MIXING PROCESS ON THE INTERACTION LENGTH OF A JET IN A CROSS FLOW

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An investigation is made into the concentration distribution along the trajectories of nitrogen and helium jets interacting with an air cross flow.

In investigating the dissipation of industrial gas discharges into the atmosphere, i.e., the emissions from pipes, stacks, and flues of various diameters, it is usual not to consider the process of decrease in the concentration of the escaping gas on the gas jet—cross wind interaction length.

The presence of the interaction zone is taken into account only by introducing a so-called effective discharge height $H_{eff} = H + \Delta h$ [1-3]. In this case, the coordinate origin is conventionally transferred to the point where the value H_{eff} is reached, and the subsequent calculations are based on the assumption that dissipation proceeds solely under the influence of the wind.

In reality, however, as follows for example from the results of [4, 5], at a point 20-30 diameters downstream from the mouth of the discharge pipe relative to the cross flow, the concentration reaches 5-10% by volume of the initial concentration in the source.

In a number of cases, for example in determining the fire risk zones for hot gas emissions, the maximum permissible concentration in the atmosphere is of the same order. Therefore, in order to estimate the dilution zone, it is necessary to know the trajectory of the jet and the concentration distribution on precisely this interval.

At present, we have no rigorous theoretical equations either for the trajectory of a jet in a cross flow or for the concentration distribution along the trajectory. Therefore, in order to estimate these quantities we must have recourse to empirical relations.

The trajectory of a jet in a cross flow can be approximated [6-9] using power-law emprical relations of the type:

$$z^* = Aq^m x^{*n}, \tag{1}$$

where A, m, and n are numerical coefficients which differ from one author to another; usually, $m = 0.4$-0.6 and $n = 0.2$-0.5.

Clearly, there are various reasons for these discrepancies: the experimental conditions (open or closed channel, flow from an orifice or from a pipe, etc.); use of a relation of type (1) to describe the velocity, temperature, and concentration trajectories which, as established for example in [4-6], are all different; and the purely empirical nature of relation (1).

At the same time, the qualitative solution for the trajectory of a gas jet in an open atmosphere obtained in [10] in accordance with the "unblown jet" model shows that the jet trajectory should be asymptotic due to the presence in the expression for the trajectory of the quantity $\exp(-\lambda x)$. Clearly, by expanding $\exp(-\lambda x)$ in powers of λx and retaining only a certain number of terms of the series, we can obtain an expression for the jet trajectory $z = f(x, \ldots)$ of the power-law type (1) but with a value of the exponent n that depends on the number of terms selected. In [3, 4, 6] jets of hot air discharged from pipes into an air cross flow in closed ducts measuring 650 × 650 [3] and 180 × 200 mm [4, 6] were investigated. In [3] an empirical relation of asymptotic type was proposed for the jet trajectory on the so-called hydrodynamic interval of ascent.

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In [6] the trajectory is of the power-law type. Attention should also be drawn to the absence of generally accepted relations for calculating the concentration distribution on the jet—cross flow interaction length. Thus, for example, the data of [4] show that the distribution of the mean (over the jet cross section) concentration along the length of a curve trajectory can be described by an expression similar in structure to that for the concentration distribution along the axis of a straight jet [12]. At the same time, in [6] for the distribution of the maximum concentration along the length of the trajectory an expression with a quite different structure is given.

Our analysis and a comparison with the data of [4, 5] show that the concentration distribution along the trajectory of a jet in a cross flow can be described by a relation such as that proposed in [4] for the mean concentration, but with another value of the numerical coefficient and the exponent of q, and with allowance for the entrance length of the jet, whose existence was experimentally established in [5].

The dependence of the entrance length on q can be described by the relation

$$L_e^* = \frac{L_e}{d_0} = 0.9q^{0.25}, \tag{2}$$

which is confirmed by the experimental data of [5]. Accordingly, for isothermal conditions and equal gas jet and cross flow densities the expression for calculating the concentration distribution along the trajectory has the form

$$L^* = \frac{L}{d_0} = \left[0.8\left(\frac{1}{c} - 1\right) + 0.9\right] q^{0.25}. \tag{3}$$

At the same time, the absence of data on the effect of a significant difference in jet and cross flow densities on the behavior of the jet, which may be expressed both through the dynamic heat ratio q and directly through the density ratio and the buoyancy force, makes it impossible to determine the precise location of the concentration trajectory and the distribution of the starting-gas concentration along it in this particular case.

In order to establish this effect more accurately, we carried out experiments on nitrogen and helium jets in an open cross flow of air. The nitrogen and helium were discharged from tubes 6 and 10 mm in diameter. The air flow, created by a blower passed through a cylindrical duct 490 mm in diameter and 3500 mm long. At distances of 500 and 1000 mm from the blower perforated diaphragms, with apertures 12 mm in diameter, were mounted in the duct to equalize the velocity field over the cross section. To the end of the duct a convergent channel with an outlet diameter of 400 mm was attached, to create a cross flow with an almost uniform exit velocity distribution. The velocity of the cross flow at the exit from the convergent channel could be varied on the interval 3-10 m/sec.

The tube feeding the gas into the air cross flow was positioned in the plane of symmetry z—x of the convergent channel 20 mm downstream from the exit and at right angles to the direction of the cross flow. The mouth of the tube was approximately 50 mm below the centerline of the convergent channel. Under these conditions, for the values of the q parameter investigated, the jet—cross flow mixing zone always lay within the "cone" of the entrance length of the jet, i.e., in the flow region with a uniform velocity distribution outside the mixing zone. The q parameter was varied from 1 to 196 for nitrogen and from 0.72 to 196 for helium; q was varied both by varying the gas exit velocity and by specifying different cross flow velocities. The gas concentration at a given point of the mixing zone was determined from the admixture of oxygen from the cross flow air. The oxygen concentration was measured with a "Fluorite" type gas analyzer. The gas—air mixture was continuously sampled with a fine sampler tube mounted on a special plotter and connected to a micropump, and fed to the gas analyzer.

The trajectory of the jet was determined as the line of concentration maxima in the plane of symmetry z—x of the mixing zone. On processing the experimental data it was found that the concentration trajectory of the nitrogen jet can be described by an asymptotic relation similr in nature to that of [3]:

$$z^* = 1.8\sqrt{q}\,\frac{\exp\sqrt{x^*} - 1}{\exp\sqrt{x^*} + 1} = 1.8\sqrt{q}\,\mathrm{th}\,\frac{\sqrt{x^*}}{2}, \tag{4}$$

while for a helium jet

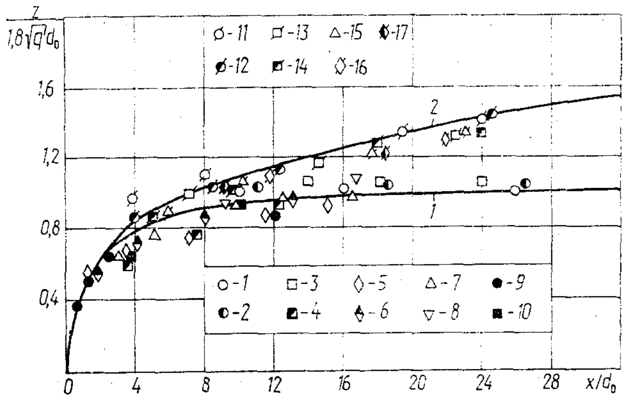

Fig. 1

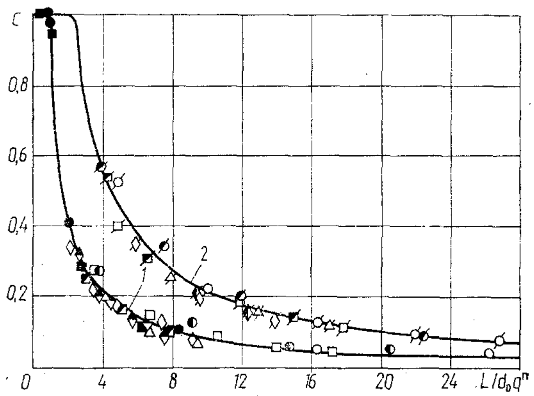

Fig. 2

Fig. 1. Concentration trajectories of nitrogen jets. 1) $q = 1$, $w_a = 8.4$ m/sec, $d_0 = 10$ mm; 2) respectively, 3, 8.4, 10; 3) 5, 8.4, 10; 4) 11, 9.5, 10; 5) 14, 8.4, 10; 6) 32, 3.7, 10; 7) 57, 3.7, 10; 8) 196, 3.7, 6; 9, 10) data of [5] for $q = 16$ and 64, respectively; curve 1 corresponds to calculations based on Eq. (4); helium: 11) $q = 0.72$, $w_a = 8.4$ m/sec, $d_0 = 10$ mm; 12) respectively, 1.6, 8.4, 10; 13) 3.7, 8.4, 10; 14) 11, 6.4, 10; 15) 33, 3.7, 10 and 6; 16) 57, 6.4, 6; 17) 196, 3.7, 6; curve 2 corresponds to calculations based on Eq. (5).

Fig. 2. Concentration distribution along the length of nitrogen and helium jet trajectories: 1) calculations based on Eq. (3); 2) on Eq. (8). Designation of experimental points same as in Fig. 1. c) Volume fractions.

$$z^* = 1.8\sqrt{q}\left(\text{th}\,\frac{\sqrt{x^*}}{2} + 0.016x^*\right). \tag{5}$$

The second term in relation (5) characterizes the effect on the jet of the buoyancy force and in general corresponds to the data of [3, 11]. The curves constructed from (4) and (5) and the experimental data are plotted in Fig. 1. The agreement between calculation and experiment is satisfactory. It should be noted that at $x^* \leqq 15$ the concentration trajectory of a nitrogen jet in an air cross flow coincides with the dependence given in [6].

For a nitrogen jet in an air cross flow the asymptote is

$$z^*_{\text{as}} = 1.8\sqrt{q}, \tag{6}$$

which lies somewhat above that given in [3, 11].

For a helium jet the corresponding expression is

$$z^*_{\text{as}} = 1.8\sqrt{q}(1 + 0.016x^*). \tag{7}$$

The data obtained indicate that the nature of the concentration distribution along the trajectory is the same as that along the axis of a free turbulent jet [12], i.e., on the "main" part of the jet the concentration is inversely proportional to the arc length of the trajectory reckoned from the end of the "entrance" length with allowance for the corresponding effect of the q parameter and the density ratio (see Fig. 2). The good agreement between calculation and experiment confirms the correctness of our relation (3). The same curve also fits the data of [5] for an air jet in an air cross flow with $q = 16$ and $q = 64$, where the concentration of the starting gas was determined from the concentration of carbon dioxide introduced into the air jet.

Corresponding treatment of the data on the distribution of the maximum concentrations in the helium jet (i.e., on the concentration trajectory) shows that, with an accuracy sufficient for practical purposes, it can be described by the relation

$$L^* = \left[0.8\left(\frac{1}{c} - 1\right) + 0.9\right]\sqrt{\frac{\rho_a}{\rho_0}}\,q^{0.2}. \tag{8}$$

The above data indicate with reasonable certainty that on the so-called "active" interval of interaction between a jet and a cross flow the concentration trajectory of the jet is asymptotic in character, and the relations describing the concentration distribution along the trajectory have the same form as that describing the distribution of the volume concentration of the effluent gas along the axis of a free jet [12], but with an additional factor that takes into account the effect of the gas—cross flow dynamic head ratio on the fall in concentration.

NOTATION

H_{eff}, effective emission height; H, height of the discharge pipe above the surface of the earth; Δh, uplift of the jet trajectory above the end of the pipe; $z^* = z/d_0$, $x^* = x/d_0$, dimensionless vertical and horizontal coordinates; z, x, distances from the end of the pipe in the direction of discharge of the jet and in the direction of the cross flow; d_0, diameter of the pipe channel; $q = \rho_0 u_0^2/\rho_a w_a^2$, hydrodynamic parameter; ρ_0, ρ_a, densities of the effluent gas and the cross flow; u_0 and w_a, jet exit velocity and the speed of the cross flow; $L^* = L/d_0$, L, dimensionless and dimensional lengths of the jet trajectory; $L_e^* = L_e/d_0$, L_e, dimensionless and dimensional jet entrance lengths; c, volume concentration of starting gas.

LITERATURE CITED

1. Code of Practice for Calculating the Atmospheric Dissipation of Toxic Substances Contained in Industrial Emissions. SN369-74 [in Russian], Gosstroi SSSR, Moscow (1975).
2. I. N. Leikin, Design of Vents and Discharge of Industrial Emissions into the Atmosphere [in Russian], Khimiya, Moscow (1970).
3. L. A. Rikhter, E. I. Gavrilov, V. I. Kormilitsyn, and A. M. Gribkov, "Dissipation of emissions from smokestacks," in: Processes of Dissipation of Toxic Impurities in the Lower Layer of the Atmosphere [in Russian], Izd. Akad. Nauk ESSR, Tallin (1976), pp. 8-28.
4. S. I. Trofimchenko, V. A. Dvoinishnikov, and A. F. Khritinin, "Development of a single jet and a system of jets in a cross flow," Teploenergetika, No. 12, 63-64 (1980).
5. K.Schymanietz, A. W. Quick, and R. Staufenbiel, "Konzentrationsmessungen an querangeblasenen Freistrahlen zur Bestimmung der Mischungsverhältnisse," Forschungsbericht des Landes Nordrhein-Westfalen, No. 2652. Fachgruppe Maschinenbau/Verfahrenstechnik, Westdeutscher Verlag (1977).
6. S. I. Trofimcenko, "Mixing characteristics of a single round jet developing in a cross flow," Tr. MÉI, 524, 39-44 (1981).
7. Yu. V. Ivanov, "Trajectories of live blast jets," Sov. Kotloturbostr., No. 8, 18-23 (1952).
8. G. S. Shandorov, "Flow from channels into stationary and moving media," Zh. Tekh. Fiz., 27, No. 1, 32-38 (1957).
9. E. Le Grives, "Mixing process induced by the vorticity associated with the penetration of a jet into a cross flow," Trans. ASME, J. Eng. Power, 100, No. 3, 465-475 (1978).
10. N. N. Talerko and M. V. Buikov, "Calculation of jet trajectories in the surface layer of the atmosphere," in: Physics of Clouds and Active Influences [in Russian], No. 170, Tr. UkrNIGMI, Kiev (1979), pp. 9-96.
11. É. P. Volkov, "Investigation of the rise of jets above the mouths of gas pipes," Inzh.-Fiz. Zh., 36, No. 4, 700-707 (1979).
12. G. G. Shevyakov, V. P. Tomilin, and Yu. A. Kondrashkov, "Effect of buoyancy force on the length of the mixing zone of a free turbulent jet," Manuscript Dep. with VINITI, No. 3671-80 (1980).