Journal of Engineering Physics and Thermophysics, Vol. 78, No. 6, 2005

VERTICAL LOW-HEAD JET IN A TRANSVERSE FLOW

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UDC 533.6.071.4

The action of a turbulent flow on an injected normally low-head axisymmetric jet has been investigated experimentally. Empirical dependences describing the geometry of the jet axis in a transverse air flow have been obtained. It has been shown that the maximum temperature and velocity curves do not coincide; the thermal axis lies lower than the dynamic axis. The expressions obtained describe a change in the axial values of the velocity and the temperature in the direction of propagation of the jet. It has been shown that the attenuation of dimensionless axial parameters in the jet carried away by the transverse flow is more rapid than that in the case of a submerged jet and a wake.

A round jet developing in a transverse carrier flow is of interest not only as a complex gasdynamic problem but primarily because of its wide use in different technical devices. The basic parameters of the jet are the trajectory, the range, and the drop in velocity and temperature along the axis.

The geometry of a jet carried away by a flow is rather intricate, which is due to different dynamic conditions on its windward and leeward sides. By the geometry of the jet one usually means the position of its axis, which is the line connecting points with a maximum flow velocity or temperature.

We know of different approaches to solution of the problem on determination of the geometry of a jet in a carrier flow. To describe the axis (maximum-velocity point) of an air jet flowing out of a round nozzle into the lateral flow, G. S. Shandorov has proposed, based on experiments, the formula [1]

$$\frac{x}{d} = \frac{q_1}{q_0}\left(\frac{z}{d}\right)^{2.55} . \tag{1}$$

Yu. V. Ivanov has obtained another empirical equation for round jets:

$$\frac{x}{d} = \left(\frac{q_1}{q_0}\right)^{1.3}\left(\frac{z}{d}\right)^{3} . \tag{2}$$

He carried out experiments with a high-head jet of a rectangular cross section, too [2], and arrived at the conclusion that in this case to determine the position of the axis one can use in the first approximation expression (2), replacing the diameter d by the equivalent diameter $D = 4F/P$, where F is the area of the initial jet cross section and P is its perimeter.

Also, there are theoretical solutions in determining the geometry of the jet axis. The equation of the jet trajectory has been obtained in [1] with the use of the method of addition of the vectors of the flow and the velocity average over the flow rate. The method of addition of the stream functions of the jet and the carrier flow has been obtained in [3]. In [4], it has additionally been taken that the component (perpendicular to the direction of an unperturbed flow) of the total momentum of the jet remains constant and the horseshoe shape of the jet is replaced by an ellipsoidal one.

All the theoretical solutions may be considered to be roughly approximate and suitable only for a small range of parameters of the jet and the flow. The complex pattern of motion of jet particles and consequently the complexity of formation of velocity and temperature fields make it impossible to accurately describe the trajectory of the jet in a

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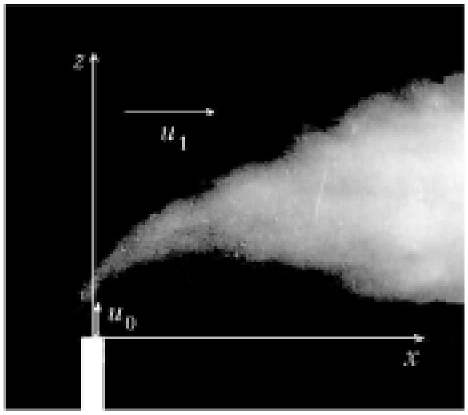

Fig. 1. Smoke-filled jet.

carrier flow by theoretical methods, much less in a wide range of relative velocity heads of the jet and the flow. We have to restrict ourselves to empirical description of experiments, which enables us to have quite reliable data in the region of boundary conditions under which the experiments have been carried out.

Most works on flow in normal injection of the jet [5] deal with the conditions of injection of jets with a comparatively high velocity head (as compared to the head of the carrier flow) into the channel. In certain problems, in particular, for propagation of ventilation ejections in transverse flows, we have a small ratio of the velocity heads of the jet and the flow. Such flows have not been adequately studied.

A physical model of the flow under study represents an axisymmetric air jet ejected from a tube of diameter $d = 0.022$ m at a right angle to the direction of motion of an air flow. Figure 1 gives the smoke-filled jet obtained by the author. A wind tunnel [6] of length 5.5 m and cross section 0.8 × 0.5 m was used to investigate the geometry of the jet in the carrier flow. The jet propagated in the tunnel in such a manner that its boundaries were at quite a large distance from the walls of the tunnel's measuring part. This enabled us to speak of the free motion of the jet. In the experiments, consideration was given to air flows with a velocity $u_1 = 1.7$–1.9 m/sec in the tunnel's part under study and to vertical axisymmetric jets with a velocity $u_0 = 1.8$–4.7 m/sec at the center of the mouth of the source (tube).

The values of the Reynolds numbers for air jets formed in vertical tubes were $\mathrm{Re}_0 = 2.7\cdot10^3$–$6.9\cdot10^3$, where $\mathrm{Re}_0 = u_0 d/\nu$. A uniform flow with number $\mathrm{Re}_1 \approx 8.5\cdot10^4$, where $\mathrm{Re}_1 = u_1 D/\nu$ ($D \approx 0.71$ m), was formed in the central part of the tunnel. The experiments were carried out with isothermal and slightly nonisothermal jets with the use of a PT-22 hot-wire anemometer whose reduced measurement error amounts to no more than 10% for the air-flow velocity and to no more than 1.5°C for the temperature.

From the experimental data we constructed the velocity and temperature profiles of isothermal and slightly nonisothermal jets (Archimedes number $\mathrm{Ar} = gd\Delta T_0/(2u_0^2 T_1) = 2.8\cdot10^{-4}$–$1.0\cdot10^{-3}$) in vertical cross sections at different distances from the tube. These data enabled us to find the locus of a jet at which the velocity and the temperature are maximum. It is this locus (jet axis) that determines the rise of the jet above the source.

The investigations were carried out for the relative velocity heads of the jet and the carrier flow $q = 0.85$–6.12. The densities of the jet and the carrier flow were equal to $\rho_0 = \rho_1$.

For the points of maximum velocity of the jet of air flowing out into the transverse flow we have obtained the empirical formula

$$\frac{z}{d} = \left(\frac{q_0}{q_1}\right)^{0.51} \left(\frac{x}{d}\right)^{0.41} \tag{3}$$

for $q = 2.5$ and 6.12. The relative error of the calculated values of z/d is no higher than 10%.

For the relative velocity heads $q = 2.0$, 3.10, and 5.55 of a slightly nonisothermal jet we have obtained the empirical expression for the points of maximum temperature [7]

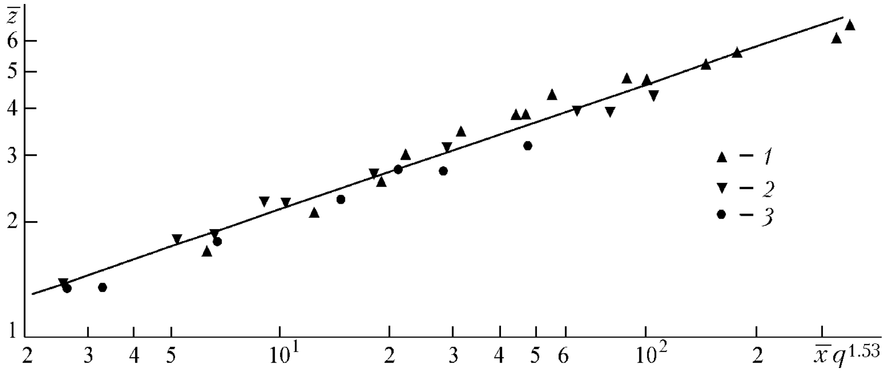

Fig. 2. Rise of the jet above the source mouth: q = 5.55 (1), 3.10 (2), and 2.0 (3).

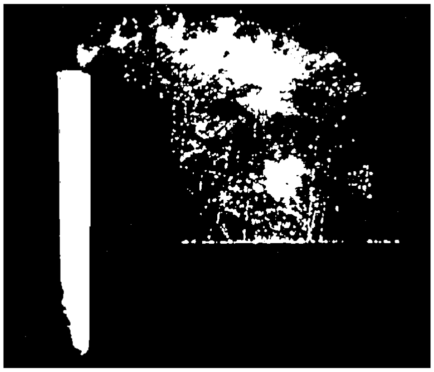

Fig. 3. Smoke-filled jet in the transverse air flow.

$$\frac{\bar{x}}{\bar{z}^3} = \left(\frac{q_1}{q_0}\right)^{1.53}. \tag{4}$$

To determine the rise of the jet above the source we may represent (4) in the form

$$\bar{z} = q^{0.51}\bar{x}^{0.33}. \tag{5}$$

Figure 2 shows a generalized geometry of the jet in the carrier air flow. The solid curve indicates the rise of the jet above the mouth of the source, which has been computed from (5). The experimental values of $\bar{z}$ coincide with the calculated ones fairly well, and the maximum relative error is no higher than 12%.

The measurements of the velocity and temperature fields, visual observations, and photography of smoke-filled jets have shown that the maximum-velocity points are closer to the upper boundary of the jet and approach the upper limit rather closely with decrease in q. The maximum-temperature curve lies lower than the maximum-velocity curve in the cross sections of the nonisothermal jet. When $q < 1$, the behavior of the jet strongly changes in the transverse flow. Figure 3 shows the jet that descends below the tube sections at a rather short distance from the source when q = 0.85.

Using the experimental data of the velocity profiles in the isothermal jet (q = 2.5 and 6.12), we have obtained the empirical dependence

$$\frac{u_m - u_1}{u_0 - u_1} = \frac{0.8}{\bar{x}^{0.9}} \tag{6}$$

for the values of the dimensionless relative axial velocity in the range $\bar{x}$ = 2.27–14.55 considered.

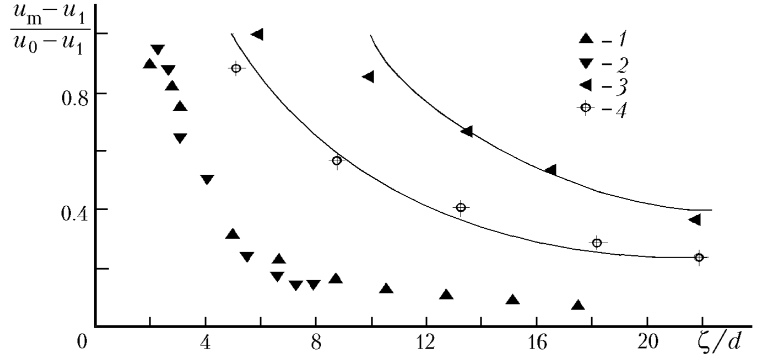

Fig. 4. Change in the excess relative axial values of the velocity in the jet carried away by the transverse flow with distance from the source mouth for q = 6.12 (1) and 2.5 (2) and the analogous dependences [8] for the wake for q = 3.17 (3) and the submerged jet (4) for $\rho_1/\rho_0 = 1.34$.

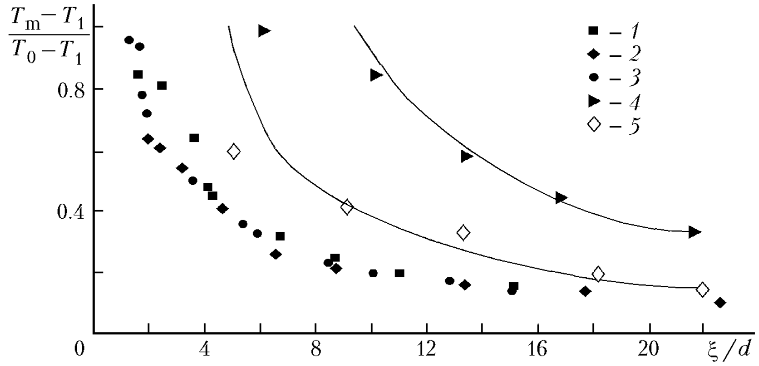

Fig. 5. Change in the excess relative axial values of the temperature in the jet carried away by the transverse flow with distance from the source mouth at q = 5.55 and ΔT_0 = 12.5 K (1), 3.1 and 15 (2), and 2.0 and 16 (3) and the analogous dependences [8] for the wake at q = 3.17 and ΔT_0 = 230 K (4) and the submerged jet at ΔT_0 = 105 K (5).

Figure 4 gives experimental data on the excess dimensionless axial values of the velocity of air jets. Also, for the sake of comparison, this figure gives the results for a wake and a submerged jet [8] that show a less intense reduction in the axial velocity than that in our experiments. However, at a fairly large distance from the source, we observe the dimensionless axial velocity values approaching each other for the jets considered.

Based on the experimental data for slightly nonisothermal jets with q = 2.0, 3.1, and 5.55, we have obtained the dependence ($\bar{x}$ = 2.73–20.91)

$$\frac{T_m - T_1}{T_0 - T_1} = \frac{1.03}{\bar{x}^{0.75}} \tag{7}$$

for the values of the dimensionless relative axial temperature.

Figure 5 gives experimental results on the change in the relative axial temperature in the jet. For the sake of comparison, this figure gives the data for the wake and the submerged jet [8]. It is noteworthy that the reduction in the dimensional axial velocity in our case is somewhat more rapid than that for the wake and the submerged jet. However, the difference in the initial part of the jets is rapidly smoothed out with distance from the source mouth.

It has been shown in the work that the attenuation of the axial values of the velocity and the temperature in the jet carried away by a transverse flow is more intense than that in the submerged jet and the wake. This coincides with the data of some researchers (see [9]) assuming that the axial velocity of the jet in the transverse flow is attenuated more rapidly than the velocity on the submerged-jet axis and the intensity of attenuation of the axial velocity increases as the ratio of the carrier-flow velocity and the initial jet velocity grows.

The experiments have shown that in low-head heated jets carried away by a transverse flow, the position of the temperature maxima differs from the position of the velocity maxima. When the relative velocity heads q are low, in certain problems associated with the temperature or concentration fields, it is more preferable to take the points of maximum temperature as the jet axis.

The trajectory of the jet axis $\overline{z} \sim \overline{x}^{1/3}$, analogous to that obtained by us, is given in a number of works, including the investigations of the propagation of gas jets in a gas [9] or liquid jets in a liquid [10]. Such a result has also been obtained in the calculated dependence for a high-head liquid jet when it is carried away by a gas flow [11].

The distinctive features of the heat and mass exchange of a jet carried away by a flow in the initial portion are, apparently, determining for further flow of the jet and its interaction with the environment.

NOTATION

a and b, width and height of the channel cross section; D, conventional channel diameter determined from the equality of the cross-sectional areas of the channel and the round pipe ($ab = \pi D^2/4$); d, diameter of the outlet section of the nozzle (tube); g, free-fall acceleration; $q = q_0/q_1$, ratio of the velocity heads of the jet and the flow; $q_0 = \rho_0 u_0^2/2$ and $q_1 = \rho_1 u_1^2/2$, velocity heads in the initial cross section of the jet and in the carrier flow respectively; T_0, absolute temperature in the initial cross section of the jet; T_1, absolute temperature in the carrier flow; T_{m}, maximum temperature in the jet cross section in question; ΔT_0, difference of the absolute temperatures in the initial cross section of the jet and in the carrier flow; u_0 and u_1, flow velocities of the jet in the initial cross section of the carrier flow, respectively; u_{m}, maximum velocity in the jet cross section in question; x, z, coordinates of the Cartesian coordinate system; $\overline{x} = x/d$ and $\overline{z} = z/d$, longitudinal and vertical dimensionless coordinates of the points of the jet axis; the origin of the coordinates is at the center of the tube cut; ζ, intrinsic curvilinear coordinate of the points of maximum velocity of the jet; the origin of the coordinate is on the tube cut; ν, kinematic viscosity of air; ξ, intrinsic curvilinear coordinate of the points of maximum temperature in the jet; the origin of the coordinate is on the tube cut; ρ_0 and ρ_1, densities of the jet and the flow. Subscripts: 0, initial jet cross section; 1, carrier flow; m, maximum value.

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