THE EFFECT OF CONVECTIVE HEAT EXCHANGE ON PLASMATRON CHARACTERISTICS

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Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 8, No. 1, pp. 157-160, 1967

ABSTRACT: Experimental data on plasmatron efficiency are generalized. Data for the 760-32 mm Hg pressure range are used to obtain a criterial equation for the efficiency and a generalized current-voltage characteristic.

At pressures $\lesssim 10^3$ mm Hg and temperatures < 10 000° K the effect of the intrinsic arc radiation on the plasmatron walls can be ignored [1, 2]. The efficiency is then determined by convective heat transfer; by definition,

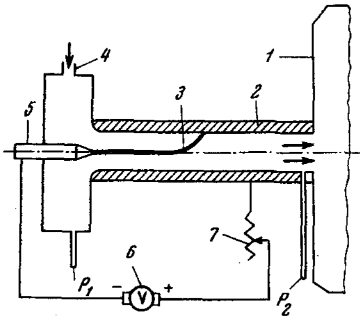

Fig. 1

$$\eta = G\Delta h / IU = 1 - Q / IU. \tag{1}$$

For a single-chamber plasmatron (Fig. 1) we have

$$Q = \alpha\,(h_2 - h_w)\ \pi dl. \tag{2}$$

Here h_2 is the mass-average enthalpy of the gas at the plasmatron exit; α is the heat exchange coefficient averaged over the surface πdl. The quantity so defined also takes into account heat exchange in the electrode spots.

For ordinary conditions ($h_w \ll h$ and $h_1 \ll h_2$) Eqs. (1) and (2) yield

$$\frac{1-\eta}{\eta} = 4\frac{l}{d}S \qquad S = \frac{\alpha}{g}. \tag{3}$$

Here S is the Stanton number and g is the mass stream velocity.

We know [3] that when there are no perturbations of the boundary layer at the channel walls when $h_w < h$, the local value of the Stanton number depends very weakly on the enthalpy factor $\psi = h_w/h$ in both the laminar and turbulent boundary layers ($S \sim \psi^{-n}$, where $n \leq 0.1$).

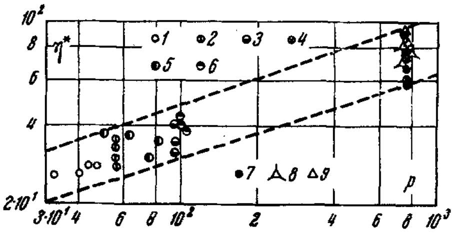

Fig. 2

The analysis of heat exchange under plasmatron conditions is complicated by the considerable longitudinal nonisothermal character of the stream and by the conditions of arc formation. As long as $h_2 \gg h_1$ the voltage gradient along the length of the arc remains approximately constant, and the variation of the mass-average enthalpy over the channel cross section is a function of the relative distance x/d only.

The following relation is valid for extremely diverse boundary conditions in a laminar boundary layer:

$$S \sim R_x^{-1/2} P^{-2/3}; \quad \left(R_x = \frac{gx}{\mu}\right). \tag{4}$$

Here R_x is the Reynolds number and P is the Prandtl number. On the basis of (3) and (4) we can take

$$\frac{1-\eta}{\eta} R_d^{1/2} P^{2/3} = f\left(\frac{l}{d}, \varepsilon\right) \tag{5}$$

for the conditions of heat exchange in the plasmatron channel.

Here ε is some parameter which allows for the breakdown effect.

Once we have an expression for the efficiency we can compute the current-voltage characteristic, provided we know the relation for the complexes $Ud\sigma_0/I$ or $I^2/Gd\sigma_0\Delta h$. If by $\Delta h \approx h_2$ in this case we mean the increase in the mass-average enthalpy of the gas in the plasmatron, we have

$$Ud\sigma_0 / I = Gd\sigma_0 h / I\eta. \tag{6}$$

Let us assume that

$$Ud\sigma_0 / I = \varphi\,(R,\ P,\ \varepsilon, \ldots). \tag{7}$$

At present there is no satisfactory method of choosing the "determining" value of the conductivity. Data on the thermophysical properties of gases at plasma temperatures are themselves quite scarce. For this reason we attempt to find the current-voltage characteristic in the form [4-6].

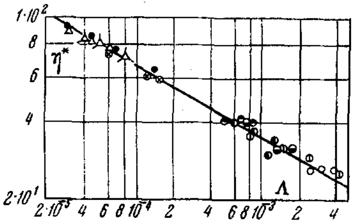

Fig. 3

$$Ud / I = \varphi_1\,(I^2 / Gd,\ R, \ldots). \tag{8}$$

Our purpose in the present study was to investigate a plasma heater in the low-pressure range and to investigate the general regularities of heat exchange in the plasmatron channel, i.e., to establish the degree of applicability of relation (5).

A diagram of the plasmatron appears in Fig. 1, where 1 is the vacuum chamber, 2 the anode, 3 the electric arc, 4 the gas intake, 5 the cathode, 6 the power source, and 7 a rheostat; p_1, p_2 are the static pressures in the arc chamber and in the exit cross section of the anode (cathode 5 is a tungsten rod of diameter 5 mm with a tip vertex angle of 60°; anode 2 is a copper cylinder with an inside diameter of 8 mm). The electrodes were water-cooled. The gas was fed into the chamber through six peripheral holes 1.6 mm in diameter. The twist ring was made of asbestos cement with an inside diameter of 40 mm. Power source 6 was a 220-V dc generator. The plasma jet entered vacuum chamber 1 in which the minimal pressure during the experiments was $1\cdot10^{-2}$ mm Hg. We measured the arc current and voltage, the gas consumption, the consumption and variation in temperature of the water cooling the electrodes, and the static pressures in the arc chamber and at the exit cross section of the anode at a distance of 1 mm from its end.

Experiment no.	U,V	I, A	G, g/sec	p, mm Hg	T, °K	R_d	$10^3 \Lambda$, cm	Ud/I	$10^{-3} I^2/Gd$	η	Point nos. (Fig. 2)
1	62.8	15.8	0.432	32	2550	754	1.98	3.190	0.71	0.51	1
2	33.5	56.0	0.446	40	4180	558	2.55	0.478	8.80	0.48	
3	25.4	98.2	0.446	44	5000	471	3.28	0.207	27.101	0.44	
4	23.8	152.6	0.446	47	6760	385	4.36	0.125	65.50	0.41	
5	55.5	16.7	0.441	56	2070	812	0.91	2.660	0.78	0.44	2
6	33.6	53.6	0.440	56	3620	614	1.67	0.501	8.18	0.43	
7	25.7	98.2	0.444	56	4900	480	2.50	0.201	27.20	0.42	
8	22.8	153.0	0.449	56	6560	400	4.60	0.119	65.00	0.42	
9	31.5	53.2	0.439	95	3150	671	0.83	0.473	8.05	0.39	3
10	25.0	98.7	0.441	95	4730	494	1.40	0.203	27.70	0.41	
11	22.4	152.0	0.444	95	5940	423	1.91	0.117	65.60	0.38	
12	25.0	56.0	0.438	755	2040	860	0.06	0.357	8.94	0.29	4
13	24.4	98.8	0.438	755	3380	639	0.11	0.198	27.90	0.29	
14	21.8	152.0	0.438	755	4380	527	0.16	0.115	65.80	0.28	
15	55.0	16.5	0.864	50	1390	2110	0.67	2.670	0.39	0.54	5
16	35.5	53.5	0.873	63	2430	1540	0.96	0.531	4.10	0.51	
17	31.0	95.6	0.882	76	3800	1190	1.25	0.259	12.96	0.54	
18	25.6	150.5	0.885	82	4220	1100	1.39	0.136	32.10	0.49	
19	33.5	54.0	0.880	101	2270	1630	0.55	0.496	4.15	0.50	6
20	27.8	97.5	0.880	103	3050	1370	0.74	0.228	13.51	0.46	
21	25.6	149.1	0.882	105	3870	1170	0.97	0.137	31.50	0.46	
22	33.0	25.3	0.878	750	960	2690	0.03	1.041	0.91	0.36	7
23	26.6	55.9	0.880	750	1410	2120	0.05	0.381	4.43	0.34	
24	23.6	98.5	0.882	750	2060	1710	0.07	0.192	13.80	0.35	
25	23.4	151.0	0.885	750	3040	1380	0.10	0.124	32.20	0.36	
26	29.4	55.2	1.460	755	1215	3900	0.04	0.426	2.60	0.43	8
27	26.8	97.6	1.470	755	1730	3160	0.06	0.220	8.12	0.42	
28	26.3	158.0	1.480	755	2550	2560	0.09	0.133	21.15	0.42	
29	42.3	24.5	2.480	764	703	9350	0.02	1.380	0.30	0.51	9
30	33.3	54.1	2.500	766	987	7500	0.03	0.493	1.47	0.50	
31	30.0	96.5	2.470	755	1390	6050	0.05	0.248	4.71	0.49	
32	28.6	155.2	2·470	755	1980	4800	0.06	0.147	12.50	0.47	

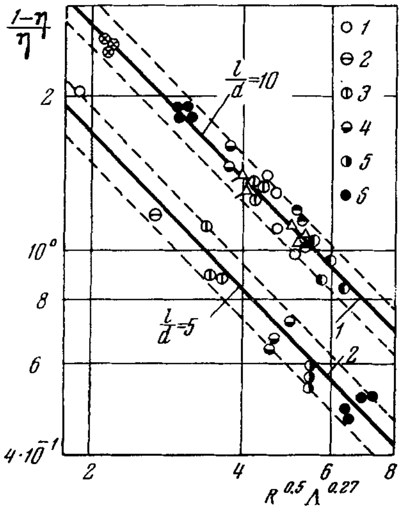
(1−η)/η
2
10⁰
8
6
4·10⁻¹
2
4
6
8
R^0.5 Λ^0.27
l/d=10
l/d=5
1
2
○ 1
⊖ 2
⦶ 3
◒ 4
◐ 5
● 6

Fig. 4

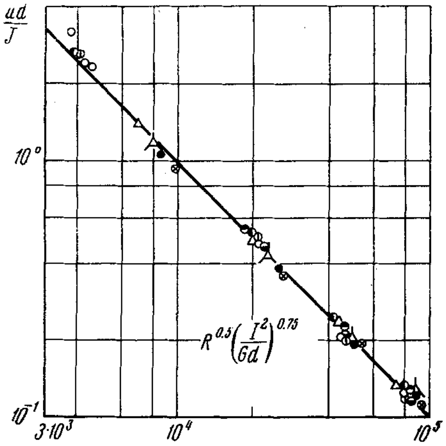
ud/J
10⁰
10⁻¹
3·10³
10⁴
10⁵
R^0.5 (I²/Gd)^0.75

Fig. 5

We used these data to determine the thermal fluxes into the electrodes, the mass-average gas temperature at the exit cross section of the anode, and the efficiency. Radiation in thermal balance was neglected. The mass-average temperature was taken as the determining quantity in computing R and Λ. Reference data from [7, 8] were used in the computations. The principal results of the measurements and computations are given in the table, where the point numbers refer to Fig. 2.

We also made experimental determinations of the degree of contamination of the plasma stream by electrode erosion products. The impurity concentration did not exceed 0.002% by weight at currents from 15 to 150 A.

In treating experimental data on efficiencies, we found that $(1-\eta)/\eta \sim R_d^{-0.5}$, which confirms the presence of a laminar boundary layer near the channel wall.

The effect of breakdown conditions on energy processes in a plasmatron is described in [9, 10]. These are usually determined by the parameter pd. The breakdown gap in our experiments was on the order of d/2 and did not vary with respect to this parameter. The dependence of Fig. 2 shows that there is considerable stratification of the experimental points with respect to the pressure p (mm Hg). Figure 3 shows the dependence of

$$\eta^* = \frac{1-\eta}{\eta}\sqrt{R_d}$$

on the mean free path Λ (cm). We see that correlation in this case is quite satisfactory.

The experimental data in the range $R_d = (0.4-9.4)\cdot 10^3$, $\Lambda = (0.02-4.6)\cdot 10^{-3}$ cm are described by the relation

$$(1-\eta)/\eta = 5.6\ R_d^{-0.5}\Lambda^{-0.27} \tag{9}$$

shown in Fig. 4.

This figure also shows a treatment of Neumann's data [11]. These data run parallel to our own, but are shifted in accordance with the different value $l/d = 5$.

The points 1, ..., 6 correspond to the values G = 0.346, 0.695, 1.182, 2.115, 2.95, and 4.22.

The data shown in Fig. 5 in the coordinates of relation (8) (the points correspond to Fig. 2) yield the following formula for the current-voltage characteristic with a scatter not exceeding ±10%:

$$\frac{Ud}{I} = 1\cdot 10^4\left(\frac{I^2}{Gd}\right)^{-3/4} R^{-1/2}.$$

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