BOILING OF CERTAIN LIQUIDS AT REDUCED PRESSURES

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The boiling of liquids at reduced pressures has so far received relatively little attention. In 1956 Van Stralen [1] measured the critical fluxes for water and a series of mixtures boiling on a thin wire in the range 50-760 mm Hg. An increase in the breakaway diameter of the vapor bubbles and a decrease in the number of active sites were noted with decrease in pressure.

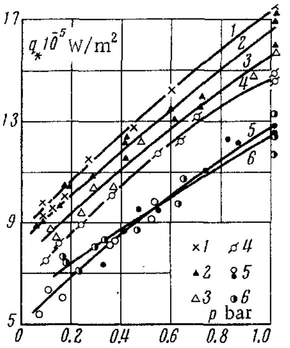

Fig. 1

Reference [2] is concerned with the boiling mechanism of water in the pressure range 0.4-1 kg/cm^2. The critical heat fluxes for water on a wire 0.5 mm in diameter were determined in [3]. The mechanism of nucleate boiling of a series of organic liquids at low pressures on a wire 0.5 mm in diameter was investigated in [4]. The authors of this paper showed that at sufficiently low pressures vapor bubbles cease to be produced in spite of the fact that the surface temperature is much higher than the saturation temperature. Earlier, in [1, 3] it was noted that on thin heaters there is no nucleate boiling and the natural convection regime is immediately followed by a transition to film boiling. In [5] a study was made of the mechanism of nucleate boiling of water in the pressure range 0.2-1 kg/cm^3.

NOTATION

A—thermal equivalent of work
g—acceleration of gravity
σ—surface tension
γ'—specific weight of liquid on saturation line
γ''—specific weight of vapor
r—latent heat of vaporization
D—diameter of heater
D_0—breakaway bubble diameter
T"—absolute temperature of saturated vapor
T_W—wall temperature
q_*—critical heat flux
τ'—liquid-heating surface contact time
τ''—vapor bubble growth time
F_0^{-1}—Fourde number.

1. In the experiments described we determined the first critical heat flux density q_* on horizontal tubes 0.2 to 5 mm in diameter at the saturation temperature under conditions of free convection. The pressures were varied from 0.05 to 1 bar. The length of the working sections was 60 mm. The heating surfaces were "run in" at atmospheric pressure and large heat fluxes for approximately 30 min. The experimental apparatus formed a closed loop consisting of a rectangular vessel-boiler, condenser, tube system, and shutoff valves. The boiler was provided with inspection windows measuring 50 × 70 mm. To create the necessary vacuum, the apparatus was evacuated with a mechanical vacuum pump of the VN-2MG type. The pressure was determined with a class-0.5 standard vacuum gauge, and below 0.1 bar with a mercury manometer. The heat flux power on the working section was measured with a type D-539 wattmeter. To measure the temperature of the liquid and the tube wall we used chromel-alumel thermocouples, whose emf was determined with a R2-1 potentiometer. The thermocouple used to determine the wall temperature was placed inside the working section. The temperature of the outside surface was calculated from a formula that took into account the temperature drop in the tube wall.

The experimental results are represented in the form of a relation between q_* (W/m^2) and the pressure p (bar) for distilled water in Fig. 1, for ethanol (concentration 96% by volume) in Fig. 2, and for benzene in Fig. 3. The points 1, ..., 6 in Fig. 1 correspond to diameters of 0.8, 1.5, 2.0, 0.5, {3.2 and 5.0} and 0.3 mm. In Fig. 2 the points 1, ..., 5 correspond to diameters of (0.5 and 0.8), 1.5, 0.2, 2.0, (3.2 and 5.0) mm. In Fig. 3 the points 1, ..., 5 correspond to diameters of 0.5, 0.8, 1.5, 2.0, (3.2 and 5.0) mm. In the experiments with water we used surfaces with a class-8 finish, in the experiments with benzene and ethanol surfaces polished with coarse-grain emery paper to a class-4 finish in accordance with Soviet Standard GOST-2789-59.

As the graphs show, the values of q_* decrease with decrease in pressure and depend on the size of the heater. The largest values of q_* are obtained for heaters 0.5-1.5 mm in diameter, for the tubes with diameters of 3.2 and 5.0 mm the values of q_* are the same. During the experiments we detected an effect due to the accumulation of heat in the wall. Therefore for the working sections we selected tubes of roughly the same thickness 0.25-0.35 mm. For tubes with a wall thickness of 0.15 mm the values of q_* for water were 10% lower than for tubes of the same diameter with a wall thickness of 0.35 mm. The effect of wall thickness and diameter on q_* was investigated in [6].

Figure 4 gives the results of experiments with water, ethanol and benzene in the form of a relation between the stability criterion for the two-phase boundary layer,

$$k = \frac{q_*}{r\sqrt{g\gamma''}\sqrt[4]{\sigma(\gamma'-\gamma'')}} \quad \text{and} \quad \Delta = D\left(\frac{\sigma}{\gamma'-\gamma''}\right)^{-1/2},$$

where the points 1, 2, 3 for water correspond to p = 1.0, 0.5 and 0.2 bar. The points 4, 5, 6 for alcohol correspond to p = 1.0, 0.5 and 0.2 bar, while for benzene points 7 and 8 correspond to p = 1.0 and 0.2 bar, D is the diameter of the heater.

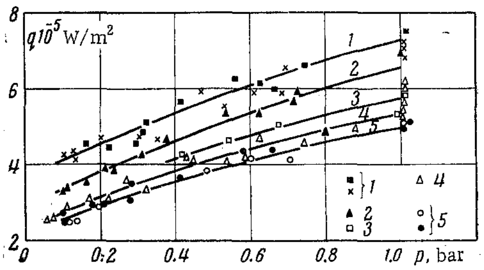

Fig. 2

In the region 0.2 < Δ < 1 there is a maximum of k; in the region Δ < 0.2 the value of k decreases; when Δ > 1.6 we get self-similarity with respect to the linear dimension. A similar relationship was obtained previously in [7] for atmospheric pressure and above. The character of this relationship is also preserved for a vacuum; however, for water and ethanol the value of k increases with decrease in p at small Δ (in Fig. 4 at p = 0.2 bar) and is practically independent of p at Δ > 1.5.

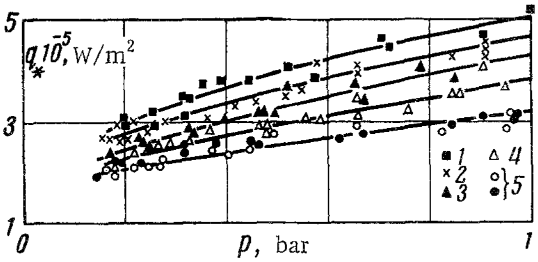

Fig. 3

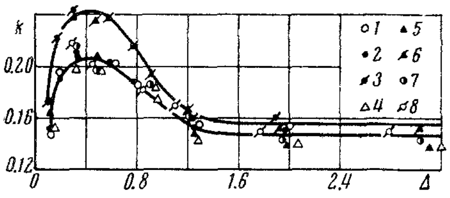

Fig. 4

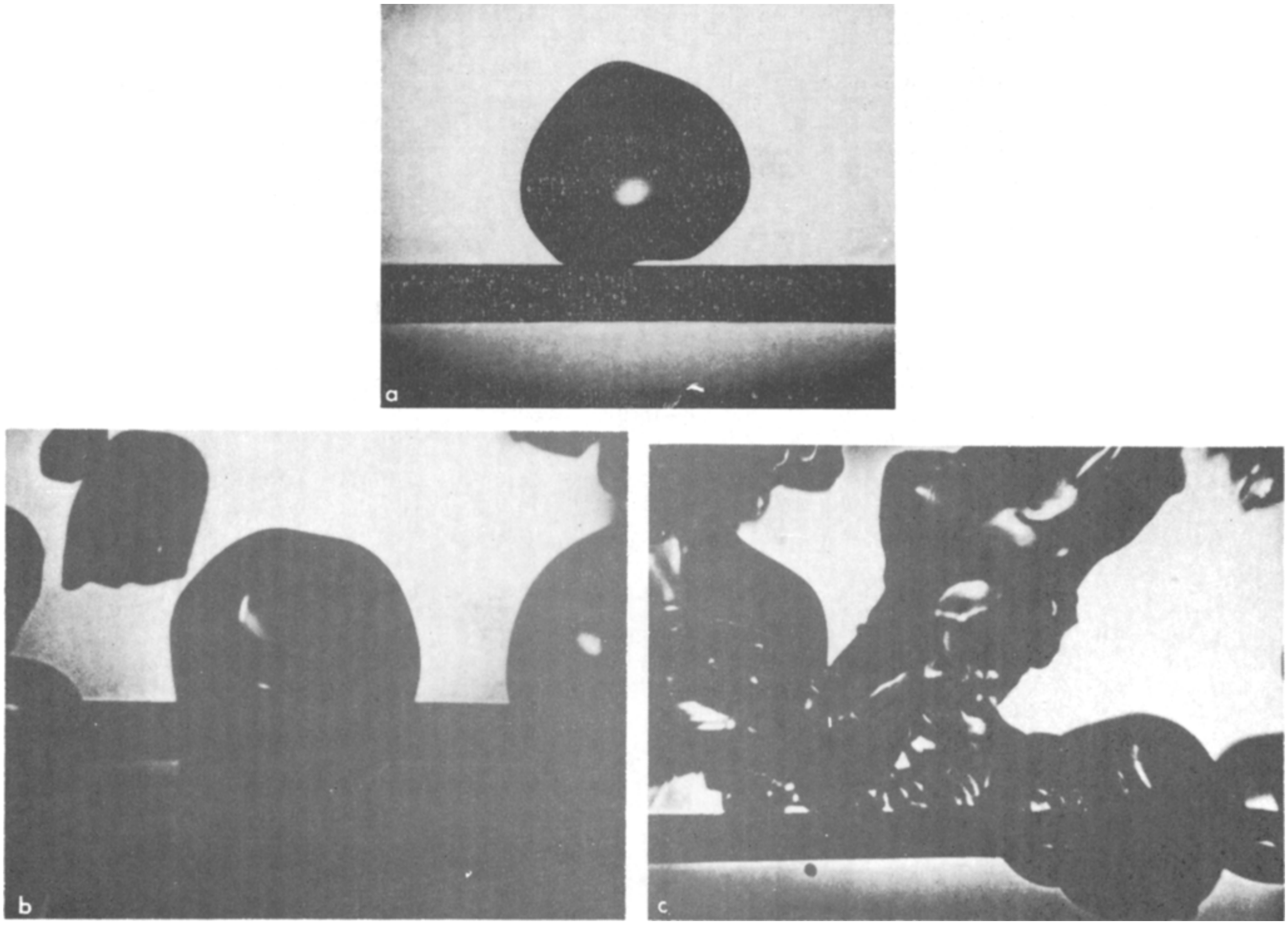

Fig. 5

p, bar	q, W/m^2	D_0, mm	U, sec^{-1}	W_0'', cm/sec	L, mm	δ_0
Water						
0.12	$2.8\cdot10^{5}$	27.0	9.0	56.0	2.66	10.15
0.15	$1.0\cdot10^{5}$	26.0	1.5	53.0	2.65	9.8
0.15	$2.0\cdot10^{5}$	22.5	4.0	51.0	2.65	8.5
0.15	$3.85\cdot10^{5}$	25.0	13.5	58.0	2.65	9.43
0.18	$0.8\cdot10^{5}$	18.0	4.0	47.5	2.64	6.82
0.18	$1.6\cdot10^{5}$	18.5	11.0	49.0	2.64	7.00
0.18	$3.3\cdot10^{5}$	20.5	22.0	55.0	2.64	7.75
0.30	$0.8\cdot10^{5}$	15.0	6.0	43.0	2.60	5.77
0.30	$1.6\cdot10^{5}$	19.0	15.0	49.5	2.60	7.3
0.50	$0.8\cdot10^{5}$	6.8	15.0	33.0	2.56	2.66
0.50	$1.6\cdot10^{5}$	10.0	20.0	35.5	2.56	3.90
0.65	$0.8\cdot10^{5}$	4.6	27.0	31.0	2.53	1.82
1.01	$0.8\cdot10^{5}$	2.5	33.0	23.0	2.50	1.0
Ethanol						
0.06	$0.6\cdot10^{5}$	28.5	3.0	59.5	1.715	16.6
0.06	$1.3\cdot10^{5}$	27.0	12.0	59.0	1.715	15.75
0.15	$0.30\cdot10^{5}$	18.0	2.0	45.5	1.68	10.7
0.15	$0.60\cdot10^{5}$	15.0	15.0	44.0	1.68	8.93
0.15	$1.3\cdot10^{5}$	17.0	18.0	48.0	1.68	10.1
0.18	$0.75\cdot10^{5}$	9.7	15.0	39.0	1.67	5.8
0.18	$1.4\cdot10^{5}$	9.6	20.0	40.0	1.67	5.75
0.31	$0.6\cdot10^{5}$	6.3	26.0	30.5	1.64	3.85
0.43	$0.3\cdot10^{5}$	3.2	27.0	24.0	1.615	1.98
1.01	$0.3\cdot10^{5}$	1.1	85.0	14.0	1.550	0.7
Benzene						
0.160	$4.3\cdot10^{4}$	15.0	5.0	48.0	1.80	8.34
0.173	$6.8\cdot10^{4}$	13.0	—	40.0	1.795	7.25
0.204	$4.3\cdot10^{4}$	10.5	8.0	40.5	1.785	5.88
0.375	$3.0\cdot10^{4}$	3.5	—	27.0	1.73	2.02

For benzene an increase in k is not observed at $p \approx 0.2$ bar.

2. To study the process of boiling under vacuum we carried out high-speed motion-picture photography with "PENTATSET-35" and "PENTATSET-16" cameras at speeds of from 1000 to 2500 frames/sec. The heating surfaces were tubes 2 and 3.2 mm in diameter and insulated plates 3-5 mm wide with the surface finish as indicated above. The results of motion-picture photography and visual observation showed that the boiling of liquids at $p < 0.3$ bar is characterized by a number of special features.

A. Large vapor bubbles are formed with a considerably lower breakaway frequency than at higher pressures. The number of active sites is sharply reduced. At $p < 0.1$ bar for alcohol and at $p < 0.2$ bar for water vapor bubbles more than 20 mm in diameter are formed. At these reduced pressures the growth of the bubbles is explosive in character and is accompanied by a crack. Large pulsations of the surface temperature are observed. With increase in pressure the breakaway diameters decrease. The nature of the boiling process under these conditions is also affected by the heat load. The table presents data on the breakaway diameter D_0, the breakaway frequency U, and the mean growth rate of bubbles at the heating surface $W_0'' = D_0/\tau''$ at the instant of breakaway for different pressures and loads. These values were obtained by averaging 10-30 measurements. At small loads large bubbles are formed with a low breakaway frequency (1-3 bubbles per second), the activity of each active site being irregular. With increase in load at constant pressure there is an increase in the rate of breakaway (or nucleation) of bubbles, boiling becomes more regular, the surface temperature pulsations are reduced, and the number of active sites grows, though not so much as at higher pressures. With further increase in the heat load there is a transition from simple, isolated to complex bubbles, which are formed as a result of merging both with neighboring bubbles on the heating surface and with bubbles that have already broken away. This type of bubble was not investigated.

Figure 5 presents photographs of the boiling of ethanol on a tube 3.2 mm in diameter at a pressure p = 0.15 bar and heat fluxes:

$$\text{a) } q = 1.2 \cdot 10^5 \text{ w/m}^2,$$

$$\text{b) } q = 0.6 \cdot 10^5 \text{ w/m}^2, \quad \text{c) } q = 1.8 \cdot 10^5 \text{ w/m}^2.$$

As follows from the table, the breakaway diameters at constant p and different heat fluxes (at which merging of the bubbles has not yet begun) vary comparatively little. The increase in nucleation rate U is due to a reduction in the heating time τ' of the liquid near the active sites (i.e., the liquid-surface contact time), while the bubble growth time τ'' at the surface remains approximately constant.

At pressures above 0.3-0.4 bar the boiling mechanism approaches that at atmospheric pressure, i.e., the breakaway diameters decrease, the rate of bubble formation increases, and the number of active sites becomes considerable even at small loads.

In [8, 9] it is pointed out that boiling in the region of large heat fluxes is accompanied by deformation of large vapor bubbles, which grow at a rapid rate on the surface; therefore in the balance of forces acting on a bubble at the moment of breakaway it is necessary to include the resistance of the liquid, for which

$$\frac{\pi D_0^3}{6}(\gamma' - \gamma'') = \pi D_0 \sigma f(\Theta) + \xi \frac{\pi D_0^2}{4} \gamma' \frac{W_0''^2}{2g}.$$

Hence we can obtain the dimensionless groups

$$\delta_0 = \frac{D_0}{L}, \quad F_0^2 = \frac{g^2 \sigma}{W_0''^4 (\gamma' - \gamma'')},$$

$$\vartheta = \frac{\gamma' - \gamma''}{\gamma'} f(\Theta) \quad \left(L = \left(\frac{\sigma}{\gamma' - \gamma''} \right)^{1/2}, \; W_0'' = \frac{D_0}{\tau''} \right).$$

Here F_0^{-1} is the Froude number, W_0'' is the mean rate of growth of the bubble at the surface at the moment of breakaway. The drag coefficient ξ for a plane spheroid is approximately 1. The mean contact angle for water, ethanol and benzene varies little with change in pressure; according to our experiments it is between 42° and 50°.

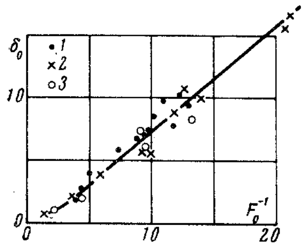

Fig. 6

Figure 6 presents the tabulated experimental data on the boiling of water (1), ethanol (2), and benzene (3) in the coordinates δ_0 and $1/F_0$.

B. The active sites may be depressions and notches in the heating surface [10, 11]. Their size must be of the order of the critical size of the vapor phase nuclei, which is given by the expression

$$R_{\min} = \frac{2\sigma T'' A}{r \gamma'' \Delta T}.$$

With decrease in pressure the value of $R_{\min}$ increases by several times. Thus, at p = 0.1 bar the quantity $2\sigma T'' A / r\gamma''$ for water and ethanol increases approximately by a factor of 10 as compared with atmospheric pressure, and the corresponding temperature heads $\Delta T = T_W - T''$, at which boiling begins, increase by a factor of about 3. Consequently, $R_{\min}$ increases by 3-4 times. An increase in the radius of the nuclei leads to retardation of the process of bubble formation on smooth surfaces. Boiling becomes more difficult and begins at relatively high heat fluxes.

Thus, for distilled water at p = 0.1 bar on a polished surface (class-8 finish) developed boiling beings at a heat load $q \approx 2 \cdot 10^5$ W/m^2, which amounts to approximately $0.25\, q_*$ (heater diameter 2 mm).

The state of the heating surface and its degree of roughness exert an effect on the boiling process at low pressures. Thus ethanol and benzene readily wet the heating surface, and the nucleation of the vapor bubbles becomes even more difficult. In experiments on the boiling of alcohol and benzene on polished surfaces even at $p \approx 0.5$ bar boiling occurs only when $q \gtrsim 1 \cdot 10^5$ W/m^2.

The regime of natural convection is immediately followed by the explosive development of an unstable film; after a certain time this disintegrates and ordinary nucleate boiling begins. The occurrence of such unstable conditions also depends on the rate of load input. When the increase in load is slow, a nucleate boiling regime may occur. At pressures below 0.3-0.2 bar on smooth surfaces a stable regime of film boiling develops without transition through the nucleate regime. On rough surfaces this transition from natural convection to film boiling is displaced into the region of lower pressures. On a wire 0.2 mm in diameter, which cannot be given a rough finish, values of the critical heat fluxes have been determined to 0.4 bar. Below this pressure film boiling occurs.

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