CHARACTERISTICS OF A PLASMATRON WITH TRANSPIRATION COOLING OF THE ANODE

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One important characteristic of a plasma heater is its efficiency, which is usually defined as the ratio of the power expended on increasing the enthalpy of the heated gas to the total power generated in the arc column. The energy losses, which often constitute more than one half of the generated power, are attributable, in large measure, to the need to cool the electrodes in order to prevent their disintegration. Studies of the thermal balances of electric arcs with high-melting rod cathodes have shown that the greater part of the energy loss is incurred at the anode. For example, in the case of a free-burning arc in an argon medium the total heat influx into the anode at currents of 50–150 A constitutes 75–90% of the total generated power [1]. Radiation can produce further energy losses at gas temperatures >10 000° K [2].

One effective way to increase the efficiency of electric arc heaters is to employ the regenerative cooling method known as "transpiration cooling." This method is gaining increasing acceptance as a means of shielding various parts of instruments from the action of high-temperature gas flows. Its effectiveness depends essentially on the relative rate of coolant discharge through the porous wall and also on the physical properties of the coolant and the main stream. The specific nature of the processes occurring in an electric arc heater is determined by the very high temperatures at the base spots of the electric arc. The electrode material must be highly heat-resistant; in addition, erosion of the material by the arc must not affect its permeability. All these requirements are satisfied by porous graphite.

In recent years, there have been several studies of arcs with transpiration cooling of the anode. Experiments on free-burning arcs were carried out by the authors of [3–6]; paper [7] describes an experimental study of a stabilizer arc. These studies demonstrated the feasibility and considerable effectiveness of transpiration cooling for plasma-heater electrodes.

The purpose of our experiments was to investigate the effect of transpiration cooling of the anode on the thermal and voltage-current characteristics of a single-chamber plasmatron with vortical arc stabilization in the 1–0.1-atm pressure range.

1. The experimental setup and measurement procedure. The diagram of the plasmatron appears in Fig. 1. Anode 2 was made of porous graphite of inside diameter 8 mm and relative length $l/d = 10$. The porosity of the graphite was approximately 25%; the average pore size was 17 μ. Cathode 4 took the form of a water-cooled tungsten rod 5 mm in diameter with a tip angle of 60°. The plasmatron was powered by dc generator 6 by way of tapped water-cooled wire-wound rheostat 7. The arc was fired by means of a high-voltage discharge. The working gas (argon) was fed in partly through vortex chamber 3 and partly through the porous anode. The plasmatron was connected to vacuum chamber 1, in which the minimum pressure during the experiments reached 1×10^{-2} mm Hg. The anode (except at the end packings) was cooled by the gas blown through it. The end packings of the anode were water-cooled. The experiments involved measurement of the arc current and voltage, of the gas discharge rates G_0 through the vortex chamber and through the anode G_W, of the discharge rate and of the change in the temperature of the water cooling the cathode and the anode end packings, as well as of the static pressures p_1 in the vortex chamber and p_2 at the end of the anode.

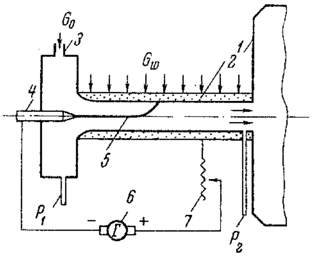

Fig. 1

Experimentally measured quantities were used to compute the thermal influxes into the electrodes, the mass-averaged enthalpy and gas temperature at the exit cross section of the anode, the heater efficiency, and the relative mass velocity of the gas through the anode surface $\tilde{j} = \rho W/\rho_0 W_0$. Radiation was not included in the thermal balance. The enthalpy of the plasma jet was also measured by means of a specially designed continuous-flow calorimeter. The resulting value lay within 10% of the enthalpy computed on the basis of calorimetric measurements of the thermal losses. The basic measured and calculated data appear in the table.

We also determined the erosion of the porous graphite anode. After 9 hr of operation of the plasmatron, the weight of the anode had decreased by 0.065 g; most of the material appeared to have been eroded during the initial period of operation of the heater (during its actuation). This was evidenced by the presence of brightly glowing particles in the heated gas stream which vanished after the heater had been operating for a while. The apparent cause of this effect was the thermal shock at the instant of heater actuation.

2. The thermal characteristic of the plasmatron. The experimental data concerning the efficiency of the plasmatron were generalized according to the procedure described in [7], whose authors obtained the structural dependence of the efficiency in the presence of a laminar boundary layer at the channel walls. With allowance for the delivery of material through the anode surface, this dependence can be expressed as

$$(1-\eta)\,\eta^{-1} R_d^{1/2} P^{2/3} = f\,(l/d,\ \varepsilon,\ \tilde{j}), \quad (R_d = \rho_0 W_0\, d/\mu). \qquad (2.1)$$

Here R_d is the Reynolds criterion computed from the parameters of the main stream and the mass-averaged output temperature. The function $\mu(T)$ was taken from [9]; P is the Prandtl number; ε is a parameter which corrects for the breakdown effect; $\tilde{j}$ is the relative mass velocity of the gas stream through the wall; l/d is the relative length of the output electrode. The data identified by numbers in the right-hand column of the table correspond to the following experimental points in Figs. 2–7: 1) crossed circles, 2) circles with vertical lines, 3) open circles, 4) open triangles, 5) open diamonds with horizontal whiskers, 6) filled diamonds with horizontal whiskers, 7) filled diamonds with vertical whiskers, 8) circles with filled left halves, 9) open diamonds, 10) circles with filled right halves, and 11) circles with filled lower halves.

Figure 2 shows the efficiency as a function of R_d for the constant value $\tilde{j} = 0.018$ at atmospheric pressure. In the range of Rd investigated, $(1-\eta) \times \eta^{-1} \sim R_d^{-1/2}$. Our experiments on the effect of the inside diameter of the anode on the plasmatron characteristics enabled us to take the Knudsen number $K = \Lambda/d$ as a parameter characterizing the breakdown conditions. Fig 4 shows $\tilde{\eta} = (1-\eta)\eta^{-1}\sqrt{R_d}$ as a function of K.

Figure 3 shows the effect of the gas stream through the surface of the anode. We see that the use of transpiration cooling resulted in a considerable decrease in the thermal load of the anode.

Figure 5 shows the thermal characteristic of the plasmatron investigated. To within ±15%, this dependence in the range of parameters

$$R_d = (0.35\text{—}11.00) \times 10^3\ ,$$
$$K = (0.23\text{—}12.25) \times 10^{-4}\ ,$$
$$\tilde{j} = 0.014\text{—}0.125$$

can be expressed as

$$(1-\eta)\eta^{-1} = 2.9\ R_d^{-0.5} K^{-0.15} \tilde{j}^{-0.25}\ . \qquad (2.2)$$

U, V	I, A	G_0, g/sec	$\tilde{j}$	p_2, atm	η	T, °K	$R_d \cdot 10^{-3}$	$K \cdot 10^4$	
39.5	16.3	0.40	0.018	0.96	0.48	1160	1.100	0.459	1
25.4	52.3	0.40	0.018	0.96	0.46	2030	0.795	0.846	
22.6	87.2	0.40	0.018	0.96	0.43	2690	0.670	1.142	
20.4	154.0	0.40	0.018	0.96	0.42	3980	0.521	1.790	
28.2	51.5	0.80	0.0205	0.98	0.56	1380	1.960	0.550	2
26.0	85.3	0.80	0.0195	0.98	0.54	1920	1.610	0.779	
24.0	149.0	0.80	0.0188	0.98	0.53	3120	1.200	1.320	
23.0	16.0	1.31	0.0211	0.98	0.66	650	5.200	0.232	3
49.6	51.1	1.31	0.0208	0.98	0.62	1020	3.800	0.393	
27.6	84.1	1.31	0.0195	0.98	0.60	1440	3.110	0.570	
25.0	149.0	1.31	0.0168	0.98	0.59	2200	2.490	0.908	
24.0	14.8	2.39	0.0220	0.98	0.75	560	11.000	0.194	4
55.5	49.1	2.35	0.0200	0.98	0.72	860	7.800	0.321	
30.3	83.2	2.37	0.0165	0.98	0.70	1190	6.400	0.471	
37.8	147.0	2.36	0.0135	0.98	0.67	1730	5.080	0.700	
22.5	15.0	0.34	0.0700	0.091	0.65	1058	0.972	4.420	5
58.8	51.1	0.34	0.0692	0.112	0.63	1700	0.740	6.030	
24.3	86.0	0.34	0.0670	0.126	0.62	2300	0.615	7.400	
22.2	152.0	0.34	0.0645	0.145	0.59	3470	0.490	10.120	
20.0	50.9	0.58	0.0480	0.97	0.60	1340	1.440	0.537	6
35.0	85.4	0.59	0.0440	0.97	0.57	1640	1.300	0.670	
22.4	149.0	0.59	0.0370	0.97	0.55	2630	1.000	1.106	
26.4	52.0	0.27	0.125	0.97	0.55	1190	0.715	0.475	7
21.8	87.2	0.26	0.126	0.97	0.54	1560	0.590	0.634	
21.8	151.8	0.27	0.100	0.97	0.53	2820	0.439	1.192	
20.6	51.2	0.80	0.0495	0.96	0.63	940	2.270	0.413	8
37.8	85.5	0.80	0.0424	0.96	0.62	1710	1.820	0.641	
24.8	151.0	0.80	0.0329	0.96	0.59	2720	1.400	1.061	
22.5	16.0	0.41	0.0665	0.99	0.61	830	1.370	0.307	9
48.0	51.4	0.41	0.0555	0.98	0.53	1420	0.975	0.566	
24.2	85.8	0.41	0.0485	0.98	0.51	2000	0.805	0.817	
28.4	51.9	0.42	0.0170	0.165	0.50	2300	0.620	5.660	10
24.0	86.5	0.42	0.0170	0.165	0.50	3100	0.435	7.860	
20.4	153.0	0.42	0.0170	0.162	0.49	4430	0.348	12.250	
26.2	52.1	0.40	0.0180	0.546	0.44	1970	0.637	1.440	11
22.6	87.0	0.40	0.0180	0.546	0.43	2660	0.501	1.990	
20.0	152.0	0.40	0.0180	0.555	0.43	3910	0.367	2.920	

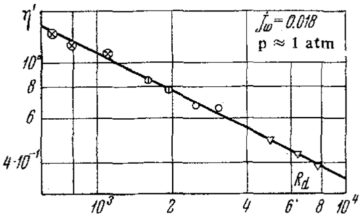

Fig. 2

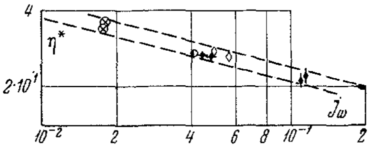

Fig. 3

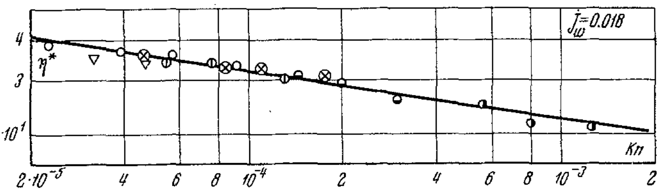

Fig. 4

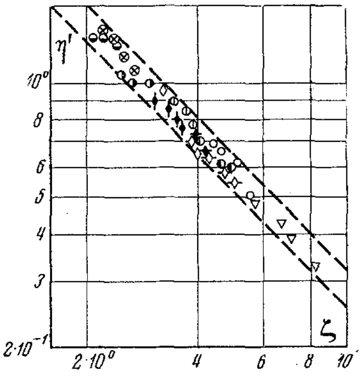

Fig. 5

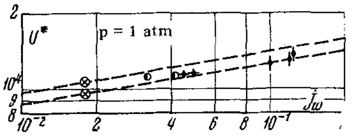

Fig. 6

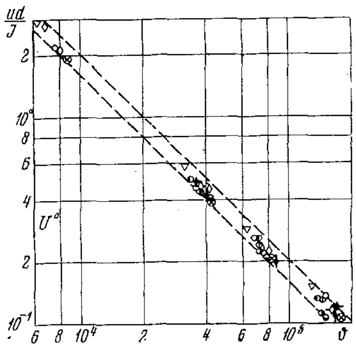

Fig. 7

3. **The voltage-current characteristic of the plasmatron.** Following [8, 10, 11], we generalized the voltage-current characteristics with allowance for coolant delivery through the anode surface by way of the equation

$$\frac{Ud}{I} = C\left(\frac{I^2}{G_0 d}\right)^m R_d^{\,n} \tilde{j}^p . \qquad (3.1)$$

The values of m and n turned out to be the same as those given in [8], i.e., −0.75 and −0.5, respectively. The effect of transpiration cooling of the anode on the voltage-current characteristic of the heater is illustrated in Fig. 6, which shows $\tilde{U} = Ud/I \times (I^2/G_0 d)^{0.75} R_d^{0.5}$ as a function of $\tilde{j}$. We see from this figure that the delivery of gas through the anode of the surface increased the resistance of the electric arc column. Figure 7 shows the generalized voltage-current characteristic on the basis of our experiments. To within ±15% this characteristic is described by the expression

$$\frac{Ud}{I} = 1.8 \cdot 10^4 \left(\frac{I^2}{G_0 d}\right)^{-0.75} R_d^{-0.5} \tilde{j}^{0.13} \qquad (3.2)$$

in the range

$$I^2/G_0 d = (0.1-100)\times 10^3, \; R_d = (0.35-11.00)\times 10^3,$$

$$\tilde{j} = 0.014-0.125 \, .$$

As is evident from the experimental data in the table, the maximum efficiency achieved in our experiments was 75%; it was not our intention, however, to achieve maximum possible efficiencies, which can approach unity.

In addition to its high efficiency, a heater with transpiration cooling of the electrodes has the advantage of relatively slight contamination of the stream by the products of electrode erosion.

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