GENERALIZATION OF THE OPERATING CHARACTERISTICS OF A SEGMENTED PLASMA GENERATOR WITH CONSTRICTED CHANNEL

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The current-voltage characteristics of a plasma generator with a segmented channel have been experimentally investigated at reduced pressures.

The most convenient means of fixing the geometry of an arc is to use an extended interelectrode insulating insert. However, in practice difficulties arise in connection with the choice of insert material owing to the rather severe thermal conditions associated with arcs burning in a channel, so that in industrial plasma generators the channel is assembled from insulated cooled metal segments [1, 2]. This design has certain disadvantages compared with plasma generators with a continuous interelectrode insert (electron leakage, increased heat transfer to the cooling walls). Nonetheless, it is now in quite extensive use.

The current-voltage characteristics, which make it possible to calculate the geometry of the plasma generator and specify its operating regime, are usually obtained experimentally, since the solution of the equations that constitute the mathematical model of the processes in a plasma generator channel is generally difficult.

The starting equations describing the processes in the channel are: the energy equation in the Heller-Elenbaas form, the equation of motion of the fluid, the equation of state, Ohm's law, and the relation describing Steenbeck's minimum principle. From these equations the similarity criteria used in analyzing the experimental data are derived. The similarity criteria are related as follows [2, 3]:

$$U = f(I, R, K, L), \quad U = \frac{v d_k \sigma}{i}, \quad I = \frac{i^2}{G d_k \sigma h}, \quad R = \frac{w d_k}{\nu}, \quad K = \frac{\delta}{d_k}, \quad L = \frac{l}{d_k}. \tag{1}$$

Here U is the criterion obtained from Ohm's law; I is the criterion derived from the energy equation; R is the Reynolds number obtained from the equation of motion; K is the Knudsen number characterizing the motion of the gas at reduced pressures; L is the geometric similarity criterion; here and in what follows σ denotes the plasma conductivity, 1/ohm; h the specific enthalpy, kcal/kg; G the gas flow rate, g/sec; $\langle p \rangle$ the mean pressure in the plasma generator channel, N/m^2; d_k, d_c the diameters of the channel and the nozzle throat, m; l the channel length, m; T the temperature of the jet, °K; w the gas velocity, m/sec; ν the kinematic viscosity, m^2/sec; δ the mean free path, m; i the current, A; and v the voltage, V.

In connection with a number of processes it is important to be able to obtain high-velocity and high-enthalpy plasma jets. There are various ways of increasing jet velocity; by increasing the gas flow rate, by reducing the pressure in the system, and by introducing specially designed nozzles at the channel outlet. Introducing nozzles leads to a change in the electrical operating parameters of the plasma generator, which depend significantly on the degree of constriction of the channel by the nozzle-orifice.

The increased pressure in the channel due to orificing leads to a change in the current-voltage characteristics of the arc. The change in pressure can be taken into account in terms of the criterion K, but nonetheless the curves are found to be stratified depending on the diameter of the nozzle-orifice. Re-

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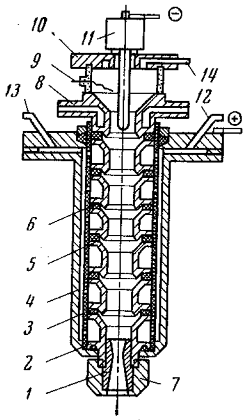

Fig. 1

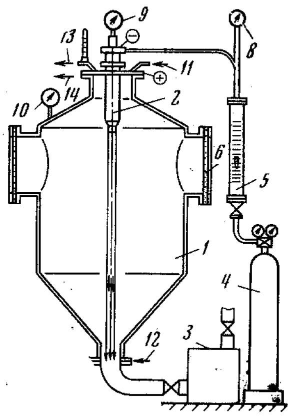

Fig. 2

Fig. 1. 100-kW segmented plasma generator: 1) nozzles 4, 8, 12 and 16 mm in diameter; 2) anode segment; 3) insulator cup; 4) housing; 5) intermediate segments; 6) intersegmental insulators; 7) captive nut; 8) auxiliary anode; 9) firing electrode; 10) quartz insert; 11) cathode holder with cathode; 12) cooling water inlet; 13) water outlet; 14) argon inlet.

Fig. 2. Experimental apparatus: 1) vacuum chamber; 2) segmented plasma generator; 3) VN-300 vacuum pump; 4) argon cylinder; 6) RS-5 rotameter; 6) observation windows; 7) plasma jet during operation; 8) OBMV-160 manometer; 9, 10) OKV reference vacuum gauges; 11, 12) water inlet; 13, 14) cooling water outlet.

calling that the Knudsen number can be expressed in terms of the Reynolds and Mach numbers ($K = M/R^{0.5}$), in accordance with the theory of similarity we can write Eq. (1) with R omitted, at the same time supplementing it with another criterion (generalized variable), so that the number of determining criteria remains unchanged. As a subsequent analysis of the experimental results showed, in the first approximation a convenient generalized variable is apparently to be found in the parametric criterion $D = d_k/d_c$; i.e., relation (1) takes the form

$$U = AI^m K^n L^n D^q \, . \qquad (2)$$

We have conducted an experimental investigation of a segmented plasma generator with nozzle-orifices. The plasma generator (Fig. 1) consisted of six segments 20 mm high with a channel diameter of 20 mm. Nozzles 4, 8, 12, 16 mm in diameter were attached to the anode segment. The gas (argon) flow rate was varied between 0.2 and 3.5 g/sec. The experimental apparatus is shown in Fig. 2. The plasma jet flowed into a chamber 800 mm in diameter and 1500 mm high. The chamber pressure during the experiments was $1.33 \cdot 10^2 - 1.33 \cdot 10^3$ N/m^2, while the channel pressure created by the nozzles varied on the interval $1.33 \cdot 10^3 - 1.33 \cdot 10^5$ N/m^2. At the same time as we recorded the current-voltage characteristics, we measured the enthalpy of the jet at the nozzle exit. The enthalpy was calculated by recording the heat balance of the plasma generator. The difference between the electric power supplied to the arc and the measured total heat losses through each segment divided by the gas flow rate gives the enthalpy of the jet at the nozzle exit [4]. From the enthalpy values, using tabulated data [5], we determined the mass-average temperature of the plasma flow at the plasma generator outlet.

The primary experimental data are presented in Table 1.

For purposes of comparison with the known criterial relations the results obtained were analyzed in generalized form in accordance with Eq. (2) for a constant parameter L = 6.

Table 1

d_c, cm	i, A	v, V	G, kcal/kg	h, kcal/kg	$\langle P\rangle$, N/m²	T, °K	K	U	I
2.0	500	81	0.62	6340	$6.34\cdot10^3$	11300	$1.93\cdot10^{-2}$	32.4	690
	475	84	1.18	4230	$9.33\cdot10^3$	10800	$1.72\cdot10^{-2}$	35.0	346
	450	90	1.84	3120	$1.23\cdot10^4$	10300	$1.56\cdot10^{-2}$	50.0	206
	400	97	3.40	1780	$1.83\cdot10^4$	9700	$1.34\cdot10^{-2}$	48.5	94
1.6	450	84	1.16	3375	$9.86\cdot10^3$	10300	$1.54\cdot10^{-2}$	37.2	331
	425	88	1.78	2700	$1.31\cdot10^4$	10100	$1.41\cdot10^{-2}$	41.5	196
	410	92	2.50	2100	$1.69\cdot10^4$	9700	$1.25\cdot10^{-2}$	44.7	135
	400	93	3.37	1700	$2.12\cdot10^4$	9300	$1.12\cdot10^{-2}$	49.0	99
1.2	500	83	0.60	5850	$9.66\cdot10^3$	11500	$1.27\cdot10^{-2}$	33.2	700
	425	89	1.90	2140	$2.02\cdot10^4$	10000	$9.35\cdot10^{-3}$	42.0	186
	410	95	2.57	1730	$2.66\cdot10^4$	9500	$7.86\cdot10^{-3}$	46.4	134
	400	101	3.24	1140	$3.18\cdot10^4$	9000	$7.10\cdot10^{-3}$	50.5	110
0.8	450	90	0.79	2110	$2.16\cdot10^4$	9950	$5.56\cdot10^{-3}$	40.0	497
	450	99	1.40	1840	$3.54\cdot10^4$	9600	$4.40\cdot10^{-3}$	44.0	294
	400	101	2.10	1270	$4.76\cdot10^4$	8800	$3.37\cdot10^{-3}$	50.4	168
	390	102	2.32	1160	$5.26\cdot10^4$	8450	$3.59\cdot10^{-3}$	52.1	150
0.4	400	110	3.71	287	$4.8\cdot10^4$	2400	$1.68\cdot10^{-3}$	55.0	320
	450	104	2.88	232	$4.9\cdot10^4$	2000	$1.28\cdot10^{-3}$	46.1	614
	450	100	2.23	252	$4.96\cdot10^4$	2100	$1.14\cdot10^{-3}$	44.3	759
	450	93	1.64	461	$5.0\cdot10^4$	3560	$1.60\cdot10^{-3}$	43.5	594
	200	73	1.04	296	$5.12\cdot10^4$	2480	$8.46\cdot10^{-4}$	73.1	277

In computing the similarity criteria the principal difficulty consists in evaluating the characteristic temperature.

Previous thermal investigations of plasma heating efficiency [6] enabled us to take as the characteristic temperature of the gas (plasma) the arithmetic mean of the temperatures at the channel inlet and the channel outlet. The velocities and the enthalpy were referred to this temperature. The scatter of the experimental data did not exceed ±10%. However, the temperature at the generator outlet is itself to be determined. Therefore, as in calculating heat-exchange apparatus, it is necessary to proceed by the method of successive approximations, first specifying this temperature and subsequently corecting it on the basis of the results of the calculation. In our case in the preliminary calculations it is possible to use the experimentally determined dependence of the temperature at the nozzle outlet on the nozzle diameter (for fixed arc powers and flow rates T = 10,000–9500° K for D = 1–2 and T = 2500° K for D = 2–5). This temperature can be used in estimating the enthalpies, the coefficient of viscosity, thermal conductivity, and density, which on the temperature ranges investigated vary monotonically or linearly with temperature. In practice, the characteristic temperature for computing the enthalpies and velocities is equal to half the flow temperature at the nozzle outlet. In estimating the electrical conductivity it is not desirable to refer its value to the above-mentioned temperature, since $\sigma = \sigma(t)$ is sharply expressed, especially at temperatures below 9000° K.

Starting from the channel-arc model, according to which the axial regions of the arc, where the temperature is above 10,000° K, are current-conducting, it was found possible to take a certain mean value of the electrical conductivity for this temperature zone, since at temperatures above 9000° K the variation of σ with temperature becomes unimportant [5]. Such an assumption, despite its incorrectness, makes it possible to express the experimental data more strictly in accordance with similarity theory than when the frequently employed dimensional complexes $U = vd_k/i$, $I = l^2/Gd_k$ are used. In computing the similarity criteria we took a value $\sigma = 10^4$ 1/ohm·m, which corresponds to a mean temperature of 10,000° K. Strictly speaking, this quantity could have been introduced into coefficient A of Eq. (2). However, in analyzing the nature and conditions of the transport processes there is a certain convenience in retaining the theoretical form of the similarity criteria and estimating their real values.

An analysis of the tabulated primary data enabled us to obtain the dependence

$$U = 1.91\, I^{-0.2} K^{-1.0} D^{-1.3}, \quad 10^2 < I < 10^3, \quad 5\cdot10^3 < K < 5^{-}10^2, \; 1 < D < 5. \qquad (3)$$

The scatter of the experimental data about the mean value of U does not exceed ±15%.

If we use the dependence $U \sim L^{0.65}$ [8], we can write

$$U = 0.6\, I^{-0.2}\, K^{-1.0} D^{-1.3}\, L^{0.65}, \qquad (0.3 < L < 11.0). \tag{4}$$

The experimental results obtained makes possible a practical evaluation of the operation of similar segmented plasma generators with constricted channels at channel pressures below $1.33 \cdot 10^5$ N/m^2.

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