NOTATION

Pe = 2Ua/D, Peclet number; Sh_Θ, local value of Sherwood number; Sh, average value of Sherwood number; Re = 2Ua/ν, Reynolds number; C, relative mass concentration of transported component; r, radial coordinate (normalized to radius of sphere); Θ, angular coordinate; a, radius of sphere; D, coefficient of diffusion; ν, coefficient of kinematic viscosity; U, velocity of impinging stream; U_*, scale of velocity in shear stream; V_r, V_Θ, radial and tangential velocity components; Ψ, stream function; μ, ratio of coefficients of dynamic viscosity of liquid in drop and of continuous medium; α, parameter characterizing shear intensity; n, rheological parameter of power-law liquid.

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EFFECT OF COMPRESSIBILITY ON THE HYDRODYNAMICS OF TWO-PHASE FLOWS

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It is shown that the resistance coefficient of a two-phase one-component mixture depends on the Mach number over a wide range of parameters.

It is known that in geometrically similar systems the hydrodynamics of single-phase streams is determined by their compressibility and viscosity.

It has been justified theoretically and confirmed experimentally that the velocity of sound in a two-phase medium with a definite ratio of the phases can be two orders of magnitude smaller than in the liquid phase and more than an order of magnitude smaller than the velocity of sound in the gas. Yet, until recently, calculational models for estimating friction loss in two-phase flow have taken account of the Reynolds number but not the Mach number.

It is shown [1] that a one-component two-phase mixture has the greatest compressibility. Experiments with high-velocity gas flows in long horizontal tubes [2, 3] showed that for Mach numbers greater than 0.75-0.85 the resistance coefficient decreases with increasing Mach number and approaches zero as M approaches unity.

In the present paper we present the dependence of the resistance coefficient on the Mach number for the flow of a two-phase one-component mixture in tubes of constant diameter. We have processed the results of our experiments on the critical outflow of boiling water through long horizontal tubes with a sharp entrance edge. The pressure at the entrance to the experimental section varied from 10^6 to $9.3 \cdot 10^6$ N/m^2; the tube diameters were $14.2 \cdot 10^{-3}$, $9.8 \cdot 10^{-3}$, and $5.8 \cdot 10^{-3}$ m; the relative length was $141 \leq L/D \leq 612$; and the mass flux density varied from $0.567 \cdot 10^4$ to $2.983 \cdot 10^4$ kg/(m^2 · sec).

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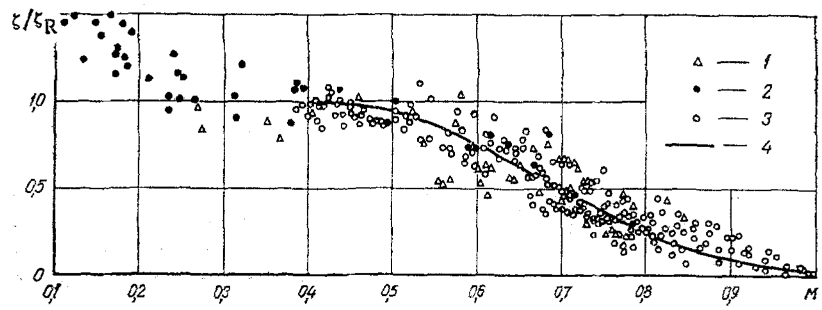

Fig. 1. Experimental values of relative resistance coefficient as a function of Mach number, determined from the velocity of sound for thermodynamic equilibrium. 1) experiments [5]; 2) experiments [4]; 3) our experiments; 4) calculated by Eq. (2).

In addition, we processed the results of [4,5] on the determination of hydraulic resistance during steam water flow under adiabatic conditions encompassing the following range of parameters: $P = (0.49\text{–}14.03) \cdot 10^6\ N/m^2$, $j = (0.093\text{–}2.52) \cdot 10^4\ kg/(m^2 \cdot sec)$, $D = 12.08 \cdot 10^{-3}$ m, $8.06 \cdot 10^{-3}$ m, $2.56 \cdot 10^{-3}$ m, and $1.01 \cdot 10^{-3}$ m.

In order to eliminate the effect of roughness we calculated the ratio of the experimental value of the resistance coefficient to the value determined by hydraulic tests in the flow region self-similar with respect to the Reynolds number.

The speed of sound in a mixture in thermodynamic equilibrium is given by the expression

$$a_{\text{mix}} = v_{\text{mix}} \frac{dP}{dT} \sqrt{\frac{T}{c_{v\,\text{mix}}}}, \tag{1}$$

where

$$v_{\text{mix}} = v' + x(v'' - v'),$$
$$c_{v\,\text{mix}} = c_v' + x(c_v'' - c_v').$$

The specific heats of water and steam at constant volume c_V', c_V'' at the saturation line on the side of the two-phase region were taken from [6]. Figure 1 shows the results of processing the experimental data mentioned above in the form $\zeta/\zeta_R = f(M)$. The distribution of the experimental points for the dependence of the resistance coefficient on the Mach number clearly shows three characteristic regions.

1. For $M > 0.5$ the effect of compressibility becomes evident.

2. For $M < 0.3$ the resistance coefficient increases sharply: At lower velocities the existence of uniform two-phase flow becomes less probable, and relative slipping between the phases appears, leading to the growth of dissipative forces.

3. A transition zone $0.3 < M < 0.5$, in which the simultaneous effects of viscous forces and compressibility appear clearly.

The experimental values of the relative resistance coefficient for $M \geq 0.4$ are described by the approximate relation

$$\zeta/\zeta_R = \exp\left[-10M^{0.75}(M - 0.4)^2\right]. \tag{2}$$

Figure 1 shows that the relative resistance coefficient calculated by Eq. (2) is in good agreement with the experimental data.

NOTATION

a_{mix}, velocity of sound in two-phase mixture in thermodynamic equilibrium; v', specific volume of water at saturation line; v'', specific volume of steam at saturation line; v_{mix}, specific volume of steam—water mixture; c_V', c_V'', specific heats of water and steam at constant volume at saturation line on the two-phase side; $c_{V\,\text{mix}}$, specific heat of steam—water mixture at constant volume; L, length; D, diameter; ζ, resistance coefficient; ζ_R, resistance coefficient for flow region self-similar with respect to Re; Re, Reynolds number; M, Mach number; j, mass flux density; P, static pressure.

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EFFECT OF THERMAL PROPERTIES OF BOUNDARIES ON STABILITY OF CONVECTIVE FLOW IN A VERTICAL LAYER

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The results of a solution of the problem of the stability of steady convective flow in a vertical layer with thermally insulated boundaries and a comparison with the opposite limiting case of ideally thermally conducting boundaries are presented.

The results of studies of the stability of closed steady convective flow between vertical parallel planes [1, 2] show that depending on the value of the Prandtl number Pr the instability is caused by mechanisms which differ in their physical nature. At low and moderate Prandtl numbers hydrodynamic disturbances leading to the formation of steady vortices at the interface of the opposing flows are responsible for the instability. At larger Prandtl numbers ($Pr > 12$) the instability has a wave nature and is connected with an increase in the convective fluxes of temperature waves.

The numerical results presented in [1, 2] were obtained on the assumption that temperature disturbances vanish at the boundaries of the layer. Such boundary conditions correspond to the limiting case when the thermal conductivity of the boundaries is much greater than the thermal conductivity of the liquid. If the thermal conductivities of the liquid and the solid masses bordering on it are comparable then temperature disturbances penetrate into the solid masses. Then the question arises of whether the relative thermal conductivity of the boundaries affects the stability of the convective flow (the conjugate problem of stability of convective flow). It is clear in advance that the hydrodynamic mechanism of the instability must be little sensitive to the thermal properties of the solid masses. As for a wave instability, since it is connected with growing temperature waves it could be expected, generally speaking, that the properties of the solid masses have a considerable effect on the critical parameters of this instability. The results presented below show, however, that the penetration of temperature disturbances into the surrounding solid masses has a weak effect on the conditions of formation of instabilities of both the hydrodynamic and the wave types.

To clarify the role of the penetration of thermal disturbances on the stability it is obviously sufficient to consider the limiting case opposite to that which one usually has in mind, namely, when the thermal conductivity of the liquid is far larger than the thermal conductivity of the boundaries. In this limiting case the boundary condition of thermal insulation must be set up for temperature disturbances.

In the closed vertical layer between the planes $x = \pm h$ a plane-parallel convective flow is established with a linear temperature profile and a cubic velocity profile:

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