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EFFECT OF THE DEGREE OF DISPERSION, THE DROP CONCENTRATION AND THEIR FINE SUBDIVISION ON THE ENERGY AND FLOW CHARACTERISTICS OF VAPOR-DROP FLOWS

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The degree of dispersion of the condensed phase and its concentration are the most important parameters of high-speed two-phase flows, which determine, in particular, their energy and discharge characteristics.

Numerous investigations have been made of two-phase flows in nozzles. A generalization of the results of these investigations is given in [1-3, etc.]. A theoretical analysis of the effect of the particle size on the flow of a mixture of gas and particles in nozzles was first given in [4] using the solution of a simplified system of differential equations. It was shown that when the slip coefficient $\nu = u_2/u_1$ increases (in the case considered this corresponded to a reduction in the particle size) the flow of a two-phase mixture through a nozzle is reduced, other things being equal. In [2, 4] an analysis is given of experimental investigations of the effect of the concentration of condensed phase y_0 when a highly disperse vapor-drop medium flows in nozzles over a wide range of values of y_0. A numerical investigation of the effect of the particle size D_0 on the characteristics of two-phase flows is given in [5]. The strong effect of D_0 and y_0 on the energy loss and the flow characteristics of nozzles in the case of the flow of two-phase mixtures was qualitatively confirmed.

It should be noted that in these investigations the fine subdivision of the particles was ignored. At the same time, in actual vapor-drop high-speed flows (particularly in the flowing parts of moist-vapor turbines) the deformation and subdivision of the liquid drops are extremely intense. This in turn leads to a considerable difference between the theoretical results obtained ignoring these processes, and experimental data. In practice, there have also been no investigations in developing methods for the artificial control of the degree of dispersion of high-speed vapor-drop flows due to intensification of the subdivision or coagulation of the particles and the energy and flow characteristics of such flows as a result of this. The development of methods of reducing the particle sizes is of considerable practical importance, particularly from the point of view of increasing the economic efficiency of moist-vapor turbines and for reducing the erosion of their components.

The main purpose of this paper is to make a numerical and experimental investigation of the effect of fine subdivision of the drops on the characteristics of vapor-drop flows, and also to study methods for the effective control of their dispersion structure. One of these methods is by introducing small quantities of surface-active materials into the flow. The surface-active material, when it interacts with the liquid phase, changes the surface tension of the drops, and, consequently, the location, mechanism, and intensity of their subdivision. In this investigation we added octadecylamine to the flow to obtain a different dispersion structure at the input to the nozzle. At the same time, the assumption that octadecylamine only affects the surface tension of the drops (i.e., the Weber number) enables us, to a first approximation, to estimate the effect of the surface-active material on the characteristics of two-phase flows.

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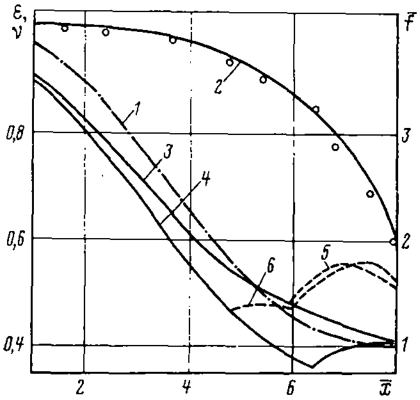

Fig. 1

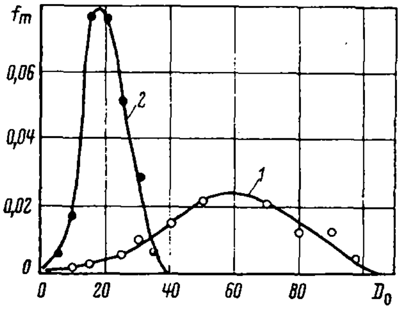

Fig. 2

Fig. 1. Change in the flow parameters along the length of the nozzles: 1) $\bar{f}$; 2) ε (calculated); 3-6) ν; 3) $D_0 = 40\ \mu$, $\sigma = 0.08$ N/m; 4) 80 and 0.08; 5) 40 and 0.02; 6) 80 and 0.02; the circles represent ε (experimental). $\varepsilon_1 = 0.6$, $y_0 = 15\%$, and $K_d = 2$.

Fig. 2. Drop size distribution density at the input to the nozzle: 1) $\varkappa = 0$; 2) $\varkappa = 56 \cdot 10^{-6}$ kg octadecylamine/kg vapor. $\varepsilon_1 = 0.6$, $y_0 = 14.2\%$. f_m, $1/\mu$; D_0, μ.

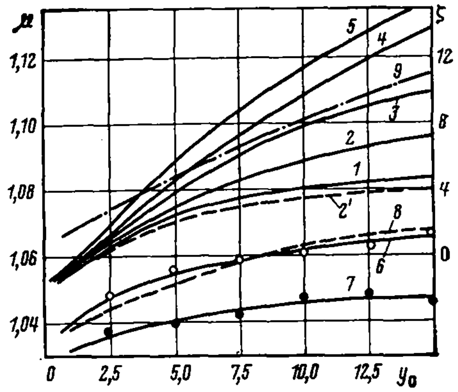

Fig. 3. Effect of the particle size on the discharge coefficient and loss of the vapor phase: 9) ζ, residual μ. 1) $D_0 = 5\ \mu$; 2) 10; 3) 20; 4) 40; 5) 60; 6, 7) experimental; 6) $\varkappa = 0$, $D_0^M = 60\mu$; 7) $\varkappa = 56 \cdot 10^{-6}$ kg octadecylamine/kg of vapor, $D_0^M = 20$; 8) according to (6), $K_d = 6$; 2') $D_0 = 80$, $K_d = 8$. $\varepsilon_1 = 0.6$, $y_0 = 15\%$, ζ, %.

The main problem of a theoretical investigation is to determine the discharge and energy loss coefficients of vapor-drop nozzle flows taking into account the aerodynamic fine subdivision of the drops and the change in the dispersion structure of the condensed phase.

The experiments were made on a closed type of moist-vapor aerodynamic tube [3]. The object of the investigation was a plane subsonic nozzle whose profile is represented by curve 1 in Fig. 1. The following quantities were measured: the pressure drop in the nozzle, the pressure distribution along the length of the nozzle, the initial degree of humidity (found from the heat and mass balance), and the mass distribution of the drops with respect to dimensions at the input to the nozzle using the method of replicas [7].

The vapor was artificially moistened by spraying the condensate with a steam sprayer. The octadecylamine was added by means of a plunger pump. The vapor was added separately from the main vapor conductor. Hence, a reduction in the dimensions of the drop at the input to the nozzle occurred due to aerodynamic fine subdivision, and not due to a change in the spraying characteristics. The degree of humidity y_0 at the input of the nozzle varied from 0 to 15%. The degree of dispersion of the drops was varied by introducing octadecylamine into the vapor-conducting channel in very small doses $\varkappa < 6 \cdot 10^{-5}$ kg per kilogram of vapor. The experimental particle-size distribution functions at the input of the nozzle are shown in Fig. 2. A considerable reduction in the size of the particles was found when octadecylamine was introduced, and the model size D_0^M decreased by a factor of more than 3 for a relative consumption of octadecylamine in amounts of 0.0056%. The discharge coefficient of the moist flow was defined as the ratio of the measured mass discharge to the theoretical. The latter was calculated assuming complete thermodynamic equilibrium for a known pressure drop in the nozzle [6].

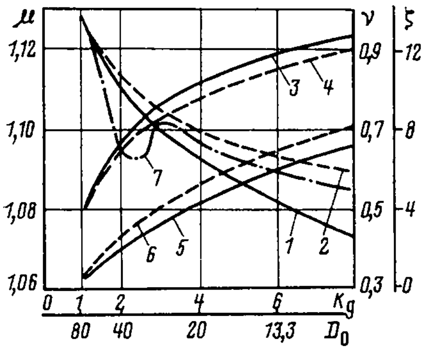

Fig. 4

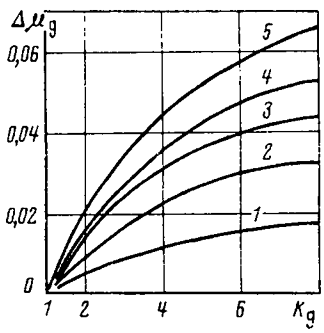

Fig. 5

Fig. 4. Effect of subdivision of the drop on the characteristics of the vapor-drop flow: 1, 3, 5) $D_0 = 80\ \mu$, with subdivision; 2, 4, 6) 80, without subdivision; 1) μ (K_d); 2) μ (D_0); 3) ζ (K_d); 4) ζ (D_0); 5) ν (K_d); 6) ν (D_0); 7) μ (K_d); $\sigma = 0.02$ N/m. $\varepsilon_1 = 0.6$; $y_0 = 15\%$; D_0, μ.

Fig. 5. Correction for subdivision to the discharge coefficient: 1) $y_0 = 2.5\%$; 2) 5; 3) 7.5; 4) 10; 5) 15; $\varepsilon_1 = 0.6$, $D_0 = 80\ \mu$.

Figure 3 shows experimental curves of $\mu = f(y_0)$ (curves 6 and 7). As might have been expected from the analysis carried out in [5], as the size of the drop decreases the discharge coefficient also decreases. Hence, the experiments qualitatively confirm the results of the theoretical investigations. However, from the quantitative point of view there is a considerable disagreement. Thus, a calculation of the discharge coefficient μ from the nomograms given in [5], constructed ignoring the fine subdivision, gives a value $\mu = 1.14$, which is 8% higher than the experimental value obtained for $y_0 = 15\%$, $\varepsilon_1 = 0.6$, and $D_0{}^M = 60\ \mu$.

A numerical investigation was made using the ordinary system of differential equations of a stationary quasi-one-dimensional two-phase flow. Previous investigations [2, 3, 5] showed that over the range of parameters corresponding to our experiment ($P_0 = 10^5$ N/m² and $D_0 > 10\ \mu$), the effect of mismatch between the velocities and the mechanical phase interaction considerably exceeds the effect of interphase heat and mass transfer on the two-phase flow characteristics investigated. On the basis of this in this investigation we used the following assumptions in the numerical analysis: no mass transfer between the phases, no interaction between the particles, consideration of the viscosity only for interaction between the phases, and the use of the quasimonodisperse model of the liquid phase. The interaction force between the phases was calculated from the equations

$$R = \frac{3C_x \varphi_2 \rho_1 u_1^2 (1-\nu)^2}{4D_0}, \tag{1}$$

$$C_x = \frac{24}{\mathrm{Re}} + \frac{4}{(\mathrm{Re})^{1/3}}, \quad \text{if} \quad 3 < \mathrm{Re} \leqslant 400, \tag{2}$$

$$C_x = \frac{12.5}{(\mathrm{Re})^{1/2}}, \quad \text{if} \quad 400 < \mathrm{Re} \leqslant 10^3, \tag{3}$$

$$C_x = 0.48, \quad \text{if} \quad \mathrm{Re} > 10^3.$$

In agreement with [3] we assumed that the fine subdivision of the drops occurs when a value of the Weber number $\mathrm{We} = \mathrm{We}_k = 12$ is reached.

We used the standard Runge–Kutta method to integrate the set of equations. The aerodynamic fine subdivision process is, in general, complex and nonunique [3]. In this investigation we chose the simplest subdivision model: The initial drop, without deformation, after reaching $\mathrm{We} = \mathrm{We}_k$, is simultaneously split up into n different parts, defined by the subdivision coefficient. Figure 1 shows the pressure distribution ε (curve 2) and the slip coefficient ν (curves 3–6) over the length of the nozzle, obtained by calculation for a pressure drop in the nozzle $\varepsilon_1 = 0.6$ and an initial humidity $y_0 = 15\%$. The points represent the experimental pressure distribution. As is seen, the flow under these conditions is necessarily accompanied by fine subdivision of the drops. A reduction in the surface tension of the drop leads to a shift in the fine subdivision cross section opposite to the flow and to an increase in the velocity of the liquid phase at the nozzle cutoff — the dashed curves 5 and 6 in Fig. 1.

Here we assume that the fine subdivision coefficient $K_d = 2$.

The results of an investigation of the effect of the initial humidity and drop size on the discharge and loss coefficients are shown in Fig. 3. The discharge coefficient μ was calculated from the equation

$$\mu = f_1(\rho_1 u_1 \varphi_1 + \rho_2 u_2 \varphi_2)/G_t, \tag{4}$$

where G_t is the theoretical discharge, calculated from the equilibrium heat transfer. The loss coefficient of the vapor phase was found from the expression

$$\xi = \left(1 - \frac{\rho_1 u_1 u_1^2}{\rho_{1t} u_{1t} u_{1t}^2}\right) \cdot 100, \ \%. \tag{5}$$

Here the index t denotes that the corresponding quantity was found from gas-dynamic tables for isoentropic expansion of supercooled vapor.

It follows from the theoretical graphs (curves 1-5 in Fig. 3) that the discharge coefficient increases as the diameter of the drop increases, and this increase is more intense the greater the initial degree of humidity. Analysis showed that a reduction in μ together with a reduction in D_0 when there is no fine subdivision occurs for two reasons: first, the vapor by accelerating the fine drops to higher slip coefficients loses a large amount of kinetic energy, and finally its velocity at the exit of the nozzle falls; second, the true volume concentration of the drop decreases as its size decreases, which corresponds to the data given in [4]. Both factors contribute equally to the change in the discharge coefficient. The large disagreement between curves 5 and 6 in Fig. 3 is due to the fact that the theoretical discharge coefficient does not take into account a number of factors which occur in actual flows, and primarily, the energy dissipation in the boundary layer and the fine subdivision of the liquid phase. A numerical investigation of the effect of the fine subdivision mechanism on the flow characteristics showed that the discharge coefficient decreases while the loss coefficient increases as the subdivision coefficient increases — curves 1 and 3 in Fig. 4. Analysis showed that for the mode with fine subdivision the parameters of the vapor phase at the exit from the nozzle are close to the values of the corresponding parameters for the mode without subdivision when the initial particle sizes are the same as the particle sizes after subdivision. In particular, this is the cause of the small difference in the loss coefficients — curves 3 and 4 in Fig. 4. The additional reduction in the discharge coefficient in the mode with subdivision is due to the fact that the drop, after subdivision, cannot be accelerated to the value of the velocity at the output, which it would have if its initial size was equal to the size after subdivision. It is natural to assume that the difference between curves 1 and 2 of Fig. 4 will be less the earlier subdivision occurs. This assumption is confirmed by calculation. Curve 1 in Fig. 4 corresponds to the subdivision cross section $\bar{x} = 6.4$, while curve 7 corresponds to $\bar{x} = 4.8$ (see curves 4 and 6 in Fig. 1). The shape of curve 7 in Fig. 4 for $K_d < 3$ is due to the fact that the drops in the nozzle are subdivided twice (see also Fig. 1, curve 6).

Figure 5 shows theoretical curves of the effect of fine subdivision on the discharge coefficient for different values of y_0. The reduction in the discharge due to fine subdivision $\Delta\mu_d$ occurs more intensively the greater the initial degree of humidity.

On the basis of the above numerical analysis we obtained a relation which enabled the theoretical discharge coefficient to be refined:

$$\mu = \mu_s(\mu_t - \Delta\mu_d), \tag{6}$$

where μ_p is the theoretical coefficient ignoring subdivision, $\Delta\mu_d$ is the increase in the discharge coefficient taking drop subdivision into account, and μ_s is the discharge coefficient of the nozzle for superheated vapor. In this case we assumed approximately that the reduction in μ due to energy dissipation in the boundary layer is the same for superheated and moist vapor. We took the value 0.98 for μ_s. The results of a calculation of μ using (6) and the curves in Fig. 5 are shown in Fig. 3, curve 8. The agreement with experimental curve 6 is satisfactory.

Naturally, the values of μ_p and $\Delta\mu_d$ depend on the specific initial and geometrical parameters of the nozzle, and also on the particle size distribution at the input to the nozzle. The results of a calculation of the discharge coefficient for different pressure drops ε_1 $(0.6 < \varepsilon_1 < 0.85)$ showed that the value of μ_p is inversely proportional to ε_1. The curves of $\mu_p(D_0)$ for $\varepsilon_1 = \text{const}$ are equidistant, which confirms that the pressure drop in the nozzle has only a small effect on the value of $\Delta\mu_d$.

The results obtained showed that an increase in the initial size of the particles leads to an increase in the discharge coefficient of the nozzle and to a reduction in the loss coefficient of the vapor phase ζ. In the given specific nozzle with $y_0 = 15\%$ and $\varepsilon_1 = 0.6$ as the particle size increases from 5 μ to 80 μ the discharge coefficient increases by 4% while the loss coefficient of the vapor phase decreases by 9%. The mechanism by which the liquid phase is subdivided has a considerable effect on the discharge and energy characteristics of vapor-drop flows. When the subdivision coefficient is increased from 1 to 8 the value of μ decreases by 5.5%, while the loss coefficient of the vapor phase increases by 9% (for the given specific nozzle with $y_0 = 15\%$ and $\varepsilon_1 = 0.6$). Under certain conditions subdivision of the liquid phase within the nozzle may lead to more intense reduction in the discharge coefficient than a reduction in the initial size of the particles. This effect is the same as the effect of the initial size of the particles and their subdivision on the quantities μ and ζ, which is more pronounced the greater the concentration of the liquid phase and the pressure gradient in the nozzle.

The refinement of the discharge coefficient taking into account the subdivision of the liquid phase enabled satisfactory agreement to be obtained between the theoretical and experimental results.

NOTATION

ν, slip coefficient; u_1, vapor velocity; u_2, particle velocity; y_0, true initial concentration of the liquid phase; D_0, initial drop diameter; D_0^M, modal initial drop diameter; $\bar{x} = x/h$, dimensionless coordinate along the length of the nozzle; x, coordinate along the length of the nozzle; h, height of the nozzle in the output section; $\bar{f} = f/f_1$; f, transverse cross-sectional area; f_1, transverse cross-sectional area at the nozzle outlet; $\varkappa$, flow-rate concentration of octadecylamine; μ, discharge coefficient; ε, ε_1, pressure drop and maximum pressure drop in the nozzle; R, interaction force between the phases; C_x, resistance coefficient of the drop; φ_2, volume fraction of the liquid phase; ρ_1, density of the vapor phase; $Re = \rho_1 D_0 (u_1 - u_2)/\mu_1$, Reynolds number; μ_1, dynamic viscosity of the vapor; $We = \rho_1 D_0 (u_1 - u_2)^2/\sigma$, Weber number; σ, surface tension of the liquid; $K_d = D_0/D_1$, subdivision coefficient; D_1, drop diameter after subdivision; G, flow rate; ζ, kinetic energy loss coefficient of the vapor phase; μ_p, theoretical discharge coefficient; μ_s, discharge coefficient for superheated vapor; $\Delta\mu_d$, correction for subdivision to the discharge coefficient; and f_m, drop size distribution density.

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