14. E. H. Carnevalle, C. Carey, and G. Larson, "Ultrasonic determination of rotational collision numbers and vibrational relaxation times of polyatomic gases at high temperatures," J. Chem. Phys., 47, No. 8, 2829-2835 (1967).
15. C. Nyeland and G. Billing, "Rotational relaxation of homonuclear diatomic molecules by classical trajectory computation," Chem. Phys., 30, 401-406 (1978).

INVESTIGATION OF A HIGH-ENTHALPY SUBMERGED JET DISCHARGING FROM THE CHANNEL OF AN ARC PLASMOTRON

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UDC 532.517.4:533.9.07

The variation of the main parameters over the length and cross section of the jet is determined experimentally and is compared with theoretical data.

To organize the efficient mixing of plasma jets with the initial products in multiarc plasmachemical reactors [1, 2] one must know, first of all, the distribution of the velocity head and specific heat flux (temperature) over the length and cross section of the jet, as well as the diameter of the jet at any distance from its orifice.

The exact analytic determination of these quantities is hindered by the considerable variation of the gas density along the jet axis, the intense swirling of the stream in the discharge channel of the plasmotron, and the action of external electromagnetic forces on the conducting section of the jet.

A submerged high-enthalpy air jet discharging from the channel of an arc plasmotron, with the average length of the arc fixed by a step, was investigated experimentally. A comparatively small section of the jet of about five diameters was studied. This was due to the requirement of compactness of the mixing devices of plasmachemical reactors. In addition, at a large distance from the nozzle cut the values of the parameters of the jet decay and the jet loses its individuality as a result of mixing of the working body of the jet with the entrained stream [3], so that prediction of its behavior in a confined space (the reactor) becomes problematical.

Test conditions: gas flow rate $(1.1\text{–}2.76)\cdot10^{-3}$ kg/sec, specific enthalpy of air (5300-8400) kJ/kg, diameter of discharge channel of the plasmotron $8\cdot10^{-3}$ and $9.5\cdot10^{-3}$ m, step diameter $(15 \text{ and } 17.5)\cdot10^{-3}$ m, respectively, step length $4\cdot10^{-2}$ m, number of ampere turns of the solenoid $(0\text{–}24)\cdot10^{3}$.

First we found the value of the specific heat flux from the jet to the calorimetric probe of enhanced sensitivity. The construction of the probe and the measurement procedure are described in detail in [4]. The dynamic head was determined with a water-cooled Pitot tube, structurally combined with the calorimetric probe. The pressure was converted into an electrical signal by a measurement complex of the IKD6TDF type. The probe allows one to make a simultaneous continuous recording of the specific heat flux and the excess pressure in a cross section of the jet. The total error in determining the specific values of the heat fluxes was 9.5% [5] and the accuracy in measuring the excess pressure was ±2.5 rel.%.

The gasdynamic and thermal radii of the jet were determined from the corresponding oscillograms and were compared with Töpler photographs. The temperature was calculated through the value of q by the method of [6]. To reduce the number of tests and formalize the statistical treatment of the results obtained, we used a central, composite, rotatable plan for the experiment [7].

The results of the measurements are presented in Table 1. To treat the test data we obtained interpolation equations describing distributions of velocity head, specific heat flux, and temperature along the jet axis as functions of the gas flow rate and the number

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F. É. Dzerzhinskii Chemical-Engineering Institute, Dnepropetrovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 47, No. 2, pp. 310-314, August, 1984. Original article submitted November 2, 1982.

0022-0841/84/4702-0980$08.50 © 1985 Plenum Publishing Corporation

TABLE 1. Experimental Results

Test No.	Parameters			Results of measurement							
				$D_0 = 15 \cdot 10^{-3}$ m				$D_0 = 17.5 \cdot 10^{-3}$ m			
	B, A•turn	G, 10^{-3} kg/sec	L, 10^{-3} m	$(\rho U^2/2) \cdot$ m, Pa	$q \cdot 10^{-4}$ W/m^2	d_U, 10^{-3}m	d_q 10^{-3}m	$(\rho U^2/2) \cdot$ m	q	d_U	d_q
1	4866	1,42	56	220	104	25,5	26,5	148	128	26	21,5
2	4866	2,42	56	565	135	23,5	28	300	166	22,5	20
3	19340	1,42	56	153	40	32	31	140	70	23,5	22,5
4	19340	2,42	56	540	115	30	29	280	140	24,5	19,5
5	4866	1,42	20	550	385	22	20	280	352	21	19
6	4866	2,42	20	940	475	17,5	20	485	360	17	19
7	19340	1,42	20	420	240	20	21,5	234	202	24	23,5
8	19340	2,42	20	970	480	17,5	18	485	294	21	17
9	0	1,92	38	640	190	20,5	23,5	330	310	21	18,5
10	24000	1,92	38	500	190	27	17,5	283	165	24	21
11	12000	1,10	38	280	125	28	21	138	128	25,5	23,5
12	12000	2,76	38	1040	105	20,5	22	452	248	18	15
13	12000	1,92	8	800	605	16	17	515	420	16	18
14	12000	1,92	68	315	86	29	22,5	175	110	24,5	21,5
15	12000	1,92	38	597	203	23	23	315	230	20,5	18

of ampere turns, proportional to the strength of the external magnetic field. For the nozzle diameter of $15 \cdot 10^{-3}$ m

$$P = \exp(5.472 - 0\ 109 \cdot 10^{-4}B + 0.848G - 0.0187L), \tag{1}$$

$$q = \exp(6{,}07 - 0.262 \cdot 10^{-4}B + 0.44G - 0{,}0367L), \tag{2}$$

$$T = \exp(8.63 - 0{,}154 \cdot 10^{-4}B + 0.146G + 0.0191L); \tag{3}$$

for the nozzle diameter of $17.5 \cdot 10^{-3}$ m

$$P = \exp(5.026 - 0.673 \cdot 10^{-5}B + 0.68G - 0{,}0156L), \tag{4}$$

$$q = 275 - 0.0176B + 305G - 8{,}36L - 75{,}8G^2 + 0{,}0255L^2 + 0{,}00393BG + 0.119 \cdot 10^{-3}BL, \tag{5}$$

$$T = 4110 - 0{,}1B + 1854G - 65.9L - 628G^2 + 0.028BG + 15{,}3GL. \tag{6}$$

The measured quantities are substituted into Eqs. (1)-(6): B in ampere turns, G in grams per second, and L in millimeters.

The discrepancy between the data calculated from (3) and (6) and the test data does not exceed 10%. The temperatures calculated at the minimum distance from the plasmotron nozzle were compared with the average-mass temperatures. The maximum value of the average-mass temperature, determined through the experimental values of the useful power of the plasmotron and the flow rate of the plasma-forming gas, is 4250°K. The highest temperature in the tests is 5400°K. Since the temperature at the axis is higher than the average-mass temperature (Re = 3820), this ratio of them can be considered as satisfactory.

Axial distributions of the dimensionless velocity head and specific heat flux showed that over the entire length of the jet (Fig. 1) the decline in the relative velocity head (curve 1) takes place more slowly than that of the specific heat flux (curve 2) for both nozzle diameters. It is characteristic that for all the investigated combinations of the parameters the distribution of the dimensionless velocity head over the length of the jet is described by the same curve 1. The variation of the relative specific heat flux for the diameter of $15 \cdot 10^{-3}$ m is described by the curve 4 in all cases. The analogous dependence for the nozzle diameter of $17.5 \cdot 10^{-3}$ m is not generalized by one curve but lies inside the hatched region 3.

From an empirical relation describing the distribution of the characteristic quantities in the main section of a turbulent nonisothermal jet [8] we calculated the length of the initial section of the jet for the experimental conditions:

$$(\rho U^2)_m/(\rho U^2)_0 = 68\,(L/D + 7W^{-0{,}1} - 5)^{-2}(1 - 0{,}02W)^{-2}. \tag{7}$$

From Eq. (7) with a superheating parameter of 15.9 the length of the initial section is $89 \cdot 10^{-3}$ m. At the same time, according to the experimental data (Fig. 1), decay of the axial parameters of the jet is already noticeable at a distance of $8 \cdot 10^{-3}$ m from the nozzle cut. Such a large discrepancy between the calculated and experimental values is evidently explained

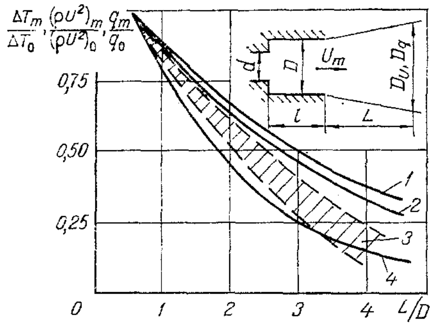

Fig. 1

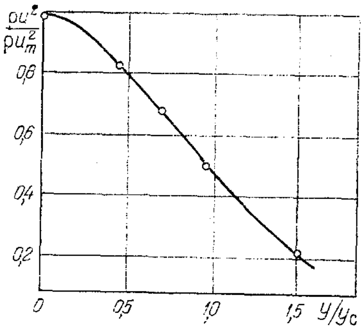

Fig. 2

Fig. 1. Variation of the dynamic head, specific heat flux, and excess temperature along the jet axis.

Fig. 2. Dimensionless profile of the dynamic head of the jet.

by the past history of the jet. The jet probably starts to form at the exit from the discharge channel of the plasmotron. The sudden expansion of the jet at the step, the action of the external electromagnetic field, and the swirling of the jet in the discharge channel lead to the fact that the axial parameters of the jet discharging from the channel of a plasmotron with a step decay considerably faster than for a jet formed in a smooth channel.

Through the analysis of the experimental data it was found that the dimensionless profiles of the dynamic head $(\rho U^2)/(\rho U^2)_m$ in the coordinates y/y_c are close to universal (Fig. 2). Experimental points found as average values from the oscillograms recorded in tests 1-15 are plotted in the figure. Twice the distance from the jet axis to the point at which the excess value of the velocity head or the specific heat flux was 10% of their axial values is taken as the width of the jet. The actual width of the jet will be somewhat greater.

The decline of the relative excess temperature along the length of the jet differs little from the analogous dependence for the velocity head. This indicates the approximate equality of the widths of the thermal and dynamic boundary layers, as confirmed by the data of Table 1.

NOTATION

T, temperature, °K; $\rho U^2/2$, dynamic head, Pa; q, specific heat flux, W/m^2; d, diameter of discharge channel, m: D, diameter of step, m; l, length of step, m; L, length of jet, m; D_U, D_q, hydrodynamic and thermal diameters of jet, respectively, m; y, coordinate normal to the longitudinal axis of the jet, m; y_c, distance normal to the jet axis to the point at which the dynamic head is half its axial value, m. Indices: 0 corresponds to the values of the parameters at the nozzle cut; m, corresponds to the parameters of the axis of symmetry of the jet.

LITERATURE CITED

1. M. F. Zhukov and Yu. I. Sukhinin, "Mixing chamber for a multiarc heater," Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 8, Part 2, 12-19 (1970).
2. A. L. Mossé and I. S. Burov, Processing of Dispersed Material in Plasma Jets [in Russian], Nauka i Tekhnika, Minsk (1980).
3. Yu. P. Vyazovskii, V. A. Golubev, and V. F. Klimkin, "Investigation of a round turbulent jet in a deflecting stream," Inzh.-Fiz. Zh., 42, No. 4, 548-554 (1982).
4. S. P. Polyakov and A. T. Neklesa, "A linear calorimetric probe of enhanced sensitivity," Inzh.-Fiz. Zh., 38, No. 6, 1011-1016 (1980).
5. S. P. Polyakov and A. T. Neklesa, "Automation of the process of measurement of heat fluxes with a linear calorimetric probe," Inzh.-Fiz. Zh., 41, No. 4, 712-716 (1981).
6. V. S. Klubnikin, "Heat transfer in a stream of ionized gas," in: Transport Phenomena in a Low-Temperature Plasma [in Russian], Nauka i Tekhnika, Minsk (1969), pp. 125-135.
7. A. G. Bondar' and G. A. Statyukha, Experiment Planning in Chemical Engineering [in Russian], Vishcha Shkola, Kiev (1976).
8. V. I. Kukes and L. P. Yarin, "Calculation of turbulent nonisothermal jets," Inzh.-Fiz. Zh., 30, No. 4, 653-656 (1976).