GENERALIZATION OF EXPERIMENTAL DATA ON FLOW FRICTION IN SURFACE BOILING

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The study of the laws of flow friction in conditions of surface boiling has been the subject of many papers (see, for example, [-7]).

In the following, a method is developed for generalizing the experimental data in the region of high subcooling (in excess of 40-50° C).

We will examine the dependence of the wall temperature t_+ and pressure head Δp on the specific heat flux q at constant values of the mass flow rate γ^ω, mean subcooling along the channel length Δt, and pressure p, as shown in Fig. 1. The following regions can be distinguished on these curves:

1. A region of nonisothermal motion without vaporization in the boundary layer, where the wall temperature t_+ is less than the saturation temperature t_- (§§ 1-2). In this region, t_+ increases and Δp decreases as q increases.

2. An intermediate region—§§ 2-3. At point 2, we have $t_+ = t_-$. The value of the heat flux that corresponds to this point is denoted by q'. As the heat flux increases; over a certain range, the wall temperature increases at the previous rate-§§ 2-3. When overheating of the wall reaches a definite value, the vaporization process sets in the boundary layer—point 3.

With further increase in heat flux, the number of active vaporization centers increases, which leads to a gradual change in the hydrodynamic situation in the boundary layer of the fluid. This region is characterized by a gradual decrease in the growth rate of t_+ with increasing q and by a change from decreasing to increasing values of Δp. The region ends at a certain point 5.

3. A region of developed surface boiling-§§ 5-6. It begins at point 5 and terminates at point 6, when so-called burnout takes place. This region is characterized by very slight variation of wall temperature t_+ and substantial increase in Δp with increasing q.

In [1, 3], the beginning of the region of surface boiling is taken at at which burnout takes place.

In [1.3], the beginning of the region of surface boiling is taken at point 4, which is the point of intersection of the continuation of the lines 1-2 and 5-6 plotted from experimental data. It is difficult to recommend this procedure. Point 4 lies in the intermediate region. If it is taken as the initial point, then the analysis will include data obtained in §§ 4-5; this may lead to a distortion of the relations pertaining to the region of developed surface boiling.

The same applies if point 3 is taken as the initial point. An empirical determination of point 3 is very difficult, since it requires visual determination of the number of active centers [8].

It would be preferable to take point 5 as the beginning of the surface boiling region. However, we lack the required relations for the determination of its parameters, because of insufficient knowledge of the heat transfer in the intermediate region 2-5. It is, therefore, expedient to determine point 5 by the following method.

The beginning of the intermediate region—point 1—can be determined with sufficient accuracy from the condition $t_+ = t_-$. Through point 7 on curve $\Delta p = f(q)$, we draw a horizontal line up to its intersection with the continuation of this curve. The point 8, thus obtained, is taken as the beginning of the region of developed surface boiling. With respect to position, this point is close to point 5. The heat flux corresponding to point 8 we denote by

$$q_0 = q' + \Delta q \qquad (1)$$

where q' is the heat flux at $t_+ = t_-$, and Δq is the change in the value of the heat flux between the points 7 and 8. Experimentally, Δq can be determined from the graph $\Delta p = f(q)$ as the magnitude of the segment 7-8, and, analytically, from the relation

$$\Delta q = f(\gamma W, \Delta t, p). \qquad (2)$$

For surface boiling we represent the flow friction of the channel in the form

$$\Delta p = \Delta p' + \Delta p'' \qquad (3)$$

where the value $\Delta p'$ at point 8 (which by definition is equal to that at point 2) can be determined from the known relations for the region 1-2 on the basis of the condition $t_+ = t_-$; the quantity $\Delta p''$ is the increment in Δp due to surface boiling. The increment $\Delta p''$ is a consequence of the vaporization process in the boundary layer and has the following causes.

a) The generation, growth, and subsequent condensation of vapor bubbles increase the rate of mass transfer between the boundary layer and the flow core, which necessarily leads to an increase in flow friction due to momentum variation in the flow. The mass transfer between the boundary layer and the flow core increases with increasing number of active centers z, and increasing frequency of bubble formation u and mean bubble diameter d.

b) Prior to the onset of bubble motion over the heating surface, the effect of a bubble on the flow is to some extent similar to that of an isolated roughness, i. e., the presence of vapor bubbles in the boundary layer creates a "vapor roughness, "which can also lead to an increase in flow friction. This assumption is examined in [9].

A possible criterion of the scale of "vapor roughness" is the mean value of the largest bubble diameter d. The number of simultaneously present vapor roughnesses is proportional to z and u.

c) Up to the moment of separation, a bubble slides along the heating surface at a speed lower than that of the fluid flow. This gives rise to additional hydrodynamic disturbances in the flow and may lead to an increase in flow friction. This component depends on the fluid—solid adhesion, which is a function of surface tension σ and contact angle θ [10].

d) The flow friction in surface boiling depends on the flow acceleration losses. There are two reasons for this. At low subcooling the vapor bubble does not condense in the boundary layer of the fluid and, after separation from the surface, drifts to the flow core in which it exists for a certain period of time; this leads to acceleration losses due to the fact that $\gamma' < \gamma'$. Acceleration losses can also arise from an increase in mean velocity due to "blocking" of the cross section by vapor bubbles.

This factor probably has a pronounced effect on flow friction only in channels with small cross sections.

On the basis of these possible reasons for an increase in flow friction in surface boiling, it may be assumed that the quantity $\Delta p''$ must strongly depend on the quantity $q'' = q - q_0$, which represents the increment in heat flux in the region of surface boiling. Then, the principal process parameters that determine the quantity $\Delta p''$ in the region of surface boiling are the heat flux q″, the mass flow rate γ^ω, the channel pressure p, the subcooling of the flow core Δt, and the channel diameter d.

In order to determine the degree of influence of these parameters, the experimental data published in [1-7] were analyzed with the following results:

1. According to data in [2], for constant values of γ^ω, p, and Δt, the quantity $\Delta p''$ increases with increasing q. In this case, the physical constants of the fluid remain constant in the flow core, and vary only slightly in the boundary layer.

2. The data in [2] also indicate that at p and Δt = const and equal values of q″, the quantity $\Delta p''$ increases in proportion to the mass flow rate γ^ω.

3. The increment $\Delta p''$ at equal values of γ^ω and Δt is practically independent of pressure [5] in the range from 10 to 150-175 atm abs.

At varying pressure and constant subcooling, there is a change in the temperature of the flow core and boundary layer, which results in a change in the physical properties of the fluid and vapor. Experiments show that this situation does not notably affect Δp and Δp". It may be assumed, therefore, that the hydrodynamic disturbances caused by "vapor roughness" and surface slip of vapor bubbles, which vary with pressure, do not have an appreciable effect on flow friction in surface boiling. The same applies to acceleration losses. Thus, for p = var and γ^{ω} and Δt = const, the increment Δp″ is due solely to variation of q″.

4. At equal values of p, γ^{ω}, and Δt, the increment Δp″ increases with decreasing subcooling Δt [2]. Therefore, the quantities which define Δp" must include the caloric characteristic c of the fluid—the heat capacity of unit mass.

5. In order to determine the effect of tube diameter d on Δp″ special experiments were performed with tubes of diameter d = 1.0, 1.5, 2.0, 3.0, 4.0, and 5.0 mm at an l/d ratio of 23 and 24, pressures p = = 25–50 atm abs, mean subcooling Δt = 50, 100, and mass flow rate γ^{ω} = $10 \cdot 10^3$ kg/m^2-sec. The results showed that Δp″/l decreases as the tube diameter d is increased from 1 to 5 mm.

Since "vapor roughness" does not have an appreciable effect on Δp″, the increase of the latter with decreasing tube diameter d is due, apparently, to the increase in the ratio of perimeter to cross section, which increases the value of the fluid mass per unit cross-sectional area transported by the bubbles from the boundary layer to the core of the flow.

The analysis indicates that the principal cause for the increase in flow friction in surface boiling at a subcooling in excess of 50° C is the transfer of fluid mass from the boundary layer to the flow core caused by the vaporization process and the change in flow momentum induced by this process.

Here we may write

$$\frac{\Delta p''}{l} = f(q'', W, \Delta t, c, d). \tag{4}$$

From the five quantities examined, it is possible to derive formally a single dimensionless complex of the form

$$K'' = \frac{\Delta p'' c \Delta t d}{q'' W l}. \tag{5}$$

Thus, if the other factors have only a slight effect, the process studied can be described by the following relation:

$$K'' = \text{const.} \tag{6}$$

The measurements were analyzed on the basis of (5).

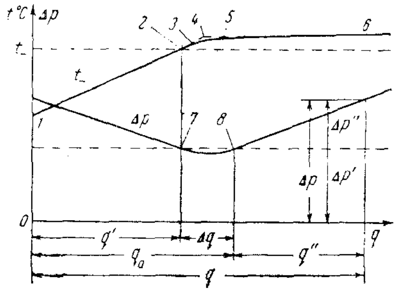


Fig. 1

The dimensionless complex was plotted along the y axis and the pressure along the x axis. The heat capacity c in expression (5) was taken at a temperature equal to $(t_- + t)/2$, where t is the temperature of the flow core.

Since the dependence of Δq on γ^{ω}, Δt, and p has not yet been established [2], and since, in many cases, this quantity could not be determined with sufficient accuracy from empirical graphs of Δp = f(q) and t_+ = f(q), in generalizing the experimental data the quantity q″ was determined from the expression

$$q'' = q - q_-. \tag{7}$$

Experimental data at values of q″ < (2 to 3) · 10^6 kcal/m^2-hr were not considered in the generalization, since they pertain to the intermediate zone 7–8 (Fig. 1). About 440 experimental points were processed. These were obtained in tests on water in which the mass flow rate was varied from 5 · 10^3 to 30 · 10^3 kg/m^2-sec, subcooling from 50 to 200° C, pressure from 10 to 175 atm abs, and tube diameter from 1 to 5 mm.

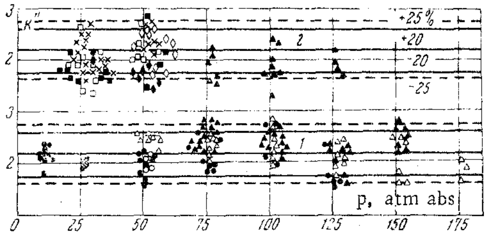


Fig. 2

As an example, Fig. 2 shows the results obtained for a 2-mm diam. tube at mass flow rates of 20 · 10^3 kg/m^2-sec (line 1) and 30 · 10^3 kg/m^2-sec and for tube diameters of 1.0, 1.5, 2.0, 3.0, 4.0, and 5.0 mm at a mass flow rate of 10 · 10^3 kg/m^2-sec (line 2). It can be seen that expression (5) agrees with experiment. The expression can be considered as an extension of the Reynolds analogy to cover the region of surface boiling.

Expression (5) can be written in the form

$$\frac{\Delta p''}{\rho W^2} = A \frac{l}{d} \frac{q''}{\rho W c \Delta t}, \quad \text{or} \quad E'' = A \frac{l}{d} S'', \tag{8}$$

where E″ denotes a modification of the Euler number E, and S″—a modification of the Stanton number S for the region of surface boiling.

The expression obtained indicates the unity of the processes of heat transfer and molar momentum exchange conditioned by the vaporization process in the boundary layer.

The results of this generalization of experimental data on the increase in flow friction in the surface-boiling region 5–6 made it possible to consider the problem of generalizing the experimental data on the total pressure drop Δp in this region. Substituting A = 2.15, from expression (8) we obtain

$$\Delta p'' = 4.3\, S'' \frac{l}{d} \frac{\rho W^2}{2}. \tag{9}$$

Taking the pressure drop in the region of developed surface boiling as the sum Δp = Δp′ + Δp″, the relative increase in flow friction, resulting from the development of the vaporization process in the boundary layer, can be written in the form

$$\frac{\Delta p}{\Delta p'} = 1 + \frac{\Delta p''}{\Delta p'}. \tag{10}$$

Further reduction of the experimental data obtained in [2] showed that in the conditions studied, Δp′ can be determined from the expression

$$\Delta p' = \xi \frac{l}{d} \frac{\rho W^2}{2} = \xi_0 \left(\frac{\mu_+}{\mu}\right)^{0.25} \frac{l}{d} \frac{\rho W^2}{2} \tag{11}$$

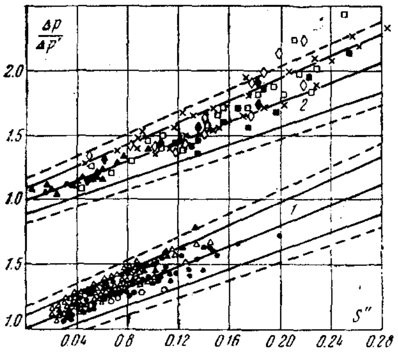
where μ_+ is the viscosity of the fluid at the wall temperature, μ is the viscosity of the fluid at the flow-core temperature ξ_0 is the resistance coefficient for isothermal motion, which is determined, within the corresponding limits of values of the R number, from the Blasius and Nikuradze formulas.

Substituting the values of Δp" and Δp′ into expression (10), we get

$$\frac{\Delta p}{\Delta p'} = 1 + 4.3 \frac{S''}{\xi_0 (\mu_+/\mu)^{0.25}} \tag{12}$$

where μ_+ is taken for $t_+ = t_-$.

Processing the same data in the system of coordinates used in (12) showed that roughly 89% of the points deviate from the line described by Eq. (12) by not more than ±10%, and roughly 97% of the points, by not more than ±15%.



Фиг. 3

As an example, Fig. 3 shows the results of processing the same data as in Fig. 2, using the same symbols. It can be seen that the distribution of the points is the same, which indicates that Eq. (12) provides a satisfactory generalization of the experimental data obtained over a wide range of variation of the characteristic parameters.

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