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FLOW OF TURBULENT GAS JETS IN A SUBMERGED SPACE

V. V. Glazkov, M. D. Guseva,
and B. A. Zhestkov

UDC 532.525.2

The distribution of parameters in the cross section and along the axis of submerged jets of helium, air, and argon is shown. Theoretical formulas are proposed and compared with the results of other authors.

In the survey literature devoted to the study of the flow of turbulent gas jets of different densities [1-9], there are different points of view on the distribution of temperatures and concentrations in the mixing zone, the width of this zone, etc.

To refine representations of the turbulent mixing of gases with different physical properties, we conducted comparison tests involving the discharge from a nozzle of radius R = 4 mm of heated jets of helium, air, and argon into an immovable air space. In the tests, the light gas ($\rho_0 < \rho_n$) was fed vertically upward, while the heavy gas ($\rho_0 > \rho_n$) was fed vertically downward. The initial parameters of the gas jets were chosen from the conditions that: 1) a turbulent flow regime begin from the nozzle edge; 2) the dynamic heads and temperatures could be measured with sufficient accuracy; 3) in the measurement cross sections up to values $u/u_m \geqslant 0.2$, the additional velocity of the gas particles due to buoyancy Δu_* would be greater than $0.02u_m$. In the calculations, it was assumed that $\Delta u_* = g\tau(\rho_0 - \rho_n)/\rho_n$, where $\tau = x/u$ is the residence time of the gas particles in the jet.

Table 1 shows initial parameters of the gas jets.

In the tests, we used a combination packing with an inlet aperture diameter of 0.7 mm to determine the dynamic head, temperature, and composition of the gas mixture. The measurements were made in the cross section x = 102 mm = 25.5R along two mutually perpendicular directions. The sought values of the parameters were judged to have been correctly determined if the data for the two directions agreed. We also determine the parameters of the gas mixture on the stream axis $x \leqslant 50R$.

Figure 1a-b shows the relative velocities, dynamic heads, and mass concentration with the discharge of helium, air, and argon from the nozzle, respectively. The relative excess enthalpies and temperatures are also shown. The solid lines in Fig. 1 represent the relations in [1, 4, 10]

$$\frac{u}{u_m} = \left[1 - \left(\frac{y}{b_u}\right)^{3/2}\right]^2 \tag{1}$$

and

$$\frac{\Delta i}{\Delta i_m} = \frac{i - i_n}{i_m - i_n} \equiv \frac{c}{c_m} = \left[1 - \left(\frac{y}{b_c}\right)^{3/2}\right]^2. \tag{2}$$

The width of the dynamic ($2b_u$) and concentration ($2b_c$) mixing zones was determined from the relations

$$b_u = 2.27b_{u=0.5u_m},\ b_c = 2.27b_{c=0.5c_m}. \tag{3}$$

It is clear from the data shown that the fields of relative excess enthalpies and mass concentrations are identical. This result was noted earlier in a study of the characteristics of boundary layers on permeable walls [11]. The identity of the mass concentration and excess

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TABLE 1. Initial Parameters of Gas Jets

Gas	u_0, m/sec	T_0K	Re·10^{-4}	$(T_0 - T_{\mathrm{n}})$ K	ρ_0/ρ_{n}
Helium	205	320	1,2	28,7	0,125
Air	117	329	5,0	33,7	0,88
Argon	78	319	4,0	26,6	1,26

enthalpy distributions is evidently valid for turbulent mixing of gases in the absence of radiant heat and mass transfer and chemical reactions (such as combustion).

The width of the dynamic and concentration mixing zones, as well as the form of the fields u/u_m and $c/c_m \equiv (i - i_{\mathrm{n}})/(i_m - i_{\mathrm{n}})$, are nearly independent of the physical properties of the jet. For example, the values of $2b_{u=0.5u_m}$ for helium, air, and argon are 19.8, 18.2, and 17.1 mm, respectively, while the values of $2b_{c=0.5c_m}$ are 24.0, 22.4, and 20.9 mm. Consequently,

$$b_i \equiv b_c = 1.2b_u, \tag{4}$$

while, if we assume that the pole of the jet coincides with the nozzle edge, the angular coefficient of expansion of the dynamic mixing zone is 0.22, 0.20, and 0.19 for helium, air, and argon, respectively.

The fields u/u_m and c/c_m are satisfactorily described by Eqs. (1) and (2). The distribution of $\Delta T/\Delta T_m = (T - T_{\mathrm{n}})/(T_m - T_{\mathrm{n}})$ is strongly dependent on the physical properties of the mixed gases. For example, at $\Delta T/\Delta T_m = 0.5$, the width of the thermal mixed zone is 1.34 for helium and 0.79 for argon relative to the width of the thermal mixing zone of the air jet. This phenomenon is connected with the effect of the thermal capacities of the mixed gases. Figure 1 shows values of $\Delta T/\Delta T_m$ computed from the formula

$$\frac{\Delta T}{\Delta T_m} = \frac{T - T_{\mathrm{n}}}{T_m - T_{\mathrm{n}}} = \frac{1 + \dfrac{c_{\mathrm{rn}}}{c_{\mathrm{r0}}}\,\dfrac{1 - c_m}{c_m}}{1 + \dfrac{c_{\mathrm{rn}}}{c_{\mathrm{r0}}}\,\dfrac{1 - c}{c}}, \tag{5}$$

in which the value of c/c_m was determined from Eq. (2). It is apparent that the agreement between the calculated and empirical data is satisfactory.

The dynamic pressure fields $\rho u^2/\rho_m u_m^2$ are nearly universal. However, in our opinion, it would be inadvisable to use this result in the calculations, since the width of this mixing zone depends on the densities of the mixed gases.

Thus, to calculate the parameters in the main part of a gas jet flowing in a submerged space, it is best that the profiles of relative velocity, mass concentration, and enthalpy, be determined from Eqs. (1), (2), and (4) and that the width of the dynamic mixing zone be determined from the formula

$$b_u = 0.2x. \tag{6}$$

Let us stop to examine the question of a change in parameters along the jet axis.

In solving the problem, we will proceed on the basis of conditions of the conservation of momentum, mass, and excess enthalpy. These conditions will be written as follows for initial and arbitrary cross sections of the jet:

$$\rho_0 u_0^2 F_0 = \int_F \rho u^2 dF, \tag{7}$$

$$\rho_0 u_0 c_0 F_0 = \int_F \rho u c dF, \tag{8}$$

$$\rho_0 u_0 (i_0 - i_{\mathrm{n}}) F = \int_F \rho u (i - i_{\mathrm{n}}) dF. \tag{9}$$

As was shown above, the distribution $c/c_m \equiv \Delta i/\Delta i_m$, $b_c \equiv b_i$, so that in solving the problem we may limit ourselves, e.g., to Eqs. (7) and (8). Introducing the notation

$$\eta = y/b_u \tag{10}$$

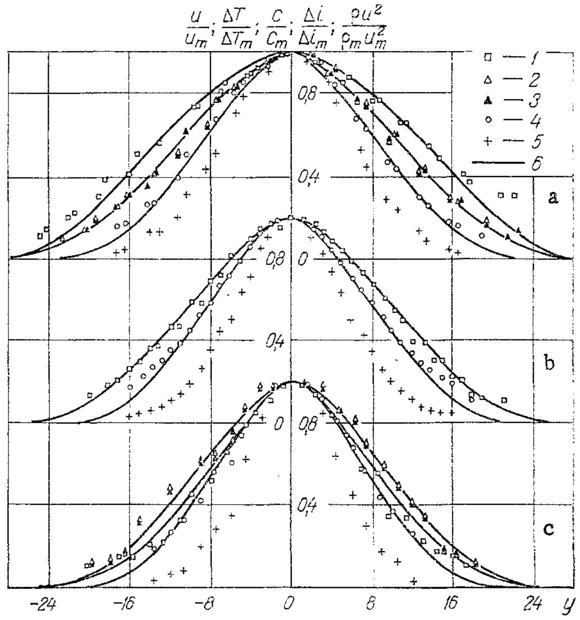

Fig. 1. Distribution of parameters in cross section (y, mm) of jet of helium (a), air (b), and argon (c): 1) $\Delta T/\Delta T_m$; 2) c/c_m; 3) $\Delta i/\Delta i_m$; 4) u/u_m; 5) $\rho u^2/\rho_m u_m^2$; 6) calculation.

and using (1), (2), (4), and (6), at $c_0 = 1$ for a circular nozzle we obtain in dimensionless form

$$1 = 2\left(\frac{u_m}{u_0}\right)^2\left(\frac{0{,}2x}{R}\right)^2\int\limits_0^1 \frac{\rho}{\rho_0}\,(1-\eta^{3/2})^4\eta\, d\eta, \tag{11}$$

$$1 = 2\,\frac{u_m}{u_0}\,c_m\left(\frac{0.2x}{R}\right)^2\int\limits_0^1 \frac{\rho}{\rho_0}\,(1-\eta^{3/2})^2\left[1-\left(\frac{\eta}{1.2}\right)^{3/2}\right]^2\eta\, d\eta. \tag{12}$$

From which

$$\frac{u_m}{u_0 c_m} = \frac{\int\limits_0^1 \frac{\rho}{\rho_0}(1-\eta^{3/2})^2\left[1-\left(\frac{\eta}{1.2}\right)^{3/2}\right]^2\eta\, d\eta}{\int\limits_0^1 \frac{\rho}{\rho_0}(1-\eta^{3/2})^4\eta\, d\eta}, \tag{13}$$

while the ratio ρ/ρ_0 takes the form

$$\frac{\rho}{\rho_0} = \frac{\rho_n}{\rho_0}\,\frac{1}{1-(m_n/m_0-1)\,c_m\frac{c}{c_m}}\;\frac{1+\left(\frac{c_{r0}}{c_{rn}}-1\right)c_m\frac{c}{c_m}}{1+\left(\frac{i_0}{i_n}-1\right)\frac{\Delta i_m}{\Delta i_0}\,\frac{\Delta i}{\Delta i_m}}, \tag{14}$$

where m_0 and m_n are the molecular weights of the mixed gases. It should be noted that in two cases, when $m_n = m_0 (c_{rn} = c_{r0})$ or when $T_n = T_0$, the ratio u_m/u_0c_m is equal to 1.046, 1.175, and 1.264 at $\rho/\rho_0 = 0$, 1, and ∞, respectively. Consequently, along the jet axis, if $\rho_n/\rho_0 > 1$, the ratio u_m/u_0c_m will decrease. If $\rho_n/\rho_0 < 1$, it will increase, approaching a value of 1.175 at ∞, In the general case, the ratio u_m/u_0c_m may change within a broader range, but it will always be less than or equal to unity.

If we establish the connection between u_m/u_0 and c_m, then, in accordince with (11), we find that

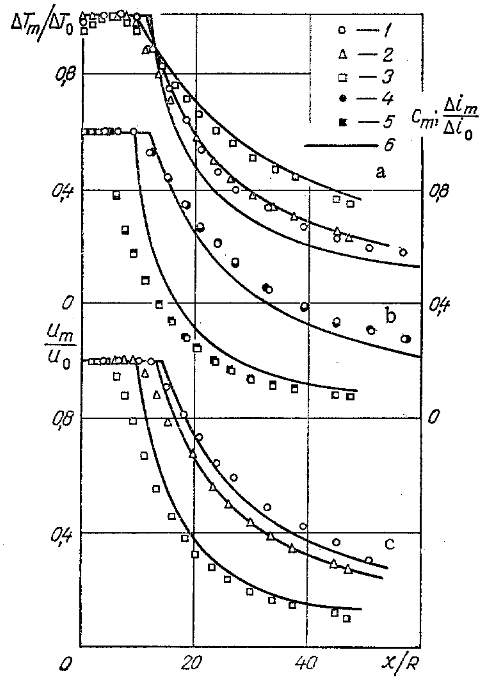

Fig. 2. Change in $\Delta T_m/\Delta T_0$ (a), c_m and Δi_m ' Δi_0 (b), and $u_m \Delta u_0$ (c) along axis of jets of: 1) argon; 2 air; 3) helium; 4) $\Delta i_m/\Delta i_0$ — argon; 5) $\Delta i_m/\Delta i_0$ — helium; 6) calculation.

$$\frac{u_m}{u_0} = \frac{R}{x} \frac{3.53}{\sqrt{\int\limits_0^1 \rho/\rho_0 (1-\eta^{3/2})^4 \eta d\eta}}. \tag{15}$$

The change in relative excess temperature along the jet axis is determined by the relation

$$\frac{\Delta T_m}{\Delta T_0} = \frac{1}{1 + \frac{c_{rn}}{c_{r0}} \frac{1-c_m}{c_m}}. \tag{16}$$

As $x \to s$, $\rho \to \rho_n$, so that (15) takes the form

$$\frac{u_m}{u_0} = 13.7 \sqrt{\frac{\rho_0}{\rho_n}} \frac{R}{x}. \tag{17}$$

Thus, at large distances from the nozzle, the axial velocity decreases in accordance with a hyperbolic law, while the range of the jet increases in proportion to $\sqrt{\rho_0/\rho_n}$.

With the discharge of the jet from a plane nozzle, the ratio

$$\frac{u_m}{u_0 c_m} = \frac{\int\limits_0^1 \rho/\rho_0 (1-\eta^{3/2})^2 [1-(\eta/1.2)^{3/2}]^2 d\eta}{\int\limits_0^1 \rho/\rho_0 (1-\eta^{3/2})^4 d\eta} \geqslant 1. \tag{18}$$

However, the limits of change of this ratio are narrower than in the discharge of the jet from a circular nozzle. For example, at $\rho_m \to \rho_n$, the value of $u_m/u_0 c_m = 1.085$ instead of 1.175 (circular nozzle).

The axial velocity changes according to the law

$$\frac{u_m}{u_0} = \sqrt{\frac{H}{x}} \frac{2.24}{\sqrt{\int\limits_0^1 \rho/\rho_0 (1-\eta^{3/2})^4 d\eta}}, \tag{19}$$

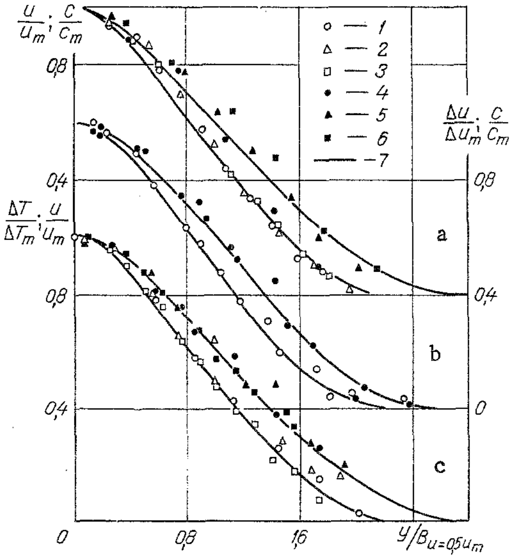

Fig. 3. Distribution of parameters in cross section of jets: a) carbon dioxide (Abramovich, Boradachev [1]): 1) $u/u_m(x/H = 20)$; 2) $u/u_m(x/H = 30)$; 3) $u/u_m(x/H = 40)$; 4) $c/c_m(x/H = 20)$; 5) $c/c_m(x/H = 30)$; 6) $c/c_m(x/H = 40)$; b) air jet with addition of helium, $c_0 \approx 0.1$ [13]: 1) $\Delta u/\Delta u_m$; 4) c/c_m; c) heated air jet, $T_0/T_n = 1.85$ (Yakovlevskii, Pechenkin [1]): 1) u/u_m $(x/R = 11)$; 2) u/u_m $(x/R = 17)$; 3) u/u_m $(x/R = 31)$; 4) $\Delta T/\Delta T_m$ $(x/R = 11)$; 5) $\Delta T/\Delta T_m$ $(x/R = 17)$; 6) $\Delta T/\Delta T_m$ $(x/R = 31)$; 7) calculation.

in conformity with which, at large distances from the nozzle ($\rho \to \rho_n$), the reduction in velocity is inversely proportional to the square root of the distance from the source and the ratio of the densities ρ_n/ρ_0:

$$\frac{u_m}{u_0} = 3.98\sqrt{\frac{\rho_0}{\rho_n}\,\frac{H}{x}}\,. \tag{20}$$

Figure 2a-c shows experimental values of u_m/u_0, c_m, $\Delta i_m/\Delta i_0$, and $\Delta T_m/\Delta T_0$ for jets of helium, air, and argon. For the sake of comparison, the solid lines show the corresponding calculated values.

It follows from Fig. 2 that the empirical values of mass concentration and excess enthalpy nearly coincide along the axes of the helium and argon jets. The range of the jets with respect to u_m/u_0 and c_m increases with an increase in ρ_0/ρ_n. On the other hand, with respect to $\Delta T_m/\Delta T_0$, range decreases with an increase in ρ_0/ρ_n. The last-mentioned fact provides additional evidence of the strong effect of the ratio of the heat carriers on the temperature of the gas mixture. The corresponding experimental and theoretical data agree satisfactorily at $x/R > 15$.

It should be noted that the agreement of the experimental and theoretical data in Fig. 2 could be improved if the position of the pole of the jet for helium and argon is taken equal to $x_p = -2R$ and $x_p = R$, respectively. In this case, the angular coefficient of expansion of the dynamic mixing zone, calculated from the data in Fig. 1, will be 0.20 for all of the gases.

Let us now compare the proposed theoretical relations with the experimental data of other authors.

Figure 3a and b shows the fields of relative velocity and mass concentration for a jet of carbon dioxide [1] and a jet of air with an addition of helium [11]. Figure 3c shows the fields of relative velocity and excess temperature for an air jet. It should be noted that in the case $c_{r0} = c_{rn}$, the distribution $\Delta T/\Delta T_m \equiv \Delta i/\Delta i_m$.

It is apparent that the calculated and empirical data agree well.

It should be remembered that in the works devoted to studying the flow of turbulent gas jets [4, 8, 9] and the mixing of gases close to permeable walls [4, 10, 11], it was shown that the thickness of the mixing zones $b_c \equiv b_i = 1.2b_u$, while the distributions of mass concentration, enthalpy, and velocity are described by single relations.

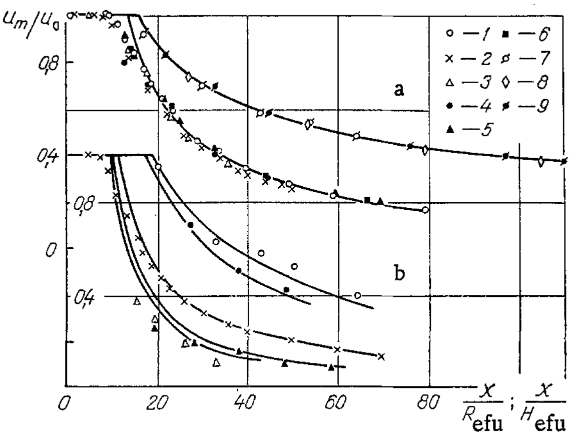

Fig. 4. Change in u_m/u_0 along axis of jets: a) isothermal air jet, circular: 1) $u_{av}/u_0 = 1$ (Yakovlevskii, Pechenkin [1]); 2) $u_{av}/u_0 = 1$ (Golubev [14]); 3) $u_{av}/u_0 = 1$ (Tryuppel' [1]); 4) $u_{av}/u_0 = 0.9$ (Tsimm [1]); 5) $u_{av}/u_0 = 0.8$ (Turkus [1]); 6) $u_{av}/u_0 = 0.8$ (Syrkin [1]); plane: 7) $u_{av}/u_0 = 0.89$ (Fertman [15]); 8) $u_{av}/u_0 = 0.87$ (Proskura [1]); 9) $u_{av}/u_0 = 0.95$ (Turkus [16]); b) circular jet, $u_{av}/u_0 = 1$: 1) Freon, $\rho_0/\rho_n = 3.7$ (Abramovich et al. [6]); 2) air, $\rho_0/\rho_n = 0.54$ (Yakovlevskii, Pechenkin [1]); 3) air $\rho_0/\rho_n = 0.071$ (Bezmenov, Borisov [17]); 4) Freon $\rho_0/\rho_n = 2.6$ (Golubev [8]); 5) helium, $\rho_0/\rho_n = 0.127$ (Golubev [8]).

However, it is shown in [8, 9] that both the angular coefficient of expansion of the jet (in the main part of the jet) and the position of the jet's pole depend on the ratio of the densities of the gases being mixed. The authors calculate that in the main part of a submerged jet $b_c \equiv b_i = 1.2 b_u = 0.24x$, i.e., the angular coefficient of expansion of the jet is constant to within ±0.02, while the pole of the jet is coincident with the nozzle edge to within ±2R.

For proof of the generality of these conclusions, let us examine data on the change in parameters along the axis of submerged jets.

In calculating parameters along the jet axis in the case of their nonuniform distribution in the outlet section of the nozzle, it is necessary to know the initial momentum, excess enthalpy, and mass of the jet. In the case where the boundary layer occupies a substantial portion of the outlet section of the nozzle, it is expedient to introduce the effective nozzle dimension

$$F_{efu} = \frac{\int\limits_F \rho u^2 dF}{\rho_0 u_0^2}, \quad F_{efc} = \frac{\int\limits_F \rho u dF}{\rho_0 u_0}, \quad F_{ef\,i} = \frac{\int\limits_F \rho u (i - i_n)\, dF}{\rho_0 u_0 (i_0 - i_n)}. \tag{21}$$

Without going into detail, we will note that for an isothermal jet in a turbulent flow regime in the boundary layer, it may be assumed with sufficient accuracy that for a circular nozzle

$$R_{efu} = R\,\frac{u_{av}}{u_0}, \tag{22}$$

while for a nozzle with plane-parallel walls

$$H_{efu} = H\left(\frac{u_{av}}{u_0}\right)^2. \tag{23}$$

Figure 4a shows values of u_m/u_0 along the axis of jets issuing from circular and plane nozzles, with values of $\rho_0 \approx \rho_n$ and $u_{av}/u_0 = 0.8$–1. Figure 4b shows values of u_m/u_0 for a Freon jet, $\rho_0/\rho_n = 3.7$ and 2.6, a helium jet, $\rho_0/\rho_n = 0.127$, and a jet of heated air, $\rho_0/\rho_n = 0.54$ and 0.07. It is assumed in these experiments that $R_{efu} = R$.

The data in Figs.3 and 4 illustrate well the correctness of the above hypotheses on the laws of flow of turbulent jets with a nearly 50-fold change in the density of the jet.

In conclusion, let us examine the question of the ejecting capacity of the jet.

The rate of flow of the gas mixture in an arbitrary cross section of a circular jet, relative to the initial flow rate, may be written thus

$$\bar{G}=\frac{G}{G_0}=2\left(\frac{b_u}{R}\right)^2\frac{u_m}{u_0}\int\limits_0^1\frac{\rho}{\rho_0}\,\frac{u}{u_m}\eta d\eta=0.283\,\frac{x}{R}\,\frac{\int\limits_0^1\rho/\rho_0\,(1-\eta^{3/2})^2\eta d\eta}{\sqrt{\int\limits_0^1\rho/\rho_0\,(1-\eta^{3/2})^4\eta d\eta}}. \qquad (24)$$

At large distances from the nozzle, when $\rho \to \rho_n$, the relative flow rate of the gas mixture in the jet

$$\bar{G}=0.141\,\frac{x}{R}\sqrt{\frac{\rho_n}{\rho_0}}, \qquad (25)$$

i.e., it is proportional to the relative distance from the nozzle and the square root of the ratio of the densities of the gases of the submerged space and the jet in the outlet section of the nozzle.

It should be noted that Eq. (25) gives values that are 10% lower than the values obtained with the empirical relation obtained on the basis of original experiments conducted to determine the ejecting properties of a jet of circular cross section at large distances from the nozzle [12]. This result also supports the validity of the above hypotheses.

NOTATION

x, linear coordinate along jet axis reckoned from its pole; y, linear coordinate perpendicular to jet axis and reckoned from this axis; R, jet radius; H, half the height of a plane-parallel nozzle; b, half the width of the mixing zone; F, area; u, velocity; ρ, density; T, temperature; i, enthalpy; c, mass concentration; G, flow rate; m, molecular weight; c_r, heat content; $Re = \rho_0 u_0 2R/\mu_0$; $\Delta u = u - u_n$, $\Delta i = i - i_n$, and $\Delta T = T - T_n$, excess velocity, enthalpy, and temperature. Indices: 0, parameters of gas in the outlet section of the nozzle; n, parameters of the gas surrounding the jet; m, parameters of the gas on the jet axis; u, c, i, and T, parameters determined for velocity, concentration, enthalpy, and temperature, respectively; ef, effective; av, mean value.

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STRUCTURE OF A SUBMERGED AXISYMMETRIC JET IN ITS INITIAL REGION

K. Kuzov and A. Melikov

UDC 532.517.4

On the basis of empirical results, a scheme is proposed for the development of a regular vortex structure in the mixing zone of the initial section of a submerged axisymmetric jet. A relation is established between different hydrodynamic characteristics in the jet.

Recent studies [1-3 etc.] have shown that large-scale vortex structures characterized by a high degree of orderliness exist within the mixing zone of the initial section of a submerged axisymmetric jet. As a result of the effect of these vortices, in the frequency spectra of turbulent energy

$$\int_0^\infty Eu(f)\,df = u'^2 ,$$

measured at points on the axis of the "potential" core, there is a distinct peak [2, 3, etc.]. As follows from [2], concentrated in this peak region of the spectrum (f_1 to f_2) is the main part ΔEu_p of the turbulent energy $\overline{u'^2}$ at the corresponding point of the flow

$$\Delta Eu_p = \int_{f_1}^{f_2} Eu(f)df.$$

Here f_1 and f_2 are frequencies at which the equality $Eu(f_1) = Eu(f_2) \approx 1.1Eu(f_0)$ is satisfied, where $Eu(f_0)$ is the spectral density immediately before the beginning of its increase in the peak region of a specific spectrum.

Regardless of differences in the initial conditions of the discharge, the relative amount of this energy is always maximal at a distance $x/D \approx 3.5$ [2]. In such a case, it may be assumed that the development of these vortex structures, the movement of which into the mixing zone is characterized by a hgih degree of orderliness, is characterized by two stages: a) initial appearance and development of vortices, accompanied by their consolidation and transition to three-dimensional form; b) destabilization of these vortices and gradual formation, during the process of their decay, of the large-scale turbulent vortex structure of a developed turbulent jet.

The goal of the present study is to use the results of [2, 4, 5] and of new experiments to confirm this hypothesis on the development of such vortices, particularly with regard to the special position of the region $x/D \approx 3.5$ of jet flow. Another goal is to provide additional information on certain hydrodynamic parameters of jets which characterize processes that take place within them.

The experiments were conducted on a special unit for generating turbulence [6]. A DISA-55M hot-wire anemometer and a standard DISA-55F31 wire probe with a wire 5 μm in

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