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A STUDY OF THE MECHANISM OF NUCLEATE BOILING AT HIGH HEAT FLUXES

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Аннотация—Представлены результаты исследования с помощью скоростной киносъемки пузырькового кипения воды при тепловых потоках, доходящих до $0{,}6q_{cr}$ и давлениях от $9{,}8.10^4$н/м^2 до 52.10^5н/м^2.

Исследования ироводились на горизонтальной изолированной снизу пластине при кипении жидкости нагретой до температуры насыщения в условиях свободной конвекцпи.

Приведены фотографии вынужденного кипения недогретой воды ц спирта в прямоугольном канале при околокритических значениях тепловых потоков.

NOMENCLATURE

D_0, separation diameter of a vapour bubble;
R, bubble radius;
U, frequency of bubble separation;
q, heat flux;
q_{cr}, critical heat flux;
τ, time of vapour bubble growth;
θ, temperature difference;
λ, heat conductivity;
r, heat of vapour formation;
c, heat capacity;
ρ, density;
a, thermal diffusivity.

PHOTOGRAPHIC investigations of nucleate boiling of liquids conducted by Jakob, Linke, Fritz [1], L. M. Zysina, S. S. Kutateladze [2] (in the thirties), and V. I. Tolubinskiy [3] (in the fifties and sixties) were carried out at small heat fluxes. Nucleate boiling was also studied by Cole [4] in water under burnout conditions and by Perkins and Westwater [5] in methanol at high heat fluxes using high-speed motion photography. Finally Gunter [6] and Treshchev [7] (in the fifties) studied the mechanism of boiling in subcooled liquid with forced convection.

1. BOILING IN A LARGE VOLUME

In the present work we have studied nucleate boiling of water with free convection, at heat fluxes up to $0{\cdot}6q_{cr}$ and pressures from $9{\cdot}81 \times 10^4$ to 52×10^5 n/m^2, and also film boiling of ethyl alcohol with a heat flux approximately equal to $1{\cdot}2q_{cr}$ and pressures ranging from $9{\cdot}8 \times 10^4$ n/m^2 to 53×10^5 n/m^2.

The experimental apparatus has already been described in reference 8. The working section was made of a length of stainless steel foil 2 mm wide placed in a drum-shaped boiler with quartz windows. The lower side of the working section was thermally insulated with Textolite, while the upper heat-transfer surface had a ground finish. Heating was carried out by passing electric current through the plate. High-speed ciné-photographs, half full-size, were taken in transmitted light, at speed from 1000 to 4000 frames/s, using high speed cameras "ЦЛ-16" and "Пентацет-35".

It was found that in nucleate boiling of water the number of vapour-formation centres increased with a heat flux density, until the whole surface was seen to be covered with bubbles. The shape of the bubbles varied and some bubbles observed were not spherical.

With a further increase of the heat flux the bubbles which were growing on adjacent vapour-formation centres joined together, as a result of which the size of bubbles separating from the surface increased, and the number of the visible vapour-formation centres diminished.

H.M.—4R

Figure 1 shows the photographs of water boiling at a pressure of 52×10^5 n/m^2 and at respective fluxes: $0{\cdot}12q_{cr}$, $0{\cdot}25q_{cr}$ and $0{\cdot}6q_{cr}$. When plots were made to find the dependence of the separation diameters, D_0, and the separation frequency, U, on the heat flux and pressure only the more probable values were used. To find these the experimental results were treated statistically, i.e. the distribution curves were plotted for each operating condition.

Figure 2 shows the influence of the heat fluxes and pressures upon D_0 and U for nucleate boiling of water. The rise in the heat flux is seen to

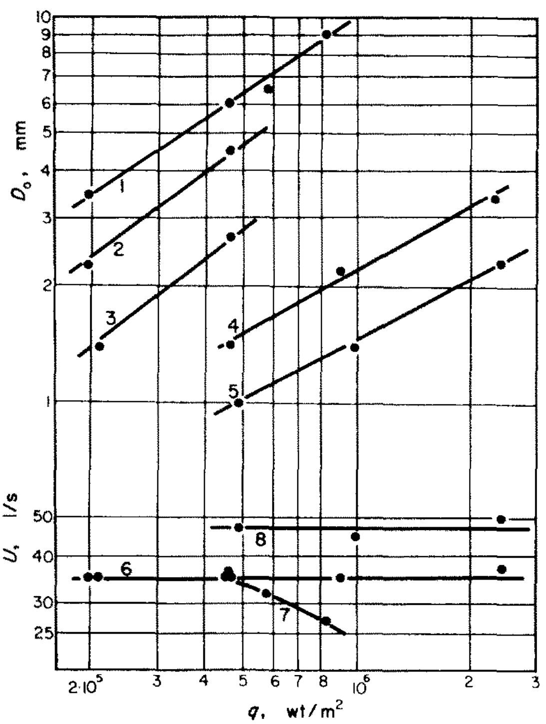

FIG. 2. Dependence of mean statistical values of D_0 and U upon the heat flux q and different pressures: (1) D_0, $P = 9{\cdot}8 \times 10^4$ n/m^2; (2) D_0, $P = 4{\cdot}9 \times 10^5$ n/m^2; (3) D_0, $P = 10{\cdot}8 \times 10^5$ n/m^2; (4) D_0, $P = 6{\cdot}10 \times 10^5$ n/m^2; (5) D_0, $P = 52 \times 10^5$ n/m^2; (6) U, $P = (0{\cdot}98\text{–}20{\cdot}6) \times 10^5$ n/m^2; (7) U, $P = 9{\cdot}8 \times 10^4$ n/m^2; (8) U, $P = 52 \times 10^5$ n/m^2.

lead to an increase of the separation diameters at all the pressures used in our tests. The frequency U does not depend on the heat flux and pressure for a wide range and is approximately equal to 35 s^{-1}. At $P = 52 \times 10^5$ n/m^2 the frequency increases up to 47 s^{-1}. There is a slight decrease in the frequency (to 27 s^{-1}) at $P = 98 \times 10^4$ n/m^2 for heat fluxes higher than $q = 4{\cdot}6 \times 10^5$ wt/m^2 (i.e. when large vapour bubbles with diameters greater than 6 mm are formed). This agrees with the results in reference 4 where boiling water was studied at atmospheric pressure near the critical heat flux or "crisis". In that case the separation diameters reached 15–20 mm at a separation frequency of 20 s^{-1}.

Table 1 contains the values of the separation diameters obtained in our experiments with the nucleate boiling of water. It also shows for comparison, the values obtained from the Labuntsov formula [9]

$$R = \sqrt{\left(\frac{2\beta\,\lambda\,\theta\tau}{r\rho''}\right)} \tag{1}$$

where $\beta \approx 10$, and from the volumetric boiling formula

$$R = \frac{2c\,\rho\theta}{r\rho''}\sqrt{(a\tau)} \tag{2}$$

where τ is the time of the bubble growth obtained from the experiments; θ is the superheat at the surface.

The values of these quantities were obtained from the data of reference 10. As seen from Table 1, the calculations using formula (1) give a slower growth of the separation diameters with the increase in the heat flux, than that observed experimentally. The absolute values of these diameters become equal at the heat flux $q = 1{\cdot}97 \times 10^5$ wt/m^2 at atmospheric pressure. For higher pressures formula (1) predicts an even slower growth with the heat flux increase.

For $P = 9{\cdot}8 \times 10^4$ n/m^2 formula (2) gives results, which are approximately twice too large but at other pressures (above $9{\cdot}8 \times 10^4$ n/m^2) it gives values several times too small. The discrepancy increases with pressure, and at $P = 52 \times 10^5$ n/m^2, for example, the calculated separation diameters are approximately seven times smaller than those obtained from the experiments.

In our work we have also used high-speed ciné-photography in order to observe the onset of the crisis in boiling. The statistical treatment

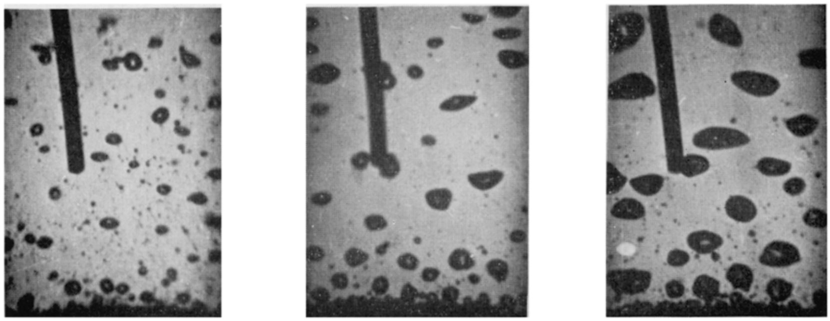

FIG. 1. Nucleate boiling of water at $P = 52 \times 10^5$ n/m^2 and different heat fluxes: (a) $q = 0{\cdot}12q_{cr}$, (b) $q = 0{\cdot}25q_{cr}$, (c) $q = 0{\cdot}6q_{cr}$.

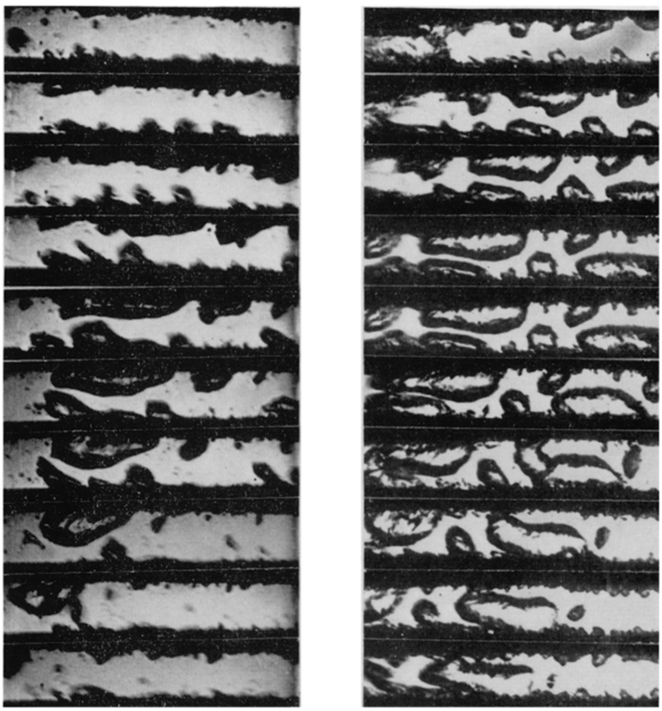

FIG. 3. Water boiling with forced motion in rectangular channel at q — $0{\cdot}9_{cr}$. $P = 1{\cdot}9 \times 10^5$ n/m^2; $\theta = 10$ degC; (a) $w = 1{\cdot}3$ m/s; (b) $w = 0{\cdot}3$ m/s.

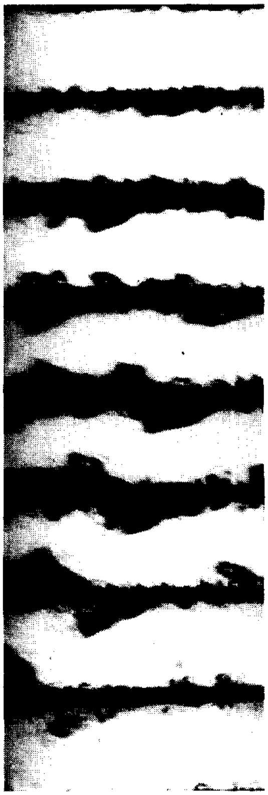

FIG. 4. Alcohol boiling with forced motion in rectangular channel at q — $0{\cdot}9q_{cr}$. $P = 1{\cdot}9 \times 10^5$ n/m^2; $\theta = 70$ degC; $w = 1$ m/s.

Table 1

q (Wt/m²)	P (n/m²)	θ (degC)	D_0 experimental (mm)	D_0 formula (1) (mm)	D_0 formula (2) (mm)	τ (s)
$1{\cdot}97 \times 10^5$	$9{\cdot}81 \times 10^4$	12·4	3·5	3·80	10·4	0·029
$4{\cdot}65 \times 10^5$	$9{\cdot}81 \times 10^4$	15·4	6·0	4·25	12·9	0·029
$5{\cdot}8 \times 10^5$	$9{\cdot}81 \times 10^4$	17·0	6·5	4·55	14·2	0·030
$8{\cdot}35 \times 10^5$	$9{\cdot}81 \times 10^4$	19·0	9·0	5·34	15·9	0·037
$2{\cdot}30 \times 10^5$	$10{\cdot}8 \times 10^5$	9·06	1·45	1·13	0·92	0·029
$4{\cdot}65 \times 10^5$	$10{\cdot}8 \times 10^5$	11·2	2·7	1·26	1·14	0·029
$4{\cdot}65 \times 10^5$	$20{\cdot}6 \times 10^5$	9·0	1·4	0·83	0·50	0·029
$9{\cdot}05 \times 10^5$	$20{\cdot}6 \times 10^5$	11·0	2·2	0·91	0·64	0·029
$23{\cdot}0 \times 10^5$	$20{\cdot}6 \times 10^5$	14·8	3·4	1·06	0·82	0·029
$4{\cdot}9 \times 10^5$	$52{\cdot}0 \times 10^5$	6·05	1·0	0·39	0·13	0·022
$9{\cdot}9 \times 10^5$	$52{\cdot}0 \times 10^5$	7·5	1·4	0·43	0·155	0·022
$23{\cdot}8 \times 10^5$	$52{\cdot}0 \times 10^5$	9·6	2·3	0·50	0·20	0·022

of such films is difficult due to a great instability of the process at the heat fluxes close to the critical. Qualitatively the occurrence of the crisis may be described as follows. As already mentioned, for the heat fluxes of over $0{\cdot}1q_{cr}$ for water, and over $0{\cdot}8q_{cr}$ for ethyl alcohol, at atmospheric pressure, the adjacent centres of vapour formation begin to amalgamate. When the heat flux is approximately equal to $0{\cdot}9q_{cr}$ (for both water and alcohol), on the heating surface there appear large vapour formations which move about at random. In fact, the heating surface becomes separated from the liquid by an unsteady vapour film. With a further increase of the heat flux, a continuous film of vapour is formed over the surface and steady film boiling develops. In the case of narrow heating surfaces the motion of the vapour film is of a pulsating character. The results of the study of film boiling of ethyl alcohol are given in reference 11.

2. BOILING WITH FORCED MOTION

The experiments on boiling with forced motion of a subcooled liquid were conducted in an open circuit apparatus. Vapour forced the liquid from a drum through the working section, i.e. through a rectangular tunnel 2 mm wide and 3 mm high. The upper and lower faces of the tunnel which was 30 mm long, were heated; the tunnel sides were made of quartz to allow photography in the transmitted light.

The working section was heated by low voltage a.c. current flowing through the upper and lower surfaces. Thermocouples mounted at the inlet and outlet of the working section measured the inlet and outlet temperatures of the liquid. Half-size and full-size ciné-photographs were taken at speeds from 3000 to 8000 frames/s. The development of the crisis in boiling alcohol and water was photographed at various degrees of subcooling and at low flow velocities from 0·3 to 2 m/s and a pressure of $1{\cdot}9 \times 10^5$ n/m².

Figure 3 (*a* and *b*) shows a number of photographs taken at half full-size of surface boiling of water at near-critical heat fluxes, with subcooling $\theta = 10$ degC at flow velocities: (*a*) $w = 1{\cdot}3$ m/s and (*b*) $w = 0{\cdot}3$ m/s. Figure 4 shows photographs taken full-size of surface boiling of ethyl alcohol at a heat flux $q \sim 0{\cdot}9q_{cr}$, subcooling $\theta = 70$ degC and the flow velocity 1 m/s. The time interval ΔT between the adjacent frames in Fig. 3 is equal to 0·001 s and in Fig. 4 to 0·0012 s. The sequence of the photographs is from top to bottom.

Under these operating conditions the boiling process consists of periodically repeated cycles lasting $\sim$0·01 s. During that time interval the vapour bubbles form and coalesce into larger bubbles of vapour. These bubbles, without separating from the surface, further increase in size and slide along the surface under the influence of the flow. The growth of the bubbles goes on for about 0·005 s, by which time they reach their maximum size, after which condensation of the bubbles begins, and lasts approximately 0·005 s, the residual vapour being entrained by the flow.

This process is illustrated in Figs. 3*a* and 4. In Fig. 3*b*, at a small flow speed, larger vapour bubbles are formed. They block up the channel section, and cover the heating surface all the time. In Fig. 4 despite the great subcooling (alcohol at the inlet is at 18°C) the vapour film of considerable thickness is formed at the surface. It quickly condenses, however, and in such a case the surface is washed by liquid alcohol (only very fine bubbles being observed at the surface), for a certain time ($\sim\frac{1}{16}$ of a cycle) until the recovery of the necessary superheat at the surface takes place.

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Abstract—A photographic study was made of nucleate boiling at high heat fluxes up to $0{\cdot}6q_{cr}$ and at pressures from $9{\cdot}8 \times 10^4$ n/m² to 52×10^5 n/m². Investigations were carried out of free convection on a horizontal plate insulated from below, with the boiling liquid heated up to a saturation temperature. High-speed ciné-photographs were also taken of the boiling of subcooled water and alcohol in forced convection in a rectangular channel at the near-critical values of the heat fluxes.

Résumé—Une étude de l'ébullition par nucléation a été faite à des flux de chaleur élevés allant jusqu'à $0{,}6\, q_{cr}$ et à des pressions allant de $9{,}8.10^4$ Pa à 52.10^5Pa. Des recherches ont été faites sur la convection libre à partir d'une plaque horizontale isolée par en-dessous, avec le liquide en ébullition chauffé jusqu'à une température de saturation. Des prises de vues cinématographiques à grande vitesse ont été prises également de l'ébullition d'eau sous-refroidie et d'alcool en convection forcée dans une conduite rectangulaire à des valeurs de flux de chaleur voisines de la valeur critique.

Zusammenfassung—Für hohe Wärmestromdichten von bis zu $0{,}6\, q_{cr}$ und Druecken von $9{,}8 \cdot 10^4$ N/m² bis $52 \cdot 10^5$ N/m² wurde das Blassensieden mit Hilfe von Photographien untersucht. Für freie Konvektion an einer horizontalen, von unten isolierten Platte mit der siedenden Flüssigkeit darüber, die bis auf Sättigungstemperatur erwärmt wurde, sind Untersuchungen durchgeführt worden. Über das Sieden von unterkühltem Wasser und von Alkohol bei Zwangskonvektion in einem Kanal mit rechteckigem Querschnitt bei Werten sehr nahr an der kritischen Wärmestromdichte wurden ebenfalls Bilder mit einer Hochgeschwindigkeitskamera gemacht.