HEAT TRANSFER IN FILM BOILING FROM ELECTRICALLY HEATED NICHROME WIRE TO BOILING WATER AT DIFFERENT PRESSURES—II

DEVI DAYAL

Samrat Ashok Technical Institute, Vidisha, M.P.

(*Received* 1 *Jan* 68,; *revised* 16 *April* 68)

Values of film thickness in film boiling have been computed for three different sizes of nichrome wires at five different sub-atmospheric pressures. The values of α, total heat transmission co-efficient, α_C heat transmission co-efficient due to conduction through the vapour film and α_R, heat transmission co-efficient due to radiation, have been calculated. The values of film thickness were found to decrease with external pressure, but were found to increase slightly with the radius of the wire. α, & α_C both increase with rise of pressure but decrease with the radius of the heated wire. α_R shows a minimum value at a pressure of 15 cm. of *Hg.* in the case of all the wire sizes. The radiation loss α_R is much smaller than conduction loss α_C.

The phenomenon of boiling assumes great significance where large quantities of heat are required to be transformed quickly from small areas such as in space flight, nuclear reactor, rocket engine, *etc.* The rate of heat transfer is different in three different types of boiling, *viz.*, nucleate, transition and film. Resuls of studies on nucleate and film boiling for nichrome wire in distilled and degasified water at different sub-atmospheric vapour pressures have been reported in an earlier communication[1]. This paper reports findings of further work on the film thickness in film boiling for different sizes of nichrome wires at five different sub-atmospheric pressures.

APPARATUS AND EXPERIMENTAL PROCEDURE

An electrically heated nichrome wire is placed horizontally under water (3·5″ below the surface). The water was in an inner chamber of a double walled vessel. The temperature was controlled by means of water in outer jacket. The pressure was that of the vapour at any temperature since the space above the inner chamber was evacuated and any evaporating water was returned by means of a condenser.

The complete experimental set-up and experimental procedure are given in Fig. 1 of the earlier communication[1].

NUCLEATE BOILIN AND FILM BOILING

As the current through the wire is gradually increased the heat transfer from the wire to the liquid changes from the convective transfer to nucleate boiling transfer. As the current is further increased a stage comes when bubble formation of the wire becomes maximum and the wire is wholly covered by bubbles. The heat transfer at this stage is the maximum in nucleate boiling. If at this stage the current is even slightly increased, a uniform vapour film is formed at the wire and the current falls as the resistance of the wire increases on account of accumulation of heat in it. The wire becomes red hot, and one observes the film boiling. The vapour film on the wire having a much lower thermal conductivity causes a decreased rate of heat transfer.

Besides the conspicuous decrease in heat transmission in film boiling, it also differs in another essential respect from nucleate building, *viz.*, that while the latter takes place from a few isolated or favoured spots, film boiling has no such preference, but occurs uniformly from all parts of the wire. One is often reminded of the phenomena of the spheroidal state where a thin layer of steam above a hot plate supports a big layer of water in the shape of spheroids. The continuous layer of steam in contact with the heated wire in our experiments is in a state of unstable equilibrium with respect to the colder water layers above it, so that the steam tends to break through the water above by the formation of a pattern of bubbles which orginate at the upper boundary of the film, later get detatched from it, and then move upwards through the water column (see Figs. 1—5). Steam escaping from the film in the above pattern of bubbles is of course being continuously replaced by fresh steam so that the above dynamical process may be conceived as more or less continuous.

It seems that in the case of film boiling the heat being conducted from the wire is, on an average, a problem of molecular conduction through the thin film of steam. The turbulent or convective transfer of the heat so conducted to the outer boundary, is later taken up by the convective and bubbling processes taking place in the water layer above the film. Besides molecular conduction of heat through the steam film, there will also be a considerable exchange of heat by radiative transfer between the wall of the wire and the outer boundary of the film.

Let us consider the heat transfer process within the film. The heated wire as well as the outer boundary of the steam layer surrounding it have the radii r_1 and r_2 respectively, so that the mean thickness of the steam layer is $r_2—r_1$. The wire temperature is θ_1 and that of the outer boundary of the steam layer is θ_2. The heat transmission through the film, by conduction and by radiation will be

$$Q = \frac{2\ \pi\ k\ l\ (\ \theta_1 - \theta_2\ )}{\text{Log}_e\ r_2/r_1} + E$$

where Q is the heat transfer by conduction and radiation expressed in watts.,

k is the molecular heat conductivity of steam (which is assumed as not varying either with pressure or with the mean temperature of the layer),

l is the length of the wire, and

E represents the heat transferred by radiation in watts.

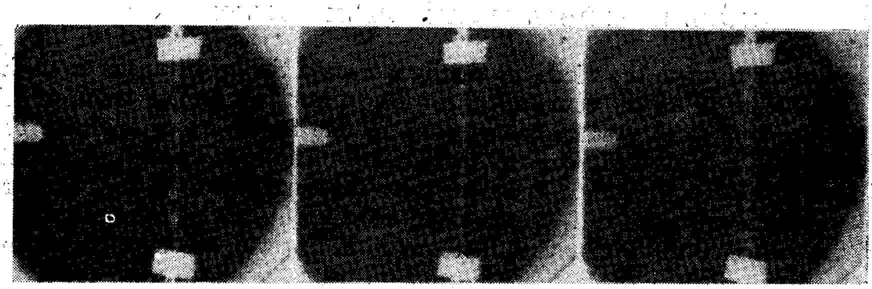
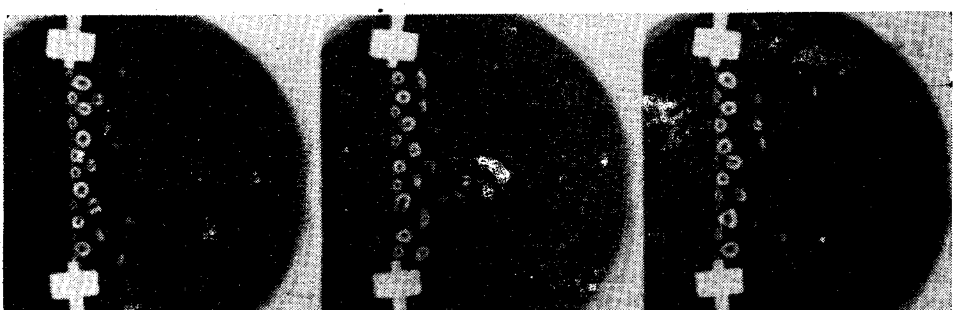


Fig. 1—Film boiling. (P = 4·2 cm. of Hg, θ wire = 1130°C, $\frac{Q}{A}$ = 66·4 Kcal/cm²/hr)

Fig. 2 (Top)—Film boiling. ($P = 9{\cdot}8$ cm of Hg, θ wire $= 720°C$, $\frac{Q}{A} = 59{\cdot}1$ Kcal/cm²/hr).

Fig. 3 (Bottom)—Film boiling. ($P = 15{\cdot}0$ cm of *Hg*, θ wire $= 800°C$, $\frac{Q}{A} = 63{\cdot}5$ Kcal/cm²/hr)



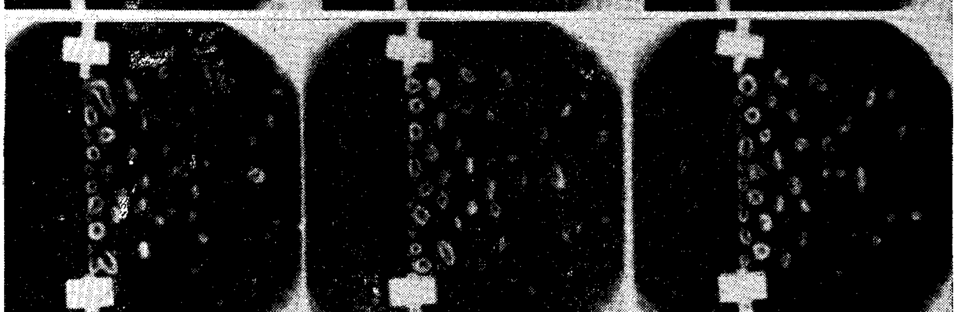


Fig. 4 (Top)—Film boiling. ($P = 23{\cdot}4$ cm of Hg, θ wire $= 770°C$, $\frac{Q}{A} = 72{\cdot}7$ Kcal/cm²/hr)

Fig. 5 (Bottom)—Film boiling. ($P = 40{\cdot}5$ cm of Hg, θ wire $= 1137°C$, $\frac{Q}{A} = 91{\cdot}6$ Kcal/cm²/hr)

In the expression above, all the quantities except r_2 are experimentally known. The radiation E may also be computed from the expression $E=\sigma(\theta_1'^4-\theta_2'^4)$, where σ is Stefan Baltzman Constant and θ_1' and θ_2' are the temperatures in absolute units of the surface of the heated wire and the water temperature respectively which are both known. The above simple approach, however, cannot be made without examining the effect of water vapour or steam absorption in the infra-red region of the spectrum with which we are here concerned. Let us first take the case when the effective absorption by water vapour is ignored.

Taking the case of the wire of gauge $S.W.G.$ 42 ($r_1=\cdot00508$ cm), we have for the experiment at pressure 5·5 cm. of Hg, with $\theta_1=1080°C$ and $\theta_2=40°C$, the total heat transmission $Q=10{,}23$ watts, and $A\sigma(\theta_1'^4-\theta_2'^4)=2\cdot378$ watts. (A = area of wire and $\sigma=5\cdot7\times10^{-12}$ watt. per cm²/sec).

Using these values we have

$$\frac{r_2}{r_1}=1\cdot866.$$

$$\text{Therefore}\quad \frac{r_2-r_1}{r_1}=\cdot866$$

$$\begin{aligned}\text{or}\quad r_2-r_1 &= \cdot866\ r_1\\ &= \cdot866\times\cdot00508\\ &= \cdot00440\ \text{cm}\end{aligned}$$

The above value of r_2-r_1, *i.e.*, the film thickness, comes out to be nearly of the same order as the wire radius, which is not inconsistent with the usual assumption made by some earlier workers[2].

We may now see how the computed value of r_2-r_1 changes, if we use values of $\frac{3}{4}E$, $\frac{1}{2}E$, $\frac{1}{4}E$, $\frac{1}{8}E$ and $\frac{1}{12}E$ for the net radiation loss. The Table 1 shows the series of values thus obtained.

TABLE 1

Assumed value for net radiative transfer from the wire to the outer boundary of the films.	Computed value of r_2-r_1, thickness of the film.
$E-A\sigma(\theta_1'^4-\theta_2'^4)$ *	·00440
$\frac{3}{4}$E	·00399
$\frac{1}{2}$E	·00366
$\frac{1}{4}$E	·00337
1/8 E	·00324
1/12 E	·00320

*$\theta'_1=\theta_1+273$; $\theta'_2=\theta_2+273$.

From the above it is clear that even a large change in the radiative exchange term does, not lead to a conspicuous change in the estimate of the film thickness. So, we may not be very far out assuming the full value of E in our later calculations.

With the above assumptions we have computed for each of the three sizes of heating wire used, the values of the thickness of the film in film boiling, the part α_c of the total heat transfer α that may be ascribed to conduction processes and the part of the heat transfer due to radiative exchange alone, *viz.* α_R. These, together with other relevant experimental data, are shown in Table 2.

TABLE 2

Pressure in cm of Hg.	θ wire—θ water $\triangle$	Radius of wire in cms.	Thickness of vapour film in film boiling in cms	Total heat transfer in film boiling in watts	Total $Q/A\triangle\theta=\alpha$ Kilo-cal/cm hr/°C	α_C concuction	α_R radiation	α_R — α_C
5·5	1040	·00508	·00440	10·23	·06801	·05224	·01582	·3029
9·2	735	Do.	·00391	6·241	·06543	·05714	·00829	·1451
15·0	660	Do.	·00282	7·530	·08102	·07388	·00714	·0966
23·4	700	Do.	·00246	8·708	·09356	·08537	·00819	·0959
37·2	779	Do.	·00185	12·35	·11550	·10520	·01028	·0977
5·5	1010	·00762	·00605	10·38	·04998	·03513	·01485	·4228
9·2	825	Do.	·00397	10·54	·06210	·05184	·01026	·1979
15·0	740	Do.	·00341	10·55	·06750	·05879	·00871	·1481
23·4	770	Do.	·00248	14·36	·08831	·07863	·00968	·1231
37·2	810	Do.	·00218	17·12	·09752	·08628	·01124	·1302
5·5	1025	·01169	·00606	18·11	·04938	·03399	·01539	·4527
9·2	840	Do.	·00388	17·65	·06015	·04947	·01068	·2159
15·0	770	Do.	·00359	15·96	·06233	·05293	·00940	·1776
23·4	800	Do.	·00274	23·89	·07782	·06739	·01043	·1547
37·2	779	Do.	·00243	25·52	·08541	·07508	·01033	·1375

From the results presented in this table we make the following observations :

(1) The computed thickness $r_2—r_1$ of the film decreases with the external pressure quite significantly.

(2) The total heat transmission α increases with rise of external pressure.

(3) The heat transmission α_c $(\alpha — \alpha_R)$ due to conduction process alone, also increases significantly with pressure.

(4) The net radiation loss shows a minimum value at a pressure of 15 cm. of H_g in the case of all the wire sizes.

(5) The value of $r_2—r_1$ shows a slight increase with the radius r_1 of the wire.

(6) The heat transfer coefficients α and α_c decrease with the radius r_1 of the heated wire.

(7) In general, the values of a_R are much smaller than a_c, the ratio of $\frac{a_R}{a_c}$ varying from 0·090 to 0·453 indicates that the radiation loss from the wire is smaller as compared to the loss by conduction.

REFERENCES

1. DEVI DAYAL, *Def. Sci. J.*, 18 (1968), 7.

2. BREEN, B. P. & WESTWATER, J. W., Effect of Diameter of Horizontal Tubes on Film Boiling Heat Transfer, *Chem. Engg. Prog.*, 58, No. 7 (1962), 67.