Int. J. Heat Mass Transfer. Vol. 12, pp. 791–796. Pergamon Press 1969. Printed in Great Britain

LIQUID BOILING IN A THIN FILM

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(*Received* 27 *September* 1967)

Аннотация—Экспериментально исследован процесс кипения жидкости в тонкой пленке, создаваемой на ограниченной поверхности путем подачи жидкости через форсунку. В опытах использовались вода, этанол, четыреххлористый углерод и бензол. Диапазон давлений 0,08–1 бар. В исследовании обнаружены некоторые новые закономерности (в частности: высокие критические нагрузки, одна точка перехода в отношении ΔT на кривой кипения, иной характер зависимости α от g и др.), которые обсуждаются в статье.

NOMENCLATURE

q,	specific heat flux [Wt/m^2];
α,	heat-transfer coefficient [Wt/m^{2}deg];
T_s,	saturation temperature [°K];
T_w,	heating surface temperature [°K];
T_*,	limit superheat temperature [°K];
T_{cr},	critical state temperature [°K];
δ,	film thickness [m];
R_{cr},	critical nucleus radius [m];
λ,	thermal conductivity of liquid [Wt/m deg];
σ,	surface tension [kg/m];
r,	vaporization heat [J/kg];
ρ', ρ'',	densities of liquid and vapour, respectively [kg/m^3];
A, n, ξ,	coefficients.

EVAPORATION and boiling of liquid in thin films have been attracting attention of many investigators. The results of studies on heat transfer and liquid boiling in a thin film formed over a finite plane surface by liquid supplied through a spray nozzle are given in the present work. Some new formulae and effects given below have been obtained in the course of these investigations.

EXPERIMENTAL APPARATUS

Liquid from the feed system was supplied to the heating surface through a spray nozzle. The liquid flow rate was balanced with the heat flux supplied, so that the quantities of the supplied and evaporated liquid under steady-state conditions were equal. The experimental section schematically shown in Fig. 1 consisted of a cylindrical brass rod 11 mm dia. and 20 mm long. Its end face served as a heat-transfer surface. The brass rod was made of one piece with a hollow brass disk of a larger diameter, inside which a 1·5 kW nichrome heater was placed. The cylindrical rod and the heater case were placed into a heat-insulating casing (not shown in Fig. 1).

The heat flux and the surface temperature were determined from the Fourier law. For this purpose copper–constantan thermocouples were imbedded along the rod. Enamelled thermocouple wires were inserted into a thin two-channel pipe of 0·8 mm dia. The holes for thermocouples 0·9–1·0 mm dia. were drilled in the brass rod. Special calibration showed that radial heat overflow was negligible. Extrapolation of the measured axial temperature distribution to the surface allowed determination of the boiling surface temperature. The heat flux was determined from the temperature gradient along the rod axis. The experimental section was within a bell jar. Vapour at the boiling surface

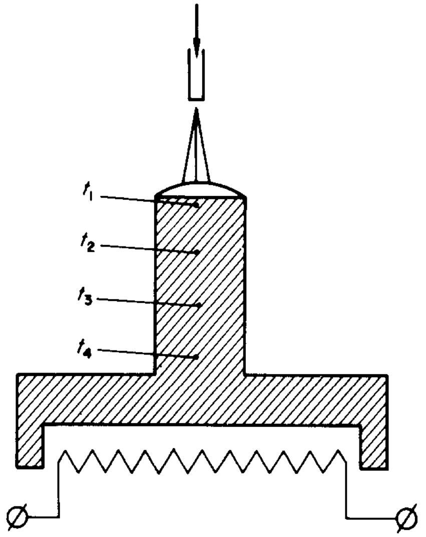


FIG. 1.

was removed and passed into a condenser cooled by tap water.

Distilled water, ethanol, carbon tetrachloride and benzene were used in the investigation. Saturation pressures ranged from the 0·08 to 1·0 bar. The majority of measurements were carried out at high heat fluxes. Under these conditions the temperature of the liquid supplied through a spray nozzle did not have any essential influence on the process.

Several spray nozzles with the orifice diameters from 0·02 to 0·2 mm were used in the experiments. The process was visualized and high-speed motion pictures of a liquid boiling at the right angle to the surface (at a rate of 2000 frames per second), were made.

EXPERIMENTAL RESULTS

Visualization and high-speed motion pictures show that with every value of heat flux associated is a definite average thickness of the boiling film completely covering the heat surface (0·03–0·3 mm). Changes of the conditions of fluid supply (distance from the spray nozzle to the heated surface, jet inclination to the heated surface, spray nozzle diameter) within wide ranges have practically no effect on the heat-transfer process. There is a considerable number of nucleation sites at the heated surface. Vapour bubbles grow quickly and go beyond the film thickness. After some period of time their outer surface is broken. Noticeable entrainment of liquid droplets (evaluated from the mass and heat balances) is observed at very high heat fluxes only. In general the boiling film is stable and the heat-transfer rate is high enough. The investigations have shown that in the case under consideration the peak heat flux is much greater than the critical heat flux in pool boiling. In Fig. 2 where q is plotted versus ΔT. data for water boiling in a thin film are shown together with the formula for pool boiling obtained on the same boiling surface.

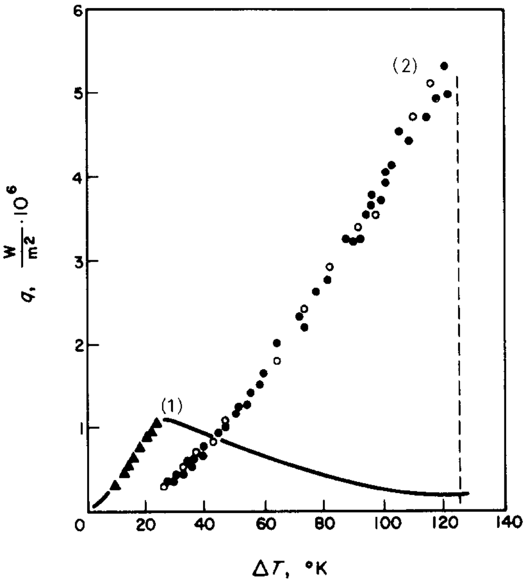


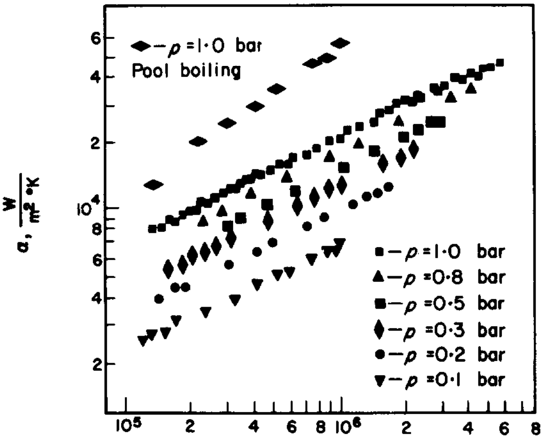
FIG. 2. Heat transfer in film boiling of water in a film.

(1) heated surface upward,
(2) heated surface downward, pool boiling conditions.

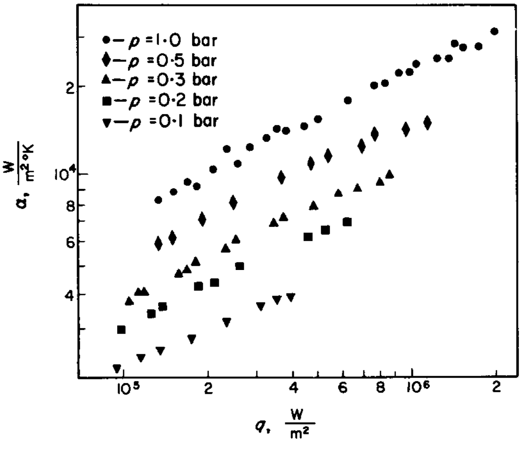
Attention should be paid to the fact that the peak flux in film boiling takes place at the temperature difference which for pool boiling corresponds to a minimum heat flux- (the

(Leidenfrost point). On reaching this temperature difference, the liquid film is broken away from the heated surface. No influence was found of the conditions of liquid supply and of the temperature on the magnitude of the peak flux. The correlations described were found typical of all the liquids used in the present experiments.

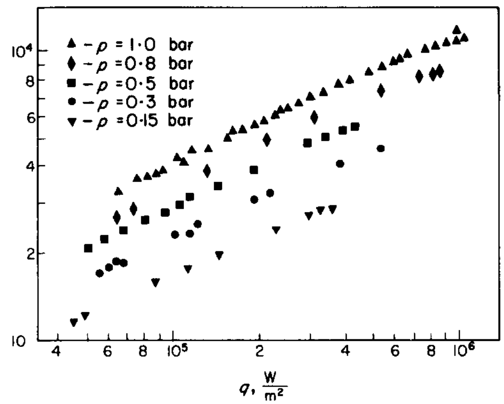
Experimental data for water, ethanol, carbon tetrachloride and benzene boiling in films at different pressures are plotted in Fig. 3 as α vs. q. The heat-transfer rate increases with the increase of heat flux up to the maximum point. The critical values of the heat flux in film boiling decrease with the decrease in pressure.



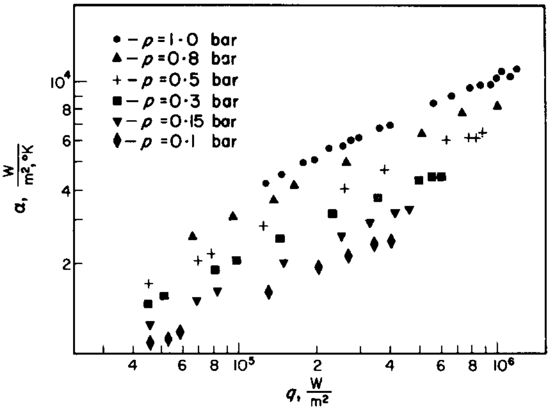
(a)



(b)



(c)



(d)

FIG. 3. Results on heat transfer:
(a) water, (b) ethanol, (c) carbon tetrachloride, (d) benzene.

DISCUSSION

The results of this study are noteworthy in two aspects.

First, the experiments have shown that the slope of the curve of heat transfer coefficient, α, versus heat flux, q, is less steep in film boiling than it is under conditions of pool boiling. The data presented in Fig. 3 show that in film boiling $\alpha \sim q^n$, the power n being $\simeq \frac{1}{2}$, while for pool boiling conditions n is higher ($\simeq\frac{2}{3}$). This may be attributed to the fact that in the process of liquid boiling in a thin film, agitation due to vapour bubbles is less pronounced. After the initial period of growth the outer surface of a bubble goes beyond the film boundaries and hence the mechanical energy of the bubble growth (unlike under pool boiling conditions) is almost unused for the intensification of the heat transfer.

From the high-speed motion pictures one may indirectly assess that the fluid flow is viscous (quasi-laminar). This conclusion results from the evaluation of the Reynolds numbers based on the average bubble growth rates, film thickness and the liquid viscosity. The corresponding values of Reynolds numbers are of the order 10^2. It is natural to suppose that under these conditions heat transfer must be determined primarily by thermal resistance to heat conductivity of the layer adjacent to the bubble growth region. If the average effective thickness of such layers is designated by δ_{eff}, then we may write approximately

$$\alpha = \frac{\lambda}{\delta_{\text{eff}}}. \tag{1}$$

Assuming that the liquid viscosity and heat capacity are not essential for the process considered, it is possible to show from general considerations of the theory of dimensions that

$$\frac{\delta_{\text{eff}}}{R_{cr}} = \text{const.}$$

where

$$R_{cr} = \frac{2\sigma T_s}{r\rho''\Delta T}$$

is critical nucleus radius.

Then we have

$$\alpha = \text{const.}\,.\frac{\lambda r\rho''}{\sigma T_s}\Delta T$$

or (since $\Delta T = q/\alpha$)

$$\alpha = A\left(\frac{\lambda r\rho''}{\sigma T_s}q\right). \tag{2}$$

Here A is a nondimensional numerical coefficient.

In Fig. 4 the results of the study are given in the co-ordinates of relation (2).† It may be seen that experimental data for all the liquids and pressures studied are in good agreement with relation (2) when the values of the coefficient is

$$A \simeq 0{\cdot}1. \tag{3}$$

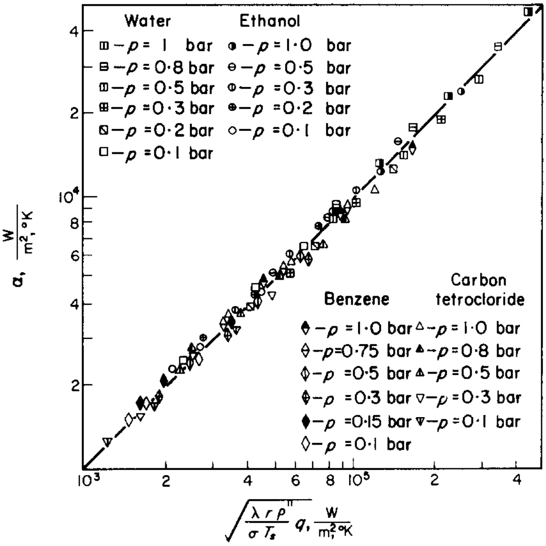


FIG. 4. Plot of the experimental data on heat transfer in coordinates of equation (2).

Thus, the correlation obtained, although approximate, represents correctly the effect of thermal properties of a liquid and operating parameters on heat transfer in film boiling.

The second peculiarity of the process in-

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† Here three experimental points are plotted for each liquid. They correspond to low, intermediate and high heat fluxes, respectively (see Fig. 3).

vestigated is connected with the burnout phenomena. Conditions of the burnout onset are associated here with the limiting temperature of the liquid superheat. In film liquid boiling there are practically no hydrodynamic restrictions on the removal of the vapour and supply of the liquid phase. Vapour removal from the film surface does not prevent the liquid from being supplied to nucleation sites. High-speed motion pictures data show that vapour bubbles are hemispheres protruding beyond the film boundaries and with a conical stem. Therefore, even though some bubbles coalesce, the liquid supply to their sites is not impeded. Owing to this fact the burnout in a thin film is a thermodynamic process (unlike the existence of the hydrodynamic conditions determining the burnout heat flux in pool boiling). Burnout arises at the moment when the surface temperature reaches the limit temperature of the liquid phase superheat. At this temperature the liquid state thermodynamic stability still occurs. At a higher temperature a spheroidal state arises. This state of affairs explains the fact that there is only one value of the critical ΔT on the curve of liquid boiling in a thin film.

At present there are two methods of evaluating the limit superheat temperature [1]: the analysis of homogeneous (volumetric) nucleation kinetics [2, 3] and the thermodynamic prediction with the assumption that $(\partial p/\partial v)_T = 0$, which is applied to a liquid phase state equation extrapolated into a metastable region [4]. The simplest (but not the most exact) method to evaluate the limit superheat temperature envolves Van der Waals' equation of state in generalized (dimensionless) parameters.

In the work of Spiegler *et al.* [4] it is shown that at $P/P_{cr} \ll 1$ the limit superheat temperature is

$$T_* = \frac{27}{32} T_{cr}. \tag{4}$$

In our experiments the surface temperature corresponding to the peak heat flux was always several degrees lower than that predicted by equation [4].

Apart from the approximative character of the thermodynamic prediction, this discrepancy may also be attributed to the fact that the disintegration temperature of a liquid phase layer adjacent to the solid surface, must, to a definite extent, depend on the cohesive forces between the liquid molecules and the surface. The analysis of the experimental data has shown that the critical temperature difference, $T_{cr} = T_{cr} - T_s$, may be correlated with the predicted limit temperature difference $\Delta T_* = T_* - T_s$, by the relation

$$\Delta T_{cr} = \xi \Delta T_* \tag{5}$$

where ξ is a coefficient depending on the properties of the heated surface in contact with the liquid. In our experiments $\xi = 0{\cdot}83$.

Substitution of the value ΔT into equation (2) permits us to determine the critical heat fluxes in liquid film boiling. Comparison of critical fluxes, q, predicted in this way with the values of q_{max} measured experimentally is given in Fig. 5.

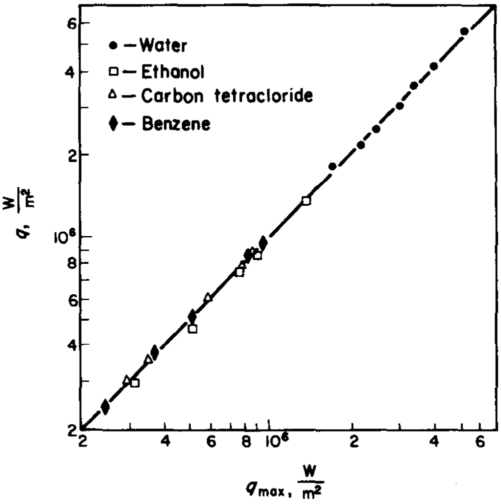

FIG. 5. Comparison of the experimental critical heat fluxes, q_{max}, and the predicted values q.

CONCLUSIONS

1. Experiments on boiling of liquid in a thin film within a pressure range of 0·08–1·0 bar have been carried out. Water, ethanol, carbon tetrachloride and benzene were used in the investigation.
2. Heat-transfer coefficients are commensurable with those in pool boiling, and described fairly by equation (2).
3. It was found that in boiling in a thin film at critical heat fluxes only thermodynamic critical phenomena occur. Critical heat fluxes in film boiling are several times as large as those in pool boiling.
4. The critical heat flux in film boiling may be calculated from equations (2) and (5).

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Abstract—Liquid boiling has been studied experimentally in a thin film formed over a limited surface area by supplying liquid through a spray nozzle. Water, ethanol, carbon tetrachloride and benzene were used in these experiments. Pressure ranged within 0·08–1 bar.

In this study some new correlations have been obtained such as higher critical fluxes in comparison with pool boiling, a single transition point on the boiling curve, q vs. ΔT different behaviour of the dependence of α vs. q and other observations which are discussed in the work.

Résumé—L'ébullition d'un liquide a été étudiée expérimentalement dans un film mince formé sur une surface limitée en fournissant le liquide à travers une tuyère d'atomiseur. L'eau, l'éthanol, le tétrachlorure de carbone et le benzène ont été employés dans ces expériences. La pression variait entre 0·08 et 1 bar.

Dans cette étude, certaines nouvelles corrélations ont été obtenus telle que des flux de chaleur plus élevés en comparaison avec l'ébullition en réservoir, un point de transition sur la courbe d'ébullition, un comportement différent de la dépendance de α vs. q et d'autres observations qui sont discutées dans l'étude.

Zusammenfassung—Das Sieden einer Flüssigkeit in einem dünnen Film, der über einer begrenzten Oberfläche durch Flüssigkeitszufuhr aus einer Zerstäuberdüse hergestellt wurde, ist experimentell untersucht worden. Wasser, Äthanol, Kohlenstofftetrachlorid und Benzol wurden bei diesen Experimenten verwendet. Der Druck lag in einem Bereich von 0,08 bis 1 bar.

Bei dieser Untersuchung sind einige neue Beziehungen gewonnen worden, wie höhere kritische Wärmestromdichten im Vergleich zum Sieden bei freier Konvektion, ein einziger Übergangspunkt auf der Siedekurve q über ΔT, verschiedenes Verhalten der Abhängigkeit von α über q und andere Beobachtungen, welche in dieser Arbeit besprochen sind.