Chapter .V

Heat Transfer and Film Boiling

Introduction

It is a matter of common experience that when a red hot metal is quenched in water, the metal first cools slowly, then rapidly and then slowly again. This can be taken as a good illustration of the three possible types of boiling, viz:- Film boiling, Nucleate boiling and Natural convection boiling. Film boiling is that type of boiling which occurs when a vapour film exists between a heated surface and a boiling liquid. In nucleate boling, vapour bubbles originate from different parts of the heated surfaces. Natural convection boiling takes place when the difference of temperature between the heated surface and the liquid is small. In the operation~~s~~ of ~~of~~ jets and rockets, there are frequent contacts between a boiling liquid and a hot surface and this is the condition for film boiling. In an electrically heated boiler or an atomic power plant where the heat input is the controlled variable, there is always a danger that the temperature of the heated object may rise abruptly if the heat input is near the critical heat flux (q/A). This danger becomes much more pronounced if the value of the heat input is above the maximum heat flux $\left(q/A\right)_{Max}$. If the abrupt temperature rise is sufficiently large, it may give rise to sudden expansion and weakening of certain parts of the system, sometimes causing breakage.

In view of the above importance of film boiling and nucleate boiling, we have tried (1) to investigate the effect of quenching electrically heated wires in different liquids and (2) to study the heat transfer by means of characteristic boiling curves (incorporating free convection boiling, nucleate boiling and film boiling) between cylindrical metal wires and boiling liquids.

Drew and Mueller and others (1937) have studied heat transfer to boiling liquids by steam condensing method. Nukiyama (1934) succeeded in obtaining almost complete boiling curves by electrically heating thin platinum wires submerged in boiling water. Natural convection boiling and nucleate boiling of water for different pressures have been studied by Addoms (1954) using thin platinum wires. Extensive study of film boiling is made by Bromley (1950) using various organic liquids.

During our study of heat transfer, we have obtained characteristic boiling curves for a number of liquids and the results of our experiments on heat transfer between cylindrical metal wires and boiling liquids have been described in this chapter. The complete boiling curves (plots of $\text{Log}(q/A)$ against $\text{Log}\,\Delta T$) for the various liquids used have been obtained for different wires, and the maximum heat flux and the critical temperature difference have been calculated. The heat flux (q/A) for unit difference of temperature between the wire and the surrounding liquid is known as the heat transfer coefficient h. Thus $h = \frac{q}{A\,\Delta T}$ The relation between this coefficient h and the temperature difference ΔT has also been studied for liquids such as water, carbontetrachloride, turpentine etc., and some typical results have been graphically illustrated (fig. 2)

Experimental

The experimental arrangement consisted of a simple Wheatstone bridge with ratio arms of 1000 ohms each. A thin platinum wire which was submerged in the boiling liquid was included in the third arm of the bridge in series with an ammeter, while a small rheostat and a Eureka wire bridge with a sliding contact formed the fourth arm of the bridge.(Fig 1)

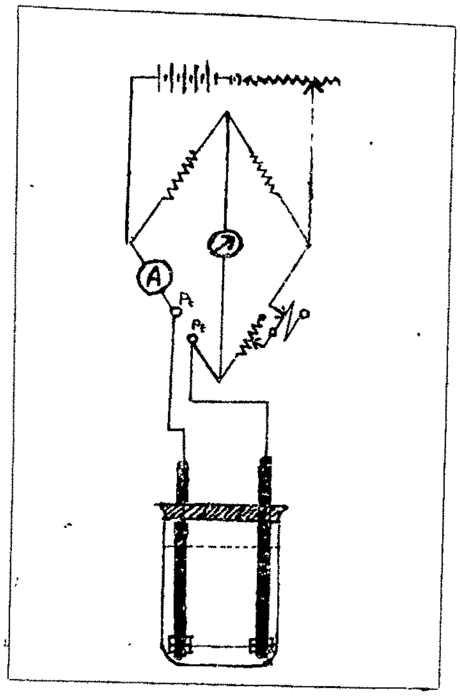

FIG. 1

The platinum wire was allowed to remain in the boiling liquid for some time before passing a current through it so that it attained the temperature of the boiling liquid. The resistance of the wire could then be calculated at this temperature if R_0 , the resistance of the wire at $0^\circ C$ and α , the temperature coefficient of resistance for the wire are known. A very small current which does not heat the wire appreciably, was then passed through the wire and a balance was obtained by adjusting the rheostat and by sliding the contact on the Eureka wire bridge. The current through the wire was then increased so as to raise its temperature. This increases the resistance of the wire, thus disturbing the balance previously obtained.

The contact is now shifted so as to restore the balance, Knowing the value of the shift and also the resistance per unit length of the Eureka wire, the change in resistance ΔR of the platinum wire could be calculated. The excess of temperature of the wire above the boiling point of the liquid could then be determined by means of the relation

$$\Delta T = \frac{\Delta R}{R_0 \alpha}$$

Results and discussion.

The input power q is equal to $\frac{C^2 R}{J}$ where C is the current passing through the wire, R is its resistance and J is the mechanical equivalent of heat. The heat flux is given by (q/A) where A is the surface area $2\pi r l$ of the wire of length l and radius r. Experimental curves showing the variation of (q/A) with the excess of temperature ΔT as also the relation between the heat transfer coefficient $\left(h = \frac{q}{A\,\Delta T}\right)$ and ΔT for water, carbon-tetrachloride, turpentine etc., using thin wires of platinum, copper and tungsten are given in figures 2 to 10

Table I.

Materials used | Platinum & Water

Log q/A	Log h	Log ΔT
0.0869	$\bar{1}.5734$	0.5135
0.4449	$\bar{1}.5414$	0.9035
0.7001	$\bar{1}.6152$	1.0849
0.9001	$\bar{1}.6608$	1.2393
1.0594	$\bar{1}.8020$	1.2574
1.1949	$\bar{1}.9066$	1.2883
1.1032	$\bar{1}.2600$	1.8432
1.1018	$\bar{1}.2381$	1.8700
1.1234	$\bar{1}.1742$	1.9492
1.1526	$\bar{1}.1364$	2.0162
1.1670	$\bar{1}.0928$	2.0742
1.1952	$\bar{1}.6099$	2.1253
1.2087	$\bar{1}.0376$	2.1711
1.2359	1.0234	2.2125
1.2485	2.9982	2.2503
1.2980	2.9508	2.3472

Table 2.

Materials used | Platinum & Turpentine

Log q/A	Log h	Log ΔT
$\bar{1}.5651$	$\bar{2}.7506$	0.8145
$\bar{1}.9219$	$\bar{2}.8816$	1.0403

Table 2 (continued)

Log q/A	Log h	Log ΔT
0.1760	$\bar{2}.9963$	1.1797
0.3794	$\bar{2}.9882$	1.3912
0.5449	$\bar{1}.0434$	1.5015
0.6814	$\bar{1}.1448$	1.5366
0.7989	$\bar{1}.2440$	1.5549
0.9028	$\bar{1}.3330$	1.5725
0.9552	$\bar{1}.4092$	1.5860
1.0780	$\bar{1}.4920$	1.5860
0.9523	$\bar{1}.1792$	1.7732
0.9790	$\bar{1}.0298$	1.9492
1.0043	$\bar{2}.9301$	2.0742
1.0283	$\bar{2}.8572$	2.1711
1.0784	$\bar{2}.8281$	2.2503
1.1089	$\bar{2}.7917$	2.3172
1.1293	$\bar{2}.7541$	2.3752
1.1491	$\bar{2}.7228$	2.4263
1.1677	$\bar{2}.6956$	2.4721
1.2164	$\bar{2}.6934$	2.5230
1.2763	$\bar{2}.6980$	2.5783
1.3414	$\bar{2}.6989$	2.6425
1.4075	$\bar{2}.7008$	2.7067
1.4540	$\bar{2}.7187$	2.7352

Table 3

Materials used	Platinum & Napthalene

Log q/A	Log h	Log ΔT
$\bar{1}.6093$	$\bar{1}.2921$	0.3172
1.9668	$\bar{1}.0797$	0.8871
0.2219	$\bar{1}.0966$	1.1253
0.4229	$\bar{1}.0966$	1.3234
0.5869	$\bar{1}.1610$	1.4259

Table 3 (continued)

Logb q/A	Log h	Log ΔT
0.7264	$\bar{1}.2129$	1.5135
0.8448	$\bar{1}.2828$	1.5620
0.9482	$\bar{1}.3723$	1.5759
1.0407	$\bar{1}.4513$	1.5894
0.9861	$\bar{1}.2130$	1.7731
0.9914	$\bar{1}.0422$	1.9492
0.9947	$\bar{2}.9205$	2.0742
1.0268	$\bar{2}.8557$	2.1711
1.1034	$\bar{2}.6540$	2.4494
1.1587	$\bar{2}.6670$	2.4917
1.2106	$\bar{2}.6829$	2.5277
1.2565	$\bar{2}.7044$	2.5521
1.3052	$\bar{2}.7209$	2.5843
1.3581	$\bar{2}.7312$	2.6269
1.4075	$\bar{2}.7445$	2.6630

Table 4

Materials used	Platinum & Carbontetrachloride

Log q/A	Log h	Log ΔT
$\bar{1}.4566$	$\bar{2}.8084$	0.6482
1.8263	$\bar{2}.5833$	1.2430
0.0791	$\bar{2}.7809$	1.2982
0.2706	$\bar{1}.0132$	1.2574
0.4290	1.1716	1.2574
0.5628	$\bar{1}.3054$	1.2574
0.6808	1.3892	1.2916
0.7832	$\bar{1}.4916$	1.2916
0.8392	$\bar{1}.5476$	1.2916

Table 4 (continued)

Log q/A	Log h	Log ΔT
0.5073	$\bar{2}$.9560	1.5513
0.5818	$\bar{2}$.6326	1.9492
0.6277	$\bar{2}$.4566	2.1711
0.6797	$\bar{2}$.3625	2.3172
0.7126	$\bar{2}$.2863	2.4263
0.7881	$\bar{2}$.2363	2.5581
0.9046	$\bar{2}$.2390	2.6656
0.9953	$\bar{2}$.2629	2.7324
1.0883	$\bar{2}$.2849	2.8034
1.1596	$\bar{2}$.3164	2.8432
1.2249	$\bar{2}$.3489	2.8760
1.2760	$\bar{2}$.3849	2.8911
1.3177	$\bar{2}$.4222	2.8955

Table 5

Materials used: Copper & Turpentine

Log q/A	Log h	Log ΔT
$\bar{1}$.9830	$\bar{1}$.0588	0.9242
0.2402	$\bar{1}$.0471	1.1931
0.4421	$\bar{1}$.0707	1.3714
0.6085	$\bar{1}$.1144	1.4941
0.7445	$\bar{1}$.2182	1.5263
0.6620	$\bar{1}$.3175	1.5445
0.9644	$\bar{1}$.4199	1.5445

Table 5 (continued)

log q/A	Log h	Log ΔT
1.0204	$\bar{1}.4759$	1.5445
0.9274	1.0158	1.5116
0.9401	$\bar{2}.9579$	1.9822
0.9798	$\bar{2}.8215$	2.1583
1.0370	$\bar{2}.7537$	2.2833
1.0810	$\bar{2}.7008$	2.3802
1.1325	$\bar{2}.6731$	2.4594
1.1714	$\bar{2}.6451$	2.5263
1.1988	$\bar{2}.6145$	2.5843

Table 6

Materials used	Copper & Napthlane

Log q/A	Log h	Log ΔT
0.0315	$\bar{1}.1199$	0.9116
0.2887	$\bar{1}.0825$	1.2062
0.4875	$\bar{1}.0820$	1.4055
0.6531	$\bar{1}.1866$	1.4665
0.7895	$\bar{1}.2790$	1.5105
0.9105	$\bar{1}.3317$	1.5788
1.0144	$\bar{1}.4141$	1.6003
0.9228	$\bar{1}.1113$	1.8115

Table 6 (continued)

Log q/A	Log h	Log ΔT
0.9702	$\bar{2}.9880$	1.9822
0.0027	$\bar{2}.8694$	2.1583
1.0917	$\bar{2}.8084$	2.2833
1.0925	$\bar{2}.7123$	2.3802
1.1522	$\bar{2}.6928$	2.4594
1.2092	$\bar{2}.6829$	2.5263
1.2637	2.6794	2.5843

Table 7

Materials used	Tungsten & Turpentine

Log q/A	Log h	Log ΔT
0.0065	$\bar{1}.2907$	0.7958
0.2687	$\bar{1}.2736$	0.9751
0.3881	$\bar{1}.2369$	1.1512
0.5085	$\bar{1}.2520$	1.2505
0.6134	$\bar{1}.3035$	1.3099
0.7104	$\bar{1}.3101$	1.4003
0.7972	$\bar{1}.3407$	1.4515
0.8758	$\bar{1}.3810$	1.4948
0.9485	$\bar{1}.4132$	1.5353

Table 7 (continued)

Log q/A	Log h	Log ΔT
1.0193	$\bar{1}.4158$	1.6035
1.0849	$\bar{1}.4291$	1.6558
1.0664	$\bar{1}.3217$	1.7447
1.0808	$\bar{1}.2392$	1.8416
1.1095	$\bar{1}.1887$	1.9208
1.1505	$\bar{1}.1048$	2.0457
1.1633	$\bar{1}.0065$	2.0968

Table 8

Materials used : Tungsten
&
Napthalene

Log q/A	Log h	Log ΔT
0.1430	$\bar{1}.2600$	0.8830
0.3037	$\bar{1}.3098$	1.9939
0.4400	$\bar{1}.3480$	1.0920
0.5576	$\bar{1}.4160$	1.1426
0.6672	$\bar{1}.3456$	1.3216
0.7606	$\bar{1}.4032$	1.3574
0.8454	$\bar{1}.4490$	1.3955
0.9270	$\bar{1}.4380$	1.4890
1.0012	$\bar{1}.4487$	1.5525
1.0673	$\bar{1}.4933$	1.5740
1.0979		

Table 8 (continued

Log q/A	Log h	Log ΔT
1.0979	$\bar{1}.5239$	1.5740
1.0624	$\bar{1}.3757$	1.6867
1.0975	$\bar{1}.2559$	1.8416
1.1374	$\bar{1}.1497$	1.9877
1.1608	$\bar{1}.0640$	2.0968

Table 9

Materials used : Tungsten
& Carbontetrachloride

Log q/A	Log h	Log ΔT
$\bar{1}.9689$	$\bar{1}.0270$	0.9419
0.1373	$\bar{2}.9573$	1.1800
0.2766	$\bar{2}.9746$	1.3040
0.4050	$\bar{2}.9724$	1.3426
0.4997	$\bar{1}.1557$	1.3440
0.5913	$\bar{1}.2473$	1.3440
0.6741	$\bar{1}.3301$	1.3440
0.7504	$\bar{1}.3956$	1.3548
0.8198	$\bar{1}.4650$	1.3548
0.8849	$\bar{1}.5222$	1.3627
0.9449	$\bar{1}.5222$	1.3627
0.7119	$\bar{1}.1714$	1.5405
0.7599	$\bar{1}.0152$	1.7447
0.7955	2.8747	1.9208

Table 9 (continued)

Log q/A	Log h	Log ΔT
0.8284	$\bar{2}.7827$	2.0457
1.1188	$\bar{2}.5038$	2.6150
1.2831	$\bar{2}.4681$	2.8150
1.3165	$\bar{2}.4105$	2.9060
1.4311	$\bar{2}.4223$	3.0088
1.4866	$\bar{2}.4513$	3.0353
1.5138	$\bar{2}.4242$	3.0893

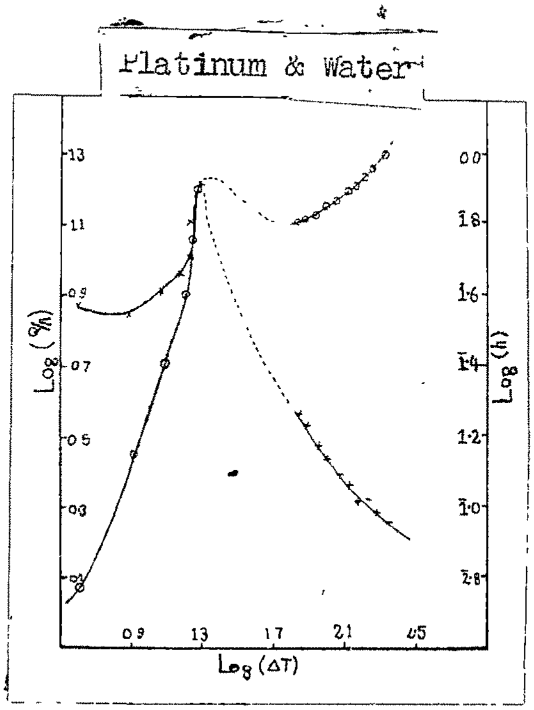

Fig. 2

The values of the maximum heat flux $(q/A)_{Max}$ and critical temperature difference $(\Delta T)_{crit}$ for the different wires and liquids used as also the values of the slopes calculated for natural convection boiling and nucleate boiling together with the heat transfer

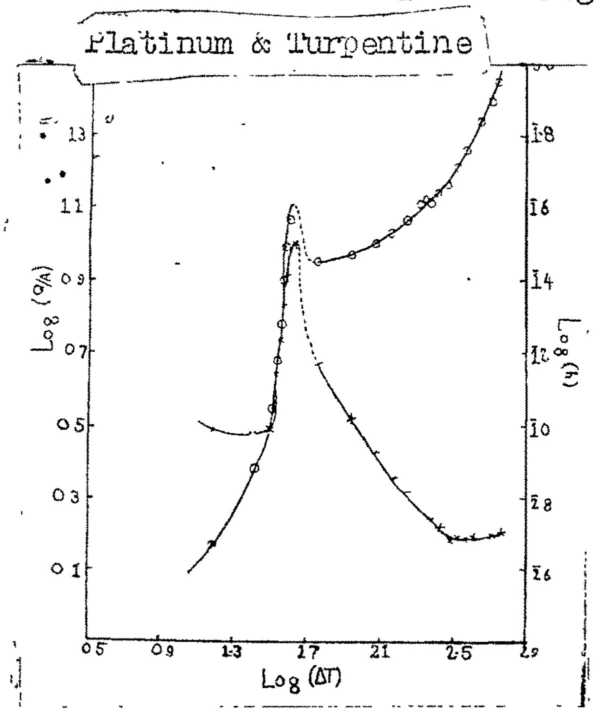

Fig 3

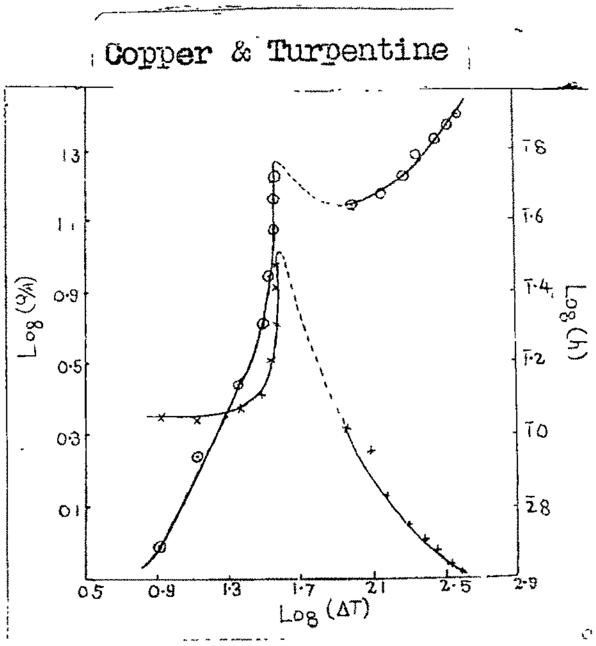

Fig 4

coefficient (h) at the peak value are shown in the following table:-

Table 10.

Liquid	Wire	Slopes for Nat. Cov. Boil.	Slopes for Nucl. Boil.	$(q/A)_{Max}$	$(\Delta T)_{crit.}$	$(h)_{max}$
Water	Platinum	0.91	3.25	15.8	19°C	0.800
Turpentine	Platinum	1.2	3.6	12.02	39.8°C	0.302
Naphthalene	Platinum	0.77	2.8	11.48	39.8°C	0.288
Carbon-tetrachloride	Platinum	0.6	2.57	6.9	19.95°C	0.355

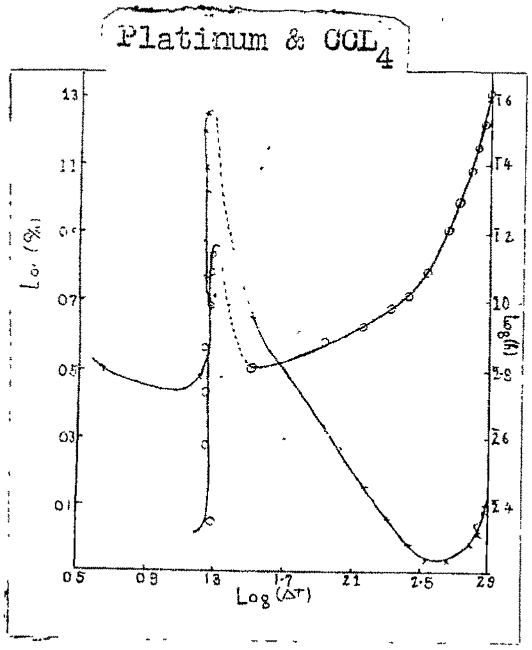

Fig. 5

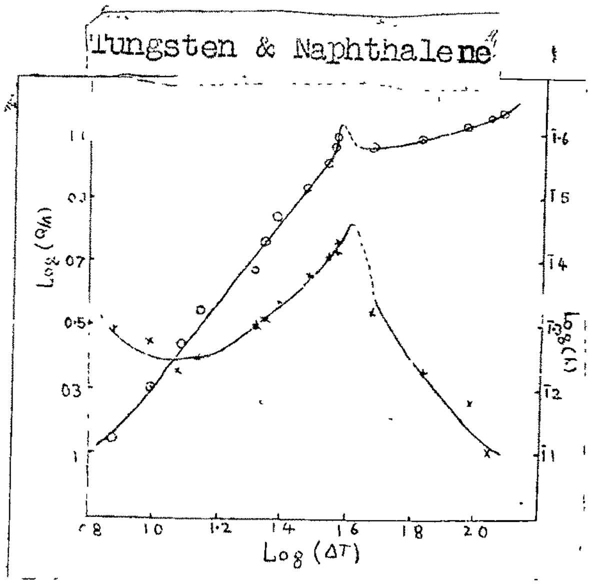

Fig. 6

Table II.

Liquid	Wire	Slopes for Nat. Cov. Boil.	 Nucl. Boil.	$(q/A)_{Max}$	$(\Delta T)_{crit.}$	$(h)_{MAX}$
Turpentine (B.P.156°C)	Copper	1.0	4.66	10.96	36.3°C	0.302
" "	Tungsten	0.9	1.6	12.6	43.6°C	0.275
Naphthalene (B.P.215°C)	Copper	0.83	2.75	10.72	39.8°C	0.263
" "	Tungsten	1.0	1.7	12.59	38.02°C	0.331
Carbontetrachloride (B.P.77°C)	Tungsten	0.71	3.0	8.7	22.9°C	0.355

Tungsten & CCl_4

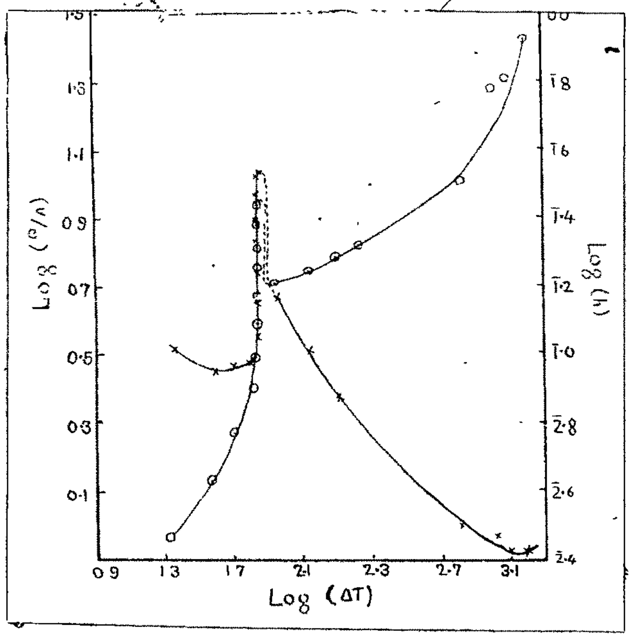

Fig. 7

Copper & Naphthalene

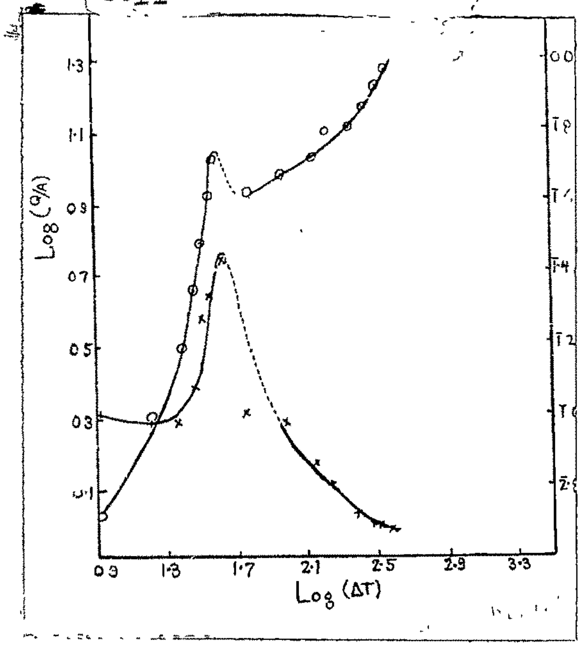

Fig. 8

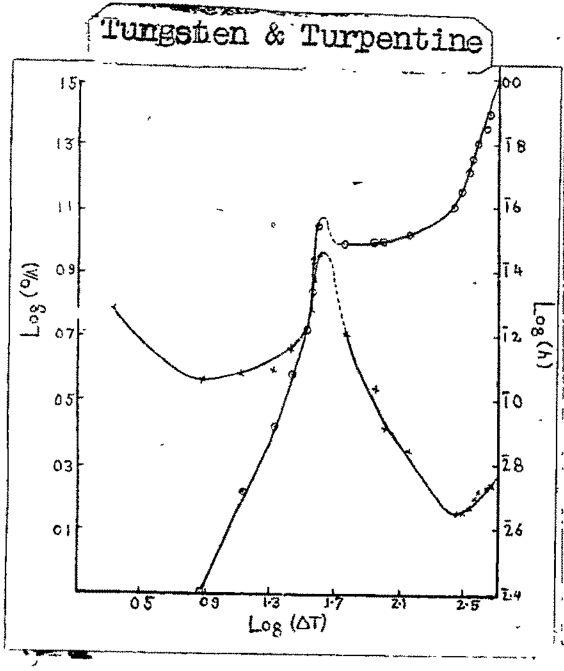

Fig. 9

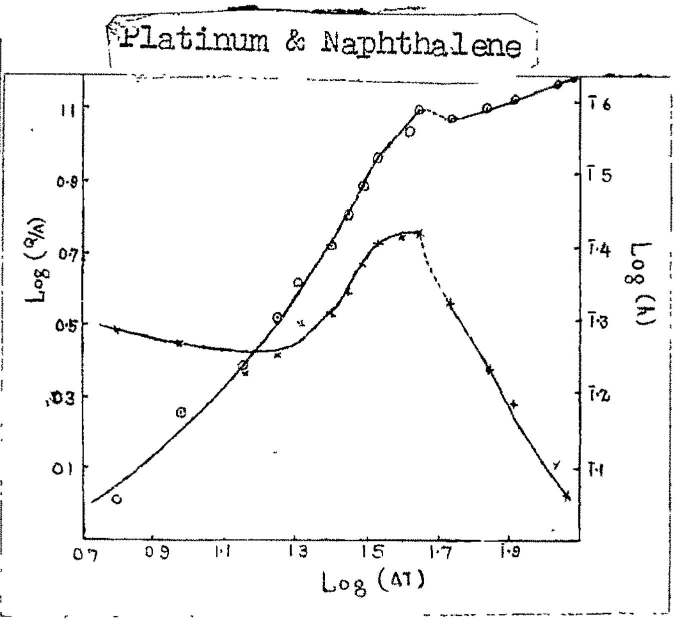

Fig. 10

When the heat flux exceeds $(q/A)_{Max}$ the system passes from nucleate boiling regime to film boiling regime after passing through a transient state of unstable film boiling. This unstable (transient) state is shown by the dotted curve in figs. 2 to 10. In the state of stable film boiling a vapour film is formed between the wire and the liquid. This film acts as a barrier in which the heat flow is due more to conduction than to convection. The formation of this barrier (vapour blanket) naturally diminishes the heat flow from the wire to liquid and hence the value of heat transfer coefficient h is also decreased as indicated by the graphs in figs 2 to 10. These graphs also indicate that if the heat flux is still further increased, the value of h goes on decreasing further. It can be seen from the figures that ...

Conlusions and dimensions

(a) The material of the wire do not seem to affect the value of the maximum heat flux $\left(q/A\right)_{Max}$ so much as the thermal properties of the liquid, especially the latent heat of vaporization.

(b) The continued decrease in the value of h with the increase of heat flux in the film boiling regime seems to be due to a slight increase in the thickness of the vapour film.

No theory of film boiling in the case of wires immersed in a liquid has been given so far, though Bromley (1950) who studied the phenomena, with a graphite tube immersed in water and some organic liquids, has derived a theoretical expression for the heat transfer coefficient making the following assumptions.

(1) A continuous vapour blanket of a small thickness 'a' exists round the tube.
(2) Vapour rises in Viscous flow by buoyant force.
(3) The liquid vapour interface is smooth in the section where most of the heat is transfered.
(4) Rise of vapour is retarded by Viscous drag on the tube and on the liquid contribution of the liquid drag is unkown: therefore it is included in a constant to be determined by experiment:

(5) The amount of heat transfer q may be assumed to be equal to rate of evaporation × $\left(h_{fg} + C_v T_x/2\right)$ where h_{fg} is the latent heat of vaporization and T_x is the excess of temperature over the surrounding.

(6) Kinetic energy and momentum changes in vapour film may be neglected.

(7) The temperature t_w of the heating surface may be assumed to be uniform around the tube.

(8) The combined effect of most errors introduced by the above assumptions may be corrected by evaluating a factor experimentally.

(9) At the liquid vapour interface the temperature of the liquid may be assumed to be equal to the saturation temperature.

Let us consider a section of a tube at right angles to its axis, and let the vapour blancket of thickness 'a' exist around the tube as shown in figure

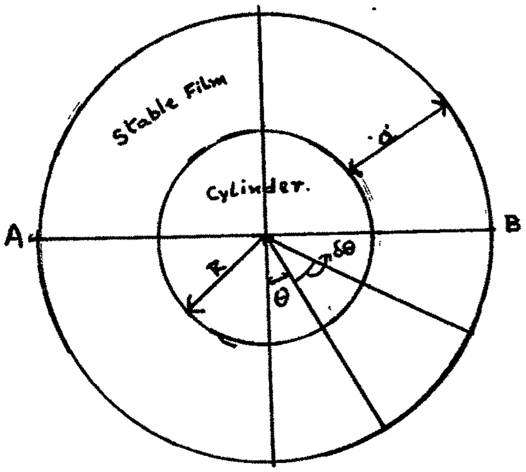

Fig. 11

Let p_0 be the pressure acting over the horizontal surface AB of the tube. Consider an element of horizontal thickness dz. Let φ and $\varphi + d\varphi$ be the angles subtended by radii of the tube with the verticle. Then we get

$$p - p_0 = g \rho_L z \text{ - - - - - - - - - - - } (1)$$

where p = the pressure acting at a surface at a depth 'z' from AB, ρ_L = density of the boiling liquid and 'g' is the acceleration due to gravity. Diffrentiating (1) we get

$$dp = \rho_L g\, dz \text{ - - - - - - - - - } (2)$$

As can be seen from, the figure

$$z = R \cos\varphi$$

and $$dz = -R \sin\varphi\, d\varphi$$

Thus $$dp = -g \rho_L R \sin\varphi\, d\varphi \text{ - - - - - } (3)$$

From assumption (5) for the surface $L R\, d\varphi$ where L is the length of tube

$$dq = h_{fg}\, dw \text{ - - - - - - - } (4)$$

where dw = rate of evaporation and

h_{fg} = latent heat of vaporization of liquid and

T_x is the excess of temperature of the tube over the surrounding liquid.

Again the amount of heat transfer dq can be expressed as

$$dq = h_c R L T_x \, d\varphi \quad \text{-------} (5)$$

where h_c is the heat transfer coefficient.

Thus we can write

$$dq = h_c R L T_x \, d\varphi = h'_{fg} \, dw \quad \text{----} (6)$$

The heat transfer through the vapour film, is by conduction, neglecting radiation, and hence

$$h_c = \frac{k_v}{a} \quad \text{---------} (7)$$

where k_v is the coefficient of thermal conductivity of the vapour and 'a' is the thickness of the vapour blanket.

Now forces acting from the flow in film are

(1) Forces due to hydrostatic pressure due to the vapour

(2) Forces due to viscosity

(3) Forces due to hydrosta~~tis~~tic pressure due to liquid on the surface of the vapour film.

Writing the force balance equation with assumption 6, we get

$$-dp = g \rho_v \, dz + df \quad \text{---------} (8)$$

where df is the presssure due to viscosity.

Now according to the theory of flow between parallel plates

$$df = \frac{12 \mu v}{a^2} R \, d\varphi \quad \text{------} (9)$$

where μ is the coefficient of viscosity of vapour and V is the mean velocity of the flow of the vapour. If one plate e.g. the liquid vapour interface, moves with vapour velocity then,

$$df = \frac{3\mu V}{a^2} R\, d\varphi \quad \text{- - - - - - - -} (10)$$

or with assumption (4)

$$df = \frac{B\mu V}{a^2} R\, d\varphi \quad \text{- - - - - - - -} (11)$$

where B is a constant.

Substituting these values in equation (8) we get,

$$\frac{1}{a^2} = \frac{g \sin\varphi \,(\rho_L - \rho_v)}{B\mu V} \quad \text{- - -} (12)$$

Again the mass of the vapour moved per second is

$$W = \rho_v a L V$$

$$\therefore \quad \frac{1}{a} = \left\{ \frac{g \sin\varphi\, \rho_v (\rho_L - \rho_v) L}{B \mu W} \right\}^{1/3} \text{from (12)} \quad \text{- - -} (13)$$

Substituting this value in equation (7) we get,

$$h_c = \left\{ \frac{k_v^3 g \sin\varphi\, \rho_v (\rho_L - \rho_v) L}{B \mu W} \right\}^{1/3} \quad \text{- - - - - -} (14)$$

Using equations (6) and (14), we get, after integrating for φ between the limits 0 and π and W between limits 0 and W,

$$W = \frac{2 (3.428)^{3/4} L}{B^{1/4}} \left\{ \frac{k_v^3 \rho_v (\rho_L - \rho_v) g R^3 T_x}{\mu_v h'_{fg}} \right\}^{1/4} \quad \text{- -} (15)$$

where the factor 2 is introduced to get W for both sides of the tube. Also from equation (6),

$$W = \frac{h_c \cdot 2\pi R L T_x}{h'_{fg}} \quad \text{-----} (16)$$

Eliminating W from equations (15) and (16) we get,

$$h_c = \text{Const.} \left[\frac{k_v^3 \rho_v (\rho_L - \rho_v) g\, h'_{fg}}{D \mu_v T_x} \right]^{1/4} \quad \text{-----} (17)$$

where D is the diameter of the tube and where

$$\text{Const.} = \frac{0.9536}{B^{1/4}}$$

Equation (17) gives Bromley's expression for the heat transfer coefficient h_c in the case of a cylindrical hollow tube immersed in a liquid. As Bromley himself has remarked (Bromley 1950) this theory is not applicable to very thin wires ($<$ 0.1 cm. in diameter). However we have tried to find out how far the formula fits in with our observations and we have therefore plotted log h_c against log $\left\{ \frac{k_v^3 \rho_v (\rho_L - \rho_v) g\, h'_{fg}}{D \mu_v T_x} \right\}$. The plot is shown in figure 12.

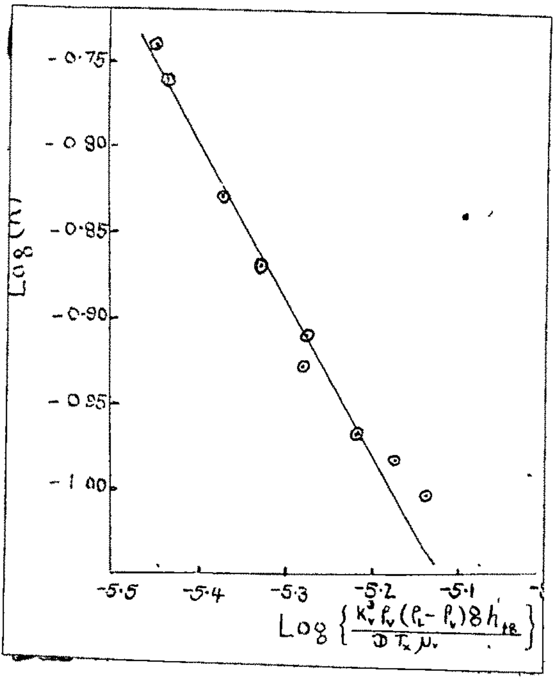

FIG. 12

which shows that a linear relation exists between log h_c and the Logarithim of the term within the brackets viz. $\left\{\frac{K_v^3 \rho_v (\rho_L - \rho_v) g h'_{fg}}{D \mu_v T_x}\right\}$ The slope of the curve comes out to be nearly unity and the constant B works out to be = 4.9×10^{-6}. Thus the value of the index n in Bromley's formula which was 0.25 according to Bromley's experiments with graphite tubes, comes out to be nearly unity in the case of our experiments with thin platinum (0.01 cm. diameter) wires.

References

Addoms J.N. 1948; "Heat Transmission by William H. McAdams, McGraw-Hill, Third Edition 1954. Asian Students' Edition. 382.

Bromley. L.A. 1950; Chem. Eng. Progr., **46**, 221.

Drew T.B. and A.C. Mueller 1937; 'Trans, Am. Inst. Chem. Engrs. **33**, 449.

Nukiyama S. 1934; 'J. Soc. Mech. Engrs'. (Japan), **37**, 367 - 374, 853 - 54.