RELATIONSHIP BETWEEN CRITICAL HEAT FLUX AND HEATER DIAMETER IN THE BOILING OF A SATURATED LIQUID IN FREE-CONVECTION CONDITIONS

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This paper gives the results of an experimental investigation of the heat fluxes for a wide range of heater diameters and pressures in the pool boiling of saturated liquids. The experimental data of many investigators are generalized in terms of the criteria k and Δ (the hydrodynamic stability criterion, introduced by Kutateladze, and the Weber number).

The results of our experiments on the effect of heater diameter on the critical heat flux in the pool boiling of water and ethyl alcohol were published in [1]. The experiments were carried out at pressures of 1 and 11 kg/cm^2, and the heater diameters varied from 0.1 to 6 mm.

As a continuation of this work we now present new results of experiments in which the heater diameter was varied from 8 to 200μ and the pressures up to 0.8 P_* for certain liquids. The experiments were conducted on the apparatus described in [2] with the heating elements horizontal. The wires were used as resistance thermometers and were connected in one of the arms of a four-arm bridge circuit containing standard resistance coils, an MSR-60 resistance box, and an M-195/1 null galvanometer. The measuring circuit did not differ fundamentally from that used in [3]. The working section was supplied from a 24-V storage battery through rheostats. The heating elements of diameter 8 and 25μ were made of tungsten wire; those of diameter 50, 100, and 200μ were made of platinum. The temperature coefficient was determined separately for each working section by measuring the resistance of the section mounted in the apparatus. The measurements were made three times: with the apparatus filled with a solution of glycerol in water (5% by weight, boiling point about 140° C), and with the apparatus filled with alcohol before the start and after the end of the measurements, by means of a single P-316 bridge. The values of the temperature coefficient obtained by these measurements were practically the same as those specified for platinum.

The use of the section as a resistance thermometer enabled us to obtain relationships for the temperature drop between the wire and liquid for various heat fluxes and to determine exactly the moment of onset of film boiling.

Figure 1 shows the results of measurements of the temperature of wires of different diameter when the heat fluxes were increased to the critical values. The figure shows that the value of $\Delta t = t_* - t''$ (temperature difference between wire and liquid) at the instant when convection changed to boiling increases fairly rapidly as the heater diameter is reduced.

This is shown in coordinates Δt, D in Fig. 2. These data agree qualitatively with similar measurements conducted in [4] on water when the heater diameter was varied from 0.1 to 0.6 mm.

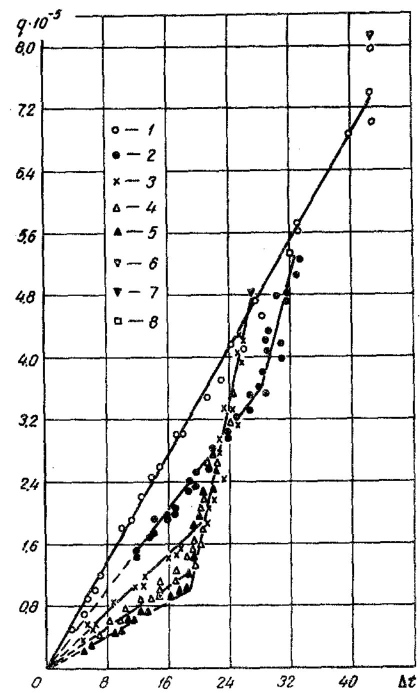

Fig. 1. Plot of $\Delta t = t_* - t''$, °C, against heat flux q, W/m^2, for different heaters (ethyl alcohol, P = 1 bar): 1) D = 0.008 mm; 2) 0.025; 3) 0.05; 4) 0.1; 5) 0.2; 6, 7, 8) critical heat fluxes.

The results of experiments on the boiling of ethyl alcohol at atmospheric pressure are shown in coordinates q_*, D in Fig. 3. To complete the picture we reproduce the data from [1] and also give new data.

Thus, the range of variation of the diameter of the heating elements was 8 μ to 10 mm. The characteristics of the heating elements are indicated in Table 1.

In the complex relationship between the critical heat flux and the diameter of the heat-emitting surface there is a distinct minimum (D = 0.1–0.05 mm) on the curve of $q_*(D)$, as well as our previously discovered maximum. Further reduction in the heater diameter again leads to an increase in the critical heat flux. The onset of film boiling on a wire of diameter 8 μ occurs at a heat load 1.6 times greater than the critical in the region of self-similarity of the heater diameter.

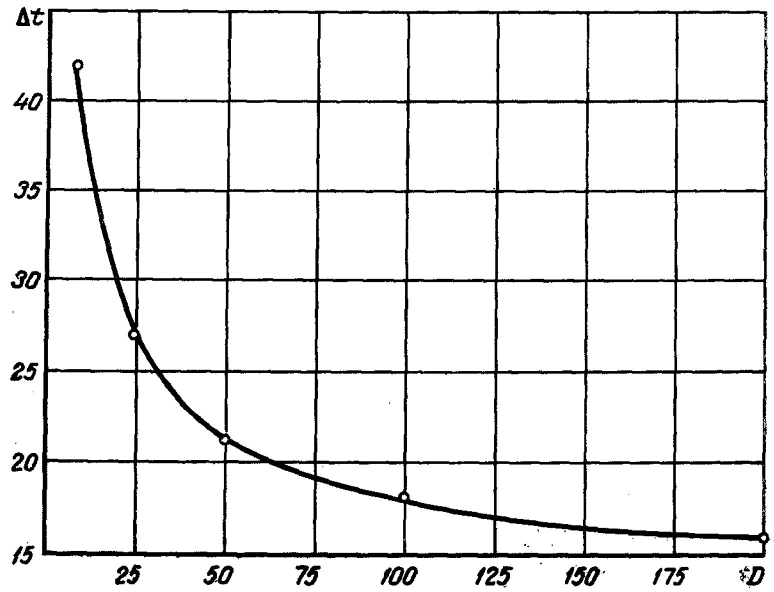

Fig. 2. Δt, °C, as a function of the heater diameter D, μ, on changeover from convection to boiling (ethyl alcohol, P = 1 bar).

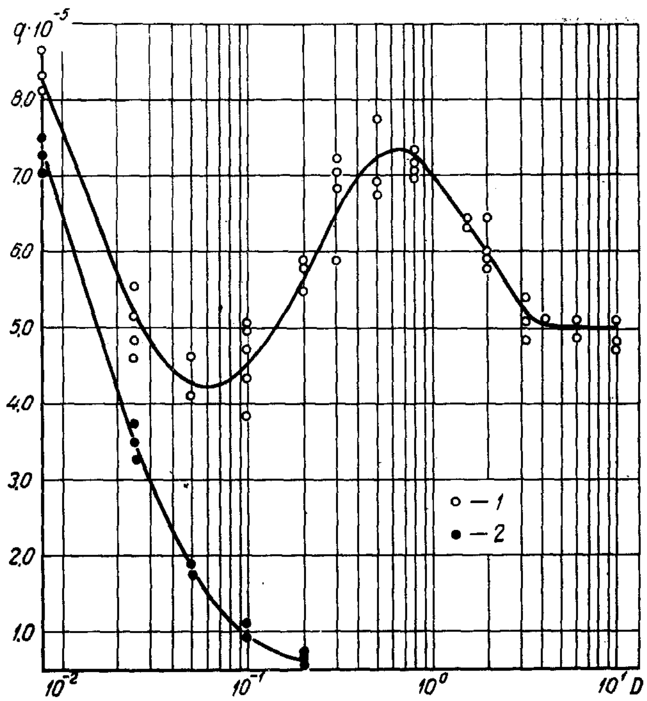

Fig. 3. Plot of q, W/m^2, against heater diameter D, mm (ethyl alcohol, P = 1 bar): 1) for critical heat flux; 2) for heat flux on changeover from convection to boiling.

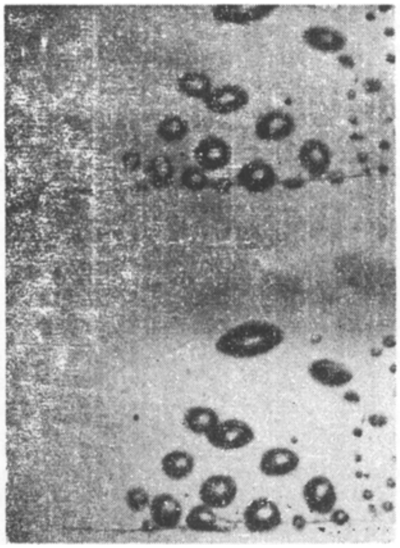

Fig. 4. Coexistence of three heat-transfer regimes (ethyl alcohol, P = 1 bar, D = = 0.025 mm).

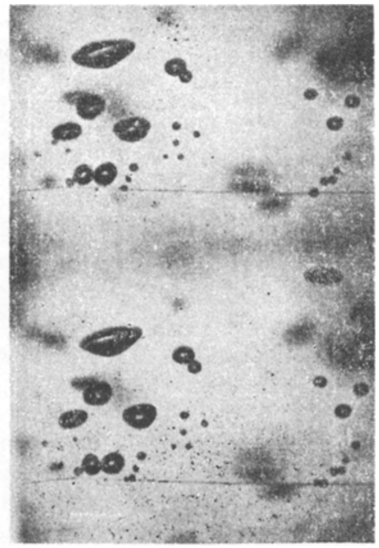

Fig. 5. Near-critical boiling on a thin wire (ethyl alcohol, P = = 1 bar, D = 0.025 mm).

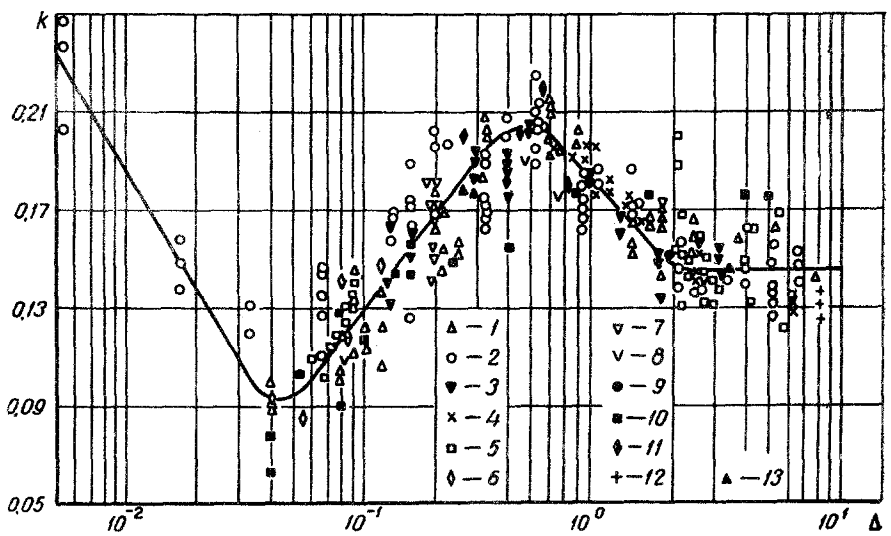

Fig. 6. Plot of dimensionless complex k against parameter Δ. Our data: 1) water; 2) alcohol; 3) benzene. Data of other investigators: 4) methanol [5]; 5) water [7]; 6) water [4]; 7) water [6]; 8) water [8–11]; 9) water [12]; 10) water [13]; 11) water [14]; 12) carbon tetrachloride [5]; 13) ethanol, methanol, n-butanol, n-propanol [12, 15].

For this region Fig. 3 shows the values of the heat fluxes at which convection gives way to boiling.

Figures 1 and 3 show that the role of convective heat transfer is very important and increases with reduction in the heater diameter. For instance, on a 25μ wire the heat flux on changeover from convection to boiling is 0.7 of the critical, and on a $8\ \mu$ wire it is about $0.9\ q_*$.

Thus, we can infer from the foregoing that the increase in q_* in the region of very small heater diameters is due to the large contribution of convective heat transfer.

When thin wires are used as working sections there are certain special features in the boiling process and the onset of the boiling crisis. On a surface of diameter $100\ \mu$ with continuous supply of heat convective heat transfer is often followed immediately by film boiling. The film formed usually breaks down spontaneously without change in the heat load and nucleate boiling begins. With further heating stable film boiling sets in. The last load is assumed to be the critical one. In experiments with surfaces of diameter 8 and $25\ \mu$ nucleate boiling occurred only when the heat was applied very gradually in steps with long intervals between the steps and a very small difference between the successive steps. When the heat load was increased steadily convective heat transfer always gave way to stable film boiling. Exactly the same picture was observed on changeover from film boiling when the heat flux was reduced. With very gradual reduction of the load nucleate boiling occurred in a narrow range of heat flux.

Figure 4 shows frames of a high-speed film (1000 frames/sec) of the coexistence of three heat-transfer regimes on a horizontal wire of diameter $25\ \mu$. On the right there are two active evaporating centers, as in ordinary nucleate boiling; film boiling is taking place in the center of the film and on the left the wire is bare, without any bubbles. The cooling of this part of the surface is due to free convection of the liquid.

Visual observations and an inspection of the frames showed that the part occupied by the vapor film comprised 1/5 to 1/2 of the total length of the heater. Periodically the part on which film boiling occurred increased or decreased and moved in each direction alternately along the heater. Observation of a particular point on the surface showed that the film boiling was replaced by convection, and the latter was again replaced by film boiling.

It was reported in [1] that the onset of the crisis on a thin wire is due to a local deterioration in heat transfer at the site of formation of a large gas bubble. Figure 5 shows the near-critical regime of boiling of ethyl alcohol on a wire with $D = 25\ \mu$. Only a few evaporating centers are active on the surface. Two of them interact with one another and the bubbles at this site fuse together. The sizes of the fused bubbles are much larger than the bubbles formed at the separate evaporating centers. With a slight increase in the heat load the site of fusion of bubbles will be the spot where film boiling begins, since the large vapor bubbles insulate the heater surface from the cooling liquid and thus cause a pronounced deterioration in the heat transfer at the particular site.

After publication [1] of the results of the experiments on the effect of heater diameter on q_* we continued the work at higher pressures. We conducted experiments on the boiling of water at pressures of 31 and 71 bar, and on the boiling of ethyl alcohol at 31 and 51 bar. We also conducted experiments with benzene at pressures of 1 and 11 bar. The $q_*(D)$ relationships obtained in these experiments were similar to those in Fig. 3.

To generalize all our experimental results and the known published data of other investigators who have used wires of various diameters as heaters [4–15] we used the criteria

$$k = \frac{q_*}{r(g\gamma'')^{1/2}[\sigma(\gamma'-\gamma'')]^{1/4}},$$

$$\Delta = D\left(\frac{\gamma'-\gamma''}{\sigma}\right)^{1/2}. \qquad (1)$$

The treatment in semilogarithmic coordinates is shown in Fig. 6. As the value of D we took the diameter for cylindrical heaters and the width for ribbon-shaped

Characteristics of Heater Elements

Characteristic diameter, mm	Total length, mm	Shape	Thickness of wall, mm	Material	Surface purity according to GOST 2789-59
0.008	15	Wire	—	Tungsten	—
0.025	40	"	—	"	—
0.05	40	"	—	Platinum	—
0.1	60	"	—	Platinum, nichrome	Class 7-8
0.2	60	"	—	Platinum, nichrome	"
0.3	60	"	—	Nichrome	"
0.5	60	"	—	Nichrome	"
0.8	60	"	—	"	"
1.0—1.2	60	Tube	0.4	Stainless steel	"
1.5	60	"	0.4	"	"
2.0	60	"	0.4—0.5	"	"
2.7	60	"	0.5	"	"
3.0—3.2	60	"	0.5	"	"
4.0	60	"	0.6	"	"
5.0	60	"	0.6	"	"
6.0	60	Ribbon	0.2	Nichrome	"
10	80	Ribbon	0.2	Stainless steel	"

Note. The 6- and 10-mm ribbons were mounted edgewise.

heaters. All our data and almost all the points of other experimenters lie with a scatter of ± 20% on one line. The scatter of the experimental data is a little greater in the region of very small heater diameters, which is probably due to the difficulty in determining exactly the onset of the crisis on a thin wire. The data of [13] in the region $0.2 < \Delta < 1.0$ with the heater horizontal are left out. In [13] there was no maximum on the curve $q_*(D)$ in this range of diameters.

According to Fig. 6, for horizontal heaters self-similarity of the complex k relative to the linear dimension of the heating surface occurs when

$$\Delta > 2. \tag{2}$$

The maximum value of the complex k occurs when

$$0.2 < \Delta < 1. \tag{3}$$

The minimum value of k occurs when

$$0.03 < \Delta < 0.1. \tag{4}$$

Visual observations and high-speed films showed that the reduction in the critical heat flux with change in the parameter $\Delta < 0.5$ was due to a local deterioration of heat transfer at sites of formation of large vapor bubbles, which insulate the heat-transfer surface from the cooling liquid.

When $\Delta < 0.03$ the role of convective heat transfer is so great that there is practically no nucleate boiling in this case and convective heat transfer is followed directly by film boiling.

NOTATION

P_* is the critical pressure (in thermodynamic sense); q_* is the critical heat flux; t'' is the liquid temperature; t_* is the wire temperature; D is the diameter for cylindrical and width for ribbon-shaped heaters; r is the heat of vaporization; g is gravitational acceleration; γ'' is the density of vapor; γ' is the density of liquid on saturation line; σ is the surface tension.

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