NOTATION

$f(\mathbf{r}, \mathbf{c})$, velocity distribution of gas molecules; $\mathbf{r} = x, y, z$, position vector in Cartesian coordinates; $\mathbf{c} = c_x, c_y, c_z$, molecular velocity vector; $f' = f(\mathbf{r}, \mathbf{c}')$, $f_1' = f(\mathbf{r}, \mathbf{c}_1')$, distribution function of particles with velocities $\mathbf{c}'$ and $\mathbf{c}_1'$ after collisions; n_{ev}, density of saturated vapor at temperature T_w; n_r, density of molecules diffusely reflected from the surface of the material; n, vapor density; $\bar{c}_z$, z-component of the average velocity; $h_w = m/2kT_w$; k, Boltzmann constant; m, molecular mass; d, molecular dmaimeter; q, energy required to evaporate an atom; I_{ev}, flux of particles evaporating from a unit area of the inner surface of the hole; I_{cp} and Q, flux of particles and total energy at the hole outlet, respectively; $g = |\mathbf{c} - \mathbf{c}_1|$, magnitude of the relative velocity of the particles.

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CHARACTERISTICS OF A DESCENDING DISPERSED-ANNULAR FLOW

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Experimental data on the loss of liquid from the surface of a film and the resistance of dispersed-annular flow are presented.

Film heat- and mass-transfer apparatus is widely used in different sectors of the economy. In such apparatus descending flow of a film of liquid and gas often occurs. The most common flow regime in heat exchange equipment at nuclear power plants is a descending, comoving regime. The film apparatus with descending direct flow operate at low pressures ($0.05 < P < 1$ MPa). Under these conditions the velocity of the gas flow, as a rule, exceeds 20 m/sec, as a result of which drops are observed to separate from the surface of the film [1, 2]. The dispersed-annular flow regime is characterized by continuous mass transfer between the film and the core of the flow, intensifying heat transfer and simultaneously increasing the hydraulic losses. Systematic studies of dispersed-annular flows concern primarily small-diameter evaporation channels ($d < 20$ mm) with insignificant fluid flow rates in thin films ($Re_1 < 3000$) and ascending motion of the mixture [3-5].

We therefore pose the problem of studying experimentally the characteristics of a descending dispersed-annular flow in pipes 30 mm in diameter under conditions characteristic

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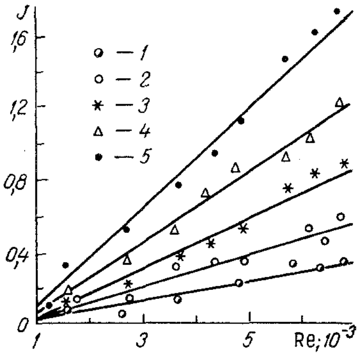

Fig. 1

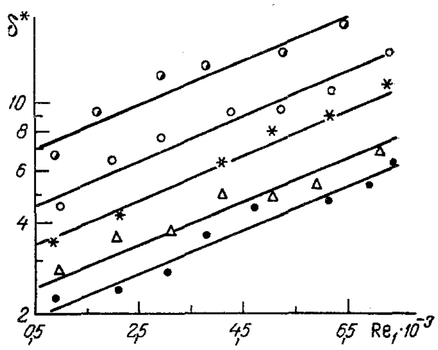

Fig. 2

Fig. 1. Specific entrainment intensity versus the Reynold's number of the film: 1) $Re_2 \cdot 10^{-4} = 3.42$; 2) 6.8; 3) 10.3; 4) 13.5; 5) 15.2 J, kg/(m^2·sec).

Fig. 2. Values of the dimensionless thickness of the film. The notation is the same as that used in Fig. 1.

for operation of technological equipment. The experimental setup consisted of a loop open to fluid and air with forced motion of the phases [6]. The measurement section consisted of a steel pipe 2800 mm long. The annular flow was organized with the help of cylindrical inserts at the top of the pipe. A porous insert for drawing off liquid flowing in the film was inserted at the bottom end of the experimental section in a special chamber. Air and liquid dispersed in it flowed into the separator. The flow rates of the liquid flowing in the film and in the core of the flow were determined by the volume method, while the amount of air was measured with the help of a precalibrated diaphragm. Pressure measurements along the pipe were made at four points at 500, 1000, 1500, and 2000 mm from the inlet. Electric probes, moved with the help of micrometric screws, were installed at these markers in order to measure the thickness of the film. The film thickness was read off a needle indicator. The moment at which the probe touched the surface of the film was recorded with an electronic relay. The thickness of the film was measured from the measured crests and troughs of the waves and was calculated as their half sum. The gauge design developed made it possible to perform measurements with an accuracy of up to 0.01 mm. In the course of the experiments the mass density of irrigation equalled 0.18-2.30 kg/(m·sec), the air velocity equalled 16-95 m/sec, and the air pressure equalled 0.1-0.4 MPa. Water, sugar solutions, and a water solution of butanol were used as the working liquids. The density varied from 980 to 1160 kg/m^3, the viscosity varied from 10^{-3} to $6.9 \cdot 10^{-3}$ Pa·sec, and the surface tension varied from 0.04 to 0.0725 N/m.

The experiments showed that the onset of liquid loss from the surface of the film in the form of drops is observed for gas velocities of 18-23 m/sec, which agrees with [1, 2]. For liquids with lower values of μ_1 and σ drop detachment occurs at lower gas velocities. The relative loss increases as the flow rates of both phases increases. Increasing the flow rate of the liquid in the film (Re_1) encourages the appearance of large-scale waves, from whose crests intense detachment of drops occurs. Increasing the gas flow rate (Re_2), though it decreases the scale of the perturbations, intensifies the dynamic action on the interface, which is what gives rise to the atomization of the film. This mechanism of decomposition was also pointed out in [4]. For gas velocities exceeding 90 m/sec and irrigation mass densities exceeding 1.7 kg/(m^2·sec) the magnitude of the loss can reach 80% of the total flow rate of the liquid. The intensity of loss is not the same along the height of the pipe and increases as the distance traversed by the film increases. At a certain distance an equilibrium flow, when the intensity of drop detachment from the surface of the film equals the deposition on the film, while the thickness of the film stabilizes, is established. It was established that stabilization occurs, for all practical purposes, at a distance of 2 m from the input section of the pipe, which agrees with [1, 4].

The values of the specific loss intensity on the stabilized section are presented in Fig. 1. An analogous character of the variation of J was also observed in [4] for ascending flows. It should be noted that the dimensionless mass fraction of loss E is a more convenient parameter characterizing drop detachment from the surface of the film [1, 2]. Generalization of the experimental data yielded the following formula for determining E:

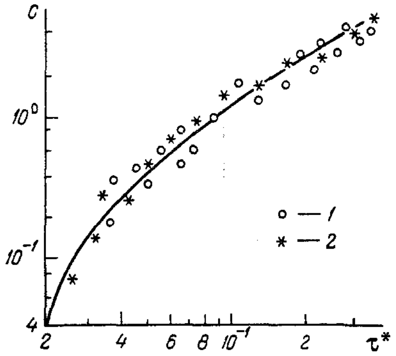

Fig. 3

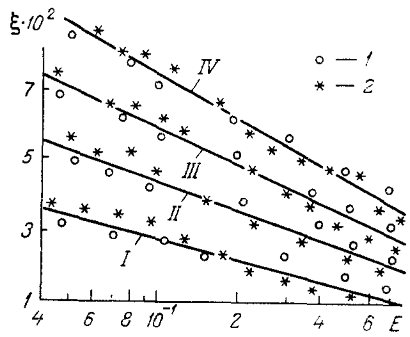

Fig. 4

Fig. 3. Mass concentration of drops in the core of the flow: 1) data of [1]; 2) data of this work. c, kg/m³.

Fig. 4. Coefficients of resistance versus the magnitude of drop loss: I) $Re_1 \cdot 10^{-3} = 0.9$; II) 2.98; III) 5; IV) 6.9; 1) calculation according to [1]; 2) experiments of this work.

$$E = 1.7\,(0.145\cdot 10^{-3}\,Re_1^{0.4}\,Fr_2^{0.5} - 0.12)\,[d\,(\mu_1 g^2 \rho_1)^{1/3}\sigma^{-1}]^{0.3}. \quad (1)$$

Comparison of the calculations performed using (1) and the procedure of [2] showed that they agree to within ±20%. This disagreement can apparently be explained by the fact that the effect of the diameter of the channel was neglected in [2].

For technological processes carried out in film apparatus and also in calculations of the critical point of heat transfer it is necessary to know the "store" of liquid flowing in the film, which is characterized by the average thickness of the film under conditions of equilibrium flow. It turned out that the thickness of the film can be determined uniquely from the flow-rate characteristics of the flow (Fig. 2). The curves (see Fig. 2) are approximated by the relation

$$\delta^* = \exp\,[2.25 + 0.17\cdot 10^{-3}\,Re_1 - Re_2\cdot 10^{-5}]. \quad (2)$$

Since it was impossible to compare explicitly the data on the film thickness with the results of other studies, we determined the correlation between the mass concentration of the liquid in the core of the flow and the magnitude of the dimensionless friction on the interface τ^*, including the thickness of the film (Fig. 3).

The tangential stress on the interface was determined from the relation [1, 5]

$$\Delta P/l = 4\tau^* = 2\xi\rho_2 w_2^2 d^{-1}. \quad (3)$$

The magnitude of the hydraulic friction was defined as the difference between the measured values of ΔP and the losses to acceleration. In calculating the latter it was assumed that the drops are accelerated up to the average velocity of the gas flow, and that there is no slipping of the phases. This caused their values to be overestimated somewhat. The calculations showed that in the range of variation of the flow-rate parameters studied the expenditures on acceleration equaled 7-11.5% of the total resistance. The relative fraction of the losses to longitudinal acceleration, measured for the same conditions in [2], varies from 6 to 10%. The largest deviation equals 1.5%, which is entirely admissible for engineering practice.

Calculations of the hydraulic resistances require data on the friction coefficient ξ. It is usually calculated in the same manner as for a single-phase gas flow in a channel with rough pipes [1, 2, 5]. In one case [2] the equivalent roughness was assumed to be proportional to the average thickness of the film, which in its turn is a function of the magnitude of the tangential stresses on the interface. In another case [5] the equivalent roughness depends on the flow-rate parameters and the physical properties of the phases, and in addition it was found that the crests of the waves are higher than the effective roughness. In [1, 5] it was pointed out that existing methods for calculating friction losses in dispersed-annular flows are laborious and must be simplified for engineering calculations. The values of the coefficients ξ for the two-phase flow under study are presented in Fig. 4. Figure 4 also shows for comparison the values of ξ calculated by the procedure of [1] based on the method of successive approximations. Comparison shows that the disagreement between the results equals on the average ±8%. The dependences shown in Fig. 4 are generalized by the formula

$$\xi = 0.03\,(1.02 - E^{0.5}) + (4.7 - 3.2\,\lg E)\,\mathrm{Re}_1 \cdot 10^{-6}. \tag{4}$$

The losses of head in descending dispersed-annular flow can be easily determined with the help of the dependences (1), (3), and (4) obtained above.

NOTATION

d and l, diameter and length of the pipe; ρ, density; μ, dynamic viscosity; w, velocity; g, acceleration of gravity, σ, surface tension; Γ, mass density of irrigation; $J = \Gamma(\pi d l_0)^{-1}$, specific loss intensity; l_0 = 1 m; E, relative mass fraction of loss; c, mass concentration of drops in the gas volume; ΔP, friction losses; τ, tangential stress on the interface; ξ, resistance coefficient; δ, thickness of the film; $\mathrm{Re}_1 = 4\Gamma\mu_1^{-1}$; $\mathrm{Re}_2 = w_2\rho_2\mu_2^{-1}$; $\mathrm{Fr}_2 = w_2^2(gd)^{-1}$; $\delta^* = \delta(g\rho_1^2\mu_1^2)^{1/3}$; $\tau^* = \tau\delta\sigma^{-1}$. Indices: 1, liquid; 2, gas.

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EFFECT OF TEMPERATURE-INDUCED PHASE SEPARATION IN TWO-PHASE FLOWS

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The results of a theoretical study of the fact that on expansion of an adiabatic two-phase flow in a nozzle the stagnation temperature of one of the phases rises above while that of the other drops below the initial value are presented.

Temperature-induced phase separation occurs with adiabatic expansion of a stationary two-phase flow in a nozzle. If after expansion the phases are stopped and rapidly separated, it is possible to obtain two systems with substantially different temperatures. This effect was confirmed experimentally by Stolyarov [1, 2], who performed experiments on the expansion of a mixture of compressed air with finely dispersed liquid particles in a nozzle. In the case of particles of water after stagnation and separation of the phases artificial snow formed at the outlet. For expansion of air with kerosene or a water solution of diethylene glycol, after stagnation and separation of the liquid phase, the temperature of the liquid phase was lower than 0°C. An analogous effect is the basis for the so-called "snow gun" [3]. According to the experimental data, the temperature-induced phase separation permits obtaining quite low temperatures and the effect can be employed for refrigeration. However, the well-known theoretical investigations of two-phase flows [4-7] do not contain an analysis of the physical essence of this effect. The purpose of this work is to give a theoretical description of the temperature-induced phase separation in a two-phase jet.

We shall first study the equilibrium adiabatic flow of a two-phase medium for which the static (thermodynamic) temperatures of the phases and their velocities are identical. We shall make the standard assumptions that the heat capacity of the liquid (solid) and gaseous

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