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MIXING OF PLASMA JETS WITH AIR

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Experiments have shown that there is a qualitative analogy between mixing twisted nonisothermal plasma jets and isothermal gas jets flowing out into a submerged space.

Mixing a plasma jet flowing out of a plasma generator with the ambient gas medium is vitally important for some technological applications of plasma (sputtering, plasmachemical processing of disperse materials, etc.). Since stabilization of an arc discharge in a vortex flow is most often used in modern plasma generators, it seems important to investigate the effect of twisting of a plasma jet, which arises here, on the jet's mixing and cooling. It is known that in isothermal gas jets this effect is quite important [1]. However, for plasma jets far from isothermicity it is not quite clear how a heat source in the vortex flow affects the distribution of parameters in the channel of a vortex plasma generator and in the plasma jet and how this ultimately affects the mixing and heat transfer processes. The author of [2] has found that a heat source in the near-axis region reduces twisting over the whole flow cross section. In [5, 6] vortex effects of the type of "dips" of the temperature and velocity head profiles in the near-axis region of the plasma jet were found, which disappeared (see [6]) after blowing about 5% natural gas, which causes heat release when it burns in the peripheral flow regions. In [7] numerical simulation has shown that an increase in the nonisothermicity of the jet facilitates damping of twisting in it.

The above allows us to suggest that the vortex effects, which persist to some extent in plasma jets, should affect mixing and cooling of the jets in the ambient air. In order to obtain additional information on the problem, in this study experiments were carried out to investigate the distribution of enthalpy and dynamic pressure in plasma jets with different vorticities and different initial enthalpy levels, generated by different types of plasma generators. The main part of the measurements was conducted with the aid of a water-cooled calorimetric enthalpy probe (known as Grey's probe) [8, 9]. These measurements were taken in a subsonic jet of a vortex plasma generator with a smooth tubular anode and an end-face zirconium cathode. In this case the arc discharge current, the voltage drop, and the flow rate of the plasma-generating air were constant and amounted to 94 A, 230 V, and 1.61 g/sec, respectively. The mean mass enthalpy of the flow at the nozzle exit section, found by calorimetry of the cooled components of the plasma generator, was 8.6 MJ/kg (the temperature was 4340 K) under these conditions. A cylindrical enthalpy probe with a length of 200 mm and an external diameter of 4 mm (this was sufficient to ensure measurement localization) was introduced across the flow. The hole for gas collection was on its side surface, facing the flow; the sucked gas flow rate was 30-50 liter/h and cooling was effected by water at 0.4 MPa. The dynamic pressure in the jet was measured with the probe with the gas flow through it closed. The velocity was determined from Bernoulli's equation using this pressure and the density determined from the enthalpy. Under the conditions stated above, with a diameter of 9.5 mm for the outlet tubular electrode, the velocity at the outlet of the plasma generator was much lower than the velocity of sound ($M \approx 0.25$). In this case the static pressure in the jet was assumed to be equal to the atmospheric pressure. The gas mass sucked by the jet from the ambient atmosphere in this section can be expressed by the dimensionless parameter

$$\Delta\overline{G} = (G_z - G)/G, \tag{1}$$

where

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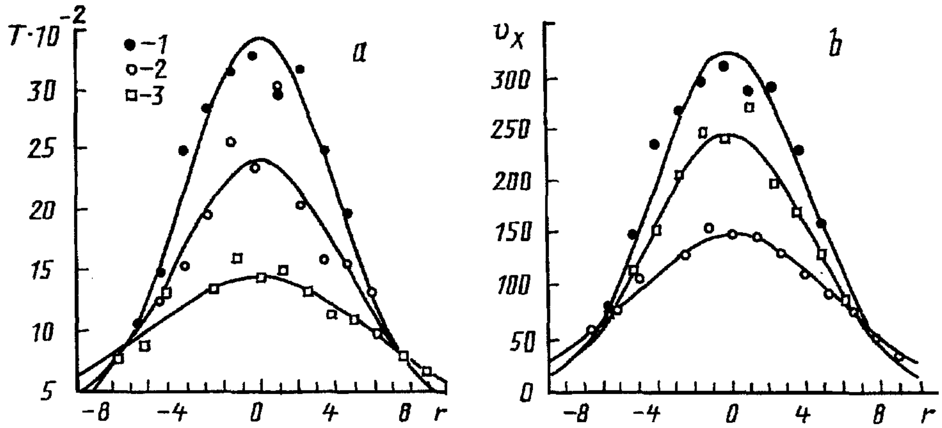


Fig. 1. Temperature T (K) (a) and axial velocity v_x (m/sec) (b) profiles of the jet as a function of the axial coordinate z (mm) and the radius r (mm): 1) $z = 13$ mm; 2) 25; 3) 50.

$$G_z = \int_0^R \rho v_x 2\pi r dr . \tag{2}$$

Enthalpy and velocity profiles were measured at three cross sections of the jet at distances of 13, 25, and 50 mm from the nozzle exit section of the plasma generator. At each of the positions measurements were taken three times with and without a gas flow through the probe. The measured temperature and velocity profiles are shown in Fig. 1. They are satisfactorily approximated by curves of the form

$$T(r) = T_0 \exp(-ar^2) + T_a \tag{3}$$

and

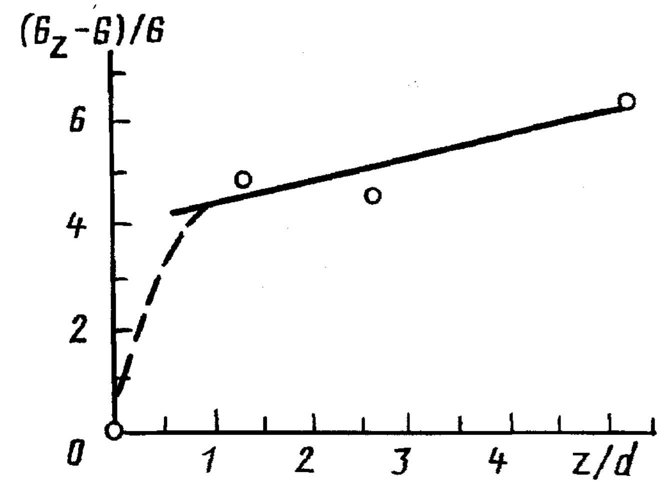
$$v_x(r) = v_0 \exp(-br^2), \tag{4}$$

where T_a is the ambient temperature.

Changes in the dimensionless mass gain $\Delta\overline{G}$ along the jet axis calculated from formulas (1) and (2) are shown in Fig. 2. In the plot one can clearly see two characteristic sections: the initial section (at $\overline{z} < 1.5$) with a substantial increase in the mass gain and the final section ($\overline{z} > 1.5$) with a moderate, approximately constant gain. This distribution of $\Delta\overline{G}$ was described in detail for isothermal twisted jets [1]. In this case we have a similar relationship for substantially nonisothermal mixing of a high-temperature plasma jet with ambient air. For an isothermal twisted jet the difference between the gain $\Delta\overline{G}$ in the initial and final sections and the integral mass gain is greater, the higher the vorticity of the jet, which is usually described by the effective twist parameter [1]

$$\varepsilon = 2\pi\rho \int_0^R r^2 v_x v_\varphi dr / 2\pi R \int_0^R r(\rho v_x^2 + P)\, dr . \tag{5}$$

For mixing of plasma jets it is interesting to carry out investigations both at different jet vorticities and at different initial plasma enthalpies, providing variation of the deviation of the mixing process from isothermicity. In order to obtain these data, we investigated jets from two more heaters with different initial enthalpies of the generated plasma jets and vorticities. One of the heaters, having a high enthalpy, was manufactured with an interelectrode insert. Its operation parameters were as follows: an arc current of 940 A, a voltage of 3.1 kV, and a discharge chamber pressure of 2.5 mPa. With this pressure in the chamber, the plasma outflow behind the nozzle exit section of constant cross-sectional area was supersonic with free expansion of the jet in the atmosphere. In this case the Mach disk was located at about 1.5 diameters from the exit section of the outlet electrode (anode). Because



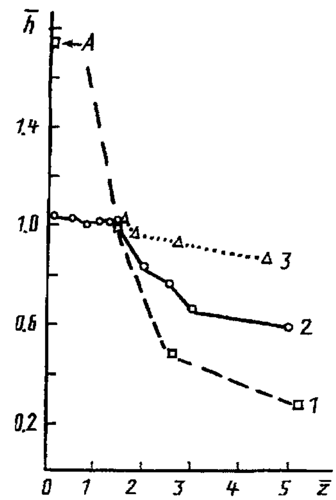


Fig. 2. Dimensionless mass gain of the jet as a function of the dimensionless axial coordinate.

Fig. 3. Changes in the dimensionless plasma enthalpy along the jet axis as a function of the dimensionless axial coordinate: 1) a highly twisted subsonic jet of a vortex plasma generator; 2) supersonic ($\bar{z} < 1.5$) and subsonic ($\bar{z} > 1.5$) jets of a plasma generator with an interelectrode insert with lower twist; 3) a subsonic ($\bar{z} > 1.5$) nontwisted jet of a plasma generator with a lateral nozzle. Point A is determined from the mean mass enthalpy at the nozzle exit section of a plasma generator.

of a high degree of the flow expantion ($P_n/P_a > 12$), a periodic structure of the flow with repeated compressions and rarefactions is absent behind the Mach disk, and the jet can be assumed to be isobaric and supersonic with the static pressure equal to the atmospheric one [10].

Thus, the jet from this plasma generator had two characteristic sections: a supersonic section at $\bar{z} < 1.5$ and a subsonic section with $\bar{z} > 1.5$. In these sections the effective twist parameter was smaller than that in the low-temperature jet of the first plasma generator (approximately 3-4 times) because of a high axial velocity. As regards the supersonic section, it is known that nontwisted supersonic jets mix with the ambient atmosphere less intensely than subsonic jets because of a higher resistance of the external boundary of the supersonic jet to external disturbances [10]. It is therefore interesting to follow the mixing of the twisted plasma jet in these sections.

Since the heat flux density to the calorimeter in the initial jet section was much larger than 10^5 kW/m^2, it was impossible to take measurements with Grey's cooled probe. Therefore, all measurements in this plasma generator were taken with noncooled disposable unsteady-state calorimeters, which were manufactured in the form of a thin copper disk 2-3 mm in thickness and 4 mm in diameter with a thermocouple set in a holder of heat-insulating composite material, caulked into the disk. With this disk thickness a regular regime of its heating ($\mathrm{Fo} = a\tau/l^2 > 0.35$) was maintained for a sufficiently long time (0.1-0.2 sec) before melting. This allowed the heat flux to be calculated in a simple way from the heating rate of the disk, which was constant in the regular regime [11]. Then, the jet enthalpy was calculated with the measured heat fluxes from a simplified version of the Fay-Riddle equation:

$$h = 2.44q\sqrt{\left(\frac{R_h}{P_0'}\right)} + 0.93\cdot 10^6 . \tag{6}$$

This relation is widely used in diagnostics of plasma jets with high deceleration enthalpy, in particular, in hypersonic wind tunnels [12]. In the present case the maximum enthalpy of the air flow reached $45\cdot 10^6$ J/kg (the temperature was 9500 K).

Apart from this plasma generator, similar measurements were taken in a vortex plasma generator with a lateral outflow of the plasma jet, which provided generation of a nontwisted jet with an effective twist parameter close to zero. The jet flowed out of the discharge chamber through the nozzle, located normal to the chamber axis, which coincides with the vortex flow axis. The operating parameters of this heater were as follows: an arc current of 500 A, a voltage of 2.4 kV, and a discharge chamber pressure of 2.5 mPa. The jet outflow was supersonic, the cylindrical nozzle had a constant cross-sectional area, and the jet freely expanded in the atmosphere. The Mach disk was also located at about 1.5 diameters from the nozzle exit section. The initial enthalpy was 2 MJ/kg (the temperature was 1800 K).

In order to obtain comparable mixing characteristics of different jets, the enthalpy was made dimensionless. For this, the enthalpy at a distance of 1.5 diameters from the nozzle exit section was taken as a scale. This was reasonable since the interface between two different regions of the jet occurred in this section. For the first plasma generator the boundary of the transition from the most intense to a moderate increase of the mass gain was located in this section and for the second and third ones, the boundary of transition from supersonic to subsonic flows was located there.

A comparison of the changes in the dimensionless enthalpy along the axis, characterizing the mixing process, is shown in Fig. 3 for all the three plasma generators. The points shown in the plot are averages of 4 to 12 measurements. One can see from the figure that, in spite of the differences in the initial enthalpy levels, in the subsonic part of the jet, where all the other dimensionless parameters, except the twist, were similar, the curves separate because of the twisting parameter. In this case the most rapid decrease of the enthalpy, indicating intense mixing, is observed in the low-velocity jet with the largest twist and the slowest decrease is found in the nontwisted jet; the jet with a moderate twist is also moderate in the mixing intensity. Variation of the absolute enthalpy level in a wide range (2-45 MJ/kg) did not violate this relation. This indicates that the relations of mixing of twisted jets remain valid qualitatively for substantially nonisothermal jets, too.

It is also seen from Fig. 3 that mixing of supersonic plasma jets with the ambient atmosphere occurs at a very small rate, which is indicated by a slight enthalpy decrease in the supersonic section of the jet from the second plasma generator (at $\bar{z} < 1.5$).

The general relations of mixing of plasma jets with atmospheric air obtained here can be useful in designing commercial plasma apparatus, in which mixing processes are of decisive importance for optimal organization of the operation processes.

NOTATION

$\Delta\overline{G}$, dimensionless mass gain; G_z, G, integral mass flow in the current and initial sections of the jet; ρ, density; v_x, axial velocity; R, r, external and current radii of the jet; $z = z/d$, where d is the nozzle diameter and z is the dimensionless axial coordinate; v_φ, twisting velocity; P, static pressure; P_n, pressure at the nozzle exit section; P_a, ambient pressure; Fo, Fourier number; a, thermal diffusivity of the calorimeter material; τ, time; l, thickness of the calorimeter plate; h, enthalpy; q, heat flux density; R_h, radius of the calorimeter head; P_0', pressure behind the shock wave.

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