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STRUCTURE OF A SUBMERGED AXISYMMETRIC JET IN ITS INITIAL REGION

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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 show 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

VMEI im. V. I. Lenin, Sofia, People's Republic of Bulgaria. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 39, No. 5, pp. 788-793, November, 1980. Original article submitted August 27, 1979.

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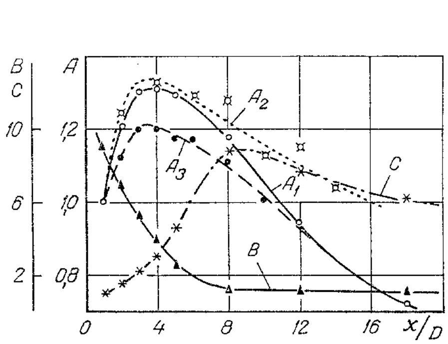

Fig. 1

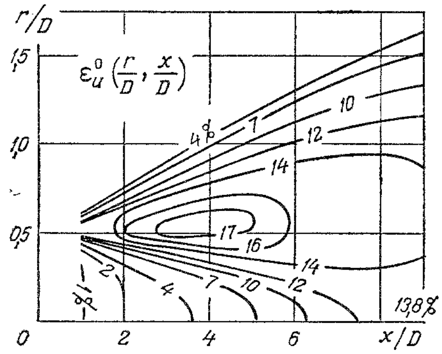

Fig. 2

Fig. 1. Certain hydrodynamic characteristics of a submerged jet: A_1, B, C — D = 50 mm, $\bar{u}_0$ = 50 m/sec, ε_u^0 = 0.54%; A_2 — according to [4]; A_3 — according to [5].

Fig. 2. Field of ε_u^0 = const in a submerged axisymmetric jet with the data of the nozzle outlet: D = 50 mm, u_0 = 50 m/sec, ε_u^0 = 0.54%.

diameter and 1.2 mm long were used.

The existence of the characteristic region (in the cases of x/D ≈ 3.5 being examined) in the development of an ordered system of vortices in the mixing zone of the initial section of a submerged jet is also confirmed by the path of curves showing the change in A (Fig. 1):

$$A = (u_r')_{max}/(u_{r1}')_{max}.$$

In this case, $(u_r')_{max}$ is the maximum value of the longitudinal pulsative component of velocity in an arbitrary cross section along the jet, while $(u_{r1}')_{max}$ is the same value in the section x/D = 1. Figure 1 shows the change in A calculated on the basis of the empirical data in [4, 5]. It is apparent from the figure that the maximum value of A for all three curves is located at x/D ≈ 3.5. The difference in the value of A for the cases examined may be attributed to different conditions of jet discharge. Also shown in Fig. 1 is data on the change in the coefficients B and C:

$$B = (u_r')_{max}/u_{ax}', \quad C = u_{ax}'/(u_{ax}')_1.$$

Here u_{ax}' is the longitudinal pulsation of velocity on the axis of the arbitrary cross section, while $(u_{ax}')_1$ is the same value for the section x/D = 1.

The path of the curve of B shows the continuous change in the profile of turbulent pulsation u' and its gradual transition to the corresponding profile of developed turbulence (B = 1). In the present case, this profile begins to form after x/D ≈ 10 (B ≈ 1.1). This is also shown by the curve of C, which has a maximum at x/D ≈ 9. The steep slope of the B curve at low x/D testifies to the active exchange of turbulent energy between the fluid in the mixing and central regions of the initial section of the jet.

Detailed study of the field of longitudinal pulsation of velocity in the initial region of the submerged jet (Fig. 2) and after an agitating grid (flat plate with holes) (Fig. 3) shows the existence of a region in the mixing zone of the jet (x/D ≈ 3.5 and r/D ≈ 0.5) in which the velocity pulsation (ε_u^0) has a maximum value. The equivalent initial diameter D_e of the flow after the agitating grid was used in Fig. 3 as the characteristic dimension [7].

The data shown in Fig. 4 also supports the hypothesis of two stages in the development of a regular vortex structure in submerged jets. Figure 4 shows data on the change in $\Delta\overline{E}u_p$, $\partial u'/\partial x$, $\overline{U}$, $\partial\bar{u}/\partial x$, $(\bar{u}'^2)^{1/2}/\bar{u}_0$, $p'/\rho\bar{u}_0^2$ along the jet axis (r = 0), as well as for $(u'^2)^{1/2}/\bar{u}_0$ and $p'/\rho\bar{u}_0^2$ in the mixing zone along the line r/D = 0.5.

Analysis of the data in Fig. 4 and in the preceding figures shows that there are two zones in the region of increasing turbulence along the flow axis (x/D < 9). In the first of these zones (x/D ≲ 3.5), with lesser gradients of velocity pulsation along the axis (curve C in Fig. 1 and the curve $\partial u'/\partial x$ in Fig. 4), the increase in the intensity of the turbulent pulsations is connected mainly with the inducing effect of the system of large-scale vortices of the mixing zone, where turbulent intensity is also increasing (curves A in Fig. 1 and curves $(u'^2)^{1/2}/\bar{u}_0$ and $p'/\rho\bar{u}_0^2$ in Fig. 4). The higher rate of increase in turbulent pulsations along the axis of the section 3.5 < x/D < 9 compared to the section x/D ⩽ 3.5 may be explained by decay of

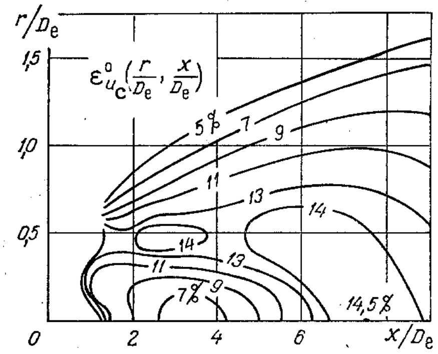

Fig. 3. Field of ε°_{uc} = const in the flow after the agitating grid: D = 117 mm, $\bar{u}_0$ = 10 m/sec, diameter of grid openings 10 mm, spacing between grid openings 21 mm, grid thickness 8 mm.

the ordered vortex structure in the mixing zone and the direct effect of this vorticity on the fluid in the central region of the flow. Also as a result of this, the large-scale turbulent structure of the developed turbulent jet is formed.

It is apparent in Fig. 4 that the curve $\partial u'/\partial x$ has two distinct maxima. The first, at a distance $x/D \approx 3.5$, coincides with the region along the jet axis in which ΔEu_p has a maximum, as well as with the region where the maximum values of $(\bar{u}'^2)^{1/2}/\bar{u}_0$ and $p'/\rho u_0^2$ are located in the mixing zone of the flow ($r/D \approx 0.5$). This once again indicates the presence of a correlation between the turbulent structure of the flow in the mixing zone and in the "potential" core and confirms that at $x/D \approx 3.5$ the large-scale three-dimensional vortex structure in the mixing zone reaches its highest stage of development. The second maximum of the curve $\partial u'/\partial x$ is found at $x/D \approx 7$ and is located approximately (1-1.5) in front of the maximum on the curve of $\partial \bar{u}/\partial x$ on the jet axis. It is also apparent that $\partial u'/\partial x$ approaches a constant value after $x/D \approx 12$. The latter is an indication of the already developed turbulent motion and may be used as a criterion for determining the moment of final decay of the ordered vortex structure.

Together with this, the measurements in this work, as in [8], show that there is a static pressure gradient Δp_{st} along the jet axis in a submerged axisymmetric jet (Fig. 4). Keeping other results [9, 10] in mind, it may be concluded that the presence of longitudinal and transverse static pressure gradients in a submerged axisymmetric jet is natural and is due to the occurrence of the tangential Reynolds stresses characteristic of nonisotropic jet turbulence.

The experiments show that in the case of a normal submerged jet (with a uniform velocity profile and low degree of turbulence, $\varepsilon^{\circ}_u < 5\%$ in the initial section), the quantities $(u'^2)^{1/2}$ and $p'/\rho u_0^2$ reach their maximum values along the flow axis at $x/D \approx 8.5$. At this point, Δp_{st} has a minimum value. Proceeding on the basis of the fact that u', v', and w' have maximums at the same place on the jet axis [5], in the case $x/D \approx 8.5$ it may be concluded that the location of the minimum of Δp_{st} on the axis agrees well with Townsend's hypothesis on the existence of a proportional relationship between transverse pulsations of velocity v' at a given point of the flow and the rarefaction δp at this point ($\delta p = -\rho \overline{v'^2}$). This is also supported by the results obtained in [10]. Thus, the location of the minimum of Δp_{st} on the jet axis may be used as a criterion to determine the region on the axis in which the turbulent pulsations of velocity and pressure have maximum values.

It is also apparent from Fig. 4 that Δp_{st} on the axis is equalized with the atmospheric pressure in the section $x/D \approx 3.5$. The quantity Δp_{st} decreases sharply after this section (rarefaction), which is probably related to the appearance of intense transverse pulsations of velocity v' resulting from the decay of the ordered vortex structure in the mixing zone.

The results obtained here permit the following conclusions:

1. In the development of an ordered vortex structure in the mixing zone of the initial section, there are two regions: a) in the first region (to $x/D \approx 3.5$), vortices form and continuously increase in size, gradually changing into three-dimensional structures; b) in the second ($3.5 < x/D < 10$) region, the ordered large-scale vortex structures in the mixing zone

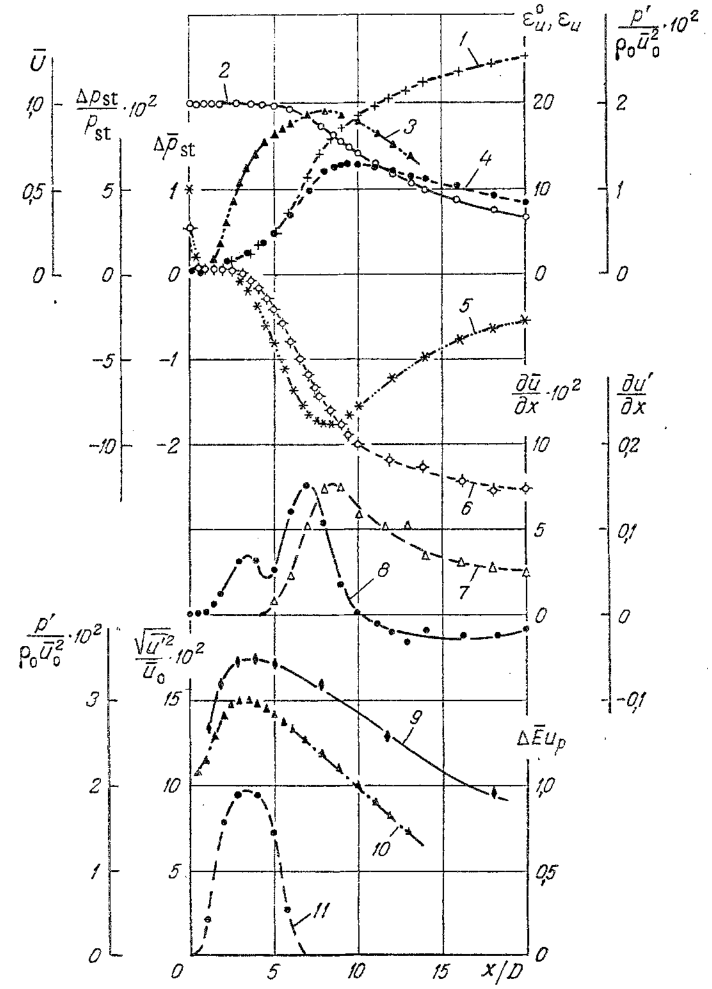

Fig. 4. Change in certain hydrodynamic characteristics in the initial region of a submerged axisymmetric jet at D = 50 mm and $\bar{u}_0$ = 50 m/sec. Data for $p'/\rho_0\bar{u}_0^2$ (r = 0 and r = 1/2D), in accordance with [11], obtained at D = 100 mm, $\bar{u}_0$ = 60 and 100 m/sec: 1) ε_u (r = 0); 2) $\bar{U}$ (r = 0); $p'/\rho_0\bar{u}_0^2$ (r = 0); 4) ε_u° (r = 0); 5) $\Delta\bar{p}_{st}$ (r = 0); 6) $\Delta p_{st}/p_d$ (r = 0); 7) $\partial\bar{u}/\partial x$ (r = 0); 8) $\partial u'/\partial x$ (r = 0); 9) $(u'^2)^{1/2}/\bar{u}_0$ (r = 1/2D); 10) $p'/\rho_0\bar{u}_0^2$ (r = 1/2D); 11) $\Delta\bar{E}u_p$ (r = 0). ε_u°, ε_u, %.

are gradually destroyed and, together with the turbulence already present in the central zone of the flow, form the large-scale structure of the developed submerged turbulent jet.

2. There is a directly proportional relationship between the turbulent pulsations of pressure and velocity at arbitrary points throughout the volume of the flow.

3. The turbulent pulsations of pressure and velocity have maximum values in regions with minimum static pressure on the jet axis.

NOTATION

x, distance along flow from outlet section of nozzle; D, diameter of outlet section of nozzle or diameter of grid; $F_0 = \pi D^2/4$, area of outlet section of nozzle; $\bar{u}_0 = Q_0/F_0$, average (over the section) velocity at the nozzle outlet or in front of the grid; $\bar{u}$, average (over time) velocity at an arbitrary point of the flow; $\bar{u}_c$, same, at a point of the core of the flow after the agitating grids; $(u'^2)^{1/2}$, rms value of longitudinal turbulent pulsation of velocity; u', v', w', components of turbulent pulsation of velocity along coordinate axes; Δp_{st_0}, static pressure on axis of outlet section of jet; Δp_{st}, same at a point of the flow; p_d, dynamic pressure; p', pressure pulsation; ρ_0 = const, density of fluid; f, frequency; Eu, spectral density of turbulent energy; $\bar{U} = \bar{u}/\bar{u}_0$, dimensionless velocity; $\Delta\bar{p}_{st} = \Delta p_{st}/\Delta p_{st_0}$, dimensionless pressure; $\varepsilon_u^\circ = \sqrt{\bar{u}'^2}/\bar{u}_0$ ($\varepsilon_{uc}^\circ = (\bar{u}'^2)^{1/2}/\bar{u}_c$), absolute intensity of turbulence; Q_0, initial flow rate of fluid.

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RELATIONSHIP BETWEEN AVERAGE (OVER TIME) VELOCITY AND LONGITUDINAL TURBULENT PULSATION OF VELOCITY ON THE AXIS OF A JET

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Results are presented from an experimental study of a submerged axisymmetric jet with different initial conditions. Criteria are found for determining the location of the point with maximum pulsations on the jet axis.

The microstructure of submerged jets has recently become the subject of numerous investigations which have attempted to discover the mechanism of turbulent heat and mass exchange [1-4 et al.]. For example, it has been established [1, 2, 4] that in the lateral flow of a submerged jet around a plate, heat exchange in the region of the stagnation point reaches its maximum value when the plate is located about 8D from the outlet section of the jet. This distance coincides with the position on the jet axis at which $(\overline{u'^2})^{1/2}$ has a maximum value. It was also shown in [1, 2, 4, et al.] that heat exchange is intensified with an increase in the initial turbulence. A change in the initial turbulence affects both the macrostructure and microstructure of the jet [2, 4, 5]. Most important in this regard is the fact that the location of the point on the flow axis at which $(\overline{u'^2})^{1/2}$ has its maximum depends on the initial turbulence. When the latter is greater than 5%, this point already no longer coincides with the section $x/D \approx 8$. Thus, it is very important that another criterion be found to determine the

VMEI im. V. I. Lenin, Sofia, People's Republic of Bulgaria. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 39, No. 5, pp. 794-797, November, 1980. Original article submitted August 27, 1979.

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