HEAT EXCHANGE BETWEEN SUBSONIC AND SUPERSONIC PLASMA JETS AND A PLANE SURFACE

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UDC 536.24.083

The thermal and gasdynamic parameters of subsonic and supersonic plasma streams are investigated. The permissible size of test models for the subsonic mode is determined.

In thermal and gasdynamic investigations in high-temperature jets it is necessary to know the distribution of the stream parameters under the conditions of flow of the jet onto a plane surface of the model. At present the main sources of high-temperature gas streams are plasmotrons [1], in which the region of a uniform distribution of the parameters is relatively small compared with the cross section of the entire jet [2-4]. Therefore, the choice of the optimum size of the test model is important, especially when plasmotrons of low and moderate power are used.

Measurement Method

The source of the high-temperature jet was a linear plasmotron with magnetic-vortex stabilization of the arc. The diameter of the exit cross section of the plasmotron electrode was 10 mm. For operation in the subsonic mode, the nozzle profile was cylindrical, while for the supersonic mode (jet discharge into a vacuum) the nozzle had a critical cross section 5 mm in diameter. With an anode length of 80 mm the anode spot of the arc fell short of the exit cross section by about one third of this distance, which assured some equalization of the gas parameters over the jet cross section. The construction of the plasmotron and its parameters are given in [5].

The enthalpy in the plasma jet was measured with an enthalpy probe [6] with an outer diameter of 5 mm and a receiver opening 1 mm in diameter.

It was shown in [7] that the results of a measurement with this probe depend strongly on the ratio G_{samp}/G_{imp} (where G_{samp} is the flow rate of gas passing through the probe; G_{imp} is the flow rate of gas impinging on the receiver opening 1 mm in diameter). With a flow-rate ratio of $G_{samp}/G_{imp} = 10\text{-}100$ the values of the enthalpy obtained may be 2.5-3 times lower than the results of spectral measrurements. Only starting with $G_{samp}/G_{imp} \leqslant 5$ can one assume that the probe is giving reliable results. In this connection we constructed the dependence of the measured enthalpy on the gas flow rate through the probe, which helped to determine the maximum allowable value of G_{samp} for an air plasma. For all the measurements the ratio G_{samp}/G_{imp} did not exceed three.

Besides the enthalpy probe, we used tungsten–rhenium thermocouples to determine the temperature in nitrogen and air plasmas up to 2000°C [8]. A comparison of the measurement results confirmed the correctness of the choice of the flow rate of sampled gas through the enthalpy probe.

The average-mass enthalpy of the gas at the nozzle cut of the plasmotron was determined from the energy balance. To determine the stagnation pressure we used the same probe in conjunction with a standard manometer and micromanometer.

Distributions of the stagnation enthalpy over the length and over cross sections of a subsonic air-plasma jet are shown in Fig. 1a, b. Curves I and II (Fig. 1a) characterize the variation of the enthalpy at the axis of the jet and its average-mass enthalpy, respectively.

Institute of Problems of the Study of Materials, Academy of Sciences of the Ukrainian, SSR, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 40, No. 6, pp. 965-969, June, 1981. Original article submitted May 6, 1980.

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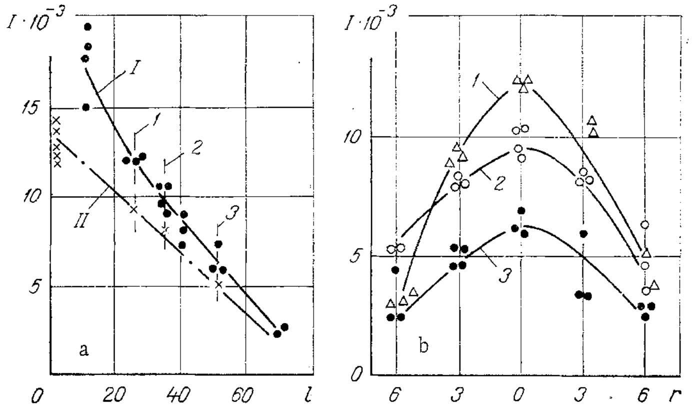

Fig. 1. Distributions of stagnation enthalpy over the length (a) and cross sections (b) in an air-plasma jet at a gas flow rate of 1.4 g/sec: a: I) enthalpy at jet axis; II) average-mass enthalpy; b: 1, 2, 3) cross sections at distances of 27, 35, and 50 mm from nozzle cut. I, kJ/kg; l, r, mm.

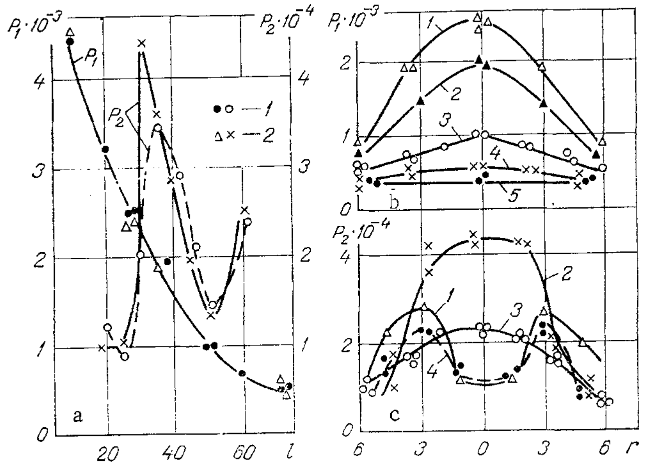

Fig. 2. Distributions of dynamic pressure over length (a) and cross sections in subsonic (b) and supersonic (c) plasma jets at a gas flow rate of 1.4 g/sec: a: 1) air plasma; 2) nitrogen plasma; b: 1, 2, 3, 4, 5) cross sections in a subsonic air plasma at distances of 27, 35, 50, 70, and 100 mm from nozzle cut; c: 1, 2, 3, 4) cross sections in a supersonic air plasma at distances of 25, 35, 50, and 25 mm from nozzle cut; 1-3) air plasma; 4) nitrogen plasma. P, N/m^2; l, r, mm.

The distributions of dynamic pressure over the length and over cross sections of subsonic and supersonic air- and nitrogen-plasma jets are shown in Fig. 2a, b, c. Curves P_1 and P_2 (Fig. 2a) characterize the pressure variation along the axes of subsonic and supersonic jets. Points 1 and 2 (Fig. 2a) correspond to the pressure distributions in air and nitrogen plasmas.

All the measurements were made at a gas flow rate of 1.4 g/sec. The error in measuring the enthalpy of the stream does not exceed 20% and for the stagnation pressure 17%.

The heat fluxes along the length of the plasma jet were determined with a water-cooled calorimeter and a transient probe with a sensor 10 mm in diameter. The results of measurements by the exponential method practically coincided with the data obtained by the cooled-calorimeter method.

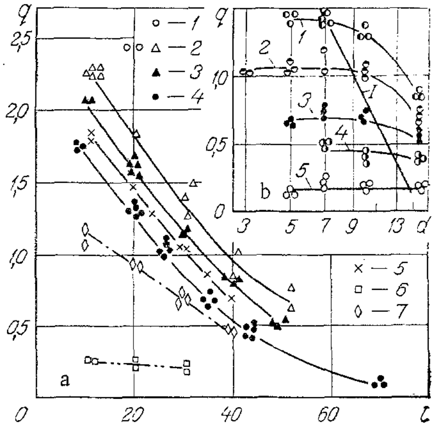

Fig. 3

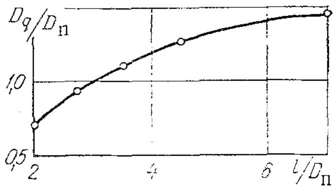

Fig. 4

Fig. 3. Distributions of heat-flux densities over length and cross sections in an air-plasma jet: a: 1, 2, 3, 4) air, flow rates 2.5, 1.8, 1.6, and 1.4 g/sec; 5) nitrogen, 1.4 g/sec; 6) argon, 3 g/sec; 7) carbon dioxide, 0.82 g/sec; b: 1, 2, 3, 4, 5) cross sections in an air plasma at distances of 20, 27, 35, 50, and 70 mm from nozzle cut. q, kW/cm^2; d, l, mm.

Fig. 4. Variation of diameter of zone of constant heat-flux density as a function of distance to nozzle cut.

The distribution of heat fluxes over a cross section was determined at distances of 20, 27, 35, 50, and 70 mm from the nozzle cut of the plasmotron using a transient probe of thermal parameters [9]. The measurements were made with five probes of the same thermal design, differing in geometrical dimensions. The heights δ of the sensors were 5, 7, 12, 16, and 24 mm; the diameters were 3, 5, 7, 10, and 16 mm, respectively. A Chromel—Alumel thermocouple was calked to the lateral surface of the sensor at a distance of $\sqrt{3}/3\,\delta$ from the nonworking end. This position of the thermocouple junction permits the treatment of the experimental results by the midpoint method [10]. In the experiments the probe was mounted flush with a plane wall of heatproof material 50 mm in diameter with a tight fit. The heat flux was cut off after the probe temperature reached the order of 600-700°C. An N-700 loop oscillograph was used as the secondary instrument.

Discussion of Results

The variation of the convective heat-flux density of the plasma jet with the plasmotron operating on air, nitrogen, carbon dioxide, and argon is shown in Fig. 3a, b. It is seen (Fig. 3a) that the heat-flux density depends both on the flow rate and on the type of working gas. For example, an increase in the air flow rate from 1.4 to 1.8 g/sec (points 2, 3, and 4) led to a proportional increase in the heat-flux density. It should be noted that the average-mass enthalpy at the nozzle cut was kept practically constant at all air flow rates through the appropriate control of the power applied to the plasmotron.

A small increase in the convective heat-flux density in comparison with an air plasma is observed in a nitrogen stream (points 4 and 5). This is explained by the fact that the stagnation enthalpy of a nitrogen plasma is somewhat higher.

The relatively low value of the dissociation energy of carbon dioxide prevented the attainment of high mass flow rates of it in the given plasmotron construction, which led to a considerable decrease in the heat flux (points 7). A still lower level of heat flux was obtained for an argon plasma, characterized by a high mass flow rate but a low stagnation enthalpy (points 6).

The calculated values of the heat-flux density obtained from the equation of Fay and Riddell for an equilibrium boundary layer [11] using the average-mass values of the enthalpies at the nozzle cut of the heater are 20% lower than the experimental data. If the value of the enthalpy at the jet axis is used in the calculations, then the disagreement between the experimental and calculated values is considerably reduced. Evidently, because of the outflow of the jet in interacting with the plane surface the enthalpy profile at the outer limit of the boundary layer is evened out and approaches the value of the enthalpy at the jet axis.

Actually, the results obtained in the study of the heat-flux density distribution show that, despite the uneven distribution of enthalpy and stagnation pressure over cross sections of the plasma jet, even at a distance of 2.5 diameters from the nozzle cut of the plasmotron the zone of constant heat flux is about equal to the diameter of the jet in this cross section (see Fig. 3b). To more clearly delimit the zone of constant heat flux we laid out the diameter of the calorimeter along a logarithmic scale. Here we also plotted the arbitrary straight line I defining the zone of constant heat flux in different cross sections. The dependence $D_q = f(l)$ is drawn in relative units in Fig. 4 for the given straight line I. It is seen from this figure that at a distance of seven diameters from the nozzle cut the diameter of the section of constant heat flux exceeds the nozzle diameter by 1.5 times.

Consequently, the diameter of test models in the subsonic stream can considerably exceed not only the region of uniform distribution of enthalpy and stagnation pressure but even the size of the exit cross section of the heater.

This approach to the selection of the model size and the working cross section is inapplicable if the research is conducted in a supersonic gas stream.

As shown by the measurements of the total pressure distribution in the interaction of an overexpanded jet with a barrier, dips are observed at a certain distance from the nozzle cut (Fig. 2c), while the pressure variation over the length of the jet has a sawtooth character (curves P_2 of Fig. 2a). Consequently, in the zone of a drop in the total pressure one observes a decrease in the heat-flux density, which is about half its value beyond the limits of this zone. This character of the pressure variation at a barrier is evidently explained by the influence of suspended compression shocks, the location of which depends on the nozzle geometry and the thermal parameters of the jet.

NOTATION

I, enthalpy of gas; l, distance from nozzle cut of heater to the jet cross section under consideration; r, radius of plasma jet; P_1, excess pressure in subsonic gas jet; P_2, pressure in supersonic gas jet; q, heat-flux density; D_q, diameter of zone of constant heat-flux density; D_n, diameter of nozzle cut of heater; d, diameter of heat-flux probe.

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