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EXPERIMENTAL DETERMINATION OF PARAMETERS OF A PLASMA JET

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Experimental results from the diagnostics of argon plasma flows used for an ablation investigation of materials in the range of Mach numbers $M \leq 3.5$ and deceleration enthalpy up to 7,000 kcal/kg are presented. A schematic diagram of the equipment and the procedure of measurements are given.

Ablation investigations of different materials under the action of high-energy flows, in particular, plasma jets, have been extensively used in research practice [1, 2]. In all the cases it is very important to organize plasma flows (of a high-enthalpy gas) with uniform distributions of pressure and temperature (enthalpy) over the cross section of the flow in the zone of its action on the sample, and to determine the region of the flow for placing the sample. This information can so far be obtained only from experiment.

In the present work we give the results of such measurements obtained during the study of the behavior of samples in high-enthalpy supersonic flows.

In [3, 5] results of thermal and electrical measurements are presented; these measurements were carried out on plasmotrons with a segmented channel operating with argon and intended for creating high-energy flows.

The overall scheme of the gasdynamic bench is shown in Fig. 1. After heating in the plasmotron channel and passing through the damping chamber the operating gas flow enters the nozzle device (8) and flows out of the nozzle in the form of a supersonic plasma jet (10) into the operating vacuum chamber (1). The required pressure in the operating chamber is maintained with the use of a VN-300 vacuum pump (3).

The damping chamber with 50 mm diameter and 70 mm height is placed immediately after the discharge channel of the plasmotron; its diameter is 20 mm and it is water-cooled just as the section of the plasmotron channel. The use of the damping chamber makes it possible to ensure mixing of the flow at the entrance into the nozzle and to obtain a plasma flow with sufficiently uniform distribution of the parameters along its section in the operating vacuum chamber behind the nozzle. The diameter of the critical section of the operating

TABLE 1. Operating Regimes of the Plasmotron

Regime number	I, A	N, kW	η, %	p_0', torr	G, g/sec	q_0, kcal/m·sec	$\bar{I}_0$, kcal/kg	i_0, kcal/kg
1	170	8	41	32	0,8	630	1000	2100
2	300	16	35	23	0,8	1400	1700	3000
3	400	24	34	23	0,85	2000	2300	3900
4	500	33	32	24	0,85	2800	3000	1900
5	600	43	32	28	0;9	3300	4000	5900
6	700	54	32	29	0,9	4000	4300	7100

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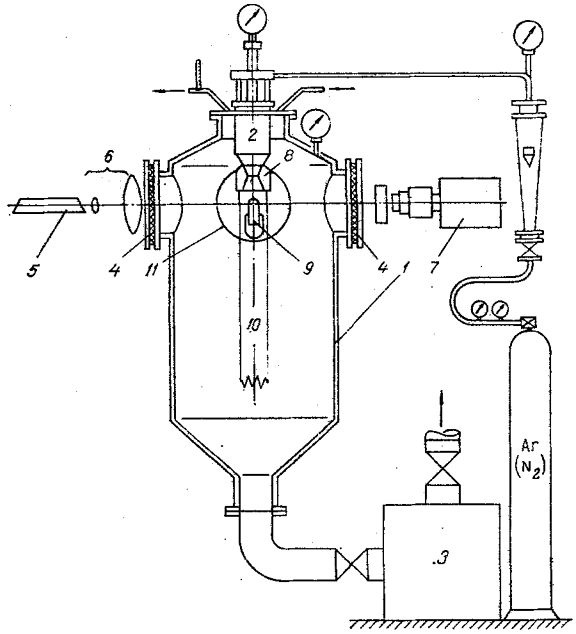

Fig. 1. A schematic diagram of the gasdynamic bench: 1) vacuum chamber; 2) plasmotron; 3) vacuum pump; 4) inspection windows; 5) laser for shadow photography; 6) collimator; 7) photorecorder; 8) damping chamber and nozzle; 9) sensor or investigated sample; 10) plasma flow; 11) sluice chamber.

nozzle was 12 mm and the diameter of the exit section was 30 mm, which ensured a flow with M = 3.5. The nozzle was also water-cooled.

Inspection windows of optical glass 108 mm in diameter were placed in the operating chamber at the level of the nozzle end. A vacuum valve of 160 mm diameter and a sluice chamber with a vacuum seal for the passage of the cooled support, on which the flow sensor or the sample of the investigated materials are mounted, were also placed in the same plane perpendicular to the axis of the window.

With a gradual motion of the support, the sensors or the samples are introduced into the operating part against the plasma flow. The intense water-cooling of the surface of the total-pressure sensor and the support is accomplished with an NSh-40 gear pump.

The gasdynamic and thermal diagnostics of plasma flows were carried out on this bench. The diagnostics involved the determination of the following parameters: mean mass enthalpy of the flow $\bar{i}_0$, Mach number M, deceleration pressure p_0', and thermal flux at the critical point of the sensor q_0 (see Table 1).

The mean mass enthalpy at the end of the nozzle gives only a general idea of the level of energy contained in the flow, since, depending on the outflow regime, the distributions of enthalpy and other parameters over the cross section of the flow can be very different and far from uniform. Therefore, in the experiments for the

TABLE 2. Dependence of the Time Elapsed before the Start of the Melting of Copper Sensors on the Heat Flux

q_0, kcal/m²·sec	h, mm		
	10	20	30
500	20	37	48
1000	9,2	16,8	26
2000	4,4	8,1	11,4
3000	2,8	5,0	6,4
4000	2,0	3,4	5,0
5000	1,6	2,3	2,7

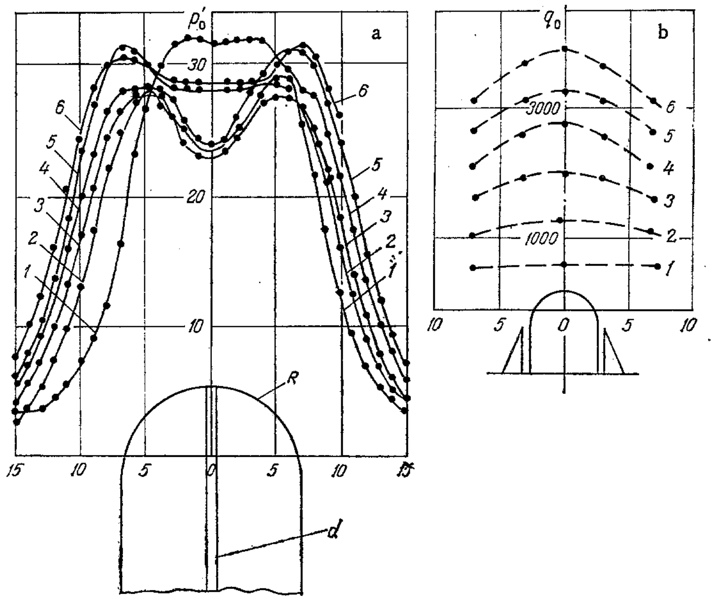

Fig. 2. Distribution of total deceleration pressure (a) and heat fluxes (b) over the cross section of the flow for regimes shown in Table 1. p_0, torr, q_0, kcal/m^2 · sec; along the abscissa, unit of measurement in mm.

diagnostics of the jets we investigated also the distribution of the deceleration pressure and the heat fluxes over the cross section of the plasma flow. The data thus obtained permit us to determine also the distribution of the deceleration enthalpy over the cross section of the jet by using the equations of supersonic gasdynamics [9]. The measurements also enabled us to estimate the maximum admissible diameter of the samples for conducting ablation investigations, for which the sample lies entirely in the zone with relatively constant parameters.

The mean mass enthalpy of the flow $\bar{i}_0$ was determined by calorimetry. For this purpose the heat losses in each section of plasmotron Q_i, the cathode and mixing chambers, and the nozzle device were measured on the bench. These measurements amounted to recording the temperatures of the cooling water at the entrance into and exit from each element and its flow rate. The scheme of measurements was given in [4].

The mean mass enthalpy of the flow at the end of the nozzle was determined from the following formula:

$$\bar{i}_0 = \frac{N - \Sigma Q_i}{G},$$

where N = UJ is the power of the arc discharge, and U and J are, respectively, voltage and current of the arc; ΣQ_i is the sum of the heat losses; G is the flow rate of the plasma-forming gas.

The same data enable us to calculate also the thermal efficiency of heating of the gas in the plasmotron, i. e., the efficiency (η, %) of the plasma device:

$$\eta = \frac{N - \Sigma Q_i}{N}.$$

The Mach number M of the flow was determined from the amount of separation of the shock wave at the total-pressure sensor and also from the loss of total pressure in the direct condensation jump in front of the sensor. The total-pressure sensor had the shape of a blunted cylinder at the critical point of which a capillary tube of 1 mm diameter was soldered in. The total pressure was measured by a U-shaped mercury vacuum meter. Pressure in the cathode chamber of the plasmotron (at the entrance to the channel) was measured by a standard VKO type spring vacuum meter; the pressure in the operating vacuum chamber was measured by a VSB resistance vacuum meter. Using the cooled support, the total-pressure sensor was inserted into the plasma flow oriented along its axis; the critical point of the sensor was found to be at a distance of 5-6 mm from the end of the nozzle.

The method of melting calorimetry [6, 7] was used for measuring heat fluxes.

The procedure of measurements was as follows: a cylinder of diameter d and height h, made from a material with known thermophysical properties and thermally insulated from the sides and the bottom end, is inserted into the plasma flow in such a way that the heat is supplied to it only from the front end; after inserting the sensor into the flow, the time elapsed from the instant of insertion to the start of melting of the front end is recorded.

If the heat flux to the sensor is constant, then the average heat flux to the surface of the sensor $\bar{q}$ can be estimated from the measured time.

The model of one-dimensional heating of a plate of thickness h with a thermally insulated bottom surface is used for computing the heat flux. In this case the change of temperature of the front end with time will be described by the equation [8]

$$\Delta T = \frac{\bar{q}t}{\rho c_p h} + \frac{\bar{q}h}{\lambda} \times \left[\frac{1}{3} - \frac{2}{\pi^2}\sum_{k=1}^{n}\frac{(-1)^k}{k^2}\exp\left(\frac{-at\pi^2k^2}{h^2}\right)\cos(\pi k)\right]. \tag{1}$$

For known thermophysical properties of the material of the sensor (c_p is the specific heat, a is the thermal diffusivity, λ is thermal conductivity, and ρ is the density) and known melting temperature T_m, by knowing the initial surface temperature of a sensor of height h and the time t_m elapsed before its melting, we can calculate the average heat flux supplied to the front end of the sensor. The dependence of the time elapsed before the start of the melting on the heat flux was computed for copper sensors of different lengths for the initial temperature of the sensor equal to 30° (Table 2).

The calorimeter was constructed in the form of copper cylinders (sensors) 20 and 30 mm in height and 5 mm in diameter with a plane or hemispherical front end; the cylinders were screwed into a textolite sheet protecting the sensor from the action of heat fluxes from the lateral surfaces and also heat-insulating the rear end. The time elapsed before the start of the melting of the sensor was determined visually (with the use of the optical tube of a KM-6 cathetometer) as well as with macrocinematography.

Since only the average values of the heat fluxes $\bar{q}$ to the surface of the sensor were determined in the experiments, the conversion from the average heat flux $\bar{q}$ to the heat flux at the critical point q_0 is done according to the formula [9] $q_0 = \bar{q}/K$, where K = 0.66 for the plane face and K = 0.78 for the hemisphere. The heat fluxes at the axis and at distances of 3 and 7 mm from the axis were measured with the use of melting sensors.

The deceleration enthalpy i_0 at the axis of the jet was determined from the results of measurement of heat fluxes and the deceleration pressure p_0' using the formula [9]

$$i_0 = i_w + \frac{q_0\sqrt{R}}{C\sqrt{p_0'}}, \tag{2}$$

where i_w is the enthalpy of the flow at the surface of the sensor, R is the radius of blunting of the sample, and C is a constant coefficient.

If formula (2) is somewhat transformed using the formulas for deceleration enthalpy and deceleration pressure $i_0 = \frac{1}{2}V_\infty^2$ and $p_0' = \rho_\infty V_\infty^2$, then we obtain the well-known [10] formula for determining heat flux at the critical point of a blunt body with blunting radius R moving with velocity V_∞:

$$q_0 \sim \rho_\infty^{1/2} V_\infty^3 R^{-1/2}. \tag{3}$$

The procedures described above were used for gasdynamic and thermal diagnostics of argon plasma flows; the operating regimes chosen for the investigations were those used in the ablation investigations of materials. The values of the basic parameters of six regimes in which the tests were carried out are shown in Table 1. The values of the mean mass enthalpy of the flow $\bar{i}_0$ were in the range 1000-4000 kcal/kg.

The values of heat fluxes q_0 to the critical point of a hemispherical copper sensor with R = 2.5 mm, placed along the axis of the flow, and also the values of the axial enthalpy i_0 calculated from them (Table 1) show that, as expected, the quantity i_0 is considerably larger than the value of the mean mass enthalpy $\bar{i}_0$ obtained from calorimetry for all operating regimes.

The value of the coefficient C in formula (2) for the measured values of q_0 and p_0' was chosen on the basis of calibration experiments with fluoroplastic-4 samples and was 0.15 (for argon).

The obtained distributions of pressures and heat fluxes over the cross section of the jet shown in Fig. 2a, b permit us to determine the zones of flow where the variations of q_0 and p_0' do not exceed 20%. This zone has a diameter of 14 mm; therefore, for conducting ablation investigations samples were prepared with diameter not exceeding this size. The ablation tests of the samples in the chosen operating regimes permitted us to obtain the dependence of the effective ablation heat H_{eff} on the deceleration enthalpy of the flow i_0 which, as is well known [9], determines the behavior of certain types of ablation materials.

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A THERMAL-DIFFUSION MODEL OF THE EROSION OF ELECTRODES IN AN MHD GENERATOR

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We propose a diffusion-heat-conduction model of erosion at a cathode spot, on the basis of which we estimate the characteristic lifetimes of cathode spots and the erosion of electrodes made of graphite, copper, iron, and chromium under the conditions of an MHD generator. We show that the rate of erosion depends substantially on the geometric shape of the cavity.

The most complete measurements of the macroscopic parameters of cathode spots on copper electrodes in a stream of plasma with an easily ionizable additive were apparently made in [1]. The measurements indicated a heat flux of $Q_0 \simeq 20$ W/A for both cold and hot electrodes and a spot lifetime of $\tau \simeq (10^{-3}\text{-}10^{-2})$ sec, depending on the average current I = (2-5) A at the spot, where τ denotes the time required for the spot to move a distance of the order of its diameter; an erosion value of G = (0.1-0.7) μg/C and other parameters were also measured.

It seems unexpected that it is possible to obtain a τ(I) that agrees with the experimental results, starting only with the balance of electrode vapor concentrations in the region of the spot, if we take as the initial parameter the heat flux Q_0, which it is natural to correlate with the cathode potential drop, amounting to about 15-20 V, and therefore consider practically independent of time, electrode temperature, and other conditions, and

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