EFFECT OF A TRANSVERSE ENTRAINMENT FLOW ON THE CHARACTERISTICS OF A TURBULENT JET

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We have experimentally investigated the influence of a transverse entrainment flow (wind) on the trajectory of a turbulent jet, as well as on the distribution of the concentration of the gas being discharged along that jet (hydrogen, helium, nitrogen). The entraining flow of air is formed in open space. Its trajectory falls out along points corresponding to the maximum concentrations in the lateral cross section of the jet. We have derived empirical relationships between the jet trajectory and the gas-concentration distribution along that trajectory in their dependence on the hydrodynamic parameter.

In the narrow interval of the hydrodynamic parameter q = 1-200 [1-3] we have experimentally investigated the characteristics of turbulent jets under the conditions prevailing in an entrainment flow, including the trajectory and distribution of concentration.

In actual practice, for example, in the discharge of various gases to the atmosphere, this parameter can vary from an exceedingly small quantity all the way to infinity. We are thus very much interested in studying the characteristics of the jet as the range of variations in the parameter q expand.

With this purpose in mind, we conducted a number of experiments on an installation such as that described in [1]. By appropriately selecting the elements of the installation (demountable nozzles), by varying the discharge velocity of various gases (hydrogen, helium, and nitrogen), by setting the temperature of the nitrogen and the helium, as well as by setting the velocity of the entrainment flow, we were able to produce jets for a broad range of the hydrodynamic parameter q = 1-45,000.

It should be noted that the influence of the Archimedean force on the characteristics of the jet was small. The maximum Archimedes number reached values of 0.0026, whereas in [3] a noticeable effect was observed at Ar = 0.023.

Hydrogen at a temperature of T_0 = 293 K was chosen as the working gas, and also nitrogen and helium at T_0 = 100 and 293 K. The hydrogen and helium measurements in the jets were carried out by a thermoanamometer method, while the nitrogen measurements were performed with a "Flyuorit" gas analyzer [1]. The measurement error for both of these methods did not exceed ±10%.

The line of maximum concentrations in the lateral cross sections was taken as the trajectory.

The experimentally determined points of the trajectory, shown in generalized coordinates in Fig. 1, are satisfactorily described by an asymptotic function in the range q = 1-∞:

$$Z^* = 2{,}2\,\mathrm{th}\,(X^*)^{0,5}. \tag{1}$$

And here, with q ≥ 45,000, at a distance of approximately 300 calibers of the tube orifices, the jet is virtually a straight line from the discharge point.

Of considerable interest is the influence exerted by the wind on the distribution of concentrations along the trajectory. The concentration measurements showed that the smaller q, i.e., the higher the wind velocity and the lower the gas discharge velocity, the more rapid the attenuation of concentration. And here, as in the case of free jets, the inversely proportional relationship of concentration to distance along the axis of the jet is retained. Thus, Fig. 2, in $V^* \sim L^*$ coordinates, shows a family of straight lines, each of which corresponds to a jet with a specific value of q. The coefficient characterizing the incorporation of the air into the jet as a result of the vortices formed in the interaction of the jet with the air is contained in implicit form in the tangent to the slope of these straight lines.

It may consequently be assumed that the distribution of concentration along the trajectory differs from the corresponding distribution in the free jet only insofar as this relates to the coefficient that is dependent on q. In general form, this relationship can be written as follows:

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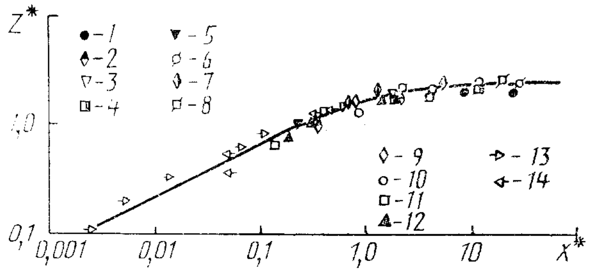

Fig. 1. Generalized trajectory of jet in entrainment flow: nitrogen: 1) q = 1.0; 2) 34; 3) 200 (all at $T_0 = 293$ K); 4) 11; 5) 180 (all at $T_0 = 100$ K); helium: 6) 0.69; 7) 196 (all at $T_0 = 293$ K); 8) 3.7; 9) 66 (all at $T_0 = 100$ K); hydrogen: 10) 9.3; 11) 279; 12) 3480; 13) 37,000; 14) 45,000 (all at $T_0 = 293$ K). Curve represents calculation in accordance with formula (1).

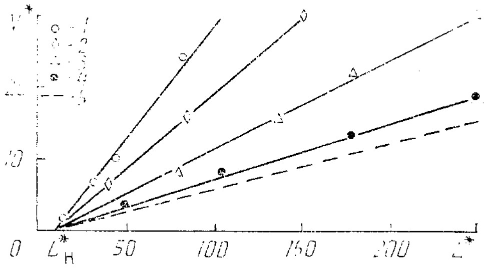

Fig. 2. The complex V* as a function of trajectory length: 1) q = 9.3; 2) 190; 3) 3500; 4) 45,000; 5) q = ∞.

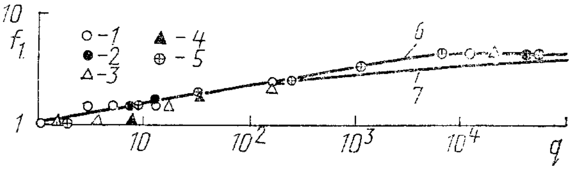

Fig. 3. The coefficient f_1 as a function of the hydrodynamic parameter: nitrogen: 1) $T_0 = 293$ K; 2) 100; helium: 3) 293; 4) 100; hydrogen: 5) 293; 6) calculation according to formula (3); 7) calculation according to formula (4).

$$L^* - L^*_{in} = f_1 f_2, \tag{2}$$

where $f_2 = M_aT_a/M_0T_0)^{0.5}V^*$ is a complex common to all of the jets, including the free jets [4].

Having divided the left- and right-hand sides of expression (2) by f_2, we obtain the relationship between the coefficient f_1 and q. Figure 3 shows the appropriately processed experimental data. We see that f_1 diminishes with a reduction in q. With sufficiently large values of q > 6300, f_1 reaches magnitudes of $1/4K = 4.44$, corresponding to free jets [4]. The experimental data in Fig. 3 are described by two straight lines:

$$\begin{aligned} f_1 &= q^{1/6} \text{ when } 1 \leqslant q < 6300, \\ f_1 &= \frac{1}{4K} \text{ when } q \geqslant 6300. \end{aligned} \tag{3}$$

We can choose an asymptotic function f_1 in the range q = 1-∞, as follows:

$$f_1 = \frac{1}{4K} \operatorname{th}(q^{1/6}/4). \tag{4}$$

Thus, on the basis of an experimental study into jets of hydrogen, nitrogen, and helium in the entrainment flow (the wind) we derived an asymptotic equation for the trajectory. It is demonstrated that the distribution of gas concentration in the jets flowing into the transverse entrainment flow, as in the case of free jets, is inversely proportional to the distance.

We have derived a relationship between the coefficient characterizing the entrainment of the air by the jet and the hydrodynamic parameter q.

The results of these studies can be used, for example, to determine the shape and dimensions of the zones of dangerous concentrations in the case of gas discharge into the atmosphere, as well as in various branches of engineering, where we deal with the transverse injection of one gas into the moving flow of another.

NOTATION

X, Z, horizontal and vertical coordinates, m; d, tube diameter, m; $q = \rho_0 u_o^2/\rho_a u_a^2$, hydrodynamic parameter; ρ_0, ρ_a, density of gas and air, kg/m^3; u_0, u_a, velocity of gas and air, m/sec; $Ar = (\rho_a/\rho_0 - 1)gd/u_0^2$, Archimedes number; C, volumetric concentration at jet axis; $L^* = L/d$, dimensionless distance along jet trajectory; $L_{in}^* = L_{in}/d$, dimensionless initial segment of jet; T_0, T_a, temperature of gas and air, K; M_0, M_a, molecular weight of gas and air; th, hyperbolic tangent; K = 0.05625, empirical coefficient; g, acceleration of gravity, m/sec^2; $X^* = X/dq^{0.5}$, dimensionless complex; $Z^* = Z/dq^{0.5}$, dimensionless complex; $V^* = (1/c - 1)$, dimensionless complex.

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INTENSIFICATION OF HEAT-EXCHANGE PROCESSES IN THE PRESENCE OF A SURFACE WITH VARIABLE ROUGHNESS

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We investigate and evaluate the influence of variable roughness on the transfer of heat and momentum in the flow of disperse systems with precipitate deposition, and also on the efficiency factor for various thicknesses of deposit, and on the Re and Pr numbers.

The flow of disperse systems in tubular heat-exchange equipment is frequently accompanied by the deposition of a variety of particles onto the surfaces, these particles exhibiting a low coefficient of thermal conductivity. As a result of this particle deposition, the heat-exchange surface (i.e., of the deposited layer) is characterized by some level of roughness that is dependent on the dimensions of the deposited particles. We know that an increase in deposition thickness in tubes leads to an increase in linear velocity [1, 2], promoting a significant change in the coefficients of heat release and resistance. This increase in the velocity of flow leads to the entrainment of the finely dispersed component of the particles, thus increasing the surface roughness of the layer as a consequence of the deposition of large particles. In the case of large particle dimensions the height of the roughness projections may attain its maximum ($\Delta = a_{max}$), thus altering the structure of the turbulent boundary layer and leading to variable roughness in the surface of the layer, dependent on the thickness of the latter. As was noted in [3], the presence of roughness significantly changes the coefficient of effective utilization of these rough surfaces, in dependence on the deposition thickness.

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