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ANALOGIES BETWEEN HEAT AND MOMENTUM TRANSFER IN A FORCED LIQUID FLOW WITH SURFACE BOILING IN A CHANNEL

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Consideration is made of the characteristics of heat- and momentum-transfer phenomena in a forced liquid flow under conditions of surface boiling in a channel.

There are very few analytical studies of the hydrodynamics of a forced liquid flow under conditions of surface boiling in a channel. The attempt to apply a Reynolds analogy to describe this process [1] is well known, and the analogy yielded good results for the case of a Prandtl number close to unity. In the literature there are also generalizations of experimental data on the basis of similarity theory [2-5] which satisfactorily describe the experimental results, as a rule, that are characterized by Prandtl numbers close to unity. The subject of the present study is the development of the relationship between friction and heat exchange for surface boiling in a forced flow of nonmetallic liquid for a relatively broad range of the Prandtl number.

We study the forced liquid flow in a channel under conditions of surface boiling for underheatings sufficiently deep to consider the steam content of the flow to be equal to zero. We assume that the momentum transfer onto the channel wall is conditioned both as a usual eddy viscosity characteristic for a single-phase flow and a specific mechanism for the intermixing of the liquid mass at the underheating surface characteristic of the boiling process. We assume that in the general case the shearing stress corresponding to the mechanism of the momentum transfer interacts with the so-called heat flow of boiling q_{bp} that is equal to the difference between the total heat flow on the wall and the convective heat flow of a single-phase liquid under the same dynamic and temperature conditions. For these assumptions the shearing stress on the wall is

$$\tau = \tau_0 + \tau_{bp}. \quad (1)$$

It is evident that the calculation of τ_{bp} should be based on the determined representations of the character of the process of surface boiling. We assume that the basic factor conditioning both momentum and heat transfer under conditions of surface boiling is the intermixing of the mass of the liquid phase of the heat-transfer agent that is produced by the boiling process. The steam bubbles in the initial period on the wall at the highest intensity of their mixing action are considered immovable with respect to the flow core. We can also consider that the microcirculation of the liquid arising in the region of the growing bubble is symmetric with respect to the bubble. Consequently, under these assumptions the liquid volume adjoining the bubble on the average will be immovable with respect to the channel wall.

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The liquid particles entering the zone of the growing bubble from the flow core lose all their velocity on the average and yield all their momentum to the wall. However, the temperature of not all the particles is equal to the wall temperature, since, according to the model assumed, the immediate contact with the wall is not required for the total loss of the velocity. Since in the initial period of the bubble growth all the particles are still localized between the wall and the isothermic surface with a temperature equal to the saturation temperature, we can assume that the liquid particles leaving the zone of local stagnation for the flow core have, on the average, the temperature t'_{liq} intervening between the wall temperature and the saturation temperature.

For further transformations we consider t'_{liq} an unknown quantity which, however, does not vary along the channel length.

We can determine τ_{bp} according to the following analogy with the heat transfer:

$$\tau_{bp} = \frac{(q - q_{sp})\,\bar{U}}{c_p\,(t_{hs} - t'_{liq})}. \quad (2)$$

Assuming that $q_{sp} = \alpha_0 \Delta t_x$, on the basis of Eqs. (1) and (2) for the gradient of the pressure inside the channel, we have

$$\frac{dP}{dx} = \xi_0 \frac{\rho \bar{U}^2}{2d} + \frac{4q\bar{U}}{c_p \Delta t'_x d} - \frac{4\alpha_0 \Delta t_x \bar{U}}{c_p \Delta t'_x d}. \quad (3)$$

We assume the constancy of the heat load along the channel length (q = const) and we obtain the following functions from the balance condition:

$$\Delta t'_x = \Delta t'_{in} - \frac{4qx}{c_p \bar{U} \rho d}, \quad (4)$$

$$\Delta t_x = \Delta t_{in} - \frac{4qx}{c_p \bar{U} \rho d}. \quad (5)$$

Furthermore, after integrating Eq. (3) along the channel length and after a series of transformations, we have

$$\Delta P = \int_0^L \frac{dP}{dx} dx = \Delta P_0 \left\{ 1 + \frac{2d}{\xi_0 L} \ln\left(\frac{\Delta t'_{in}}{\Delta t'_{out}}\right) - \frac{8\alpha_0}{c_p \bar{U} \rho \xi_0} \left[1 + \frac{t_{hs} - t'_{liq}}{t_{out} - t_{in}} \ln\left(\frac{\Delta t'_{in}}{\Delta t'_{out}}\right) \right] \right\}. \quad (6)$$

It is evident that we must determine t'_{liq} for the practical application of the function obtained. We base the determination of t'_{liq} on the assumption that the microflow caused by the bubble growth has a laminar character and that in the first approximation it can be characterized by the distributions of the velocities and temperatures in the laminar boundary layer on the plane plate. We assume that the temperature on the external boundary of the microflow is equal to the temperature of the saturated liquid, and the velocity is equal to the mean flow velocity in the channel. We also determine the thickness of the dynamic (δ) and temperature (δ_1) boundary layers in the first approximation along the length of the quasilinear distributions of these parameters according to a corresponding Pohlhausen solution.

With these assumptions the mean temperature of the liquid in the transverse section of the microflow is

$$t'_{liq} = \frac{\int_0^{\delta_1} \rho U t\, dy + t_s \int_{\delta_1}^{\delta} \rho U dy}{\int_0^{\delta} \rho U dy} = t_s + \frac{\int_0^{\delta_1} \rho U (t - t_s)\, dy}{\int_0^{\delta} \rho U dy}. \quad (7)$$

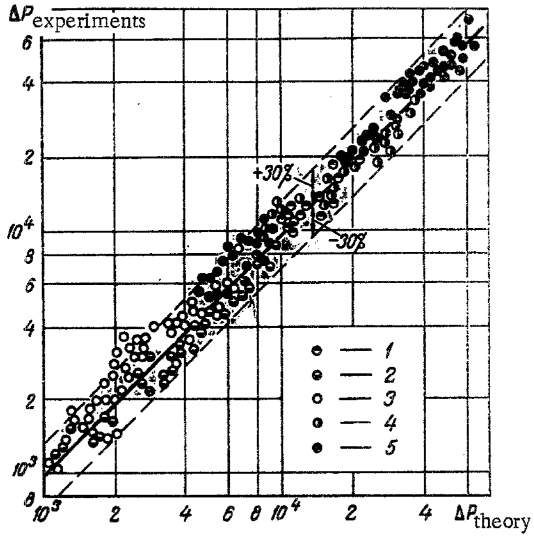

Fig. 1. Comparison of Eq. (6) with experimental data: 1) experiments [1]; 2) [2]; 3) [3]; 4) [7]; 5) [8]. ΔP, N/m^2.

The profiles of the velocities and temperatures in the layer, according to these assumptions, are determined according to the functions

$$U(y) = A\bar{U}\sqrt{\frac{\bar{U}}{\nu x}}\,y, \tag{8}$$

$$t(y) = t_s - a(\mathrm{Pr})\,\Delta t\sqrt{\frac{\bar{U}}{\nu x}}\,y. \tag{9}$$

After substituting these functions into (7), we obtain

$$t'_{\mathrm{liq}} = t_s + \frac{\Delta t\,\frac{\delta_1^2}{2} - \Delta t a(\mathrm{Pr})\sqrt{\frac{\bar{U}}{\nu x}}\,\frac{\delta_1^3}{3}}{\frac{\delta^2}{2}}. \tag{10}$$

Considering that

$$\delta_1 = \frac{\eta_1}{\sqrt{\frac{\bar{U}}{\nu x}}} \text{ and } \delta = \frac{\eta}{\sqrt{\frac{\bar{U}}{\nu x}}},$$

we transform function (10) to the following form:

$$t'_{\mathrm{liq}} = t_s + \Delta t\left(\frac{\eta_1}{\eta}\right)^2\left[1 - \frac{2}{3}\,a(\mathrm{Pr})\,\eta_1\right]. \tag{11}$$

As the obtained function shows, the mean temperature t'_{liq} for the simplified assumptions does not depend on the x coordinate. On the one hand, this result is convenient to a certain extent, since the need for introducing additional assumptions to determine the extent of the microflow decreases. On the other hand, it does not contradict the fact that the microflow should not remove heat from the wall, since the enthalpy of the layer increases with respect to x in relation to the increasing expenditure of liquid in it.

To determine the specific form of function (11), the dimensionless thicknesses of the linear distribution of the temperature η_1 and of the velocity η should be taken from the Pohlhausen solution indicated above according to the specific value of the Prandtl number.

So, for example, under the condition Pr = 1

$$a = 0.332\sqrt[3]{\mathrm{Pr}},\ \eta_1 = \eta \approx 2.5$$

and function (11) takes the form

$$t'_{liq} = t_s + 0.45\Delta t. \tag{12}$$

Under the condition Pr = 30

$$a = 0.339\sqrt[3]{\mathrm{Pr}},\ \eta \approx 1.0;\ \eta \approx 2.5$$

and

$$t'_{liq} = t_s + 0.047\,\Delta t. \tag{13}$$

We must note that since the inlet and outlet liquid temperatures related to each other by the heat balance of the section enter Eq. (6), the equation is applicable during boiling in the radial clearance both in the case of one-sided and two-sided heating.

The solution obtained in the present study is compared in Fig. 1 with the experimental data of [1-3, 7, 8]. The experimental material is obtained for the surface boiling of various liquids (water, butyl alcohol) in channels of various geometry (pipe, annular channel with one-sided, as well as two-sided, heating) in a wide range of the variation of the saturation pressure. The temperature of the heated wall for the surface boiling of water is determined for the comparison by means of the empirical equation (1) in [9] (with the exception of [1, 7] in which the experimental data is given according to the temperatures of surface boiling). The pressure drops for a single-phase turbulent flow are determined according to the Nikuradze equation [6] with the correction for the nonisothermality of the flow in [11] taken into account (with the exception of [7, 8] in which the experimental data and generalizations are given according to the hydrodynamics of a single-phase flow). The coefficients of heat transfer for the single-phase turbulent flow are determined according to the Mikheev equation [10]. The physical parameters of the liquid are given according to the mean temperature between the wall temperature and the saturation temperature.

The experimental data [8] are given according to Fig. 3 of the indicated study. The experimental curves presented in this figure have three characteristic sections: the section without the presence of boiling on the wall, the section of surface boiling, and the section where the pressure gradient in the precritical zone ($q \geqslant 0.7\ q_{cr}$) sharply increases. The experimental points of the middle section are used for the comparison. The experimental data for the most narrow radial clearance (0.77 mm) are not brought in from the data of [3] for the comparison presented here. The data obtained for this clearance are approximately 100% higher than those calculated. We can explain the discrepancy by the fact that for a very small clearance width the assumption of a zero value for the steam content in the flow is admissible only for very deep underheatings. With such a small clearance the presence of even the smallest bubbles on the wall leads to an increasing velocity in the flow core with respect to the values assumed in our calculation, which should be reflected, correspondingly, on the results of the comparison.

On the whole, the results of the comparison made allow us to conclude that the solution obtained describes the experimental data in the literature with satisfactory accuracy.

NOTATION

τ, wall shear stress; x and y, longitudinal and normal coordinates; t_{hs}, t_s, temperatures of a heating surface and a saturated liquid; t_{liq}, liquid temperature in the flow core; t_{in}, t_{out}, inlet and outlet liquid temperatures; t'_{liq}, mean temperature of a liquid leaving a bubble zone; $\Delta t = t_{hs} - t_{liq}$; $\Delta t' = t'_{liq} - t_{liq}$; a_0, ξ_0, ΔP_0, coefficients of heat transfer, hydraulic resistance, and pressure drop in a single-phase turbulent flow; q, specific heat flux; P, static pressure; ΔP, pressure drop in a channel; $\overline{U}$, velocity mean liquid over a cross section; d, L, equivalent diameter and channel length; ρ, c_p, ν, Pr, density, heat capacity, kinematic viscosity, and Prandtl number for a liquid; δ, δ_1, thicknesses of quasilinear dynamic and temperature boundary layers; α, η, parameters of Pohlhausen's solution for a laminar boundary layer.

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METAL BOILING UNDER THE ACTION OF AN ELECTRON-BEAM HEAT SOURCE

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The dynamics of vapor bubble growth in a metal alloy under the action of a volume heat source are considered. The possibility of existence of a threshold superheating value below which the boiling process is impossible is demonstrated.

It is well known that the action of an electron beam on a metal specimen forms a significant volume heat source (for U ∿ 100 keV, electron path length $r_0 \sim 10^{-2}$ cm) with a maximum in the interior [1, 2]. Such a mode of energy liberation significantly increases the heating zone (in comparison to a laser beam), creates conditions for heating in a volume below the surface, and thus stimulates volume boiling of the material. Thus in studying the process of mass loss under electron-beam action two possible mechanisms must be considered: 1) boiling of material from the surface; 2) volume vapor formation at artificial centers. Matter evaporation from the surface has been examined in detail in a number of studies [3, 4].

We will consider the second mechanism. It should be noted that formation of vapor at centers arising because of density fluctuations will not be considered, since in experiments on electron-beam action on metals the intense volume vapor formation process is observed at temperatures of 3000-4000°K, while fluctuations begin to play a significant role only at temperatures $T \sim T_{cr}$, significantly higher [4].

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