.8	3.85	2.20	1.11	156
108	40.2	2.86	0.63	0.72	102
109	40.9	6.04	5.26	1.48	250
110	40.2	7.10	6.54	2.70	443
111	40.2	2.78	0.60	0.64	104
112	40.8	7.32	6.94	2.02	371
113	40.8	7.94	7.60	2.68	489
114	40.2	6.14	5.20	1.30	240
115	60.3	3.16	0.86	1.63	155
116	61.1	6.02	4.81	3.68	348
117	59.7	3.60	1.57	1.22	116
118	59.6	3.26	1.02	1.33	149
119	61.9	7.11	6.08	3.48	390
120	60.4	3.25	1.02	1.02	116
121	58.2	7.05	6.02	2.12	294
122	60.3	8.30	7.45	3.54	490
123	59.6	3.10	0.74	0.88	39
124	59.1	7.83	6.90	2.47	378
125	62.1	8.75	7.92	3.17	575
126	59.6	3.36	1.18	0.87	44
127	58.9	7.61	6.65	2.12	316
128	61.6	9.31	8.52	3.29	575
129	80.4	3.46	1.35	1.93	177
130	80.2	10.00	9.28	4.16	387
131	78.6	3.74	1.79	1.44	134
132	77.8	4.15	2.40	1.86	202
133	78.8	7.40	6.42	4.24	460
134	76.8	3.73	1.77	1.46	159
135	77.1	7.45	6.46	2.58	354
136	76.4	9.27	8.48	4.10	561
137	74.1	3.52	1.44	1.12	153
138	72.7	7.54	6.58	2.72	382
139	74.3	9.10	8.30	3.92	619
140	71.7	2.83	0.26	0.98	153
141	69.5	8.65	7.81	2.67	470
142	79.4	6.80	5.73	4.36	401
143	72.9	8.56	7.71	3.10	543
144	69.1	5.23	3.84	1.36	240
145	22.6	2.91	0.40	0.70	70

Table 1 - Part 2

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.387-Inch Outside Diameter Tube without a Screen

Run			t_i	Δt_o	h	h_{co}	U
No.	Volts	Amps	°F	°F	$\frac{BTU}{(hr)(ft)^2(°F)}$		ft/sec
146	3.77	236	1101	831	85.3	77.8	3.52
147	5.31	322	1687	1496	92.6	76.2	3.52
148	4.89	300	1389	1202	97.1	85.9	5.04
149	3.96	243	974	792	96.0	90.0	5.04
150	6.10	360	1763	1568	113.8	95.9	5.04
151	5.15	319.5	1296	1108	141.0	131.2	6.80
152	4.38	265.5	908	724	151.0	145.6	6.80
153	6.66	388.5	1793	1593	119.0	100.5	6.80
154	6.40	393.5	1460	1263	161.8	149.6	11.00
155	5.62	344	967	758	207.0	201.1	11.00
156	7.70	441	1001	1593	172.8	164.3	11.00
157	7.16	434	1502	1300	193.3	180.5	13.78
158	6.35	379	905	713	274.0	268.7	13.78
159	8.20	480	1831	1617	197.3	178.3	13.78
160	7.12	407	2017	1812	129.6	105.9	3.34
161	7.60	470	1184	982	294.5	286.3	7.93
162	8.84	545	1352	1138	343.0	332.7	11.25
163	9.76	599	1398	1174	403.0	392.2	13.72
164	8.74	528	1112	903	416.0	408.8	13.72
165	9.59	535	2349	2118	196.1	143.6	10.97
166	8.60	484	1708	1494	225.0	206.5	7.89
167	8.30	586	1568	1358	241.0	227.2	10.69
168	6.13	358	1827	1630	108.9	89.6	3.63

Table 1 - Part 2

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D \Delta t_o}{U k_v \rho_v \lambda'}}$	A	$\Delta t_{sc}\sqrt{\frac{Cp_l \rho_l k_l}{\Delta t_o k_v \rho_v \lambda'}}$	B
146	23.2	3.14	0.81	0.95	103
147	22.2	2.76	0.13	0.52	52
148	20.9	2.78	0.18	0.65	76
149	20.5	3.06	0.62	1.02	119
150	20.1	2.88	0.34	0.44	52
151	21.3	3.95	2.10	0.78	104
152	21.7	4.32	2.50	1.19	159
153	19.9	2.58	-0.22	0.44	67
154	20.7	3.26	1.02	0.60	100
155	22.9	4.62	3.02	1.14	192
156	21.7	3.32	1.12	0.46	76
157	20.7	3.46	1.35	0.57	105
158	21.1	5.49	4.17	1.14	213
159	20.3	3.16	0.85	0.41	77
160	76.9	3.66	1.67	1.40	126
161	74.1	7.61	6.67	2.88	390
162	70.9	7.11	6.09	2.28	359
163	71.9	7.91	6.99	2.26	398
164	58.4	8.31	7.44	2.43	434
165	60.4	2.51	-0.39	0.84	258
166	58.7	4.91	3.41	1.36	187
167	40.3	4.74	3.21	1.04	168
168	40.7	3.07	0.70	0.85	84

Table 2 - Part 1

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.496-Inch Outside Diameter Tube without a Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{BTU}{(hr)(ft)^2(°F)}$	h_{co}	U ft/sec
169	4.34	316	1262	1087	78.9	69.4	3.85
170	3.84	279	1049	870	76.3	69.5	3.85
171	5.02	372.5	1518	1334	87.7	74.3	3.85
172	4.56	336	1242	1061	89.4	80.2	5.12
173	4.22	308	1060	874	92.5	85.6	5.12
174	5.25	379	1428	1244	100.1	88.2	5.12
175	4.77	377.5	1134	952	118.2	110.4	7.92
176	5.89	429	1340	1264	125.6	113.4	7.92
177	6.52	464	1653	1464	130.0	114.5	7.92
178	6.30	462	1367	1180	154.5	143.6	10.93
179	5.84	415	1078	894	169.1	162.1	10.93
180	7.49	610	1767	1571	165.5	147.5	10.93
181	6.90	498	1345	1156	188.0	177.4	13.75
182	6.76	470	1126	940	214.1	206.5	13.75
183	7.93	567	1723	1528	186.0	168.9	13.75
184	4.79	353.5	1339	1157	91.1	80.5	3.69
185	4.26	304.7	856	676	119.4	114.4	3.69
186	5.57	400	1631	1446	97.1	86.6	3.69
187	5.09	366	1008	826	141.9	135.5	5.06
188	5.23	360	937	755	153.1	147.4	5.06
189	5.45	400	1448	1264	107.1	94.9	5.06
190	5.92	424	1553	1368	114.9	100.9	5.06
191	6.46	475	985	799	243.0	236.9	7.92
192	7.14	514	1803	1611	143.0	124.1	7.92
193	6.99	511	1647	1456	154.1	138.4	7.92
195	7.50	560	1073	883	300.5	293.5	10.96
196	8.41	590	1181	988	318.5	310.3	10.96
199	6.00	400	1592	1406	107.0	93.3	3.81
200	4.66	255	911	730	115.0	109.5	3.81
201	6.02	434	1785	1598	102.5	83.9	3.81
202	5.76	436	1062	877	181.0	174.1	5.10
203	5.90	472	1828	1640	106.4	86.9	5.10
204	5.87	442	1080	896	182.5	175.4	5.10
205	6.92	516	1054	867	260.0	253.2	7.92
206	7.48	560	1241	1050	251.9	242.8	7.92
207	8.37	590	2166	1966	158.8	131.0	7.92
208	8.44	640	1305	1109	307.8	298.0	10.95
209	8.10	600	1139	946	324.0	316.3	10.95
210	9.00	665	1415	1216	311.0	299.6	10.95
211	9.59	702	1376	1175	362.0	351.2	13.62
212	8.79	656	1136	940	381.5	379.9	13.62
213	9.94	736	1476	1271	363.2	350.9	13.62
214	8.80	650	1227	1031	350.0	341.2	13.62
215	8.30	704	1517	1317	281.0	267.9	13.62
216	5.43	407	1031	848	164.3	157.7	3.73

Table 2 - Part 1

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda'}}$	A	B
169	21.9	2.98	0.53	78
170	22.2	3.04	0.60	103
171	21.1	3.04	0.60	60
172	20.2	3.00	0.57	86
173	20.3	3.26	0.98	106
174	21.3	3.18	0.89	75
175	19.3	3.36	1.19	113
176	19.9	3.28	1.07	91
177	19.5	3.14	0.83	67
178	22.1	3.60	0.16	101
179	22.0	4.21	2.48	137
180	20.1	3.40	1.25	63
181	22.3	3.96	2.12	132
182	20.5	4.55	2.94	156
183	20.3	3.50	1.41	85
184	39.3	3.50	1.41	129
185	38.5	5.25	3.85	208
186	38.3	3.31	1.11	84
187	37.3	5.19	3.78	203
188	37.5	5.70	4.43	226
189	40.9	3.44	1.32	138
190	40.7	3.56	1.52	124
191	39.2	7.26	6.26	246
192	39.3	3.34	1.16	118
193	40.8	3.81	1.89	138
195	40.4	7.61	6.66	278
196	40.1	7.30	6.30	236
199	59.3	3.90	2.03	157
200	60.3	4.85	3.24	326
201	58.1	3.28	1.06	169
202	60.8	6.63	5.53	310
203	60.5	3.28	1.06	164
204	61.1	6.68	5.59	304
205	59.8	7.95	7.04	376
206	59.0	7.29	6.29	302
207	58.2	3.24	0.99	131
208	61.7	7.56	6.60	344
209	62.4	8.15	7.26	414
210	60.9	7.44	6.43	303
211	57.5	7.87	6.94	330
212	61.4	8.74	7.91	450
213	59.8	7.75	6.82	391
214	43.1	7.80	6.87	292
215	41.5	5.86	4.62	211
216	80.1	7.03	6.00	362

Table 2 - Part 2

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.496-Inch Outside Diameter Tube without a Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{BTU}{(hr)(ft)^2(°F)}$	h_{co} $\frac{BTU}{(hr)(ft)^2(°F)}$	U ft/sec
217	5.68	436	1721	1535	101.2	84.0	3.73
218	5.26	419	1592	1407	97.8	83.1	3.75
219	6.09	462	1221	1035	173.9	165.1	5.25
220	6.88	504	1335	1145	197.0	186.6	5.25
221	7.34	521	2003	1809	133.3	109.7	5.25
222	7.24	583	1190	999	268.0	259.6	7.98
223	7.27	556	1087	998	256.2	249.1	7.98
224	7.40	595	1272	1080	258.0	248.5	7.98
225	9.26	694	1492	1290	315.0	302.4	11.00
226	8.41	640	1283	1088	312.5	302.9	11.00
227	9.69	711	1625	1420	307.5	292.5	11.00
228	9.14	716	1350	1150	359.5	349.1	13.72
229	8.32	670	1199	1003	351.5	343.1	13.72
230	7.47	665	1252	1058	297.2	288.0	13.72
231	4.79	354	1334	1157	91.1	80.5	3.69
232	5.92	407	1553	1368	114.9	100.9	5.06
233	5.45	400	1448	1264	107.1	94.9	5.06
234	6.99	511	1647	1456	154.1	138.4	7.92
235	5.66	404	1425	1241	116.0	104.2	3.72
236	3.67	336	1019	840	94.4	87.9	3.72
237	4.27	394	827	646	164.5	159.8	5.00
238	5.79	535	1010	824	230.0	223.6	8.00
239	6.19	576	938	751	300.0	294.1	10.98
240	6.97	601	1849	1647	160.7	141.1	10.98
241	6.13	568	928	741	304.5	298.9	10.98
242	7.50	725	1184	984	350.0	341.8	13.71
243	8.71	759	1374	1172	355.0	344.2	13.71
245	5.51	505	1137	952	184.4	176.6	13.18
246	8.79	655	1136	940	387.5	379.9	13.62
247	6.09	461	1221	1035	173.9	165.1	5.25
248	7.24	582	1190	999	268.0	259.1	7.98
249	7.27	555	1087	998	256.2	249.1	7.98

Table 2 - Part 2

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta t_o}{Uk_v\rho_v\lambda'}}$	A	B
217	78.0	3.35	1.18	175
218	76.9	3.51	1.43	199
219	75.1	6.11	4.92	320
220	72.3	6.79	5.72	276
221	70.7	3.55	1.49	153
222	77.5	7.80	6.87	414
223	73.3	7.96	7.05	417
224	70.7	7.35	6.36	347
225	75.8	7.41	6.43	346
226	70.0	7.66	6.72	396
227	64.3	7.00	6.03	264
228	75.8	7.86	6.94	441
229	69.4	7.90	6.98	476
230	65.5	6.59	5.98	426
231	39.3	3.50	1.41	129
232	40.7	3.56	1.52	124
233	40.9	3.44	1.32	138
234	40.8	3.81	1.89	138
235	42.9	4.44	2.79	130
236	41.9	3.91	2.04	197
237	43.4	6.40	5.26	314
238	39.5	7.09	6.10	280
239	39.7	7.68	6.69	342
240	40.9	3.16	0.86	137
241	41.1	7.85	6.92	360
242	41.3	7.84	6.91	294
243	40.5	7.66	6.71	314
245	17.3	4.15	2.39	128
246	61.4	8.74	7.91	450
247	75.1	6.11	4.92	320
248	77.5	7.80	6.87	422
249	73.3	7.96	7.04	417

Table 3

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.638-Inch Outside Diameter Tube without a Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h BTU/(hr)(ft)^2(°F)	h_{co} BTU/(hr)(ft)^2(°F)	U ft/sec
250	3.25	479	1098	916	65.6	58.2	3.66
251	3.14	439	998	818	67.0	60.7	3.66
252	3.75	518	1161	978	80.2	72.0	3.66
253	4.10	559	1459	1274	71.9	59.7	3.66
254	4.04	559	1320	1135	79.2	69.0	5.11
255	3.49	493	1039	857	80.1	73.4	5.11
256	3.25	457	934	753	78.6	72.9	5.11
257	4.07	566	1229	1044	88.5	79.5	7.98
258	3.48	502	838	657	107.9	103.1	7.98
259	4.78	664	1349	1161	110.0	99.4	10.88
260	4.20	601	1076	892	110.9	103.8	10.60
261	5.34	754	1245	1054	153.5	144.4	13.03
263	5.09	756	858	670	232.5	227.6	12.85
264	4.12	577	1408	1223	77.0	65.5	3.80
265	3.96	526	1183	999	83.0	74.6	3.80
266	3.52	507	1085	903	78.5	71.3	3.80
267	4.41	625	1355	1168	94.5	83.8	5.18
268	4.08	586	924	740	130.0	124.4	5.18
269	4.69	653	1526	1337	91.6	78.2	5.18
270	5.48	785	1128	936	186.0	178.4	7.88
271	5.47	792	1010	819	214.1	207.8	9.52
272	5.25	761	1086	896	180.8	173.7	7.35
273	5.25	711	1035	844	179.7	173.1	6.68
274	5.39	746	1688	1494	138.0	91.8	6.68
275	4.21	596	922	737	134.6	129.1	3.60
276	4.78	658	1675	1484	86.5	70.3	3.60
277	6.06	574	667	481	292.5	289.0	3.60
278	5.04	704	1621	1429	99.6	84.5	5.05
280	5.44	750	1812	1617	101.0	82.0	5.05
281	5.38	780	1169	978	173.8	165.7	6.30
282	5.46	795	1182	990	177.5	169.2	6.30
283	4.41	631	1469	1282	87.2	74.7	3.38
284	4.90	681	1736	1545	86.5	69.1	3.38
285	5.52	775	1108	917	187.5	180.1	5.22
286	5.45	794	1293	1100	159.0	149.3	5.35

Table 3

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda'}}$	A	B
250	23.1	2.96	0.49	99
251	23.3	2.90	0.38	98
252	23.8	3.64	1.63	95
253	22.6	3.08	0.72	72
254	21.9	2.89	0.37	86
255	21.7	3.18	0.89	117
256	21.6	3.16	0.85	133
257	21.3	2.70	0.00	113
258	24.2	3.54	1.44	206
259	20.9	2.86	0.31	118
260	20.7	3.10	0.74	148
261	21.3	3.84	1.94	139
263	21.7	6.16	4.98	226
264	44.7	3.14	0.82	138
265	42.9	3.70	1.73	170
266	43.2	3.56	1.50	190
267	42.2	3.46	1.35	159
268	41.5	5.38	4.03	258
269	41.3	3.13	0.80	132
270	38.9	6.19	5.01	230
271	40.2	6.56	5.45	297
272	40.6	6.29	5.13	245
273	40.7	6.54	5.43	248
274	41.5	3.11	0.76	128
275	58.2	6.69	5.60	304
276	56.3	3.26	1.02	132
277	57.1	4.50	2.88	436
278	56.7	3.34	1.16	161
280	58.2	3.32	1.12	160
281	58.1	6.39	5.25	290
282	57.7	6.52	5.40	284
283	63.0	3.76	1.82	173
284	71.5	3.26	1.02	151
285	85.9	7.31	6.32	394
286	75.1	6.25	5.08	300

Table 4

Experimental and Calculated Data on the Film Boiling of Benzene from a 0.387-Inch Outside Diameter Tube without a Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h	h_{co}	U ft/sec
					Btu/(hr)(ft)^2(°F)		
438	3.93	222.2	1100.	914	76.1	68.7	4.60
439	3.33	191.1	964	780	65.3	59.8	3.75
440	3.76	216.0	1124	938	69.2	61.5	3.75
441	3.98	228.1	1066	880	82.5	75.5	5.20
442	3.67	209.0	947	762	81.6	75.8	5.20
443	4.54	260.1	1040	852	111.0	104.3	7.675
444	5.21	296.1	1292	1101	112.6	102.8	7.675
445	5.69	324.0	1265	1111	133.7	124.3	10.68
446	5.90	280.0	1007	816	163.9	157.6	10.68
447	6.21	351.9	1292	1096	162.0	153.0	13.25
448	5.47	312.0	1068	877	157.1	150.1	13.25
449	4.16	237.9	1203	1016	77.8	69.1	4.23
450	4.64	264.0	1343	1154	85.1	74.5	4.23
451	4.90	277.9	644	457	241.5	238.1	7.96
452	6.18	347.6	1494	1289	134.2	111.5	7.96
453	6.10	353.8	791	598	292.2	287.9	11.04
454	6.96	391.9	1470	1268	174.1	161.7	11.04
455	7.80	435.0	1627	1418	194.0	179.0	12.58
456	4.69	269.9	1267	1078	94.0	84.5	4.28
457	4.28	244.2	703	518	163.8	160.1	4.28
458	5.35	308.0	680	491	272.0	268.4	8.08
459	6.63	384.0	1012	815	252.8	246.5	8.08
460	7.16	407.0	1629	1424	159.0	143.9	8.08
461	7.01	413.3	975	776	302.0	295.9	10.02
463	6.39	374.2	822	627	308.2	303.6	10.82
463	7.61	448.5	948	745	370.5	364.9	13.46
464	6.92	406.0	804	607	289.5	285.1	13.46
465	4.96	300.0	932	752	160.1	154.5	4.33
466	5.67	328.5	1600	1404	107.0	93.2	4.33
467	5.56	332.0	687	497	301.0	297.4	7.90
468	6.28	378.0	906	810	236.5	231.2	7.90
469	7.38	439.0	1024	822	290.2	283.8	10.65
470	6.77	406.0	876	679	328.5	323.5	10.65
471	7.47	462.7	945	742	376.5	370.9	13.45
472	7.06	422.3	784	587	416.0	411.8	13.45

Table 4

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D \Delta t_o}{U k_v \rho_v \lambda'}}$	A	B
438	18.5	2.14	-1.26	53
439	19.4	2.16	-1.21	62
440	17.9	2.10	-1.37	47
441	20.5	2.24	-1.06	64
442	19.5	2.37	-0.70	75
443	23.3	2.52	-0.38	87
444	23.3	2.20	-1.11	63
445	20.7	2.43	-0.60	70
446	20.7	3.34	1.16	100
447	21.6	2.73	0.60	84
448	19.9	2.80	0.20	96
449	40.7	2.16	-1.21	98
450	40.6	2.19	-1.14	81
451	40.9	6.37	5.22	302
452	39.9	2.24	-1.00	89
453	40.7	6.42	5.27	286
454	41.4	2.80	0.20	110
455	41.6	2.71	0.20	97
456	60.1	2.54	-0.32	134
457	60.5	5.81	4.56	310
458	68.3	7.12	6.09	411
459	68.1	6.01	4.79	248
460	67.9	2.70	0.00	110
461	68.1	6.19	5.10	294
462	68.7	6.79	5.72	418
463	67.5	7.07	6.04	356
464	67.7	5.85	4.61	208
465	77.4	5.31	3.94	296
466	77.4	2.42	-0.60	117
467	80.4	7.96	7.04	466
468	80.5	6.31	5.15	340
469	79.5	5.99	4.78	378
470	80.5	7.16	6.14	490
471	80.1	7.19	6.18	488
472	80.7	8.35	7.48	631

Table 5

Experimental and Calculated Data on the Film Boiling of Benzene from a 0.496-Inch Outside Diameter Tube without a Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$	h_{co} $\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$	U ft/sec
473	3.23	276	963	780	70.4	64.4	4.32
474	3.71	320	1177	993	74.4	66.0	4.32
475	4.05	352	1021	837	106.2	99.6	7.93
476	4.62	400	1248	1062	108.7	99.4	7.93
477	4.92	414	1217	1030	129.0	120.1	10.85
478	4.35	382	941	754	138.6	132.9	10.85
479	4.92	432	1052	866	154.0	147.1	13.20
480	3.44	298	1020	838	75.5	68.9	3.82
481	3.00	262.5	778	596	81.1	76.8	3.82
482	4.22	363.5	602	418	231.0	227.9	7.82
483	5.06	439	1254	1067	130.9	121.5	7.82
484	4.82	464	740	554	255.0	251.0	9.88
485	6.08	526	1414	1222	164.6	153.0	9.88

Table 5

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda'}}$	A	B
473	22.2	2.46	-0.49	78
474	22.1	2.33	-0.79	56
475	20.1	2.76	0.07	82
476	18.1	2.51	-0.38	55
477	19.0	2.64	-0.11	69
478	23.2	3.24	0.99	126
479	22.6	3.12	0.78	109
480	41.1	2.74	0.09	120
481	40.9	3.21	0.94	178
482	40.5	6.92	5.93	314
483	39.9	3.08	0.71	119
484	40.5	6.75	5.67	287
485	41.3	3.23	0.98	110

Table 6

Experimental and Calculated Data on the Film Boiling of Benzene from a 0.638-Inch Outside Diameter Tube without a Screen

Run			t_i	Δt_o	h	h_{co}	U
No.	Volts	Amps	°F	°F	$\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$		ft/sec
620	5.65	800	1225	1028	178.2	169.4	8.48
621	5.19	734	1024	830	186.9	180.4	8.48
622	5.65	796	1039	893	204.3	197.1	10.32
623	4.34	591	825	636	168.0	163.4	5.75
624	4.66	680	1026	834	155.8	149.3	5.75
625	3.69	526	770	584	134.2	130.0	5.41
626	4.12	565	1218	1029	90.4	81.5	5.41
627	4.35	600	757	570	185.0	180.9	8.12
628	4.62	656	883	693	176.9	171.8	8.12
629	4.82	680	756	567	233.8	231.8	11.55
630	5.65	774	1008	803	220.5	214.3	11.55
631	3.69	519	1226	1040	71.1	62.1	5.35
632	3.27	451	949	764	77.9	72.1	5.35
633	3.98	544	916	730	118.9	113.4	8.20
635	4.38	605	1184	994	107.8	99.4	11.63
636	4.12	569	1126	939	101.0	93.3	11.63
637	4.68	644	943	753	162.1	156.4	13.50

Table 6

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta t_o}{Uk_v\rho_v\lambda'}}$	A	B
620	78.1	4.79	3.26	252
621	73.9	5.49	4.17	312
622	71.7	5.28	3.90	299
623	72.5	6.45	5.32	350
624	72.9	5.49	4.17	256
625	52.3	5.32	3.95	272
626	50.9	2.87	0.33	135
627	49.9	6.06	4.86	317
628	50.9	5.58	4.28	269
629	50.8	6.52	5.40	379
630	48.1	5.64	4.36	246
631	31.9	2.20	-1.12	83
632	30.1	2.82	0.23	118
633	31.1	3.64	1.62	157
635	28.1	2.42	-0.58	110
636	27.3	2.32	-0.81	114
637	27.5	3.88	2.00	166

Table 7

Experimental and Calculated Data on the Film Boiling of Carbon Tetrachloride from a 0.387-Inch Outside Diameter Tube without a Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$	h_{co} $\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$	U ft/sec
580	4.41	268	968	782	123.0	117.0	4.42
581	4.96	300	782	596	202.0	197.7	8.20
582	5.57	328	998	808	183.5	177.2	8.20
583	5.60	335	796	609	250.5	246.1	11.02
584	6.17	372.5	1108	924	202.0	195.6	11.02
585	6.15	372	904	712	260.5	255.2	13.29
586	6.68	409	1160	963	230.0	222.1	13.29
587	3.68	221.8	816	634	106.1	101.5	4.69
588	4.43	268	746	562	171.9	167.9	8.25
589	5.18	315.5	1062	873	152.8	145.4	8.25
590	4.89	291	659	474	243.7	240.3	11.00
591	5.55	340	955	765	200.0	194.2	11.00
592	5.75	349	842	652	249.5	244.7	13.33
593	6.22	377.5	1001	808	236.0	229.8	13.33
594	3.21	192	1102	921	53.8	46.4	4.61
595	3.88	231	655	473	155.1	151.7	8.18
596	4.43	272	1102	916	106.2	98.8	8.18
597	4.44	268	669	485	198.9	195.4	11.01

Table 7

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta t_o}{Uk_v\rho_v\lambda'}}$	A	B
580	81.6	7.71	6.77	440
581	80.0	9.19	8.40	710
582	79.4	8.60	7.76	532
583	76.5	9.89	9.16	774
584	75.3	8.29	7.42	530
585	74.0	9.66	8.91	716
586	72.3	8.57	7.72	531
587	60.4	6.30	5.14	332
588	60.7	7.70	6.76	476
589	60.4	7.09	6.06	321
590	61.9	9.17	8.18	631
591	62.4	8.10	7.20	428
592	62.4	9.05	8.24	545
593	61.8	8.75	7.92	445
594	27.0	3.13	0.80	125
595	26.3	6.70	5.61	278
596	28.3	4.84	3.33	171
597	27.8	7.50	6.54	330

Table 8

Experimental and Calculated Data on the Film Boiling of Carbon Tetrachloride from a 0.496-Inch Outside Diameter Tube without a Screen

Run			t_i	Δt_o	h	h_{co}	U
No.	Volts	Amps	°F	°F	$\frac{Btu}{(hr)(ft)^2(°F)}$		ft/sec
598	3.90	340	968	787	110.9	104.9	4.25
599	4.54	441	1007	824	148.0	141.6	8.16
600	4.35	394	769	587	183.9	179.7	8.16
601	4.56	448	842	659	195.9	191.2	11.00
602	4.95	481	1040	855	175.7	169.0	11.00
603	4.81	481	864	680	214.6	209.6	13.26
604	2.85	254.5	625	446	1020	98.8	3.97
605	3.07	283	792	613	89.2	84.8	3.97
606	4.12	376	841	660	148.1	143.3	8.36
607	4.71	431	1147	963	133.2	125.3	8.36
608	4.38	429	903	720	165.0	159.6	11.16
609	5.18	480	1152	967	162.3	154.4	11.16
610	2.54	232	599	421	87.8	84.6	4.48
511	3.53	327.5	714	534	137.0	133.2	8.30
512	4.14	382.5	1476	1293	76.8	64.1	8.30
513	3.91	379	800	619	152.1	147.6	11.10

Table 8

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D \Delta t_o}{U k_v \rho_v \lambda^{*}}}$	A	B
598	91.9	7.96	7.05	480
599	79.8	7.80	6.87	540
600	76.7	9.44	8.67	697
601	76.3	8.82	8.00	709
602	68.3	8.06	7.16	510
603	72.3	8.84	8.02	725
604	53.4	7.01	5.47	431
605	53.4	6.44	5.31	370
606	49.2	7.59	6.64	445
607	49.6	6.89	5.95	291
608	50.6	7.41	6.43	439
609	49.8	7.36	6.38	331
610	31.3	5.56	4.26	273
611	28.9	6.80	5.73	281
612	28.2	3.52	1.43	121
613	28.5	6.70	5.62	280

Table 9

Experimental and Calculated Data on the Film Boiling of Carbon Tetrachloride from a 0.638-Inch Outside Diameter Tube without a Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h Btu/(hr)(ft)^2(°F)	h_{co} Btu/(hr)(ft)^2(°F)	U ft/sec
614	2.46	368	1116	936	35.6	28.0	3.72
615	3.32	472	755	573	111.0	106.9	8.09
617	3.37	480	983	801	76.2	70.0	4.0
618	4.08	571	1064	876	105.1	98.1	6.1

Table 9

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda'}}$	A	B
614	27.3	2.62	-0.17	113
615	25.4	6.35	5.20	230
617	30.0	6.24	5.07	248
618	46.4	7.11	6.08	249

Table 10

Experimental and Calculated Data on the Film Boiling of Hexane from a 0.387-Inch Outside Diameter Tube without a Screen

Run			t_i	$\Delta t_o'$	h	h_{co}	U
No.	Volts	Amps	°F	°F	$\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$		ft/sec
508	2.98	191.1	720	559	74.3	70.5	3.96
509	3.92	239.8	716	553	130.7	126.9	8.74
510	4.82	288	1044	876	130.0	123.4	8.74
511	4.99	301	975	807	149.0	143.1	10.93
512	4.27	250	695	531	162.0	158.4	10.93
513	5.45	325.5	993	823	173.9	167.8	13.47
514	4.63	272	727	562	180.2	176.4	13.47
515	4.00	233.9	680	516	145.0	141.5	3.70
516	5.25	299.5	525	359	355.0	352.4	8.13
518	6.62	392	783	609	346.0	341.8	10.92
519	5.91	349	637	467	358.0	354.8	40.92
520	6.62	387.5	659	486	426.5	423.2	13.88
521	7.60	449	861	681	405.5	400.7	13.88
522	3.82	227	909	746	93.1	87.8	3.98
523	4.37	246.2	470	307	284.5	282.2	8.08
524	5.04	296.	665	498	242.7	239.3	8.08
525	5.23	300.7	561	394	323.0	320.2	10.90
526	6.03	360	1115	942	187.0	179.6	10.90
527	6.10	358	666	496	357.8	354.4	13.18

Table 10

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda'}}$	A	B
508	19.3	1.99	-1.67	65
509	10.1	2.34	-0.78	100
510	9.1	2.01	-1.61	53
511	9.1	2.09	-1.39	66
512	9.8	2.62	-0.16	114
513	8.5	2.21	-1.09	70
514	8.7	2.62	-0.16	113
515	86.1	3.96	2.12	288
516	76.5	6.69	5.60	562
518	68.8	5.57	4.27	340
519	69.1	5.89	4.66	496
520	69.1	6.22	5.05	488
521	66.4	5.51	4.19	319
522	49.6	2.24	-1.01	96
523	40.3	5.27	3.89	325
524	40.3	4.60	3.01	216
525	40.0	5.06	6.22	321
526	38.3	2.45	-0.51	110
527	37.1	5.35	3.99	250

Table 11

Experimental and Calculated Data on the Film Boiling of Hexane from a 0.496-Inch Outside Diameter Tube without a Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{Btu}{(hr)(ft)^2(°F)}$	h_{co} $\frac{Btu}{(hr)(ft)^2(°F)}$	U ft/sec
486	3.67	318.5	1064	902	81.5	74.6	3.86
487	2.90	263.5	838	678	70.2	65.4	3.86
488	4.11	365	987	824	114.0	107.9	7.82
489	3.49	303	722	561	118.2	114.4	7.82
490	4.43	400	980	816	135.9	129.9	10.72
491	5.00	439	1125	960	143.6	136.0	10.72
492	5.50	480	1139	972	170.7	163.0	13.38
493	4.99	434	966	801	169.1	163.2	13.38
494	4.28	382.5	1189	1036	98.7	90.3	3.82
495	4.76	415	509	346	359.5	357.0	8.16
496	5.51	495	772	606	283.5	279.3	8.16
497	5.92	526	735	568	346.0	342.1	10.92
498	6.74	601	940	770	332.5	326.9	10.92
499	6.42	591	770	600	400.0	395.9	13.42
500	7.44	660	753	581	532.0	528	13.42
501	3.56	335.3	1077	915	80.7	73.6	3.74
502	4.46	408	822	659	173.8	169.2	8.13
503	4.99	464	1194	1028	140.7	132.3	8.13
504	5.89	517	1035	867	227.5	221.0	10.90
505	4.64	455.5	622	458	292.0	288.9	10.90
506	5.84	521	735	570	295.0	291.1	13.26
507	6.48	576	1274	1103	213.5	204.1	13.26

Table 11

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda}}$	A	B
486	17.8	2.41	-0.62	33
487	18.6	2.35	-0.78	48
488	19.6	2.56	-0.28	52
489	19.6	2.99	0.55	82
490	18.6	2.64	-0.11	60
491	19.5	2.52	-0.38	49
492	19.6	2.69	-0.01	53
493	19.2	2.98	0.53	70
494	75.1	2.36	-0.72	114
495	71.8	7.61	6.66	540
496	68.7	5.94	4.72	300
497	66.4	6.34	5.19	356
498	62.6	5.60	4.30	226
499	68.9	6.55	5.44	380
500	61.5	8.81	7.98	354
501	43.9	2.04	-1.58	78
502	43.2	3.54	1.44	169
503	43.2	2.36	-0.72	93
504	40.8	3.66	1.66	127
505	41.2	5.42	4.08	275
506	38.8	4.90	3.40	220
507	38.3	2.78	0.18	92

Table 12

Experimental and Calculated Data on the Film Boiling of Hexane from a 0.638-Inch Outside Diameter Tube without a Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h	h_{co}	U ft/sec
					$\frac{}{(hr)(ft)^2(°F)}$		
528	2.29	344	759	599	52.1	48.0	4.17
529	3.18	424	728	566	94.8	90.9	8.04
530	3.66	497	1071	907	81.0	73.0	8.04
531	3.66	497	949	782	93.9	88.2	11.05
532	3.32	446	791	628	94.5	90.2	11.05
533	3.67	497	822	658	111.1	106.5	13.86
534	3.94	530	887	722	115.7	110.6	3.60
535	4.79	640	720	553	221.5	217.7	7.91
536	5.30	727	961	790	197.9	192.1	7.91
537	5.54	749	803	632	265.9	261.5	10.80
538	2.88	392	940	778	56.8	51.2	3.72
539	3.81	475	496	333	219.5	217.1	7.93
540	4.16	559	888	723	127.0	121.9	7.93
541	4.57	598	824	658	168.0	163.4	10.81
542	4.79	640	995	827	149.5	143.4	10.81

Table 12

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda'}}$	A	B
528	19.7	1.63	-2.82	64
529	18.6	2.23	-1.04	88
530	15.7	1.57	-3.06	40
531	16.4	1.69	-2.61	59
532	17.9	1.86	-2.05	85
533	18.2	1.96	-1.95	91
534	78.9	3.84	1.94	192
535	70.9	5.39	4.04	340
536	65.5	4.35	2.67	202
537	59.7	5.42	4.09	274
538	36.8	1.70	-2.57	82
539	39.7	5.31	3.94	302
540	39.3	2.86	0.30	136
541	37.9	3.22	0.96	177
542	36.0	2.60	-0.19	124

Table 13

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.387-Inch Outside Diameter Tube with Small Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$	h_{co} $\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$	U ft/sec
287	6.01	332.5	1527	1334	121.1	107.7	3.96
288	4.44	261.8	1113	929	101.2	93.7	3.96
289	4.06	240	1019	836	94.1	87.6	3.96
290	5.68	328	1372	1181	127.8	118.9	5.68
291	4.70	278.5	1076	891	118.9	111.8	5.68
292	6.52	376	1412	1216	163.5	152.1	8.02
293	5.03	300	947	761	160.8	155.0	8.02
294	7.20	415	1465	1264	192.1	179.9	10.88
295	5.48	327	804	617	235.6	231.1	10.88
296	8.06	454	1475	1269	234.0	221.8	13.71
297	6.17	368	800	610	302.0	297.6	13.71
298	6.26	358	1489	1294	140.2	127.5	5.45
299	4.85	284	635	451	247.8	244.5	5.45
300	5.25	304	1403	1214	106.1	94.7	3.60
301	4.15	247	981	799	84.0	77.9	3.60
302	7.61	427.5	1726	1520	173.1	156.2	7.90
303	5.92	352	712	524	322.5	318.7	7.90
304	8.96	495	1945	1729	208.0	186.5	11.02
305	7.05	424	810	615	394.0	389.5	11.02
306	8.92	526	1117	907	420.1	411.6	13.68
307	7.34	401	1972	1767	135.1	112.6	3.50
308	5.96	310	825	638	239.0	234.4	3.50
309	6.72	409	1134	939	237.0	229.4	5.15
310	6.16	376	905	714	263.5	258.2	5.15
311	7.87	477	1044	841	361.5	353.8	8.20
313	7.45	481	814	616	471.0	466.5	11.08
314	9.00	621	1148	931	487.0	479.4	11.08
315	7.46	580	998	794	443.5	437.4	13.88
316	5.71	336	1598	1406	110.2	95.5	3.50
317	5.24	268	1120	934	121.0	113.4	3.50
318	6.73	388.5	1737	1538	138.0	120.7	5.15
319	5.79	362.5	895	706	234.1	228.9	5.15
320	7.90	477	1153	949	322.5	314.7	8.00
321	7.18	368	924	732	385.0	379.5	8.00
322	9.02	535	1179	969	405.0	397	11.02
323	8.62	520	1098	890	409.0	402.9	11.02
324	9.95	600	1279	1057	459.0	449.9	13.70

Table 13

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta t_o}{Uk_v\rho_v\lambda}}$	A	B
287	17.0	3.88	2.00	49
288	17.5	3.56	1.51	78
289	19.1	3.34	1.16	95
290	18.9	3.66	1.66	73
291	19.0	3.58	1.55	104
292	17.1	3.90	2.03	77
293	17.0	4.19	2.45	128
294	15.0	3.93	2.07	92
295	17.7	5.26	3.88	184
296	17.2	4.30	2.71	93
297	19.1	5.80	4.55	216
298	39.5	4.20	2.46	145
299	40.1	7.18	6.17	407
300	40.5	3.62	1.60	124
301	41.1	3.14	.82	202
302	37.9	3.80	1.88	121
303	37.5	8.39	7.52	386
304	41.0	3.66	1.66	133
305	41.5	8.81	7.98	429
306	39.5	8.49	7.64	310
307	83.8	7.61	6.66	294
308	82.2	9.45	8.68	476
309	80.1	7.69	6.75	378
310	79.1	8.07	7.13	460
311	76.7	9.39	8.61	500
313	77.9	10.59	9.9	785
314	74.0	11.41	10.77	524
315	82.3	8.99	8.18	720
316	62.9	3.60	1.57	154
317	62.9	4.59	3.00	252
318	60.0	3.61	1.59	155
319	61.3	9.74	8.99	392
320	60.3	8.44	7.58	347
321	61.1	10.23	9.52	460
322	59.2	9.04	8.24	386
323	59.5	9.15	8.36	422
324	60.3	9.09	8.29	355

Table 14

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.496-Inch Outside Diameter Tube with Small Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$	h_{co} $\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$	U ft/sec
325	4.51	384	1398	1216	89.4	78.0	4.05
326	3.62	320	1037	858	83.6	76.9	4.05
327	5.43	456	1605	1419	109.4	94.4	5.68
328	4.26	385	1208	1026	100.2	91.5	5.68
329	5.69	486	1463	1276	137.0	124.6	7.98
330	4.84	431	1107	924	142.0	134.6	7.98
331	6.07	540	1437	1248	166.0	154.1	11.00
332	5.51	491	1137	952	179.1	170.0	11.00
333	6.76	578	1377	1186	206.0	195.0	13.82
334	6.90	599	1042	852	305.5	298.8	13.82
335	4.51	401	1380	1197	95.1	84.9	3.69
336	4.25	377.5	1225	1044	95.9	86.9	3.69
337	6.80	485	1600	1410	147.1	132.3	5.20
338	4.92	458	908	726	190.0	184.6	5.20
339	6.98	578	1678	1485	171.2	155.0	7.82
340	5.66	521	856	671	277.5	272.0	7.82
341	7.19	635	1065	874	330.0	323.1	10.88
342	6.60	600	936	745	334.5	328.9	10.88
343	7.85	688	1029	836	407.8	401.3	13.61
344	7.73	688	1047	853	394.0	387.3	13.40
345	4.99	440	1460	1258	107.9	95.5	3.92
346	4.80	418	1280	997	126.1	117.8	3.92
347	5.73	530	1062	876	219.2	212.3	5.48
348	5.94	551	1180	993	208.2	199.9	5.48
349	7.07	640	1169	977	292.5	284.4	7.89
350	8.18	729	1185	988	381.0	372.8	10.90
351	9.01	780	1157	956	464.0	456.1	13.58
352	6.02	504	1818	1629	117.8	98.6	3.98

Table 14

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D \Delta t_o}{U k_v \rho_v \lambda'}}$	A	B
325	22.9	3.18	0.89	75
326	23.8	3.29	1.08	116
327	21.2	3.14	0.82	73
328	21.5	3.26	1.02	100
329	20.6	3.58	1.54	86
330	22.2	4.10	2.32	135
331	20.7	3.80	1.88	103
332	20.6	4.38	2.71	141
333	20.3	4.35	2.67	120
334	20.3	6.65	5.56	166
335	43.0	3.62	1.60	135
336	43.1	3.82	1.91	159
337	43.7	4.63	3.06	131
338	43.5	7.00	5.96	280
339	39.5	4.30	2.60	132
340	45.7	8.40	7.54	374
341	41.5	8.41	7.55	303
342	42.7	8.60	7.76	366
343	42.3	8.79	7.96	336
344	42.4	8.74	7.91	336
345	62.0	3.90	2.03	184
346	59.5	5.06	3.62	238
347	61.8	7.39	6.41	324
348	63.9	7.32	6.32	295
349	60.5	8.68	7.84	336
350	61.9	9.66	8.90	392
351	59.1	10.72	10.40	431
352	82.7	3.96	2.12	186

Table 15

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.638-Inch Outside Diameter Tube with Small Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{Btu}{(hr)(ft)^2(°F)}$	h_{co} $\frac{Btu}{(hr)(ft)^2(°F)}$	U ft/sec
421	3.14	464	966	785	72.9	66.9	4.40
422	3.14	464	1002	821	69.5	63.1	3.99
423	3.60	519	1242	1059	70.0	60.8	3.99
424	3.68	530	1030	848	91.2	84.6	5.53
425	3.84	569	1219	1035	83.9	75.1	5.53
426	4.14	608	776	592	171.9	167.5	7.96
427	4.52	669	1308	1121	108.0	98.0	7.96
428	5.18	766	1322	1131	143.1	132.9	10.90
429	4.77	706	850	664	205.8	200.9	10.90
430	5.25	776	873	684	241.5	236.5	13.04
431	3.95	575	1309	1124	79.90	89.8	3.77
432	3.72	544	1042	859	94.20	87.5	3.77
433	4.56	676	1122	935	133.8	126.2	5.38
434	5.34	785	1100	909	186.5	179.2	7.32
435	5.04	752	988	799	192.1	186.2	7.32
436	4.56	670	1170	983	128.7	120.5	4.18
437	5.10	755	1124	934	167.1	159.5	5.58

Table 15

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D \Delta t_o}{U k_v \rho_v \lambda'}}$	A	B
421	24.9	3.06	0.67	133
422	23.9	3.10	0.74	121
423	22.5	3.02	0.60	90
424	22.3	3.52	1.42	126
425	21.8	3.12	0.79	101
426	20.9	5.69	4.42	195
427	20.5	3.33	1.14	101
428	20.5	3.80	1.88	114
429	20.7	5.94	4.72	202
430	20.4	6.41	5.27	188
431	43.3	4.41	2.75	149
432	43.4	4.41	2.75	201
433	40.1	5.29	3.92	199
434	39.6	6.45	5.32	233
435	40.4	6.55	5.44	266
436	60.3	5.59	4.29	252
437	59.5	6.55	5.44	295

Table 16

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.387-Inch Outside Diameter Tube with Large Screen

Run	Volts	Amps	t_i	Δt_o	h	h_{co}	U
No.			°F	°F	$\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$		ft/sec
364	4.62	260	1200	1015	95.2	86.6	4.03
365	4.21	236	954	772	103.6	97.7	4.03
366	4.95	280	1183	997	111.9	103.6	5.42
367	4.50	255	956	772	119.8	113.9	5.42
368	5.87	330.5	1122	932	168.6	161.0	7.95
369	6.20	346.5	1251	1059	164.1	154.9	7.95
370	6.90	386	1164	968	222.8	214.8	11.00
371	6.65	376	886	694	292.0	286.9	11.00
372	7.81	440	1047	849	328.2	321.6	13.24
373	4.85	280	1150	964	114.0	106.0	3.95
374	5.50	310	1421	1231	111.9	100.2	3.95
375	5.79	329.5	1254	1063	144.8	135.6	5.18
376	5.60	323	1148	969	149.1	141.2	5.18
377	7.08	406	1007	811	286.5	280.3	8.02
378	8.41	445	863	663	457.0	452.2	10.70
379	8.34	486	1154	948	346.2	338.4	10.85
380	7.62	456	990	791	355.5	349.5	10.85
381	9.28	520	1112	908	347.5	340.2	13.72
382	8.75	510	996	789	459.5	453.5	13.72
383	5.54	324	1183	994	146.1	137.8	3.63
384	5.17	292	881	696	175.9	170.8	3.63
385	6.65	386	1042	848	244.4	237.8	5.42
386	6.14	356	861	670	267.0	257.1	5.42
387	8.23	475	1141	936	338.0	330.4	7.98
388	7.76	448	930	730	385.5	380.0	8.22
389	8.83	510	1044	836	437.0	430.5	10.78
390	9.29	547	944	724	569.5	564.0	13.68
391	6.01	351	1156	965	177.2	170.4	3.52
392	7.09	406	966	771	302.2	296.4	5.54
393	8.17	479	996	793	400.0	393.9	7.91
394	9.20	535	1011	801	499.0	492.9	10.85
395	9.94	585	1000	784	602.0	596.0	13.63

Table 16

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda'}}$	A	B
364	23.3	3.26	1.20	95
365	23.8	3.73	1.77	129
366	22.3	3.36	1.19	105
367	22.8	3.74	1.78	141
368	21.3	4.31	2.62	128
369	21.1	4.12	2.35	113
370	21.8	4.66	3.10	138
371	23.3	6.58	5.48	220
372	22.8	6.23	5.06	190
373	42.0	4.04	2.24	193
374	41.9	3.66	1.66	129
375	41.4	4.47	2.84	176
376	41.1	4.71	3.16	208
377	38.5	7.55	6.59	266
378	46.0	11.00	10.34	458
379	42.5	7.75	6.82	285
380	43.3	8.14	7.25	352
381	42.5	6.99	5.95	332
382	43.1	9.37	8.59	390
383	63.4	5.44	4.10	242
384	64.1	6.50	5.38	338
385	63.2	7.76	6.83	352
386	62.9	8.40	7.54	410
387	61.4	8.84	8.02	355
388	60.7	10.10	9.38	464
389	58.6	9.96	9.23	433
390	62.3	11.83	11.21	586
391	79.5	6.87	5.81	303
392	78.3	9.62	8.86	466
393	76.3	10.70	10.20	521
394	74.9	11.40	10.66	589
395	71.7	12.39	11.80	635

Table 17

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.496-Inch Outside Diameter Tube with Large Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h	h_{co}	U ft/sec
					$\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$		
396	3.43	312	990	811	81.9	75.7	3.55
397	4.10	375.5	981	800	120.3	114.1	5.38
398	4.99	453	1031	848	161.1	154.5	7.92
399	5.54	515	1110	924	194.8	187.4	10.56
400	6.15	569	873	686	321.0	316.0	13.88
401	4.07	355	831	646	146.9	142.2	3.72
402	5.12	464	1019	835	179.3	172.8	5.33
403	6.61	582	988	800	304.0	297.8	8.05
404	7.47	674	1059	866	366.5	359.7	10.80
405	8.10	745	1064	868	444.0	437.2	13.58
406	5.53	497	1208	1023	169.6	160.9	3.55
407	6.40	576	1148	960	242.4	234.5	5.23
408	7.95	708	1196	1002	353.0	344.6	8.16
409	5.01	457	1050	866	167.0	160.2	3.88
410	6.47	570	1163	974	239.0	230.9	5.46

Table 17

[illegible]

[illegible]

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta t_o}{Uk_v\rho_v\lambda'}}$	A	B
396	24.3	3.55	1.49	115
397	24.5	4.25	2.53	150
398	22.1	4.72	3.17	147
399	19.9	4.97	3.50	138
400	20.6	7.31	6.32	218
401	42.5	6.44	5.31	264
402	38.9	6.19	5.01	204
403	42.1	9.08	8.27	209
404	41.3	9.44	8.67	304
405	40.0	10.24	9.52	320
406	80.9	7.25	6.25	292
407	77.2	8.76	7.93	368
408	67.1	10.28	9.57	365
409	62.1	7.04	6.00	285
410	62.5	8.44	7.58	294

Table 18

Experimental and Calculated Data on the Film Boiling of Ethyl Alcohol from a 0.638-Inch Outside Diameter Tube with Large Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h	h_{co}	U ft/sec
					$\frac{Btu}{(hr)(ft)^2(°F)}$		
412	3.36	496	1190	1009	65.9	57.4	3.75
413	3.68	550	1119	936	86.9	79.3	5.35
414	4.42	660	1087	801	147.6	140.4	7.98
415	5.03	745	1100	911	139.0	131.7	10.90
416	3.67	545	939	756	106.2	100.5	3.68
417	4.59	681	1006	995	126.4	119.9	5.46
418	5.43	800	1126	935	188.1	180.5	6.96
419	4.40	654	1132	946	122.1	114.4	3.75
420	5.78	776	1124	932	178.9	171.4	5.43

Table 18

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D \Delta t_o}{U k_v \rho_v \lambda'}}$	A	B
412	21.6	2.86	0.31	85
413	21.8	3.33	1.74	110
414	21.1	4.57	2.97	140
415	19.7	3.88	1.88	141
416	40.7	5.02	3.56	208
417	40.9	5.45	4.12	210
418	40.7	6.64	5.55	227
419	62.9	5.76	4.49	259
420	60.5	7.16	6.14	299

Table 19

Experimental and Calculated Data on the Film Boiling of Benzene from a 0.387-Inch Outside Diameter Tube with Large Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(^\circ\text{F})}$	h_{co}	U ft/sec
656	6.94	386	1169	969	224.0	215.9	5.40
657	6.38	355	948	752	243.9	238.2	5.40
658	8.03	446	1040	837	321.9	315.3	9.13
659	7.33	406	851	652	370.0	365.2	9.13
660	8.92	490	967	758	466.6	460.8	13.08
661	8.67	480	847	640	526.0	521.3	13.18
662	4.83	267.5	916	727	143.0	137.5	5.32
663	5.35	299.5	1276	1083	118.9	109.3	5.32
664	6.29	334.5	802	608	293.5	289.1	9.02
665	7.05	392	1014	815	274.0	267.7	9.02
666	8.13	454.5	1000	794	337.0	330.9	13.15
667	7.30	403.5	769	571	416.5	412.4	13.15
668	3.89	202	784	599	105.6	101.3	5.25
669	4.44	248	1008	821	108.1	101.7	5.25
670	5.33	296	908	710	180.2	174.9	9.00
671	6.12	339.5	1249	1103	152.0	142.7	9.00
672	6.83	380	1105	906	232.0	224.7	12.78

Table 19

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta t_o}{U k_v \rho_v \lambda'}}$	A	B
656	95.2	6.06	4.86	270
657	89.6	7.27	6.27	356
658	86.7	7.22	6.22	370
659	85.1	8.90	8.08	499
660	82.7	9.15	8.36	483
661	92.9	10.55	9.86	665
662	49.7	4.26	2.54	206
663	47.1	2.96	0.50	115
664	47.9	7.11	6.09	309
665	48.7	6.16	4.98	218
666	48.7	6.36	5.21	269
667	49.8	8.48	7.62	389
668	39.4	3.26	1.03	148
669	28.1	3.06	0.68	98
670	28.5	4.19	2.73	155
671	30.5	3.07	0.70	98
672	30.3	4.20	2.47	137

Table 20

Experimental and Calculated Data on the Film Boiling of Benzene from a 0.638-Inch Outside Diameter Tube with Large Screen

Run No.	Volts	Amps	t_i °F	Δt °F	h Btu/(hr)(ft)^2(°F)	h_{co} Btu/(hr)(ft)^2(°F)	U ft/sec
638	6.09	820	1079	882	228.2	221.2	8.35
639	5.16	731	786	594	257.5	253.2	8.35
640	5.76	795	850	656	282.5	277.7	10.54
641	4.69	667	969	779	162.9	156.8	5.28
642	4.32	595	715	527	197.1	193.4	5.28
643	3.79	519	682	496	159.9	156.3	5.28
644	4.11	575	854	667	143.8	138.9	5.28
645	4.60	627	611	423	276.0	272.9	9.62
646	5.03	690	774	584	230.3	226.1	9.62
647	5.78	800	836	641	292.0	287.3	13.10
648	5.74	792	917	722	254.5	249.1	13.10
650	3.19	440	759	573	97.7	93.5	5.04
651	3.37	510	1171	982	70.0	61.7	5.04
652	4.32	530	675	487	190.0	186.5	9.05
653	4.22	578	748	559	177.0	173.0	9.05
654	4.89	666	733	540	244.0	240.1	12.84
655	5.40	746	1199	998	163.5	154.3	12.84

Table 20

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D \, \Delta \, t_o}{U k_v \rho_v \lambda'}}$	A	B
638	83.5	6.61	3.51	324
639	78.7	8.32	7.45	485
640	73.7	7.91	6.99	467
641	73.5	6.14	4.96	273
642	74.5	8.10	7.20	406
643	49.1	6.56	5.45	282
644	48.9	5.64	4.35	218
645	49.2	8.49	7.64	414
646	49.1	6.95	5.90	330
647	48.9	7.46	6.49	346
648	50.5	6.32	5.16	316
650	33.9	4.09	2.31	173
651	28.5	2.30	-.86	78
652	25.5	5.98	4.76	249
653	27.9	5.50	4.18	200
654	28.5	6.43	5.30	234
655	27.2	3.56	1.52	111

Table 21

Experimental and Calculated Data on the Film Boiling of Carbon Tetrachloride from a 0.387-Inch Outside Diameter Tube with Large Screen

Run No.	Volts	Amps	t_i °F	Δt_o °F	h $\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(°\text{F})}$	h_{co}	U ft/sec
564	4.50	268.2	694	510	191.5	187.8	4.23
565	6.32	364	1080	886	219.2	212.2	8.16
566	5.59	320	541	354	409.3	406.6	8.16
567	6.32	384	823	630	311.9	307.3	10.93
568	6.80	411	1069	873	259.6	252.7	10.93
569	6.47	379.5	569	388	511.0	508.2	13.25
570	7.20	431	981	783	322.0	316.0	13.25
571	3.78	234.2	808	626	114.9	110.3	3.89
572	4.91	295.5	653	468	252.0	248.6	8.10
573	5.44	330.5	952	763	191.5	185.7	8.10
574	5.57	338	704	516	296.0	292.3	10.86
575	5.94	367	942	751	236.5	230.8	10.86
576	6.18	376	764	573	330.0	225.9	13.31
577	6.86	414.6	936	740	311.5	305.9	13.31
578	3.28	200	918	737	71.4	65.9	4.23
579	4.42	268	692	508	190.9	106.2	8.01

Table 21

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda'}}$	A	B
564	87.7	11.72	11.10	664
565	82.1	10.41	9.71	512
566	79.4	16.70	16.26	1050
567	77.8	12.48	11.89	761
568	75.4	10.70	10.20	552
569	75.4	16.92	16.48	1195
570	74.0	12.02	11.41	661
571	71.3	7.48	6.51	312
572	52.0	11.01	10.35	558
573	51.3	9.00	8.19	364
574	50.6	11.49	10.85	571
575	50.3	9.66	8.90	415
576	52.2	8.15	7.26	605
577	50.6	11.52	10.88	469
578	47.4	4.41	2.75	149
579	36.7	4.83	3.32	266

Table 22

Experimental and Calculated Data on the Film Boiling of n-Hexane from a 0.387-Inch Outside Diameter Tube with Large Screen

Run	Volts	Amps	t_i	Δt_o	h	h_{co}	U
No.			°F	°F	$\frac{\text{Btu}}{(\text{hr})(\text{ft})^2(^\circ\text{F})}$		ft/sec
543	4.87	288	639	473	240.0	236.8	4.08
544	6.02	356.5	648	498	350.0	346.6	7.65
545	7.65	448	1158	975	284.8	277.0	7.65
546	7.49	441	858	679	395.5	390.8	11.02
547	6.54	382	615	443	457.	454.0	11.02
548	7.47	439	718	541	492.8	488.1	13.26
549	6.97	406	596	422	544.0	541.1	13.26
550	4.75	285.8	958	792	138.1	132.3	5.71
551	4.84	280	538	372	282.0	279.4	7.90
552	6.05	360	1207	1033	170.5	162.0	7.90
553	6.06	359	693	522	335.5	331.9	11.08
554	6.80	409	1084	907	248.0	241.0	11.08
555	7.36	430	1093	912	281.5	274.5	11.08
556	6.11	388.2	581	410	470.0	467.2	13.30
557	6.82	407	759	584	386.0	382.0	13.30
558	4.02	240	1033	868	88.9	82.3	3.95
559	4.31	256	748	583	152.5	148.5	7.88
560	4.79	287	950	783	142.2	136.5	7.88
561	4.45	284	670	505	202.0	198.6	10.68
562	5.36	320	958	789	176.0	170.2	10.68
563	5.41	317	666	498	279.0	275.6	13.26

Table 22

Run No.	Δt_{sc} °F	$h_{co}\sqrt{\frac{D\,\Delta\,t_o}{Uk_v\rho_v\lambda'}}$	A	B
543	80.1	6.44	5.31	331
544	73.5	6.87	5.81	386
545	68.9	4.64	3.07	150
546	64.8	6.16	4.98	282
547	63.5	7.50	6.54	442
548	63.0	7.31	6.32	407
549	66.1	8.13	7.24	527
550	39.1	2.74	0.04	103
551	38.4	5.38	4.03	269
552	37.2	2.60	-0.19	78
553	37.3	5.44	4.10	217
554	37.4	3.48	1.38	108
555	38.0	3.91	2.04	109
556	40.5	6.99	5.86	340
557	38.1	5.65	4.36	222
558	23.7	1.99	-1.66	46
559	20.5	2.86	0.31	92
560	20.9	2.42	-0.58	64
561	21.2	3.33	1.14	127
562	21.1	2.58	-0.23	74
563	20.9	4.14	2.38	141

Table 23

Diffusivity of Heat Calculated By Equation 50 for Film Boiling of Ethyl Alcohol from 0.387" O. D. Tube

Run No.	U ft/sec	A	α ft^2/hr
116	3.5	4.81	0.226
117	3.5	1.51	0.115
119	5.2	6.08	0.408
120	5.2	1.02	0.129
122	8.0	7.42	0.566
124	10.9	6.90	1.01
125	10.7	7.92	0.615
128	13.1	8.55	1.542
131	3.6	1.79	0.213
132	5.02	2.40	0.232
133	5.02	6.42	0.318
134	5.02	1.77	0.202
135	8.05	6.48	0.846
136	8.05	8.48	0.573
138	10.9	6.58	0.968
139	10.9	8.30	0.590
141	13.7	7.81	1.110
142	3.6	5.73	0.246
143	13.67	7.71	0.810
144	13.67	3.84	0.973
152	6.8	2.58	0.555
155	11.00	3.02	0.796
156	11.00	1.12	0.690
157	13.78	1.35	0.65
158	13.78	4.17	1.510
161	7.93	6.66	0.715
162	11.25	6.09	0.969
163	13.725	6.99	1.230
164	13.725	7.44	1.183
166	7.89	3.41	0.814
167	10.69	3.21	1.160

SAMPLE CALCULATIONS

The data of run number 124, which was the boiling of ethyl alcohol from a 0.387-inch outside diameter tube at a liquid velocity of 10.85 feet per second at the nozzle, are used to illustrate the method of calculation.

The current through the rod was 505 amperes and the voltage drop across the five-inch test section was 8.25 volts. The heat generated in this five-inch section is

$$q = 505 \times 8.25 \times 3.412 = 14,210 \ \frac{\text{Btu}}{\text{hr}} \ .$$

The temperature of the inside of the tube was determined to be 1170°F by a thermocouple inserted to the center of the tube. The temperature of the outside surface is found from the following relationship[1]

$$t_i - t_T = \left(\frac{q}{A} \right) \left(\frac{D}{2k_g} \right) \left[\frac{1}{2} - \left(\frac{D_i^2}{D^2 - D_i^2} \right) \ln \frac{D}{D_i} \right],$$

where k_g is the conductivity of the graphite and D_i is the inside diameter of the tube. The value of the thermal conductivity of the graphite was taken from information supplied by the National Carbon Company.

$$t_T = 1170 - \left(\frac{q}{\pi \cancel{D} \frac{5}{12}} \right) \left(\frac{\cancel{D}}{2k_g} \right) \left\{ .5 - \left[\frac{(0.1875)^2}{(0.387)^2 - (0.1875)^2} \right] \ln \frac{0.387}{0.1875} \right\},$$

$$t_T = 1170 - \frac{14,210}{48.9} (0.1063),$$

$$t_T = 1170 - 31 = 1139°\text{F}.$$

The boiling point of ethyl alcohol under a liquid head of 2.65 feet was 175.7°F. The temperature difference across the film was, therefore,

$$\Delta t_o = 1139 - 176 = 963°\text{F}.$$

The temperature of the liquid measured by a thermocouple was found to be 116.6°F. The amount of subcooling of the liquid was 59.1°F.

$$\Delta t_{sc} = 175.7 - 116.6 = 59.1°\text{F}.$$

The observed coefficient of heat transfer was therefore,

$$h_{obs} = \frac{q}{A\ \Delta t_o} = \frac{14,210}{(0.0422)(963)} = 350\ \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(°\text{F})}\ .$$

The actual value of the coefficient of heat transfer is less due to the heat loss through the ends of the tube. The actual value can be found from the following equation:[3]

$$\frac{h}{h_{obs}} = \frac{\cosh \frac{L}{2}\sqrt{\frac{W}{\Delta t'_o\ k_g}} - 1}{\cosh \frac{L}{2}\sqrt{\frac{W}{\Delta t'_o\ k_g}} - \frac{\Delta t_{L/2}}{\Delta t_o}}\ , \qquad (60)$$

where w is the heat generation per unit volume, $\Delta t'_o$ is the temperature difference across the film if there were no conduction along the tube, and $\Delta t_{L/2}$ is the measured temperature difference across the film at the end of the section. Solving this equation by trial and error, we find

$$\frac{h}{h_{obs}} = 1\ .$$

Therefore,

$$h = 350\ \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(°\text{F})}\ .$$

The radiation coefficient of heat transfer is determined by equation (54). The absorptivity of the liquid is taken to be unity and the emissivity of the graphite to be 0.8.[6]

$$h_r = \frac{0.80}{\Delta t_o} \left[T_T{}^4 - T_b{}^4 \right],$$

$$h_r = \frac{0.8(0.1713 \times 10^{-8})}{963}, \left[(1599)^4 - (636)^4 \right]$$

$$h_r = 9.05 \quad \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(°\text{F})}.$$

The value of the convection heat transfer coefficient h_{co} is determined from equation (53):

$$h_{co} = h - 7/8 \text{ hr},$$

$$h_{co} = 350 - 7/8\ (9.05) = 342 \quad \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(°\text{F})}.$$

In order to evaluate the parameters used to correlate the data, it is necessary to determine the physical properties of the liquid and vapor.

The values of the thermal conductivity and the heat capacity of the vapor at the average film temperature are found to be

$$k_v = 0.030 \quad \frac{\text{Btu}}{(\text{hr})(\text{ft}\ )(°\text{F})},$$

$$Cp_v = 0.599 \quad \text{Btu/lb},$$

$$t_{ave} = \frac{t_T + t_b}{2} = 658°\text{F or } 1118°\text{R}.$$

The density of the vapor from equation (61) is equal to

$$\rho_v = \frac{2\rho_b T_b}{\Delta t_o} \left(1 - \frac{1}{\Delta t_o} \ln \frac{T_T}{T_b} \right),$$

$$\rho_b T_b = \frac{PM}{R} = \frac{(1.03)(46.07)}{0.729} = 65.2 \quad \frac{16°\text{R}}{\text{ft}^3},$$

$$\rho_v = \frac{2(65.2)}{963} \left(1 - \frac{1}{963} \ln \frac{1599}{636} \right),$$

$$\rho_v = 0.0530 \text{ lb/ft}^3.$$

The difference between the heat content of the vapor and the liquid at its boiling point is found from equation (62):

$$\lambda' = \lambda_o \left(1 + 0.4 \frac{Cp_v \, \Delta t_o}{\lambda_o}\right)^2 .$$

$$\lambda' = 366 \left[1 + 0.4 \frac{(0.590)(963)}{(366)}\right]^2 ,$$

$$\lambda' = 950 \quad \text{Btu/lb} .$$

The average temperature at which the liquid properties were evaluated was found to be

$$t_{ave} = \frac{175.7 + 166.6}{2} = 146.2 \quad {}^\circ\text{F} .$$

The physical properties at this temperature were

$$Cp_1 = 0.693 \quad \text{Btu/(lb)(}^\circ\text{F)},$$

$$o_1 = 46.77 \quad \text{lb/ft}^3,$$

$$k_1 = 0.0789 \quad \text{Btu/(hr)(ft)(}^\circ\text{F)},$$

$$\mu_1 = 0.2111 \quad \text{lb/(ft)(hr)}.$$

The parameters used to correlate the data can now be evaluated:

$$h_{co}\sqrt{\frac{D \, \Delta t_o}{Uk_v \rho_v \lambda'}} = 342\sqrt{\frac{(0.387)(963)}{(12)(10.85)(3600)(0.030)(0.0530)(950)}}$$

$$= 7.83;$$

$$h_{co}\sqrt{\frac{D \, \Delta t_o}{Uk_v \rho_v \lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{Uk_v \rho_v \lambda'}{D \, \Delta t_o}} = 7.83 - \frac{7.29}{7.83} = A$$

$$= 6.90;$$

$$\Delta t_{sc}\sqrt{\frac{Cp_1 \rho_1 k_1}{\Delta t_o \, k_v \rho_v \lambda'}} = 59.1\sqrt{\frac{(0.693)(46.77)(0.0789)}{(963)(0.030)(0.0530)(950)}}$$

$$= 2.47.$$

To calculate the parameter B, it was necessary to calculate the velocity of the fluid in the straightening vanes. The area of the nozzle was 5.04 square inches and the area of the pipe in which the straightening vanes were located was 28.28 square inches. The area ratio was calculated to be 0.178. The velocity of the fluid in the straightening vanes for this run was

$$U_o = U\,(0.178),$$

$$U_o = (10.85)(0.178)(3600) = 6.96 \times 10^3 \text{ ft/hr.}$$

The length l_o was the width of the 3/4-inch square honeycomb straightening vanes. By combining terms, the parameter B can be reduced to

$$B = \Delta t_{sc}\, Cp_1\, \rho_1\, \frac{(U_o l_o)^{0.45}}{(\Delta t_o\, k_v\, \rho_v \lambda')^{1/2}}\, \left(\frac{\mu_1}{\rho_1}\right)^{0.05}.$$

Evaluating this parameter we find

$$B = (59.1)(0.693)(46.77)\, \frac{(6.96 \times 10^3)^{0.45}(0.75/12)^{0.45}}{\left[(963)(0.030)(0.0530)(950)\right]^{1/2}}\, \left(\frac{0.211}{46.77}\right)^{0.05},$$

$$B = 635.$$

To take into account the effect of the nozzle on the eddy viscosity, this value of B was divided by the square root of the ratio by which the eddy viscosity decreases when passing through a contraction. Equation (72) shows that

$$\frac{\varepsilon_{m_1}}{\varepsilon_{m_2}} = \frac{U_1' \, U_1'}{U_2' \, U_2'} = 2.825,$$

$$\sqrt{\frac{\varepsilon_{m_1}}{\varepsilon_{m_2}}} = 1.68.$$

The value used for B in the figures was therefore

$$B = \frac{635}{1.68} = 378.$$

This factor was introduced into B to correct for the effect of the nozzle on the eddy viscosity, which is not taken into account in the equation used for eddy viscosity in B. The equation used for eddy viscosity in B is for the case when the turbulence is generated in a straight conduit.

Values of the diffusivity of heat, α, that were effective in this system were calculated by the use of equation (50).

$$h_{co}\sqrt{\frac{D\ \Delta t_o}{Uk_v\,\rho_v\lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{Uk_v\,\rho_v\lambda'}{D\ \Delta t_o}} = 0.136\ \Delta t_{sc}\ Cp_l\ \rho_l\sqrt{\frac{\alpha}{\Delta t_o\ k_v\,\rho_v\lambda'}}$$

$$6.90 = (0.136)(59.1)(0.693)(46.77)\sqrt{\frac{\alpha}{\Delta t_o k_v\,\rho_v\lambda'}}$$

$$0.0250 = \sqrt{\frac{\alpha}{(963)(0.030)(0.0530)(950)}}$$

$$\alpha = 1.01\ \ \text{ft}^2/\text{hr.}$$

DISCUSSION OF RESULTS

The values of the heat transfer coefficient h_{co} across the vapor film are shown plotted as a function of the amount of subcooling of the liquid with the velocity of the liquid as a parameter in Figures six through nine. At liquid velocities above eight feet per second at the nozzle, the heat transfer coefficients h_{co} are noted to be increased approximately fourfold by subcooling the liquid approximately eighty degrees Fahrenheit. These heat transfer coefficients thereby approach the values of the heat transfer coefficients in nucleate boiling.

The dimensionless parameters, which are plotted in Figure 10, are proposed in equation (47) to correlate the data when the mechanism of heat transfer into the liquid is thermal conduction. The data in Figure 10 show that the dimensionless group A, $h_{co}\sqrt{\frac{D\,\Delta t_o}{Uk_v\,\rho_v\lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{Uk_v\,\rho_v\lambda'}{D\,\Delta t_o}}$, is much greater than that theoretically predicted for thermal conduction and that there is also a dependence on velocity that has not been accounted for in the theoretical parameters. This indicates that the means by which heat is transferred into the liquid in forced convection film boiling is not by thermal conduction but by eddy conduction.

The diffusivity of heat into the liquid was calculated from equation (50) for ethyl alcohol from the data shown in Figure 10. The values thus obtained were plotted as a function of the velocity of the liquid at the nozzle in Figure 11. The values of the diffusivity are approximately one hundred fold larger than the thermal diffusivity ($\frac{k}{Cp\,\rho}$) and approach the estimated eddy viscosity of the system. This shows that the heat is transferred into the liquid by eddy conductivity and that the effect of thermal conductivity is negligible.

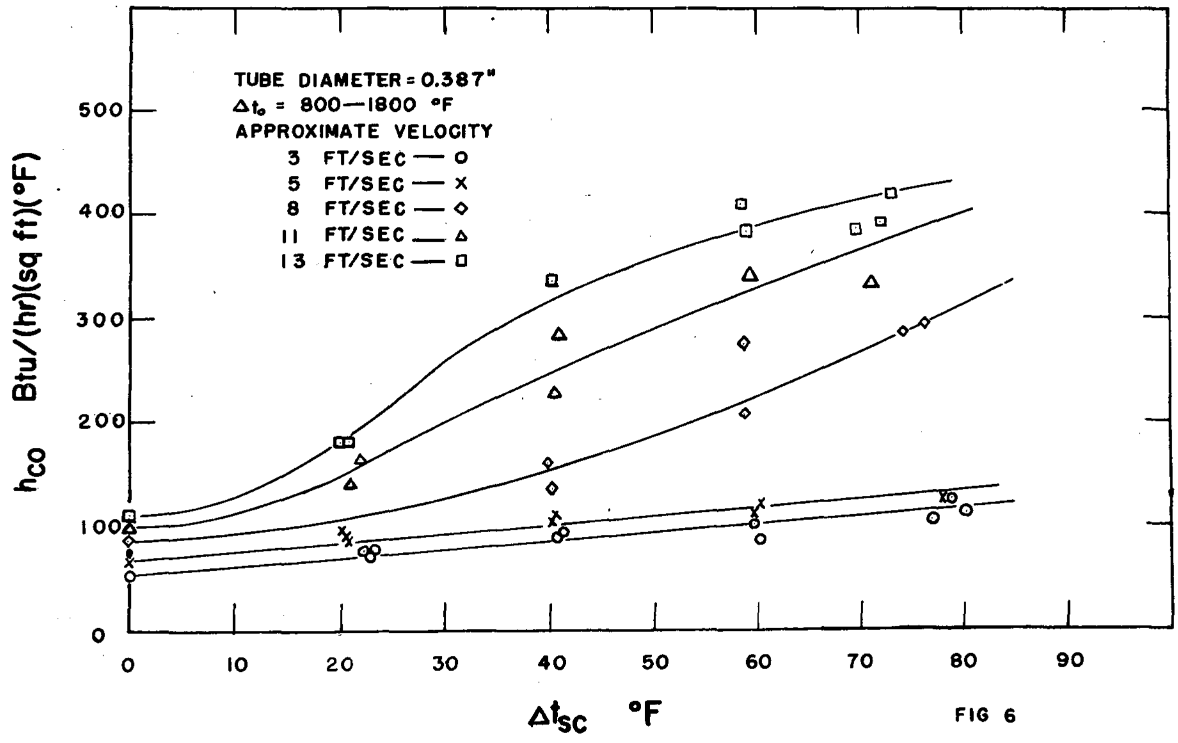


FIG 6

FILM BOILING OF ETHYL ALCOHOL

MU-7029

Fig. 6

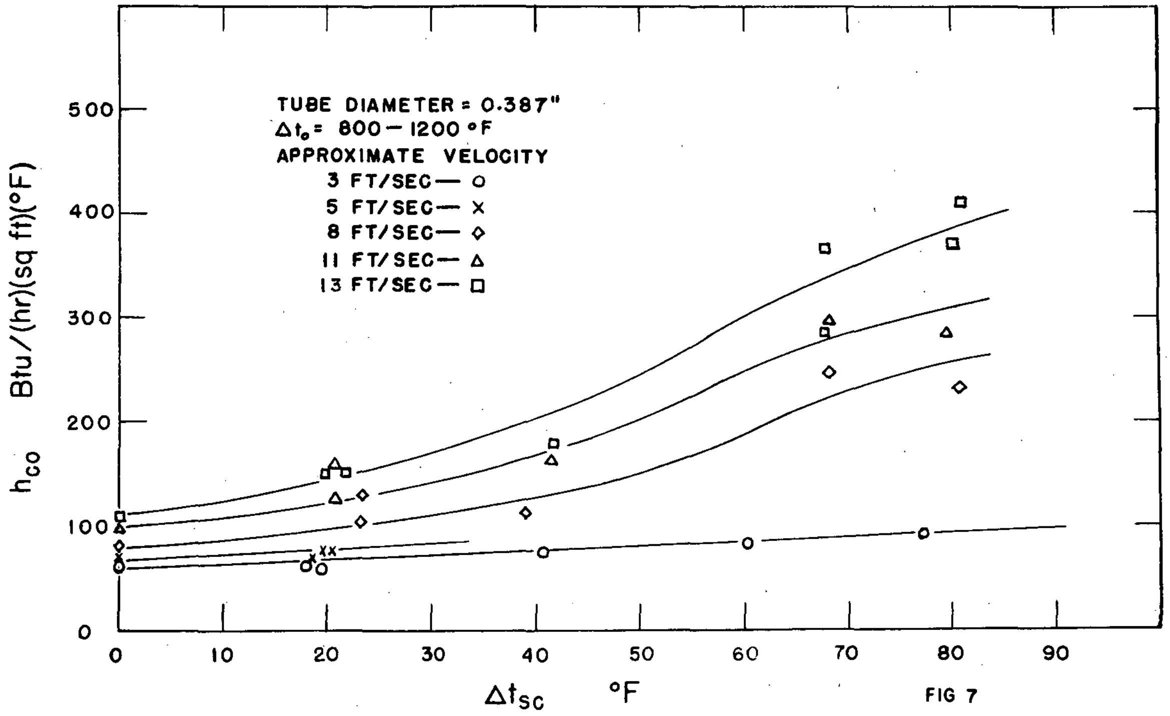


FIG 7

FILM BOILING OF BENZENE

MU-7030

Fig. 7

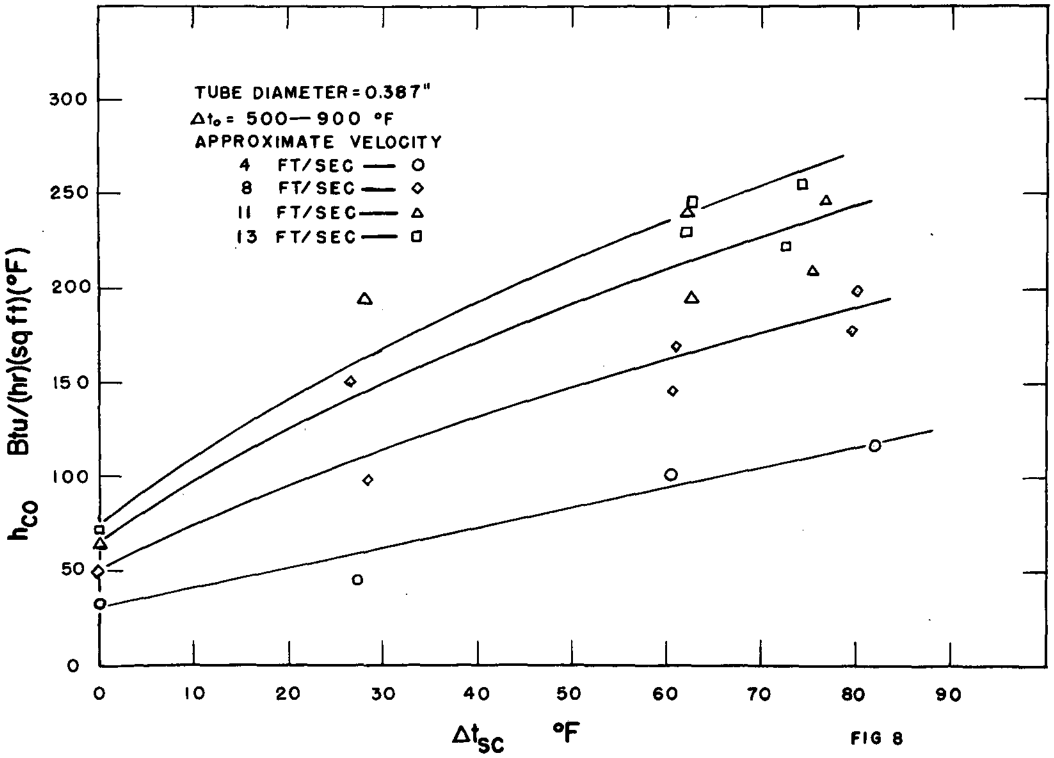


FIG 8

FILM BOILING OF CARBON TETRACHLORIDE

MU-7031

Fig. 8

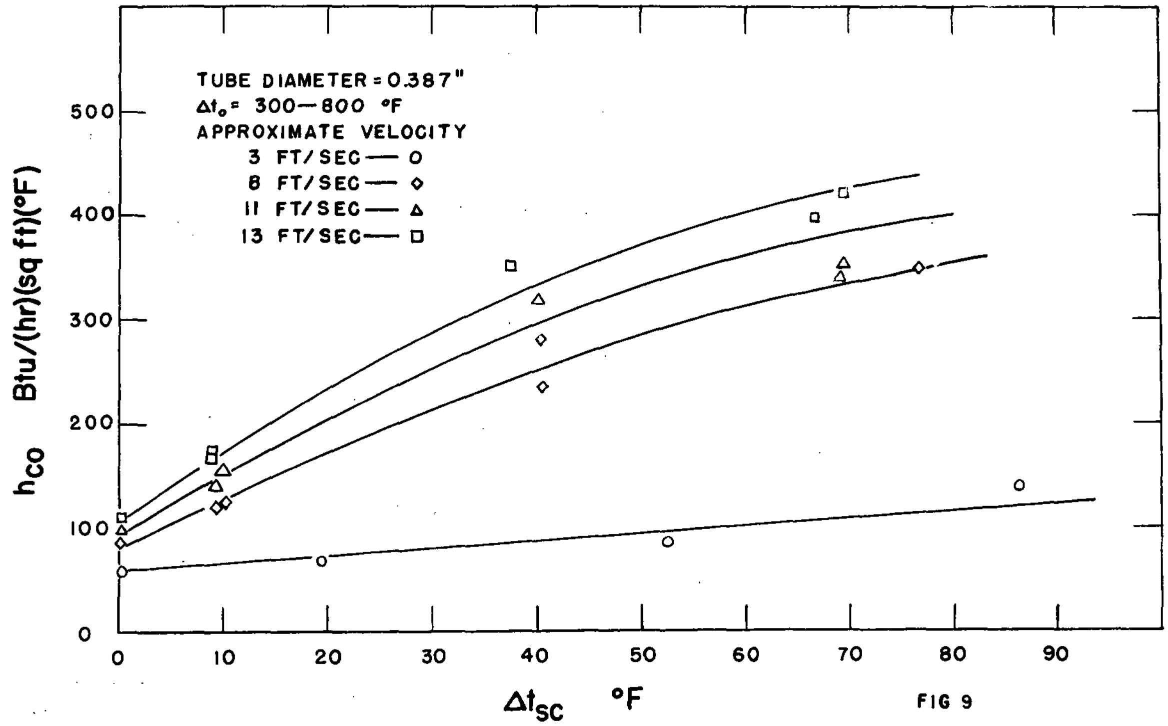


FIG 9

FILM BOILING OF HEXANE

MU-7032

Fig. 9

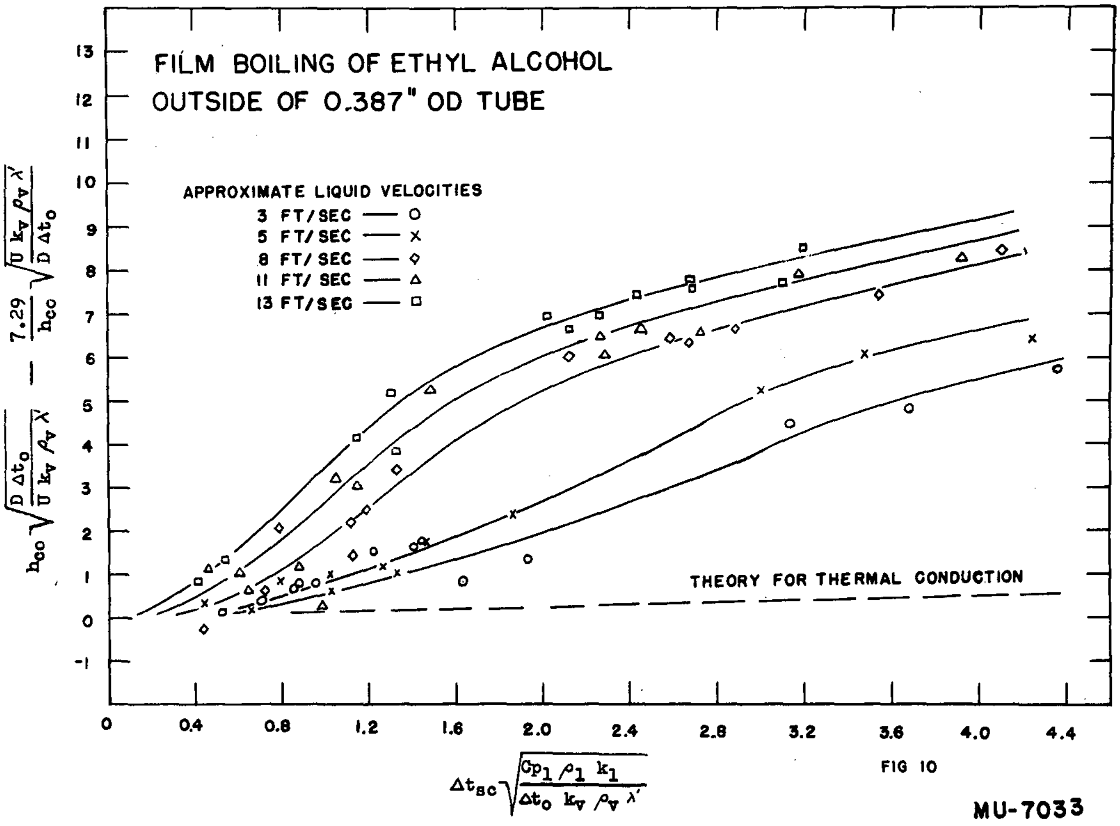
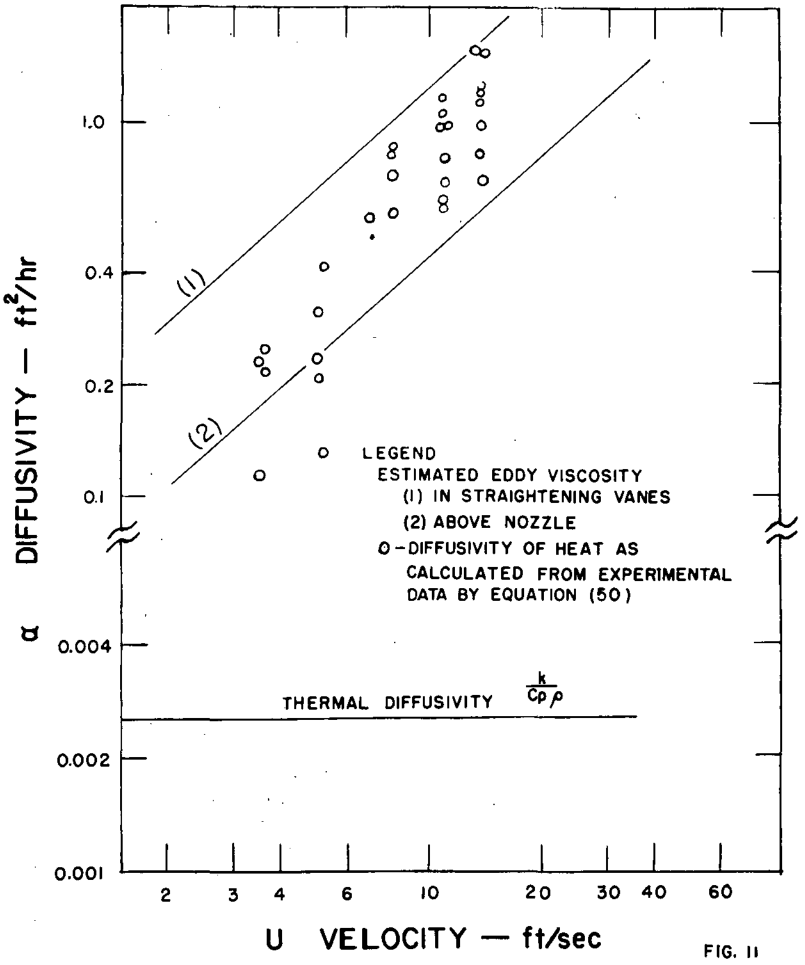

FILM BOILING OF ETHYL ALCOHOL
OUTSIDE OF 0.387" OD TUBE
APPROXIMATE LIQUID VELOCITIES
3 FT/SEC — ○
5 FT/SEC — ×
8 FT/SEC — ◇
11 FT/SEC — △
13 FT/SEC — □
THEORY FOR THERMAL CONDUCTION
$h_{co}\sqrt{\frac{D\,\Delta t_o}{U\,k_v\,\rho_v\,\lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{U\,k_v\,\rho_v\,\lambda'}{D\,\Delta t_o}}$
$\Delta t_{sc}\sqrt{\frac{Cp_1\,\rho_1\,k_1}{\Delta t_o\,k_v\,\rho_v\,\lambda'}}$
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
FIG 10
MU-7033

Fig. 10



DIFFUSIVITY OF HEAT IN ETHYL ALCOHOL

MU-7034

Fig. 11

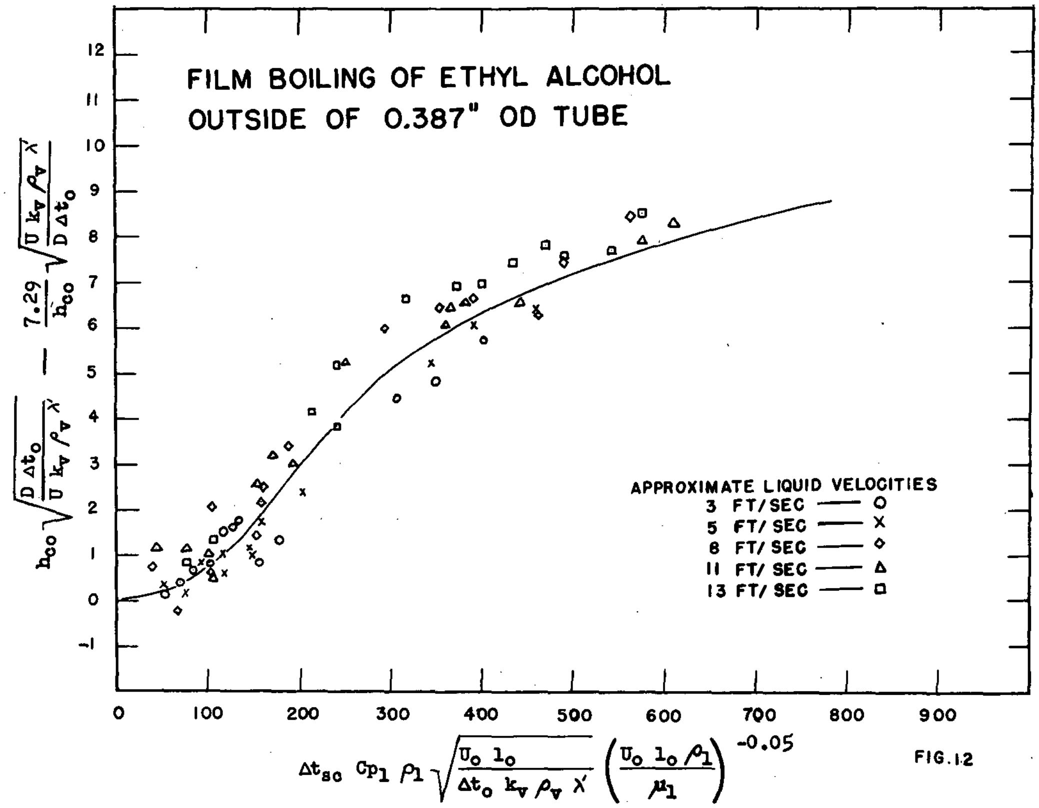


FIG.12

MU-7035

Fig. 12

Figure 12 shows the same data for ethyl alcohol as are shown in Figure 10 plotted as predicted by equation (64) for heat transferred into the liquid by eddy conduction. The systematic variation with velocity noted in Figure 10 is now no longer apparent.

It has been noted that the only significant difference between the equation for long and short contact times was that there was an additional dependence of the dimensionless group A upon the diameter of the tube for the case when the contact time was short enough to be smaller than the ratio of the scale of turbulence to the intensity of turbulence. Figure 13 shows that there is no systematic dependence upon the size of the tube and thereby indicates that the time of contact is large compared to the ratio of the scale of turbulence to the intensity of turbulence. Figures 14, 15 and 16 show the data for film boiling of benzene, carbon tetrachloride and hexane respectively. Figure 17 shows a summary of the data for all four systems. The best line drawn through all the data by eye is shown as a solid line in Figures 12 through 17.

The effect of introducing screens above the nozzle upon the dimensionless parameter A, is shown in Figures 18 through 21. The solid line in these figures represents the best line that could be drawn by eye through all the data with screens. Since Figure 18 shows the large screen to have approximately the same effect as the small screen, only the large screen was used with the other liquid systems. It is noted that the screens cause an increase in group A of approximately 30% over that shown in Figure 17. This seems reasonable since though the screens increase the intensity of turbulence markedly, they also decrease the scale of turbulence. If the time of contact had been short enough so that the eddy conductivity was independent of the scale of turbulence, we would have expected the screens to cause a much

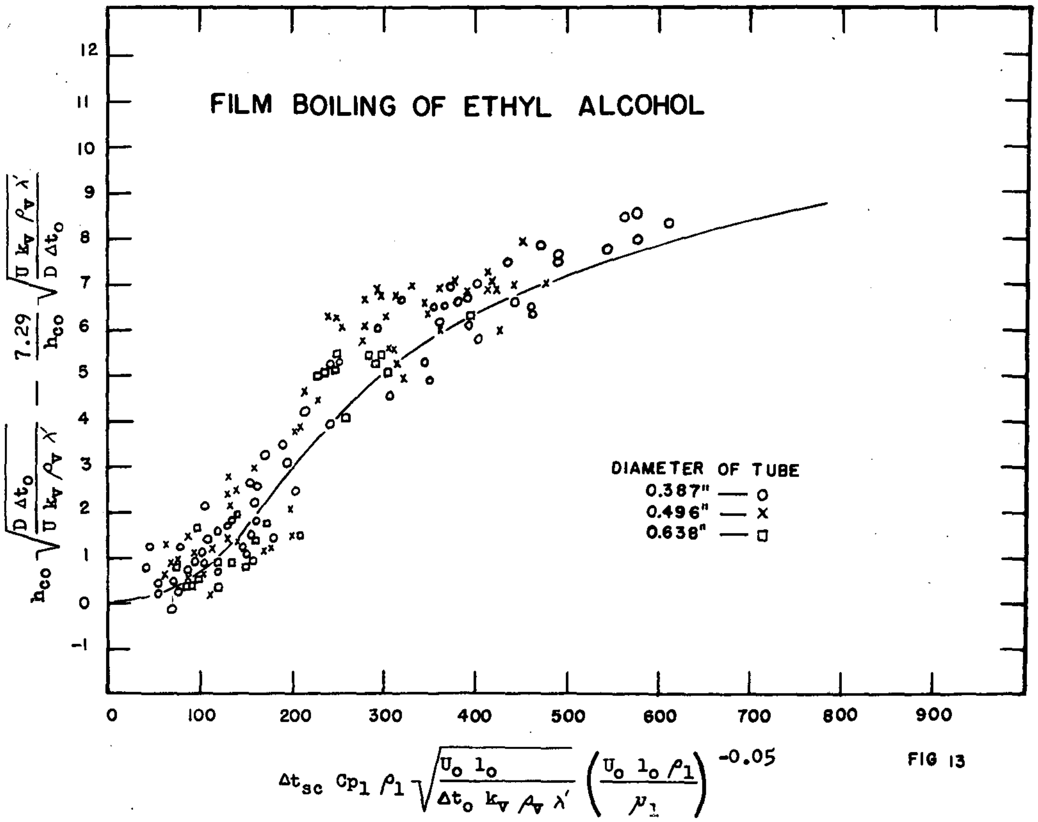
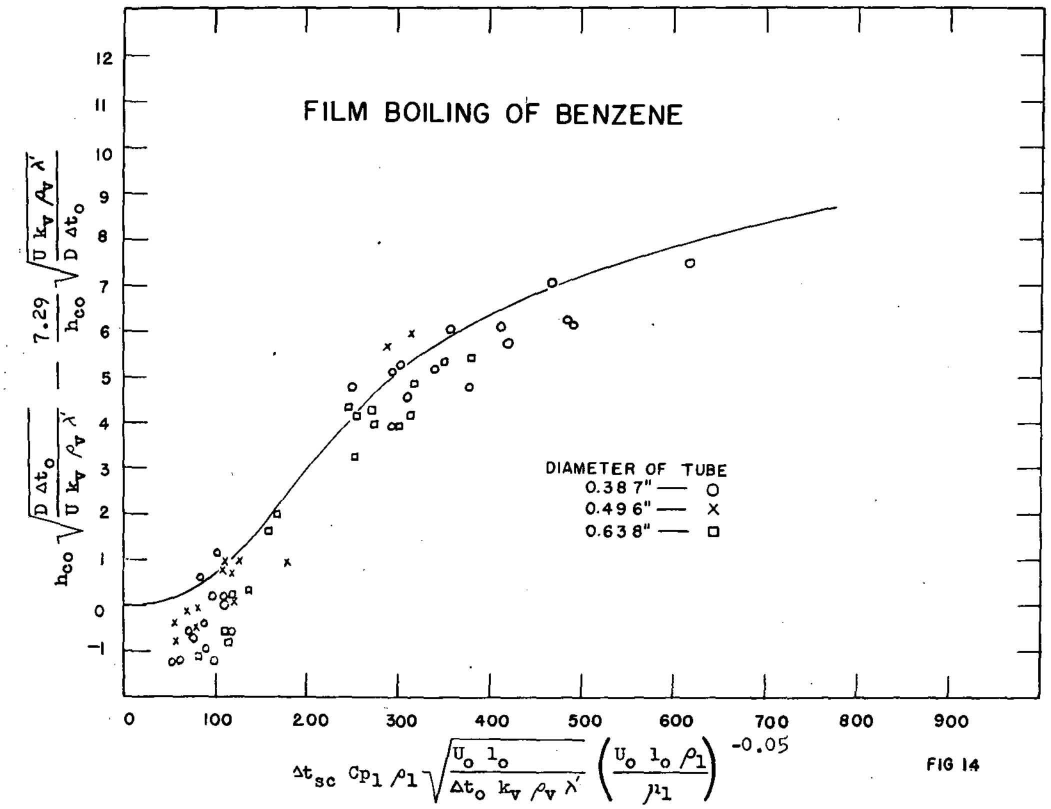


FIG 13

MU-7036

Fig. 13



MU-7037

Fig. 14

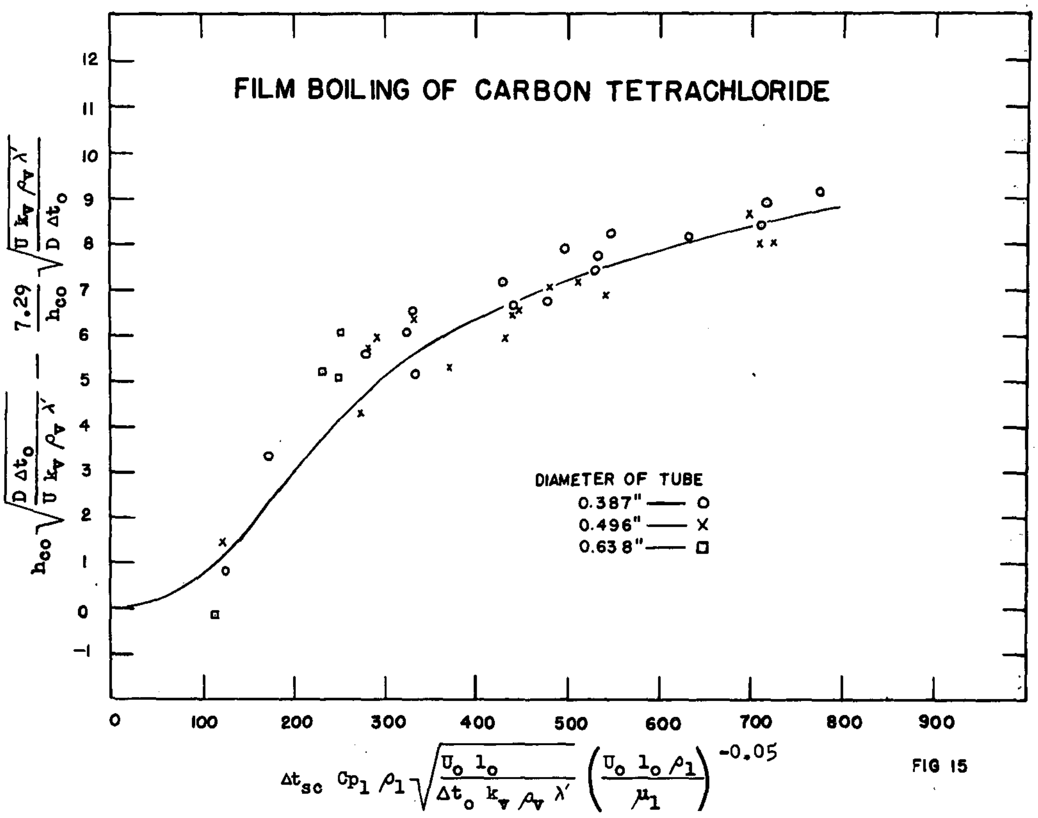
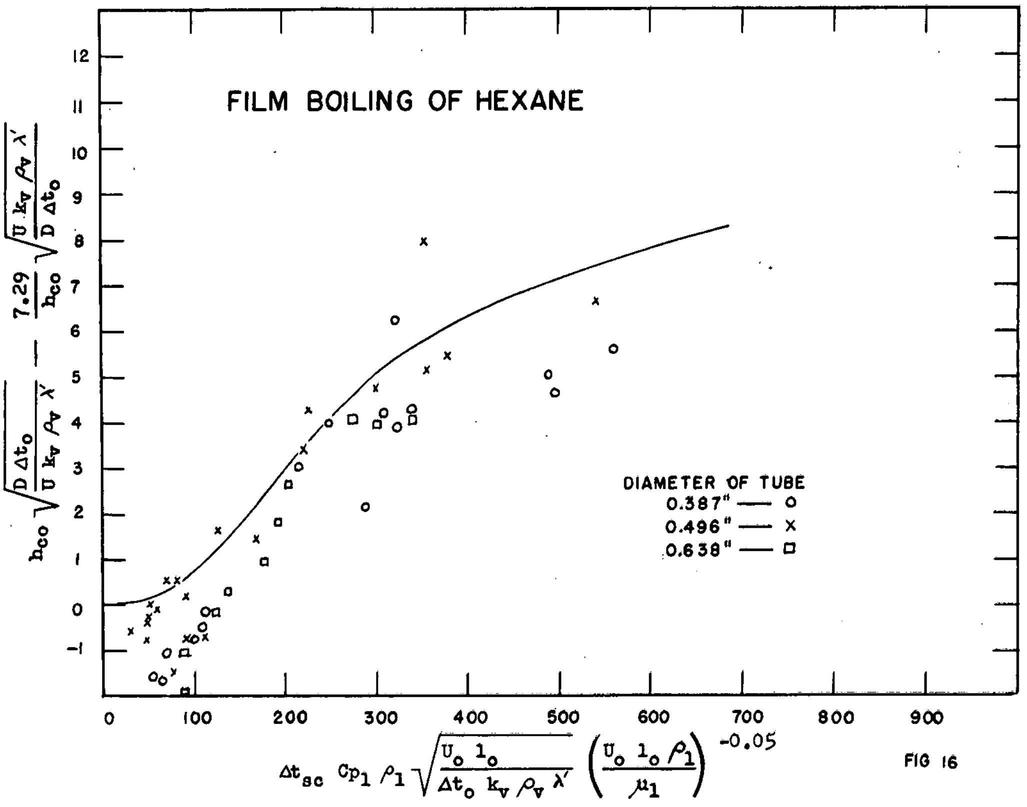


FIG 15

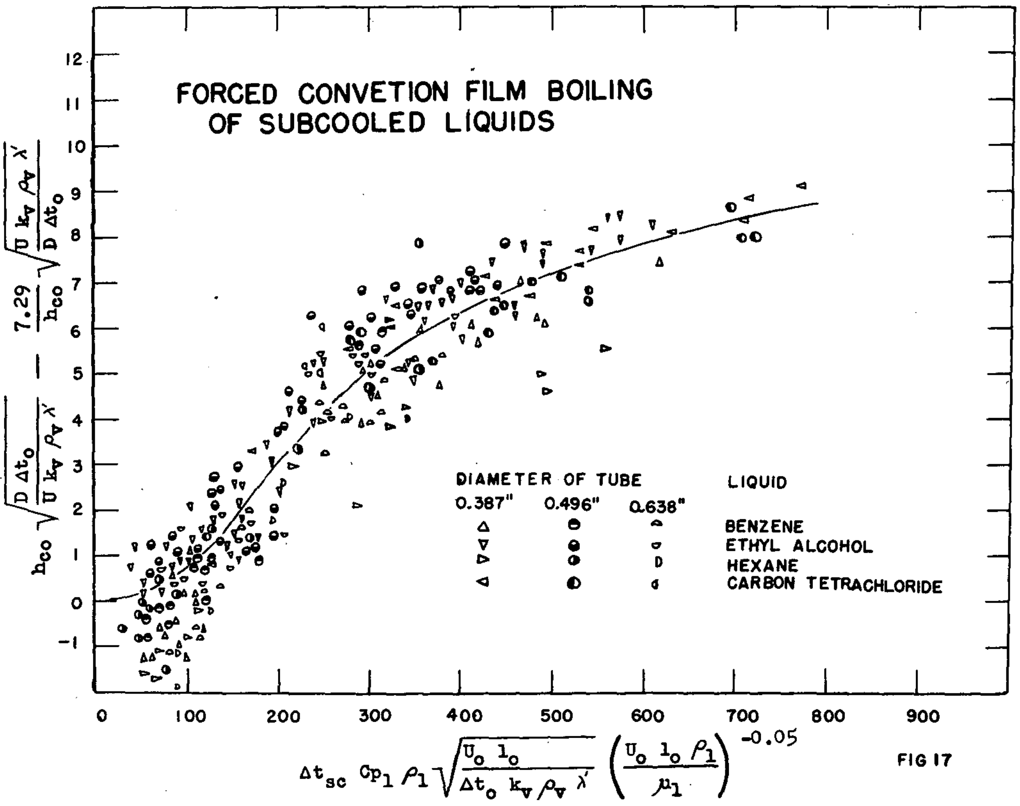
MU-7038

Fig. 15



MU-7039

Fig. 16



MU-7040

Fig. 17

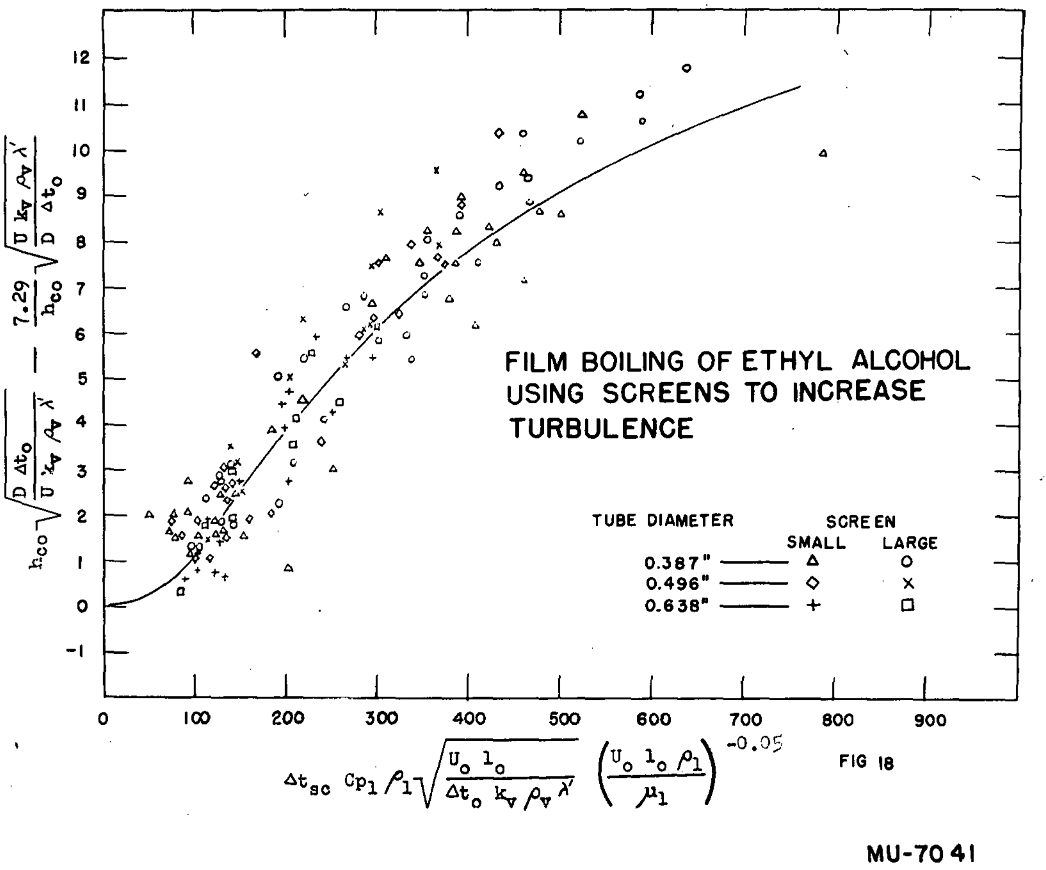
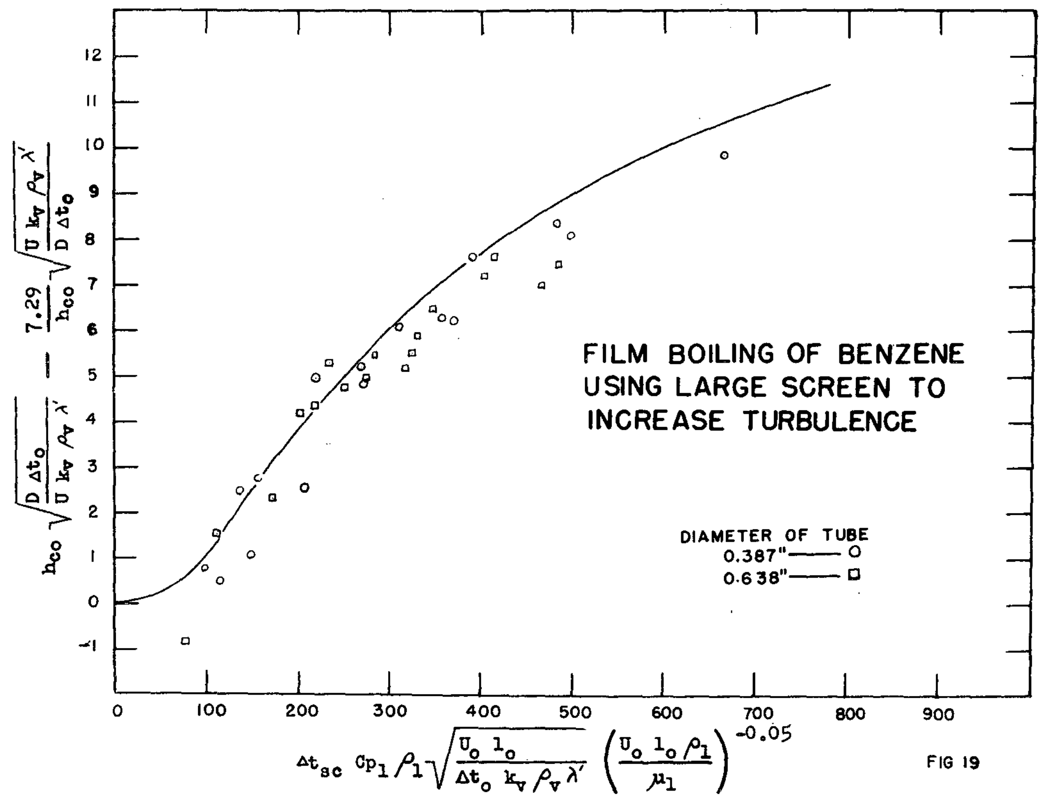

FILM BOILING OF ETHYL ALCOHOL USING SCREENS TO INCREASE TURBULENCE
TUBE DIAMETER
SCREEN
SMALL
LARGE
0.387" △ ○
0.496" ◇ ×
0.638" + □
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
0
100
200
300
400
500
600
700
800
900
$h_{co}\sqrt{\frac{D\,\Delta t_o}{U\,k_v\,\rho_v\,\lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{U\,k_v\,\rho_v\,\lambda'}{D\,\Delta t_o}}$
$\Delta t_{sc}\ Cp_l\,\rho_l\sqrt{\frac{U_o\,l_o}{\Delta t_o\,k_v\,\rho_v\,\lambda'}}\left(\frac{U_o\,l_o\,\rho_l}{\mu_l}\right)^{-0.05}$
FIG 18
MU-7041

Fig. 18



MU-7042

Fig. 19

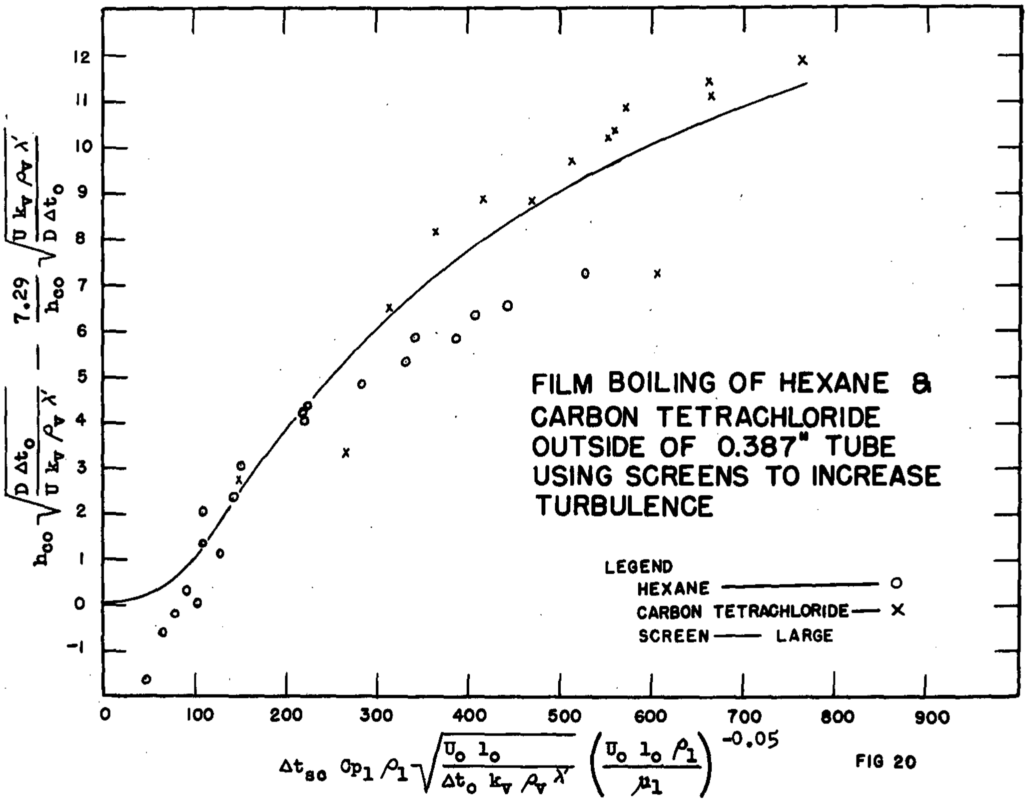


FIG 20

MU-7043

Fig. 20

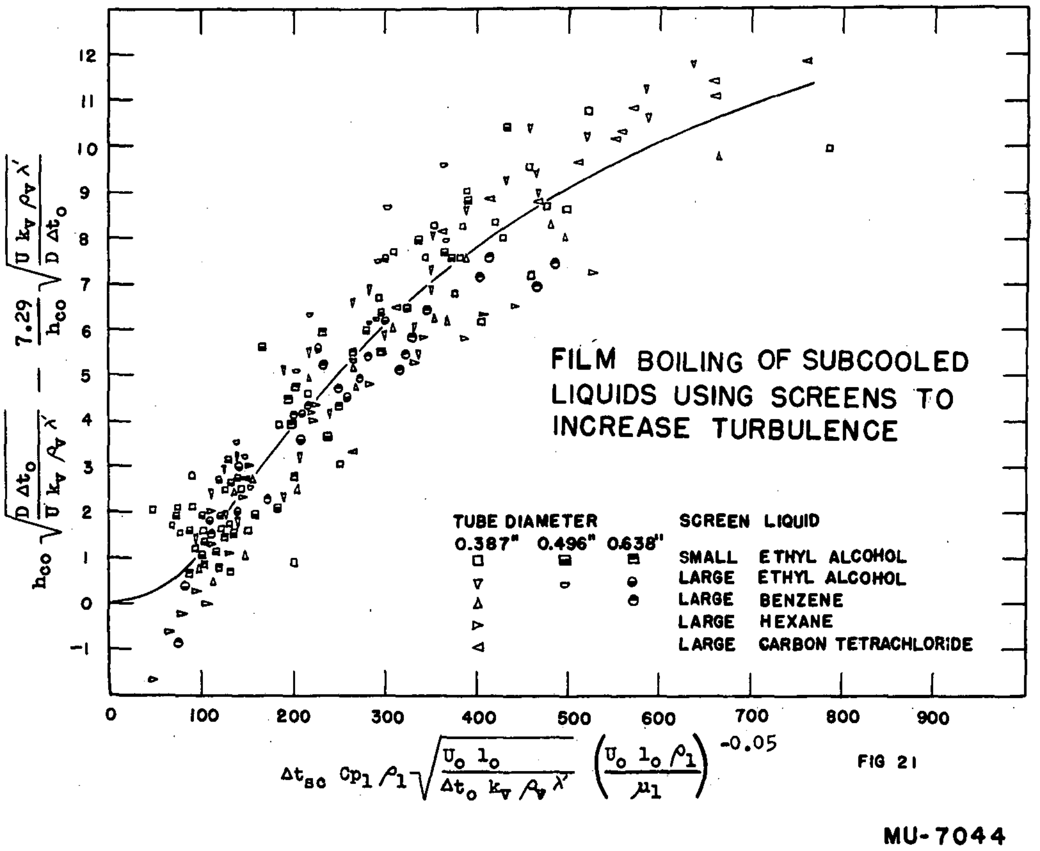

FILM BOILING OF SUBCOOLED LIQUIDS USING SCREENS TO INCREASE TURBULENCE
TUBE DIAMETER
0.387" 0.496" 0.638"
SCREEN LIQUID
SMALL ETHYL ALCOHOL
LARGE ETHYL ALCOHOL
LARGE BENZENE
LARGE HEXANE
LARGE CARBON TETRACHLORIDE
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
0
100
200
300
400
500
600
700
800
900
$h_{co}\sqrt{\frac{D\,\Delta t_o}{U\,k_v\,\rho_v\,\lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{U\,k_v\,\rho_v\,\lambda'}{D\,\Delta t_o}}$
$\Delta t_{sc}\,Cp_l\,\rho_l\sqrt{\frac{U_o\,l_o}{\Delta t_o\,k_v\,\rho_v\,\lambda'}}\left(\frac{U_o\,l_o\,\rho_l}{\mu_l}\right)^{-0.05}$
FIG 21
MU-7044

Fig. 21

greater increase in group A.

In Figures 11 through 21, the best line drawn through the data is found to be an s-shaped curve instead of a straight line which was theoretically predicted. This deviation from the theory can be explained by examining a few of the basic assumptions made in the derivation of the theory.

It was assumed that the eddy conductivity was constant with distance to simplify the unsteady state conduction equation so that a solution might be obtained. Since the velocity around the tube varies from zero to two times the approach velocity, there will be some change in eddy conductivity around the tube. The eddy conductivity is also known to be a function of the distance into the liquid stream although it is fairly constant in the central portion of the conduit.[5]

In order to solve the unsteady state conduction equation, it was assumed that the distance x was the radial distance from the film perpendicular to the lines of flow in the liquid. The error due to this assumption was minimized by using the temperature gradient into the liquid at the distance x equal to zero.

Since neither the surface area of the vapor-liquid interface nor the liquid velocity distribution around the top half of the tube could be defined, the rate of heat transfer into the liquid from the vapor film around the top half of the tube was assumed equal to that around the bottom half, although it is certainly smaller.

Due to these simplifying assumptions, it is not surprising that the data correlate on an s-shaped curve instead of the straight line that was theoretically predicted. The scatter of the data which may be noted in Figures 17 and 21 can also be partially accounted for by these simplifying assumptions.

The constant used in the parameter A is taken directly from the equation proposed for forced convection film boiling to saturated liquids. An examination of the data from which the equation for heat transfer to saturated liquids was derived shows a deviation of ± 30% of the constant 7.29 for the same liquid systems used in this study. Another source of error is found in the questionable accuracy of the physical properties at high temperatures. Of particular concern are the values of thermal conductivity and the effective heat of vaporization. The equation used herein to predict the effective heat of vaporization was developed for condensation of vapors where the temperature difference between the liquid and vapor was small compared to that found in film boiling.

There is always a certain amount of error resulting from experimental operation and measuring of operational variables. This group would be very difficult to evaluate and no attempt was made to do so rigorously; however, velocity, temperature, current, and especially voltage readings were all recognized as possible sources of error. However, the maximum error in the heat transfer coefficients was estimated to be between 10 and 20 percent. The purity of the liquids might have effected the results, since there was some decomposition of the vapors at high temperatures of the graphite tube. It is felt, however, that every attempt has been made to minimize these effects within the limitations of the equipment.

Table 24 lists the ranges of Reynold's numbers, the ranges of the estimated eddy viscosity, and the thermal diffusivity of the liquids investigated. The lowest Reynold's number is noted to be larger than the critical Reynold's number for turbulent flow in a conduit. By examining Table 24 it can be seen that the values of the

Table 24

Range of Reynold's Number Investigated

The Reynold's number is based on the straightening vane width and velocity

Ethyl Alcohol	4,630 to 17,700
Benzene	7,760 to 29,800
Hexane	10,180 to 39,000
Carbon Tetrachloride	22,800 to 87,400

Range of Estimated Eddy Viscosity Investigated

	In Straightening Vanes	At Nozzle
Ethyl Alcohol	0.496 to 1.67 ft^2/hr	0.176 to 0.591 ft^2/hr
Benzene	0.439 to 1.48 ft^2/hr	0.155 to 0.525 ft^2/hr
Hexane	0.428 to 1.44 ft^2/hr	0.152 to 0.511 ft^2/hr
Carbon Tetrachloride	0.395 to 1.33 ft^2/hr	0.135 to 0.472 ft^2/hr

Thermal Diffusivity of Liquids $(\frac{k}{Cp\,\rho})$ Investigated

Ethyl Alcohol	0.00254 ft^2/hr
Benzene	0.00376 ft^2/hr
Hexane	0.00342 ft^2/hr
Carbon Tetrachloride	0.00498 ft^2/hr

thermal diffusivity of the liquids are negligible compared to the values of the estimated eddy viscosity. It has been previously shown that the eddy viscosity closely approximates the diffusivity of heat in this system.

Since it was necessary to make a few crude assumptions in order to estimate the eddy viscosity of the system, it is felt that the values of this quantity are not known within a factor of two. Therefore, it is not recommended that Figure 17 be used to estimate heat transfer coefficients though this figure does show that it is possible to correlate data for heat transfer in forced convection film boiling to subcooled liquids by use of the theoretical parameters.

CONCLUSIONS

The heat transfer coefficients h_{co} across the film can be markedly increased by subcooling the liquid. Values of this heat transfer coefficient have been found to approach those of nucleate boiling.

It has been shown that the heat is transferred into the liquid by eddy conduction and that the effect of thermal conduction is negligible in forced convection film boiling to subcooled liquids.

It is possible to use the parameters

$$h_{co}\sqrt{\frac{D\ \Delta t_o}{U\ k_v\ \rho_v \lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{U\ k_v\ \rho_v \lambda'}{D\ \Delta t_o}}$$

and

$$\Delta t_{sc}\ Cp_l\ \rho_l\ \sqrt{\frac{\varepsilon}{\Delta t_o\ k_v\ \rho_v \lambda'}}$$

to correlate the data for heat transfer in upward flow forced convection film boiling to subcooled liquids from a horizontal rod.

APPENDIX

The Effect of Radiation

It has been determined for forced convection film boiling[3] that

$$h_{co} = h - h_r + 1/4\, h_r \left(\frac{\theta'}{\pi} \right) \tag{51}$$

Since at moderate and high liquid velocities the value of $\frac{\theta'}{\pi}$ is equal to 1/2, equation (51) reduces to

$$h_{co} = h - 7/8\, h_r \tag{52}$$

For natural convection film boiling, it has been shown[1] that

$$h_{co} = h - 3/4\, h_r \tag{53}$$

The term h_r is calculated from the following equation for parallel plates[6]

$$h_r = \frac{\sigma_1}{\frac{1}{\varepsilon_r} + \frac{1}{\alpha_r} - 1} \left[\frac{T_t^{\,4} - T_b^{\,4}}{\Delta t_o} \right] \tag{54}$$

where σ_1 is the Stefan-Boltzmann constant, ε_r is the emissivity of the hot tube, α_r is the absorptivity of the cold liquids, T_t is the absolute temperature of the heated surface, and T_b is the absolute temperature of the vapor-liquid interface.

Alternate Derivation for q_1

From a material balance of the vapor in the vapor film, we obtain

$$W = K_6 \rho_v a L V \tag{55}$$

where W is the weight rate of the liquid evaporated, K_6 is a constant of proportionality, a is the average vapor film thickness, L is the length of the tube, and V is the vapor velocity.

Since forced convection film boiling occurs at high liquid velocities, we may assume that the average vapor velocity is proportional to the liquid velocity. The heat transferred into the vapor is equal to the weight of the vapor multiplied by the effective heat of vaporization or

$$q_v = W \lambda', \tag{56}$$

$$q_v = K_7 \rho_v a L U \lambda', \tag{57}$$

where K_7 is a new constant of proportionality.

Since we are only interested in the heat that is transferred across the vapor film by conduction, we may write

$$h_{co} = k_v/a; \tag{58}$$

substituting equation (58) into equation (57) and dividing both sides by the area over which heat is transferred, we obtain

$$\frac{q_v}{A} = K_2 \frac{U \rho_v \lambda' k_v}{h_{co} D}. \tag{59}$$

This equation is equivalent to equation (9) developed for no subcooling of the liquid, though no assumptions were made in this development on the amount of subcooling of the liquid.

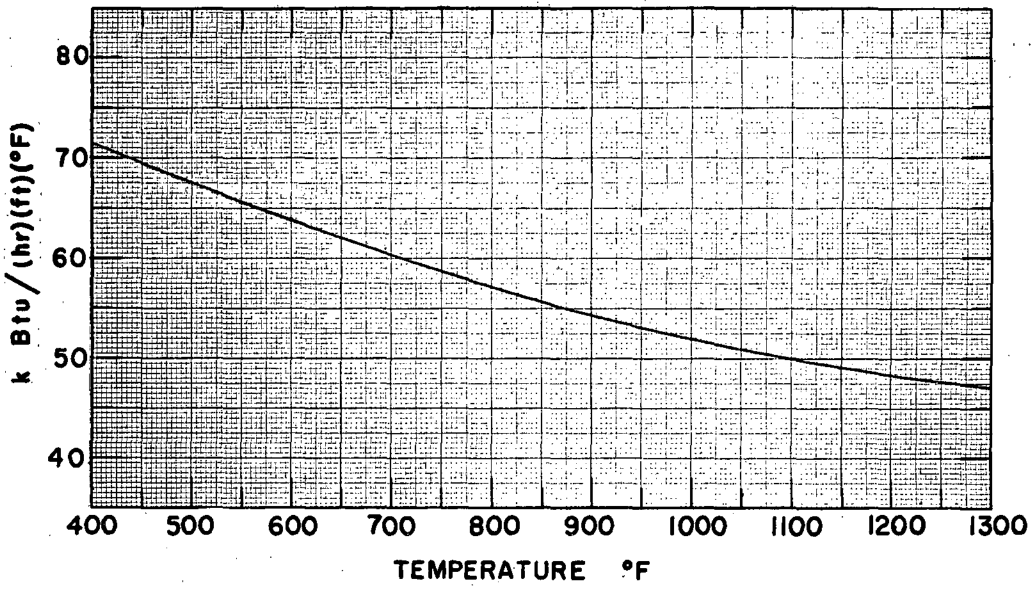
Correction for Heat Loss at Tube Ends

Graphite tubes were used because of their high thermal conductivity and moderate resistance. Due to this high thermal conductivity there was some heat lost through conduction along the tubes. To correct the heat transfer coefficient for this loss, the following expression has been developed[3]:

$$\frac{h}{h_{obs}} = \frac{\cosh \frac{L}{2}\sqrt{\frac{w}{\Delta t_o' \, k_g}} - 1}{\cosh \frac{L}{2}\sqrt{\frac{w}{\Delta t_o' \, k_g}} - \frac{\Delta t_{L/2}}{\Delta t_o}} = \frac{\Delta t_o}{\Delta t_o'}, \qquad (60)$$

where h is the corrected heat transfer coefficient, h_{obs} is the observed heat transfer coeffient, L is the length of the section over which heat transfer is measured, k_g is the thermal conductivity of graphite, w is the heat generation per unit volume, $\Delta t_o'$ is the temperature difference across the film for the same amount of heat input if there was no conduction along the tube, and $\Delta t_{L/2}$ is the measured temperature difference across the film at the end of the section.

Since $\Delta t_o'$ is an unknown quantity it is necessary to resort to a trial-and-error solution. It was found that, if $\Delta t_o'$ was assumed equal to Δt_o for the hyperbolic term as a first approximation, a second trial was usually not necessary.



THERMAL CONDUCTIVITY OF GRAPHITE

MU 2662

Fig. 22

Physical Properties of the Liquids and their Vapors

Several sources of information were consulted for the values of the physical properties, and those chosen were considered to be the most reliable. The physical properties of the liquids were found to be known to much greater degree of accuracy than the physical properties of the vapors. It was necessary to extrapolate the data over a fairly wide range in the case of the thermal conductivities of the vapors. These were extrapolated by plotting the thermal conductivity versus the absolute temperature on log-log coordinates as suggested by McAdams.[6] The vapor thermal conductivities above 1000°K were also estimated by using the relationships suggested by Bromley.[10] These estimated values were found to scatter slightly due to the inaccuracy of high-temperature viscosity data. The estimated values were found to check the extrapolated curve within ± 5%.

The boiling points under a static head of liquid of 2.65 feet were determined experimentally and by calculation from extrapolated vapor pressure data from Perry.[11] These values were found to check within experimental accuracy.

Vapor Properties

Boiling Points

Benzene	179.7°F
Carbon Tetrachloride	176.8°F
Ethyl alcohol	175.7°F
Hexane	157.5°F

Heat Capacity

Benzene	American Petroleum Institute[12]
Carbon Tetrachloride	R. V. Vold[13]
Ethyl Alcohol	A. Eucken and E. V. Franck[14]
Hexane	A. P. I., op. cit.

Thermal Conductivity

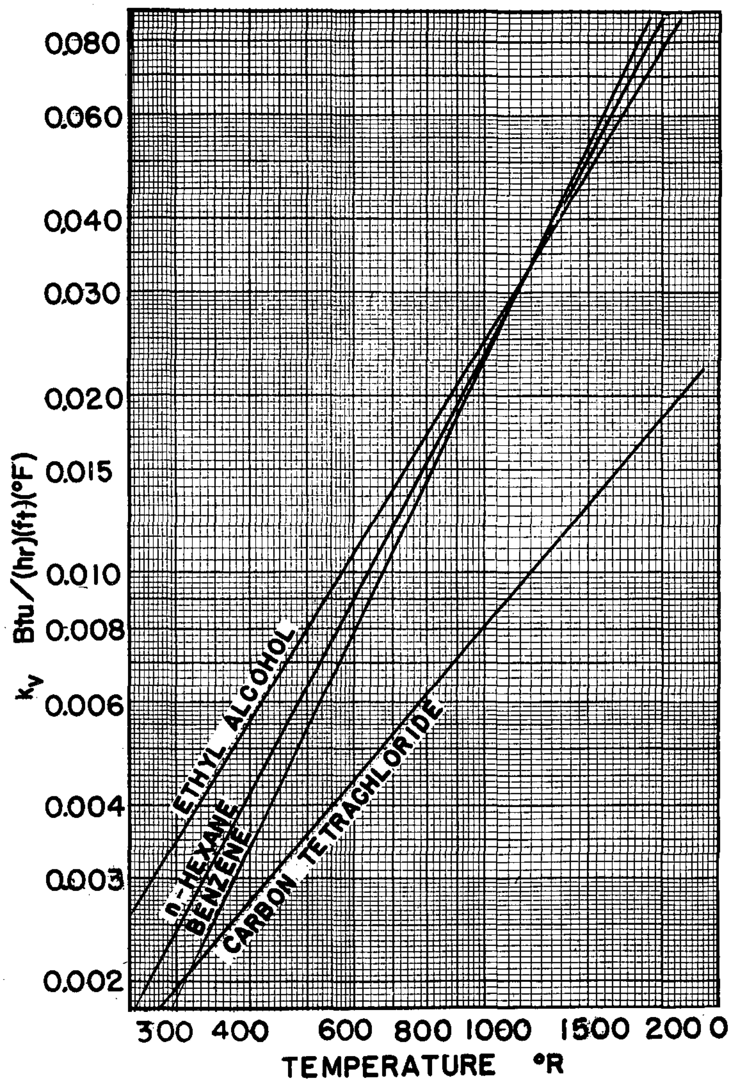
Benzene	W. H. McAdams[6]
Carbon Tetrachloride	W. H. McAdams, op. cit.
Ethyl Alcohol	L. A. Bromley, W. H. McAdams, op. cit.
Hexane	L. A. Bromley, op. cit.

Heats of Vaporization at Boiling Points

Benzene	169.2 $\frac{\text{Btu}}{\text{lb}}$	International Critical Tables[15]
Carbon Tetrachloride	83.1 "	I. C. T., op. cit.
Ethyl Alcohol	365.7 "	I. C. T., op. cit.
Hexane	143.5 "	I. C. T., A. P. I., op. cit.

Liquid Properties

Thermal Conductivity	
Ethyl Alcohol	W. H. McAdams, op. cit.
Heat Capacity	
Benzene	I. C. T., op. cit.
Carbon Tetrachloride	I. C. T., op. cit.
Ethyl Alcohol	I. C. T., op. cit. Handbook of Chemistry and Physics[16]
Hexane	D. R. Douslin and H. M. Huffmann[17]
Density	
Benzene	I. C. T., op. cit.
Carbon Tetrachloride	I. C. T., op. cit.
Ethyl Alcohol	I. C. T., op. cit.
Hexane	I. C. T., op. cit.
Viscosity	
Benzene	A. P. I., op. cit.
Carbon Tetrachloride	I. C. T., Handbook of Chemistry and Physics, op. cit.
Ethyl Alcohol	Langes Handbook of Chemistry[19]
Hexane	A. P. I., op. cit.



VAPOR THERMAL CONDUCTIVITY

Fig. 23

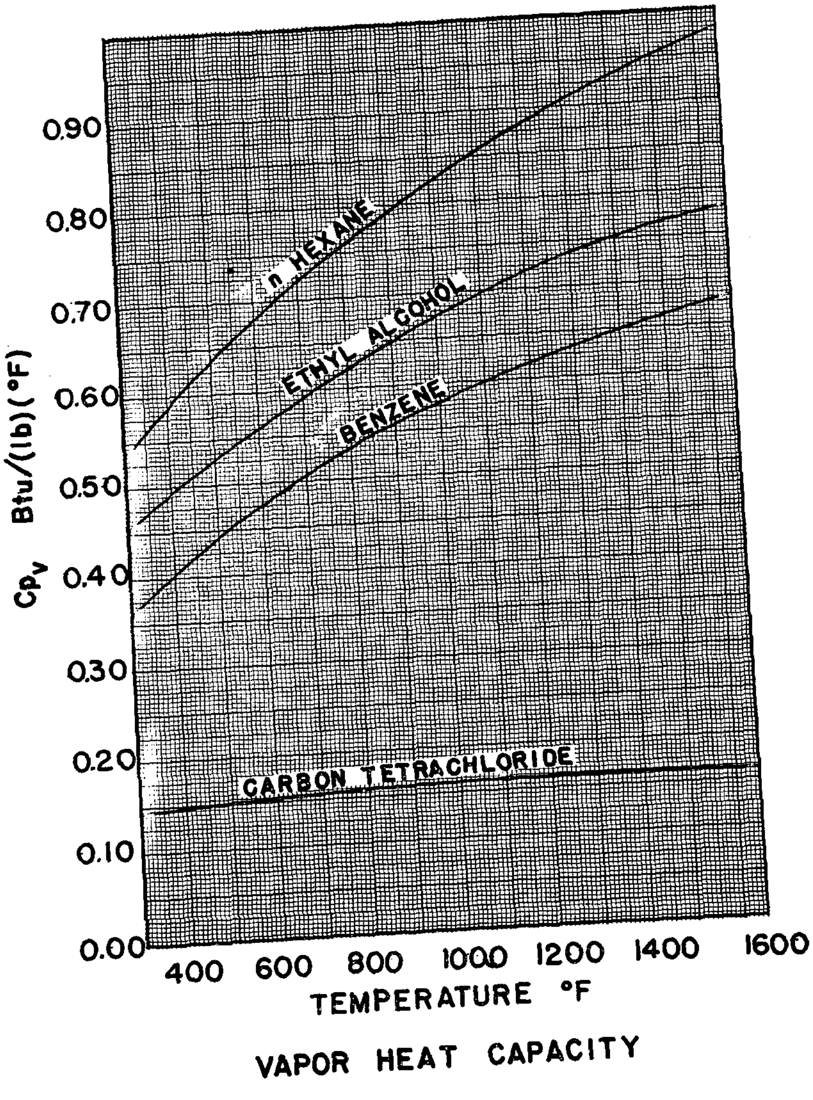
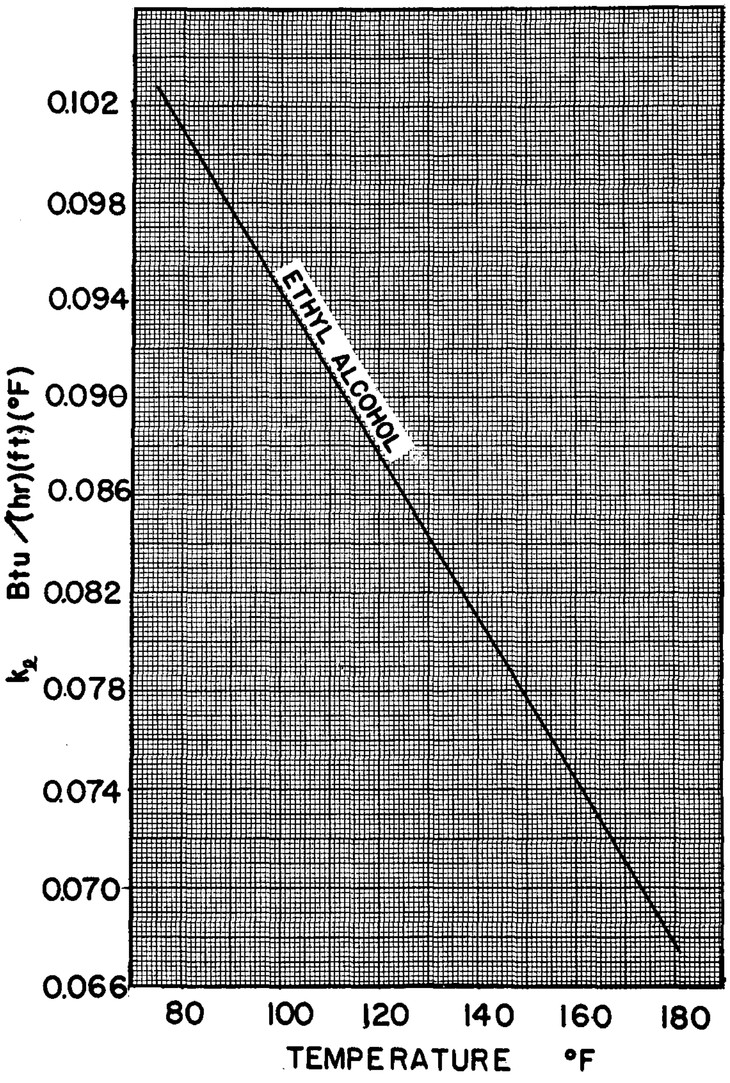
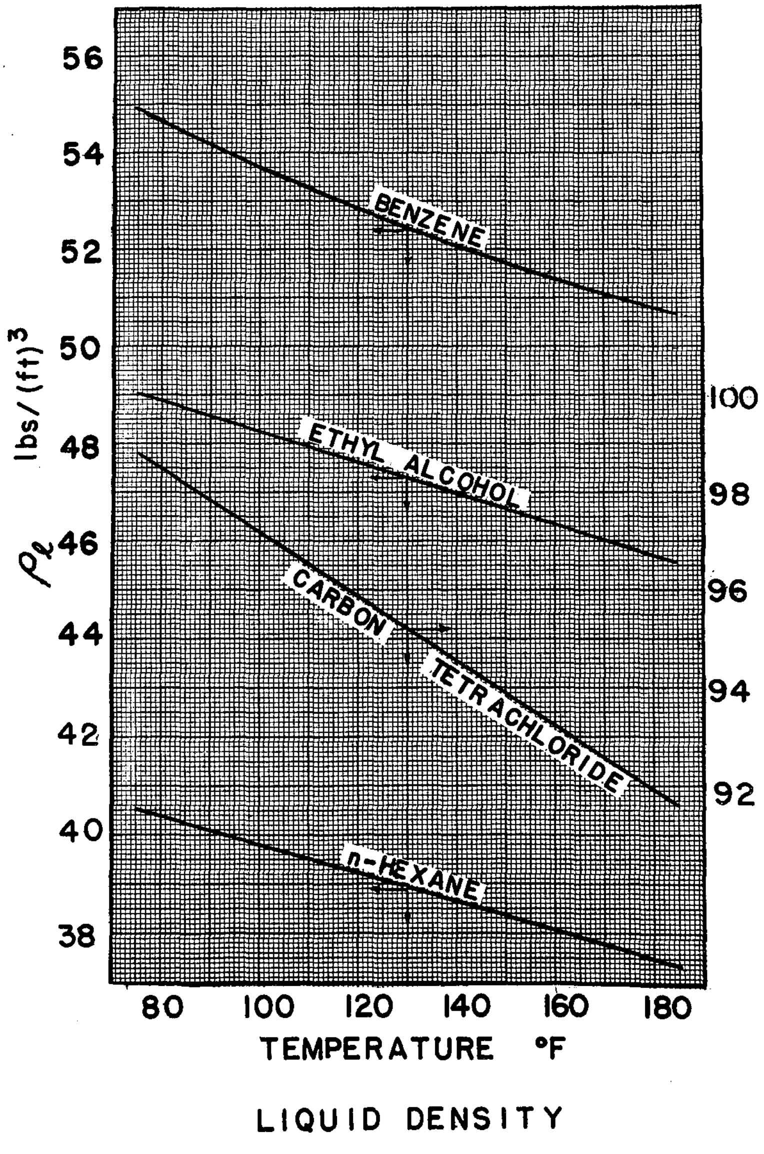

0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Cp_v Btu/(lb)(°F)
400
600
800
1000
1200
1400
1600
TEMPERATURE °F
n HEXANE
ETHYL ALCOHOL
BENZENE
CARBON TETRACHLORIDE
VAPOR HEAT CAPACITY

Fig. 24



LIQUID THERMAL CONDUCTIVITY

Fig. 25



LIQUID DENSITY

Fig. 26

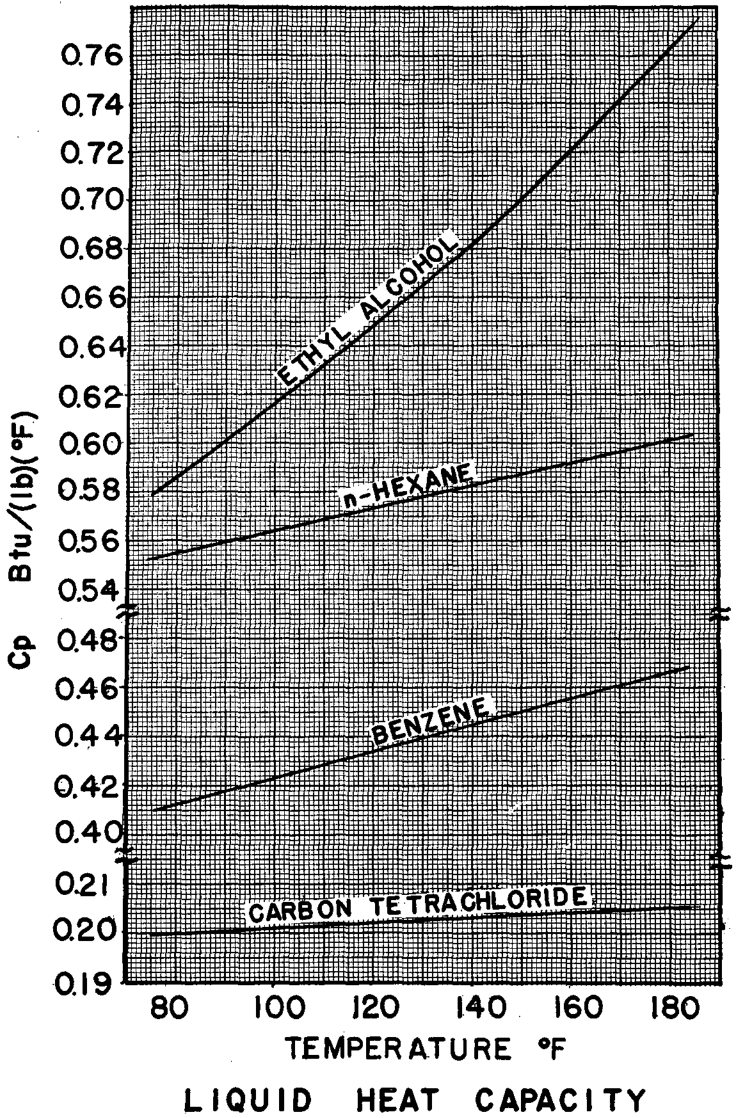

0.76
0.74
0.72
0.70
0.68
0.66
0.64
0.62
0.60
0.58
0.56
0.54
0.48
0.46
0.44
0.42
0.40
0.21
0.20
0.19
Cp Btu/(lb)(°F)
ETHYL ALCOHOL
n-HEXANE
BENZENE
CARBON TETRACHLORIDE
80
100
120
140
160
180
TEMPERATURE °F
LIQUID HEAT CAPACITY

Fig. 27

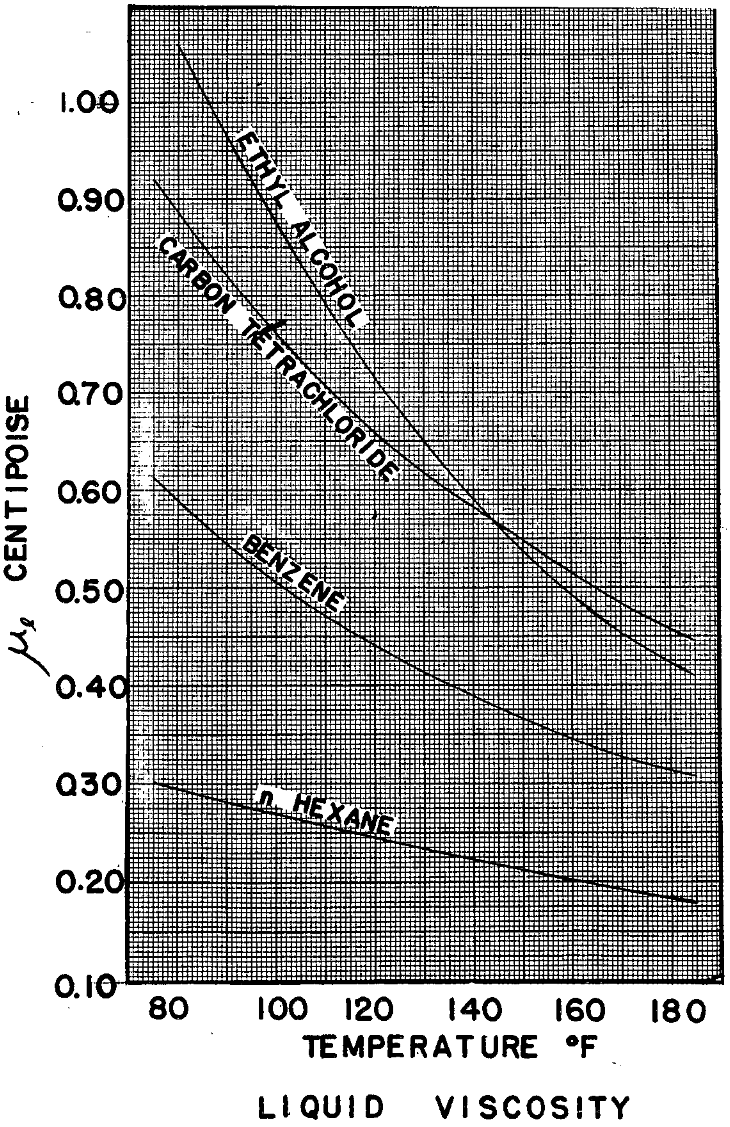

ETHYL ALCOHOL
CARBON TETRACHLORIDE
BENZENE
n. HEXANE
μ_l CENTIPOISE
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
80
100
120
140
160
180
TEMPERATURE °F
LIQUID VISCOSITY

Fig. 28

Evaluation of Physical Properties

It is necessary to be able to evaluate the correct average for the physical properties of the liquids and vapors in order to solve the film boiling equations.

It has been shown[3] that the thermal conductivity, heat capacity, and the viscosity of the vapor film may be evaluated by assuming the values at the arithmetic average temperature.

The average vapor density has been found[3] to be

$$\rho_{ave} = \frac{2\rho_b T_b}{\Delta t_o} \left(1 - \frac{1}{\Delta t_o} \ln \frac{T_t}{T_b}\right), \qquad (61)$$

where ρ_{ave} is the average vapor density, ρ_b is the density of the vapor at the boiling point, T_t is the absolute temperature of the heated surface, and T_b is the absolute temperature at the boiling point.

The difference in heat content between the vapor film at some average temperature and the liquid at its boiling point has been shown[3] to be approximately

$$\lambda' = \lambda_o \left(1 + 0.4 \frac{Cp_{ave}\, \Delta t_o}{\lambda_o}\right)^2, \qquad (62)$$

where λ_o is the heat of vaporization at the boiling point and Cp_{ave} is the average heat capacity of the vapor.

Since liquid density, heat capacity, and thermal conductivity are approximately proportional to temperature, the average physical properties will be approximately the values at the arithmetic mean temperature.

Approximation of The Eddy Viscosity of the System

Since we wish to find the eddy viscosity in the turbulent core of the stream, we will assume the velocity distribution for smooth pipes in the turbulent core from the data of Nikuradse:[19]

$$\frac{U_o}{\sqrt{\frac{\tau_o}{\rho_1}}} = 5.5 + 2.5 \ln \frac{y\sqrt{\tau_o \rho_1}}{\mu_1}, \tag{63}$$

where U_o is the velocity in the straight conduit, y is the distance from the conduit wall, τ_o is the shear stress at the wall, ρ_1 is the density of the fluid, and μ_1 is the viscosity of the fluid.

The shear stress at any point in the turbulent core, τ, is

$$\tau = \rho_1 \varepsilon_m \frac{dU_o}{dy} , \tag{64}$$

where ε_m is the eddy viscosity in the turbulent core.

Differentiating equation (63), we find the velocity gradient to be

$$\frac{dU_o}{dy} = \frac{2.5}{y} \sqrt{\frac{\tau_o}{\rho_1}} . \tag{65}$$

By a force balance, it can be shown that

$$\tau = (1 - \frac{2y}{l_o}) \tau_o , \tag{66}$$

where l_o is the diameter of the conduit.

The shear stress at the wall may be found by relating it to the Fanning friction factor f:

$$\tau_o = \frac{f}{2} \rho U_o^2 . \tag{67}$$

Substituting equations (65), (66), and (67) into equation (64) and simplifying, we obtain

$$\varepsilon_m = 0.4\sqrt{\frac{f}{2}} \quad U_o y (1 - \frac{2y}{l_o}) . \tag{68}$$

At any particular distance from the wall,

$$\varepsilon_m = K\sqrt{\frac{f}{2}}\ U_o l_o\ , \tag{69}$$

where K is a constant of proportionality.

To evaluate the eddy viscosity, we must determine the dimension l_o in the experimental apparatus. It is assumed that the level of turbulence in the system is determined by the straightening vanes, since this section is 32 diameters long and the section above the straightening vanes before the nozzle is only 2.4 diameters long. The value of l_o used to determine the eddy viscosity of the system is therefore the width of the straightening vanes and U_o is the velocity in the straightening vanes.

The eddy viscosity is decreased when a fluid is passed through a contraction in a conduit. If we assume that the scale of turbulence decreases by the same ratio as the intensity of turbulence, then the ratio by which the eddy viscosity decreases is equal to the ratio by which the energy of turbulence decreases. We can express this as

$$\frac{u'_1\, u'_1}{u'_2\, u'_2} = \frac{u'_1\, l_1}{u'_2\, l_2} = \frac{\varepsilon_{m_1}}{\varepsilon_{m_2}} \tag{70}$$

where l is the scale of turbulence, the subscript one, 1, denotes conditions before the nozzle, and subscript 2 denotes conditions after the nozzle.

It is found that the ratio by which the energy of turbulence decreases can be expressed as a function of the contraction ratio if we assume that the turbulence is iostropic and that the contraction is symmetrical.[20]

$$\frac{u'_1\, u'_1}{u'_2\, u'_2} = \frac{1}{3}\,(u + 2v) \tag{71}$$

where $u = 3/4\ C^{-2}\ (\log 4C^3 - 1)$,

$v = 3/4\ C$,

C = the contraction ratio.

Since we are mainly interested in the velocity component of turbulence which is symmetrically contracted, we will use equation (71) as an approximation of the loss in the energy of turbulence caused by the nozzle. Substituting the contraction ratio of the nozzle, which is equal to 5.62, we obtain

$$\frac{\varepsilon_{m_1}}{\varepsilon_{m_2}} = \frac{u'_1\ u'_1}{u'_2\ u'_2} = 2.825. \tag{72}$$

Combining equations (72) and (68), the estimated eddy viscosity of the system above the nozzle becomes

$$\varepsilon_{m_2} = 0.1418\sqrt{\frac{f}{2}}\ U_o\ y(1 - \frac{2y}{l_o}). \tag{73}$$

The value of the eddy viscosity in the central portion of the stream is taken as the maximum value predicted by equation (73). The maximum value of the eddy viscosity predicted by equation (73) occurs at y equal to $l_o/4$.

The friction factor[6] for smooth pipes is defined over a limited range of Reynold's number of 5,000 to 200,000 as

$$f = 0.046/\mathrm{Re}^{0.2}, \tag{74}$$

where Re is the Reynold's number.

Substituting equation (74) and y equal to $l_o/4$ into equation (73), we find the following equation for the eddy viscosity above the nozzle in the central portion of the stream:

$$\varepsilon_{m_2} = 0.00268\ U_o l_o\ \mathrm{Re}^{-0.1}. \tag{75}$$

NOMENCLATURE

Symbol	Definition	Suggested Units
a	film thickness	ft
A	heat transfer area	ft^2
A	$h_{co}\sqrt{\frac{D\,\Delta t_o}{U\,k_v\,\rho_v\lambda'}} - \frac{7.29}{h_{co}}\sqrt{\frac{U\,k_v\,\rho_v\lambda'}{D\,\Delta t_o}}$	
B	$\Delta t_{sc}\;Cp_l\,\rho_l\sqrt{\frac{U_o l_o}{\Delta t_o\;k_v\,\rho_v\lambda'}}\;\left(\frac{U_o l_o}{\mu_l}\right)^{-0.05}$	
c	U^2 multiplied by a constant	
C	contraction ratio of area	
Cp	specific heat at constant pressure	$\frac{Btu}{(lb)(°F)}$
d	differential operator	
D	outside diameter of tube	ft
f	Fanning friction factor	
g	acceleration of gravity	ft/hr^2
h	film coefficient of heat transfer	$\frac{Btu}{(hr)(ft^2)(°F)}$
h_{co}	film coefficient if there were no radiation	$\frac{Btu}{(hr)(ft^2)(°F)}$
h_r	radiation coefficient of heat transfer	$\frac{Btu}{(hr)(ft^2)(°F)}$
k	thermal conductivity	$\frac{Btu}{(hr)(ft)(°F)}$
K	constant of proportionality	
l	scale of turbulence	ft
l_o	length dimension of Reynold's number	ft
L	length of tube	ft

NOMENCLATURE
(Page 2)

Symbol	Definition	Suggested Units
M	molecular weight	
n	parameter replacing t^2	
Nu	Nusselt number	
P	pressure	atm
Pr	Prandtl number	
q_o	heat flow from tube	$\frac{Btu}{hr}$
q_l	heat flow into liquid	$\frac{Btu}{hr}$
q_v	heat flow into vapor	$\frac{Btu}{hr}$
r	radius of tube	ft
R	universal gas constant	
Re	Reynold's number	
s	time in La Place domain	
t	time	hr
t	temperature	°F
T	absolute temperature	°R
Δt_o	temperature difference across film	°F
Δt_{sc}	temperature difference between liquid and its boiling point	°F
u'	intensity of turbulence	ft/hr
u	velocity of liquid directly below tube	ft/hr
U_o	velocity of liquid in conduit where level of turbulence is determined	ft/hr
V	velocity of vapor	ft/hr
w	heat generated per unit volume	$\frac{Btu}{ft^3}$
W	weight rate of liquid evaporated	lb/hr

NOMENCLATURE
(Page 3)

Symbol	Definition	Suggested Units
x	radial distance into liquid from vapor-liquid interface perpendicular to lines of flow of a liquid	ft
x'	x in the La Place domain	ft
y	distance from conduit wall	ft
α	diffusivity of heat	ft^2/hr
α_r	absorptivity of cold liquid	
ε	eddy conductivity	ft^2/hr
θ	angle measured from bottom of tube	
θ'	separation point	
λ_o	latent heat of vaporization	$\frac{Btu}{lb}$
λ'	effective difference in heat content between vapor at its average temperature and the liquid at its boiling point	$\frac{Btu}{lb}$
∂	partial differential operator	
μ	viscosity	lb/hr(ft)
π	3.1416	
ρ	density	lb/ft^3
σ	Stefan-Boltzman constant	
σ_l	surface tension of liquid	lb/ft
τ	shear stress in fluid	lb/ft^2
τ_o	shear stress at wall	lb/ft^2

NOMENCLATURE

(Page 4)

Subscripts

ave	average
b	at the boiling point
i	inside the tube
g	graphite
l	liquid
m	eddy viscosity
T	outside the tube
v	vapor
1	conditions before nozzle
2	conditions after nozzle

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