THERMAL CHARACTERISTICS OF A PLASMA ATOMIZER

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UDC 533.9.07

The thermal characteristics of a nitrogen plasma jet are studied. Their dependence on the working conditions and the nitrogen flow rate and their variation along the axis of the jet are demonstrated.

In the solution of problems of heat exchange during the interaction of a plasma with a solid material such characteristics as the specific heat flux, the enthalpy, and the average-mass temperature of the plasma jet are important, in addition to the temperature. Calculations based on temperature data obtained through spectroscopic measurements are not free of errors owing to the fact that the jet of a plasma atomizer is a pulsating plasma formation. The frequency and amplitude of these pulsations depend on the construction of the power supply processes at the electrodes, the type and flow rate of the working gas, and other factors. Thus, in [1] and in a number of other reports it has been shown that the plasma jet pulsates in time and space with a frequency of from 100 to 3000 Hz. Accordingly, the action of the plasma jet on the surface of the interacting body will not be continuous, but pulsating. It is very difficult to allow for the effect of such pulsations on the heat exchange and at present it is obviously more expedient to use experimental data in the calculations.

In the work, therefore, we set the task of the experimental determination of the specific heat flux, enthalpy, and average-mass temperature of the plasma jet and their dependence on a change in the working conditions of the atomizer, as well as their variation over the radius of the plasma jet.

The nitrogen plasma jet of a commercial GN-5 plasmotron, which can be used under laboratory and industrial conditions, served as the object of the study. The arc plasmotrons closest to it in power have unimportant structural differences and therefore their thermal characteristics can be taken as similar.

For the studies of the radial distribution of the thermal characteristics of the plasma jet we initially used a Grey probe, the construction and use of which are described in [2-4].

The specific heat flux and the enthalpy were measured in the experiment. The average-mass temperature was determined through the enthalpy from the tables of [5]. The results of the measurements are presented in Fig. 1. The variation in enthalpy and average-mass temperature over the radius of the plasma jet under different conditions of operation of the atomizer at distances of 20 and 30 mm can be traced from the behavior of the curves.

Measurements were not made at distances of less than 20 mm from the nozzle cut because of the insufficient heat resistance of the Grey probe. Therefore, in the further studies, we used a means suggested in [6]. The construction of the probe and the effect of its physical and geometrical parameters on the accuracy in the range of the measurements are described in [7].

The probe is built in the form of a copper rod 10 mm in diameter and 15 mm long and insulated with a protective textolite sleeve with a radius of curvature R = 25 mm. The range of linear variation of the probe temperature did not exceed 600°C, which ensured the reliability of operation of the probe's copper—Constantan thermocouple. This permitted the recording of the time variation $dT/d\tau$ of the probe temperature with a time resolution of $5 \cdot 10^{-2}$ sec.

Institute of Physics, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 29, No. 5, pp. 875-879, November, 1975. Original article submitted October 16, 1974.

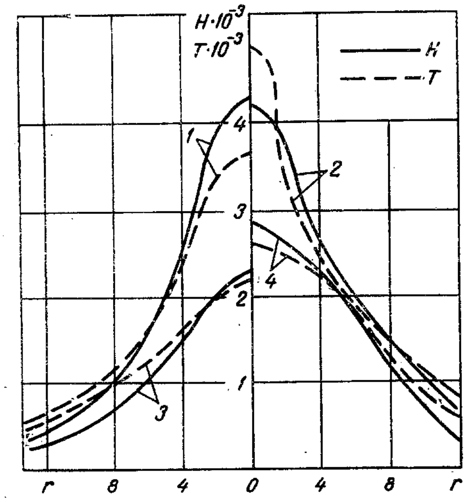

Fig. 1. Variation in enthalpy and average-mass temperature (°K) over the radius (mm) for different conditions of operation of atomizer: 1) L = 20, N = 17, G_{N_2} = 0.80; 2) 30, 30, 1.10 + 7% H_2; 3) 30, 22, 1.43; 4) L = 30, N = 21, G_{N_2} = 0.77. H, kJ/kg.

TABLE 1. Dependence of Thermal Characteristics on Plasmotron Operating Conditions

Parameters of discharge			Distance along axis of plasma jet	Nitrogen flow rate	Specific heat flux	Enthalpy	Temperature	Reduced enthalpy
current	voltage	power						
250	52	13	10	1,08	1,480	3500	3300	273
250	58	14,5	10	1,08	1,690	3800	3350	264
250*	75	19,0	10	1,10	2,280	5340	4500	280
300*	55	16,5	10	1,12	2,050	4460	3850	270
300	60	18,0	10	1,23	2,240	4840	4150	268
300*	73	22,0	10	1,10	2,310	5100	4300	238
350	63	22,0	10	1,23	2,527	5330	4500	242
350*	53	18,5	10	1,08	2,301	4830	4100	263
400	72	29,0	10	1,11	3,310	6890	6000	246
450	70	31,5	10	1,10	3,480	6550	5900	207
350	70	24,5	10	0,86	3,870	9150	7000	374
410	58	23,0	10	0,95	2,230	6660	5100	288
412	60	25,0	10	1,0	2,260	7080	5400	286
410	63	26,0	10	1,45	2,330	6430	4950	250
380	72	27,5	10	1,51	2,750	7040	5400	256
390	69	27,0	10	1,67	2,890	6200	4800	230
320	92	29,5	10	1,89	2,350	4520	3500	183
320	72	23,2	10	1,73	2,880	6030	4650	186

The enthalpy of the plasma jet was determined from the formula of Fay and Riddel, which for a nitrogen, argon, and hydrogen plasma under the conditions of partial ionization was transformed by the authors of [6] into the expression

$$q = 4.5 \cdot 10^{-4} R^{-0,5} P_0^{0,25} (P_0 - P_\infty)^{0,25} \cdot (H_0 - H_\infty),$$

where

$$q = c_p \rho l \frac{dT}{d\tau}.$$

The pressure P_0 was measured with a Pitot tube whose geometrical parameters are identical to the parameters of the mounting of the calorimetric probe. The average-mass temperature T in °K was determined from the enthalpy using the tables of [5].

The results of measurements of the specific heat flux, enthalpy, and average-mass temperature as a function of the power, the flow rate of the plasma-forming gas, and the distance along the jet axis are presented in Table 1.

The reduced enthalpy of the plasma jet as a function of the distance along the jet axis and the specific power (a), and of the percentage content of hydrogen (α_{H_2}) in the nitrogen plasma jet (b) are shown in Fig. 2.

A comparison was made with the results of the measurement of the thermal characteristics of the plasma jet obtained by the integral Grey probe for L = 30 mm. The calculated specific heat flux, summed on the basis of data of local measurements of the jet, differs from the in-

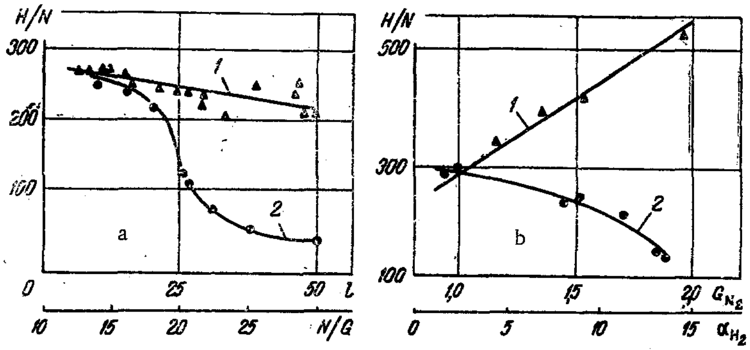

Fig. 2. Dependence of reduced enthalpy (kJ/kg·kW) on specific power (kW/h/sec) (1,a), distance along axis (2,a), percentage content of hydrogen in jet (1,b), and nitrogen flow rate (2,b).

tegrally measured flux within the limits of the experimental error. The use of the integral calorimetric probe made it possible to determine the thermal characteristics for L = 10 mm. In this case we determined the integral values of the thermal characteristics for a cross section of the plasma jet 10 mm in diameter corresponding to the probe diameter.

The obtaining of working modes of the plasmotron with only one varying parameter of the power (the current or voltage) presented some difficulty in the experimental measurements. For example, the burning up of the electrodes, a change in the flow rate of the plasma-forming gas, or the addition of hydrogen to the plasma produced simultaneous changes in both discharge parameters. As a result of this some scatter in the values of the power was observed for the individual experiments. This, in turn, hindered the comparison of the thermal characteristics in the course of the experiments. For simplification, therefore, the experimental data in Fig. 2 are analyzed in reduced coordinates: H/N is the enthalpy reduced to unit power and specific power; N/G is the power per unit flow rate of the working gas.

A comparison of the data of Table 1 marked with an asterisk shows that despite the difference in currents or voltages the equal discharge power in the different experiments permits one to obtain identical thermal characteristics and, conversely, when the voltage or current is the same but the values of the power are different the thermal characteristics of the plasma jet differ. It is obvious that when estimating these data it is desirable to orient oneself not to the current or voltage of the discharge individually but to the discharge power as a whole.

The data of Table 1 show that the heat flux and enthalpy increase relatively rapidly with an increase in the discharge power to 20-22 kW. Their growth slows with a further increase in power. Here the heat flux per unit power is constant, while the reduced enthalpy H/N declines markedly. This decline in the reduced enthalpy and slowing of the increase in enthalpy is clearly connected with the decline in the density of the plasma jet with an increase in its temperature. The decline in reduced enthalpy with an increase in specific power (Fig. 2a) is obviously connected with this.

The thermal characteristics vary sharply along the axis of the plasma jet. In this connection the investigated interval of distances from the nozzle cut can be divided into two zones: the first, up to 25 mm, where the reduced enthalpy is rather high (up to 260), and the second, beyond 25 mm, where it declines by five to six times. One can see that the thermal characteristics decline slightly up to 25 mm but then decline sharply from 25 to 45 mm, and their values differ by an order of magnitude for distances beyond 45 mm. The subsequent decline in thermal characteristics occurs more smoothly.

In the course of the experiments it was noted that this decline in the thermal characteristics along the length of the jet becomes smoother upon the addition of hydrogen to the nitrogen plasma jet.

An increase in the flow rate of the working gas within the limits of 0.86-1.73 g/sec leads to a marked decrease in the specific heat flux, enthalpy, average-mass temperature, and reduced enthalpy. However, the reduced enthalpy varies insignificantly as a function of the specific power (Fig. 2a). Obviously, an increase in the flow rate of the working gas slows the decline in the density of the plasma jet.

The thermal characteristics increase considerably upon the addition of hydrogen to the nitrogen plasma jet. Even a 15% admixture of hydrogen allows one to obtain thermal characteristics equal to the characteristics of a pure nitrogen plasma with twice the power. Since a linear dependence of the characteristics was observed with the addition of up to 15% hydrogen and almost no tendency toward a slowing of their growth was noted, the possibilities of this means of increasing them for a plasma atomizer are not yet restricted.

In comparing the results of this work with the results of the work of other authors (such as [8]) one can be convinced of their agreement within the limits of the experimental error.

The experimental data obtained and the discussion of them allow one to draw the following conclusions:

1. The effective zone of heat exchange of a plasma jet is its section at distances of up to 25 mm from the nozzle cut with a radius equal to 1-1.5 times the nozzle radius.

2. Because the plasma jet has a pulsating character its average-mass temperature is almost twice as low as its temperature obtained by spectral measurements, which must be allowed for in a calculation of the heat exchange.

3. An increase in the gas flow rate at a constant discharge power leads to a decrease in the thermal characteristics. Therefore, in choosing the working conditions of the atomizer one should match the flow rate of the working gas with the discharge power. The addition of hydrogen to a nitrogen plasma jet makes it possible to considerably enhance its thermal characteristics.

NOTATION

I, current, A; U, voltage, V; N, discharge power, kW; L, distance along jet axis from nozzle cut of plasmotron, mm; G_{N_2}, nitrogen flow rate, g/sec; q, specific heat flux, kW/cm²; H, enthalpy, kJ/kg; R, radius of curvature of protective sleeve, mm; c_p, specific heat capacity, cal/g·deg; ρ, density of probe material, g/cm³; l, length of probe, mm.

LITERATURE CITED

1. G. S. Antonov et al., in: Proceedings of Third All-Union Conference on Low-Temperature Plasma Generators [in Russian], Énergiya, Moscow (1969).
2. A. V. Lykov, V. L. Sergeev, and A. G. Shashkov, in: High-Temperature Thermophysics (A. V. Lykov, editor) [in Russian], Nauka, Moscow (1969).
3. S. V. Dresvin (editor), Physics and Technology of a Low-Temperature Plasma [in Russian], Atomizdat, Moscow (1972).
4. J. Grey et al., Prib. Nauch. Issled., 33, No. 7, 29-33 (1962).
5. L. V. Gurevich et al., Thermodynamic Properties of Individual Substances, Vol. 2 [in Russian], Izd. Akad. Nauk SSSR, Moscow (1962), p. 234.
6. V. L. Sergeev, G. M. Bezladnov, and V. D. Lyashkevich, Inzh.-Fiz. Zh., 20, No. 4, 622 (1972).
7. V. L. Sergeev, A. G. Shashkov, and L. N. Sergeeva, Inzh.-Fiz. Zh., 25, No. 4, 660 (1968).
8. M. V. Volk-Levanovich, F. B. Yurevich, and A. G. Shashkov, in: Heat and Mass Transfer and Thermal Properties of Materials (A. G. Shashkov and Yu. E. Fraiman, editors) [in Russian], Nauka i Tekhnika, Minsk (1969).