INFLUENCE OF NONISOTHERMICITY OF THE MEDIUM AND POLYMER ADMIXTURES ON A TURBULENT VERTICAL WALL JET

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The results are given on an experimental investigation of the effect of small polymer admixtures and density inhomogeneity of the ambient medium on the laws of development of plane, vertical, turbulent wall jets.

Rheological and temperature (density) factors, even when their manifestation is slight, can cause pronounced changes in the structure of wall and free turbulent liquid streams. This has been established in the experimental study of processes of hydrodynamics and heat and mass transfer in polymer solutions and various suspensions, as well as in liquids that are inhomogeneous in density or temperature.

Semiconfined vertical wall jets, which combine the main features of free and wall flows, are a convenient subject for investigating the influence of polymer admixtures and buoyancy effects on flow structure. The use of such jets in various mixing and injecting devices, hydrodynamic curtains, etc. is well understood and widely practiced. The overwhelming majority of research has been devoted to free, submerged turbulent jets. They include the best-studied case, axisymmetric, vertical, turbulent buoyant jets under the simultaneous action of fluxes of buoyancy and momentum [1-3], which, with allowance for stratification, results in considerable changes in the classical laws of development of jets. In low-concentration polymer media, the initial section of a turbulent jet undergoes considerable changes [4] (redistribution of the profiles of the mean and pulsation velocities, the energy spectrum of pulsations, etc.).

In proceeding to wall jets, we note that the experimental results in the literature pertain mainly to nonisothermal buoyant jets [5, 6]. The case of interest to us, of the ascent of a vertical wall jet with a "negative" buoyancy, has been considered in [5] for Richardson numbers of order unity ($Ri \approx 1$). As for polymer wall jets, we know of no published work on this problem.

The main experiments were carried out on an installation consisting of a water-filled transparent vessel in the shape of a vertically mounted channel with a height of 2 m and a square cross section of 200×200 mm^2. The wall jet was formed with a flat nozzle, 1×100 mm^2, with a 1:10 ratio of exit to entrance cross sections. Liquid was supplied to the nozzle from a centrifugal pump, and its excess (from the aspect of maintaining a water column of constant height in the channel) was drained off through an overflow opening in the upper part of the wall. The temperature was measured with Chromel–Copel thermocouples, with a junction diameter of 0.3 mm, embedded in the wall. The electrodiffusion method [7] was used to measure the frictional shear stress and velocity in the stream. Small amounts of potassium ferro–ferricyanide and potassium sulfate were added to the working medium (water), and all the components of the installation were made of organic glass, plastics, and stainless steel. The frictional shear-stress sensor was mounted flush with the wall, while the wedge-shaped velocity sensor was located opposite to it and could be moved in the direction perpendicular to the wall. The longitudinal z coordinate, reckoned from the rim of the nozzle to the sensors, was varied by moving the nozzle itself. The size of the platinum sensing elements of the sensors in the flow direction was 40 μm. We preliminarily determined the calibration characteristics of the wedge-shaped velocity sensor, and also estimated the time constants of both sensors. The pulsation values of their signals were recorded and analyzed with a Bruel and Kjeer 2608 rms voltmeter, a TOA-111 spectrum analyzer, and a Disa 55D70 correlator.

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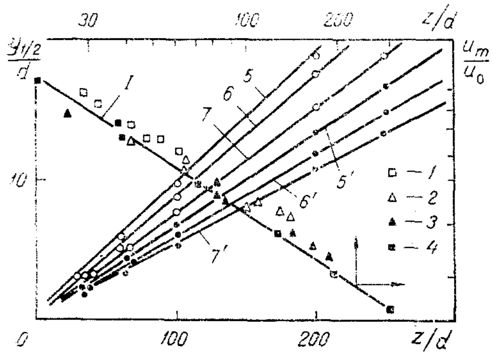

Fig. 1. Variation along the jet of the maximum velocity (1-4) and flow half-width (5-7, 5'-7'): 1) from experimental data of [8]; 2) of [9]; 3) of [10]; 4) of [11]; I) authors' data; 5, 5'; 6, 6'; 7, 7') Re = 1150, 1370, 1600, respectively (5'-7': with a PAA admixture, C_p = 0.01%.

General Characterization of a Wall Jet and Influence of Polymer Admixtures on It

In measurements of the mean velocity in cross sections, we established that the width of the jet and the rate of its increase (Fig. 1) depend on the Reynolds number up to a certain value. A further increase in Re > $1.6 \cdot 10^3$ resulted in practically no change in the geometrical parameters of turbulent flow, which gives reason to assume that it is fairly developed. This is also indicated by the self-similar shape of velocity profiles in cross sections of the jet (Fig. 2). The solid line represents the results of Refs. 8-10, which agree well with our data and may be approximated by the expression

$$\frac{u}{u_m} = 1.48\left(\frac{y}{y_{1/2}}\right)^{1/7}\left(1 - \operatorname{erf}\left(0.68\,\frac{y}{y_{1/2}}\right)\right). \tag{1}$$

The variation of the maximum velocity along the jet (Fig. 1) based on our measurements may be generalized by the power function (for z/d > 20)

$$\frac{u_m}{u_0} = 5.9\left(\frac{z}{d}\right)^{-0.64}. \tag{2}$$

The experimental data of other authors [8-10] given in Fig. 1 do not differ much from ours. The minor differences are evidently due to the influence of the initial conditions of formation of the jet in the different experiments (the compression ratio and the shape of the nozzle, the level of disturbances in the initial cross section, the presence of a boundary layer at the nozzle rims or a pressure gradient, roughness, etc.). With allowance for the above, the agreement between our experimental data and those from the literature [8-12] on measuring the frictional wall shear stress (Fig. 3) can be considered satisfactory.

For a jet of a polyacrylamide solution (PAA, C_p = 0.01%), the flow width and the rate of its increase decreased considerably (Fig. 1). The redistribution of turbulent energy of pulsation flow in a wall jet containing PAA admixtures can be judged from the form of the correlation characteristic curves (Fig. 2), obtained by analyzing signals from electrodiffusion sensors of velocity and friction mounted at the same distance from the nozzle. The increase in the cross-correlation coefficient can be treated as the result of suppression of small-scale vortices and an increase in the fraction of large-scale vortices. This is also indicated by measurements of the energy spectrum of pulsations of frictional wall shear stress and the longitudinal velocity component in the stream, presented in Fig. 3 in the form of spectral increases.

The redistribution of spectral density is accompanied by an increase in the intensity of pulsations of the longitudinal velocity components and friction. The introduction of small polymer admixtures to a wall jet also alters the regime of exchange of liquid masses between

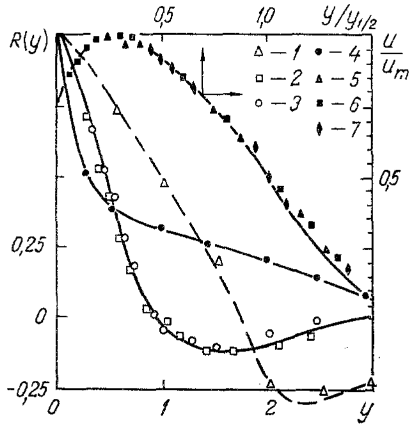

Fig. 2

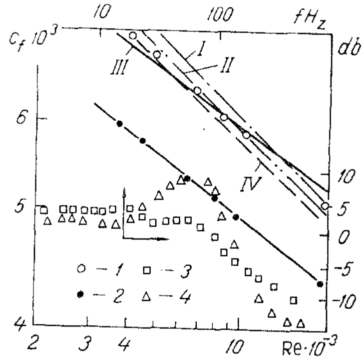

Fig. 3

Fig. 2. Distribution across the jet of the cross-correlation coefficients for velocity pulsations (1-4) and mean velocities (5-7): 1) z/d = 4; 2) 8; 3, 4) 20 (light points: without polymer admixture; dark points: with PAA admixture, C_p = 0.01%); 5) z/d = 40; 6) 200; 7) 300. y, mm.

Fig. 3. Influence of PAA admixtures on the mean and pulsation values of the frictional wall shear stress: I-IV) c_f = f(Re), C_p = 0; I) from the data of [11]; II) of [10]; III) of [12]; IV) of [8]; 1, 2) c_f = f(Re), authors' data for C_p = 0 and 0.01%, respectively; 3, 4) spectral increases in pulsation level (C_p = 0.01%); 3) velocity sensor 2 mm from the wall; 4) friction sensor at the wall.

the wall region and the outer region. The jet becomes longer-range and the intensity of turbulent mass diffusion across the jet decreases; the wall stabilizes the development of a jet containing polymer admixtures, even at considerable distances from the nozzle. In Ref. 4 with Re = $1.5 \cdot 10^4$, for example, the increase in the range of a free jet containing polymer admixtures appears up to z/d $\leq$ 20, while for a semiconfined jet it appears up to z/d $\leq$ 700. A decrease in local frictional shear stress is recorded in this case (Fig. 3).

Nonisothermicity of the Medium

When a jet propagates in a medium with a density ρ_1 that differs from the jet density ρ, additional mixing develops due to the density difference. A nonisothermal vertical jet can be characterized by the momentum and the buoyant force [2, 3]. In a theoretical analysis one usually considers limiting cases, in which forced or natural convection dominates in the jet.

An analysis of integral equations for the momentum flux and the buoyant force, under the assumption of similarity of both the velocity profiles and the profiles of excess density at different distances from the source, leads to the following expression for the maximum velocity u_m in a jet cross section under the conditions of forced and natural convection:

$$u_m = \left(\frac{2F}{k(c_f + 2k_1\alpha)}\right)^{1/3}\left(1 \pm \left(\frac{c_1}{z}\right)^{\beta}\right)^{1/3}. \tag{3}$$

Here

$$k = \int_0^1 \left(\frac{\rho - \rho_1}{\rho_m - \rho_1}\right)\frac{u}{u_m}\, d\left(\frac{y}{b}\right) \Big/ \int_0^1 \frac{\rho - \rho_1}{\rho_m - \rho_1}\, d\left(\frac{y}{b}\right),$$
$$k_1 = \int_0^1 \left(\frac{u}{u_m}\right)^2 d\left(\frac{y}{b}\right),\quad c_f = \frac{2\tau_w}{\rho u_m^2},\quad \beta = \frac{3}{2}\left(1 + \frac{c_1}{k_1\alpha}\right). \tag{4}$$

The ± signs correspond to positive and negative buoyancy and F is the buoyant force. Here we have also assumed that the jet's width b is proportional to the distance from the source [2], b = αz, while the dependence of c_f on z is negligibly weak [3]. Two limiting cases follow from Eq. (3):

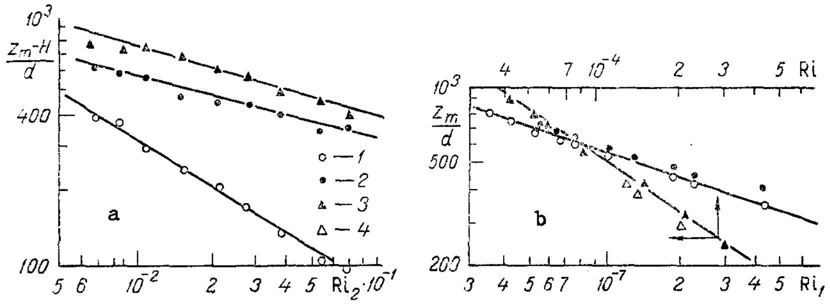

Fig. 4. Range of the jet: a) medium with a density discontinuity: 1) $C_p = 0$; 2) 0.01% PAA; 3) 0.05% WSR-301 PÉO; b) 1) $C_p = 0.2$-0.01% PAA, linearly stratified medium; 3) $C_p = 0$; 4) 0.01% PAA, escape into a lower-density medium.

1) for the domain in which forced convection dominates (i.e., $z \ll c_1$), the velocity distribution has the form

$$u_m = \left(\frac{2F}{k(c_f + 2k_1 \cdot \alpha)}\right)^{1/3} c_1^{\beta/3} z^{-\frac{1}{2}(1+c_f/k_1\alpha)}; \tag{4}$$

2) for the domain of an upstreaming jet (i.e., $z \gg c_1$), we have

$$u_m = \left(\frac{2F}{k(c_f + 2k_1\alpha)}\right)^{1/3} = \text{const}. \tag{5}$$

The transition from a forced jet to an upstreaming jet occurs at $z \simeq c_1$, and Eq. (3) is valid in this domain. If the jet has a negative buoyancy, then the minus sign is taken in (3). The range of heights z to which the jet can rise then turns out to be limited. At $z = c_1$ the velocity is $u_m = 0$, after which the jet starts to descend toward the source and the equation loses physical meaning. Converting to dimensionless quantities [2], from (3) we can obtain an expression for the maximum height z_m attained by a jet with an initial density ρ_0 higher than the density ρ_1 of the ambient medium:

$$\frac{z_m}{d} = c_2 \mathrm{Ri}^{-\frac{2}{3(1+c_f/k_1\alpha)}}, \quad \mathrm{Ri} = \frac{g(\rho_0 - \rho_1)d}{\rho_0 u_0^2}, \tag{6}$$

where c_2 is a constant. The experimental data presented in Fig. 4 in the range $2 \cdot 10^{-5} < \mathrm{Ri} < 4 \cdot 10^{-4}$ lead to the following expression for the maximum height attained by a jet:

$$\frac{z_m}{d} = 1.22\,\mathrm{Ri}^{-0.65}. \tag{7}$$

Since $c_f \simeq 0.01$ and $k_1\alpha \simeq 1$, the calculated function (6) reflects qualitatively correctly the law of propagation of a vertical wall jet in a stratified medium, which confirms the correctness of our assumptions.

In [5] the propagation of such a jet was analyzed in the range $\mathrm{Ri} \simeq 1$ (the case in which the buoyant forces are comparable in magnitude with the inertial forces).

The wall has a highly stabilizing influence on propagation of the jet. For a free axisymmetric jet [6], for example, the height of ascent is proportional to $\mathrm{Ri}^{-0.5}$ and its values turns out to be considerably lower ($\simeq$ 250 calibers for a wall jet and $\simeq$ 100 for a free jet with $\mathrm{Ri} = 3 \cdot 10^{-3}$).

On the basis of experimental data (Fig. 5) for a liquid jet propagating in a medium with a density discontinuity located at a height H from the nozzle cut, for $6 \cdot 10^{-3} < \mathrm{Ri}_2 < 10^{-1}$ the height of penetration of the jet through the density interface may be approximated by the expression

$$\frac{z - H}{d} = 16.4\,\mathrm{Ri}_2^{-0.65}, \quad \mathrm{Ri}_2 = \frac{g(\rho_0 - \rho_2)H}{\rho_0 u_0^2}, \tag{8}$$

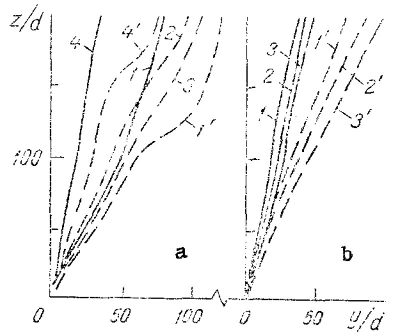

Fig. 5. Boundary of the jet: a) escape into a lower-density medium: 1, 1') Ri = $1.9 \cdot 10^{-4}$; 2, 2') $1.3 \cdot 10^{-4}$; 3, 3') $0.95 \cdot 10^{-4}$; 4, 4') $7 \cdot 10^{-5}$ (1'-4': with a PAA admixture, C_p = 0.01%); b) escape into a linearly stratified medium: 1, 1') Ri = $6.5 \cdot 10^{-8}$; 2, 2') $7.6 \cdot 10^{-8}$; 3, 3') 10^{-7} (1'-3': with a PAA admixture, C_p = 0.01%).

where ρ_2 is the density of the medium at $z > H$. A free, submerged, axisymmetric jet, according to the data of [6], penetrates through a density discontinuity to a considerably smaller height ($z_m/d \approx 400$ for a wall jet and $z_m/d \approx 90$ for a free jet with $Ri_2 = 7 \cdot 10^{-3}$).

For a vertical jet propagating in a stratified medium, the determining parameters will be momentum, the buoyant force, and the stratification parameter $G = -\frac{g}{\rho}\frac{\partial \rho}{\partial z}$. Consequently, the relation for the height of ascent of the jet will have a more complicated form than (8).

Let us consider the simple case in which the jet at the nozzle exit is characterized by the momentum alone, while the medium is stratifies. Dimensional considerations lead to the following estimate for the maximum height of ascent: $z_m \propto (M/G)^{1/3}$

Experiments were carried out for a vertical jet with an initial density ρ_0 propagating in a medium with a linear height distribution of density, with the density of the medium at the level of the nozzle cut being equal to the density of the escaping jet. The linear stratification was produced in a way similar to the case of the creation of a density discontinuity. Here the liquid temperature varied by 2°C every 50 calibers. The approximation of the experimental data obtained has the form

$$\frac{z_m}{d} = 2{,}74\,\mathrm{Ri}_1^{-0{,}33}\ ,\quad \mathrm{Ri}_1 = \frac{g}{\rho}\frac{\partial \rho_1}{\partial z}\frac{d}{u_0^2}\ , \tag{9}$$

which fully agrees with the estimate given above. As seen from Fig. 4b, by contrast with jet propagation in a medium with a different density from the initial density of the jet, stratification enhances the dissipation of turbulent kinetic energy, and the rate of increase in the maximum height of ascent of the jet as a function of the Richardson number decreases. Let us consider the influence of density inhomogeneity on a turbulent vertical wall jet containing small polymer admixtures. For the propagation of a "light" jet in a homogeneous medium with a higher density, the polymer admixture intensified turbulent exchange, and the height of ascent of the jet decreased somewhat (points 4 in Fig. 4b). The width of the jet increased in the process (Fig. 5a).

The polymer has a similar influence on the development of a wall jet in a medium with a linear density distribution (Fig. 5b). Polymer admixtures enhanced turbulent exchange, but since the density of the medium at the nozzle cut and in the escaping jet were the same, and the subsequent decrease in the density of the ambient medium occurred linearly, the increase in exchange between the polymer jet and the ambient medium was slower than in the preceding case. As a result, the jet ascended somewhat higher (points 1 and 2 in Fig. 4b).

In Fig. 4a we present data on the height of ascent of a jet containing polymer admixtures above a density interface in the medium — a discontinuity layer. The density interface layer was a distance of 300 calibers from the nozzle. The jet escaped into a medium having the same density. Because of the polymer admixtures, the jet had a higher velocity than usual (for an equal velocity of escape from the nozzle) as it approached the interface, so that, other conditions being equal, the depth of penetration through the density discontinuity become greater (Fig. 4a). It is also seen that in the absence of polymer admixtures we have $(z - H)/d \propto Re_2^{-0.65}$, while the presence of polymer leads to $(z - H)/d \propto Re_2^{-0.25}$, i.e., with an increase in the velocity of escape of the jet, $Ri_2 \to 0$, the rate of its penetration through a density discontinuity layer decreased considerably. This result can be explained on the basis of the established fact that the intensity of the longitudinal component of the pulsation velocity increases in a wall jet, as well as by the well-known phenomenon in stratified media of the conversion of the energy of the component of velocity pulsations orthogonal to the plane of the discontinuity into the energy of the other component. In our case, this means an increase in the transverse component (in the coordinates of the jet) of the pulsation velocity, accompanied by intensification of turbulent eschange and hence by "distension" of the jet and a decrease in the rate of its penetration through a medium of inhomogeneous density.

NOTATION

b, width of the jet, m; C_p, polymer concentration, %; $c_f = 2\tau_w/(\rho u^2)$, drag coefficient; τ_w, frictional shear stress, N/m^{-2}; d) transverse size of the nozzle, m; g, free-fall acceleration, $m \cdot sec^{-2}$; z, y, coordinates along the direction of flow and perpendicular to it; $y_{1/2}$, coordinate at which $u = u_m/2$; u, velocity, $m \cdot sec^{-1}$; u_m, maximum velocity, $m \cdot sec^{-1}$; u_0, rms velocity at the nozzle cut, $m \cdot sec^{-1}$; $Re = u_0 d/\nu$, Reynolds number; Ri, Richardson number; ρ, density, $kg \cdot m^{-3}$; ν, kinematic viscosity, $m^2 \cdot sec^{-1}$.

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