INVESTIGATION OF THE CHARACTERISTICS OF A PLASMOTRON WITH A VARIABLE CHANNEL RADIUS

A. I. Dautov, R. Kh. Ismagilov,
A. G. Shashkov, and Kh. M. Shavaliev

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The thermal and electrical characteristics of a plasmotron are investigated experimentally. A significant dependence of the characteristics on the law of variation of flow rate of the plasma-forming medium along the arc chamber is revealed, and the feasibility is shown of using this phenomenon for optimizing the plasmotron parameters.

The profiling of the arc chamber — plasmotron channel — gives a number of positive effects. Thus, for example, a plasmotron with an arc chamber which expands in the direction of the gas flow has a higher efficiency [1] in comparison with a plasmotron which has a cylindrical arc chamber. Calculations [2] have shown that in a number of cases the arc chamber can have a complex profile, in particular, its cathode section must be convergent. It can be supposed that the combined geometric and flow-rate effect on the processes in the arc discharge will provide even wider possibilities for optimizing the characteristics of plasmotrons. However, there are no experimental data in the literature for arc chambers of complex profile.

The purpose of the present paper, which is a continuation of [1], was to investigate a plasmotron with a convergent arc chamber, the diagram of which is shown in Fig. 1. The radius of the arc chamber along the z axis reduces according to the law $R = R_0\sqrt{1 + kLz}$, $k < 0$. Injection of the gas — air — is effected in the initial section of the channel and in different amounts through the intersection gaps of electrically neutral inserts, so that the mass flow rate of the gas, averaged over the length of a section, increases linearly along the z axis. Thus, it would be possible to compare the experimental results obtained with the data of [1, 3], in which the cases of $k > 0$ and $k = 0$, respectively, were investigated for this same air feed mechanism. In the present paper, the experiments were conducted over the following range of variation: $G_1 = 0.6$ to $4.0 \cdot 10^{-3}$ kg$\cdot$sec^{-1}, $G_i = 0$ to $0.44 \cdot 10^{-3}$ kg$\cdot$sec^{-1}, $I = 100$–200 A, with $L = 10.5 \cdot 10^{-2}$m, $R_0 = 0.5 \cdot 10^{-2}$ m, $R_1 = 0.3 \cdot 10^{-2}$ m, $k = -6.0$ m^{-1}, $l = 2 \cdot 10^{-2}$ m, $l_a = 2.2 \cdot 10^{-2}$ m, $\delta = 10^{-3}$ m, and with atmospheric pressure at the exit from the anode — the nozzle of the plasmotron.

One of the most important parameters determining the processes in the arc chamber is the strength of the electric field. The typical distributions E(z) obtained in [1, 3] and in this paper for channels with different values of the geometric parameter k are shown in Fig. 2. It can be seen that when $k \geq 0$ (curves 1 and 2), in consequence of the increase of the radius of the positive column and the enthalpy over the gas flow, the field strength is reduced sharply, which leads to a reduction of energy dissipation of the electric field in the exit section of the channel and to a reduction of power of the plasmotron as a whole. In the case $k < 0$ (curve 3), with the exception of the initial section of the arc where, according to the ideas in [4], it develops as in a free flow, the field strength increases along the z axis. An increase of E promotes a reduction of the radius of the arc chamber and, as a result of this, there is a more intense heat exchange between the positive column and the gas injected. Thus, convergence of the arc chamber in the direction of flow of the plasma can serve as an additional means of intensifying the thermal processes in plasmotrons.

Analysis of the experimental data showed that the nature of the heat flow distribution along the arc chamber depends significantly on the law of distribution of the gas flow rate. It can be seen from Fig. 1 that at high values of G_0 (dashed curves) the heat flow in the initial section is small, but along the z axis it increases monotonically. This is because with the dimensions given of the arc chamber and the pressure, the heat flow

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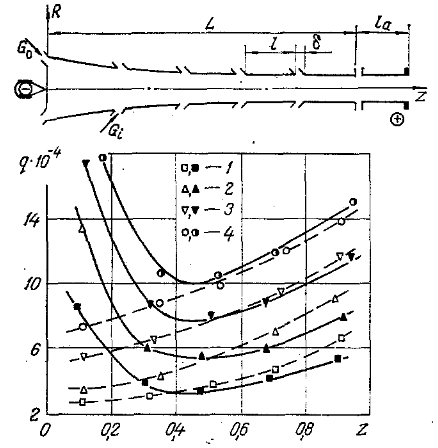

Fig. 1

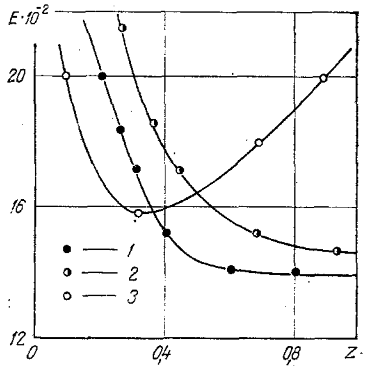

Fig. 2

Fig. 1. Distribution of heat losses along an arc chamber with $G_i = 1.0 \cdot 10^{-3}$ kg·sec^{-1}, $G_0 = 0.3 \cdot 10^{-3}$ kg·sec^{-1} — dashed lines; $G_0 = 0.1 \cdot 10^{-3}$ kg·sec^{-1} — solid lines. Points 1, 2, 3, and 4 correspond to currents of 100, 125, and 175 A. q, W/m.

Fig. 2. Distribution of E for arc chambers of different profile, with I = 100-200 A: 1) k = 0; $G_i = 1.9 \cdot 10^{-3}$ kg·sec^{-1}; $G_0 = 0.2 \cdot 10^{-3}$ kg·sec^{-1}; $L = 10.5 \cdot 10^{-2}$ m; $R = 0.5 \cdot 10^{-2}$ m; 2) k = 30 m^{-1}, $G_i = 1.9 \cdot 10^{-3}$ kg·sec^{-1}; $G_0 = 0.27 \cdot 10^{-3}$ kg·sec^{-1}; $L = 18 \cdot 10^{-2}$ m; $R_0 = 0.3 \cdot 10^{-2}$ m; $R_1 = 0.75 \cdot 10^{-2}$ m; 3) k = −6 m^{-1}; $G_i = 0.8 \cdot 10^{-3}$ kg·sec^{-1}; $G_0 = 0.2 \cdot 10^{-3}$ kg·sec^{-1}; $L = 10.5 \cdot 10^{-2}$ m; $R_0 = 0.5 \cdot 10^{-2}$ m; $R_1 = 0.3 \cdot 10^{-2}$ m. E, V/m.

q_0 is due mainly to the emission of the arc and is determined by the magnitude of I [3,4]. Convergence of the arc chamber and the approach of the positive column to the wall downstream leads to an increased loss of thermal conductivity. With a reduction of G_0, the role of energy transfer by thermal conductivity increases and in the initial section of the channel q_0 also begins to increase, which also explains the presence of a minimum in the q(z) distributions shown in Fig. 1 for small values of G_0 (solid curves). A similar effect of the gas flow rate on the nature of change of the heat flow in the initial section of a cylindrical arc chamber was noted also in [3]. Analysis of the experimental data obtained showed that with increase of G_0 the minimum of the q(z) curves is displaced in the direction of large values of z, becoming less significant, and when $G_0 \gtrsim 0.3 \cdot 10^{-3}$ kg·sec^{-1}, it vanishes.

It is well known from the numerous experimental and calculated data that when $G_i = 0$ the local heating efficiency η^* decreases in the direction of the z axis and, in sufficiently long channels, it tends to zero. In the case of inter-section injection, a multiplicity of different distributions of $\eta^*(z)$ can be realized, and the choice of their optimum, which will ensure the maximum efficiency of the plasmotron, is of great practical importance. The experiments showed that for the plasmotron studied and for the chosen law of variation of the flow rate G(z), the $\eta^*(z)$ distributions can be subdivided into three types, corresponding to different values of η^*_{in}/η^*_{out}.

1. $\eta^*_{in}/\eta^*_{out} < 1$. This distribution is characteristic for very small values of G_0, when the loss of heat in the inlet section of the channel is large, $\eta^*_{in} < \eta^*_{out}$ and the local efficiency increases along the z axis. In Fig. 3, this case is represented by curve 1.

2. $\eta^*_{in}/\eta^*_{out} = 1$. In this case η^* in the larger length of the channel maintains an approximately constant value (curve 4).

3. $\eta^*_{in}/\eta^*_{out} > 1$. Here η^* decreases in the direction of flow of the gas (curves 2 and 3).

Analysis of the experimental data showed that with a fixed arc current in the range of parameters investigated, η^*_{in} is determined by the magnitude of G_0. With increase of G_0, the local efficiency in the initial section of the channel also increases. However, an intense increase of η^*_{in} occurs only up to $G_0 \approx 0.4 \cdot 10^{-3}$ kg·sec^{-1}. It can be seen from comparison of curves 1-4 of Fig. 3 that an increase of G_0 from $0.2 \cdot 10^{-3}$ to $0.4 \cdot 10^{-3}$ kg·sec^{-1} leads to a significant increase of η^*_{in}, while further increase of G_0 up to $1.0 \cdot 10^{-3}$ kg·sec^{-1} changes

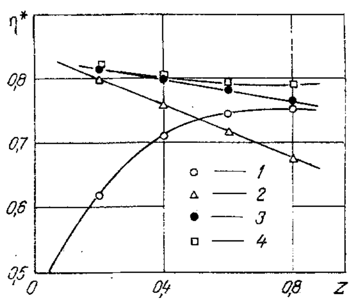

Fig. 3

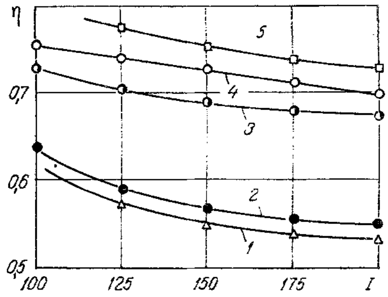

Fig. 4

Fig. 3. Distribution of local thermal efficiency along the channel, when I = 150; 1) $G_1 = 1.2 \cdot 10^{-3}$, $G_0 = 0.2 \cdot 10^{-3}$, $G_i = 0.2 \cdot 10^{-3}$ kg · sec^{-1}; 2) $G_1 = 1.2 \cdot 10^{-3}$, $G_0 = 0.4 \cdot 10^{-3}$, $G_i = 0.16 \cdot 10^{-3}$ kg · sec^{-1}; 3) $G_1 = 2.0 \cdot 10^{-3}$, $G_0 = 1.0 \cdot 10^{-3}$, $G_i = 0.2 \cdot 10^{-2}$ kg · sec^{-1}; 4) $G_1 = 3.0 \cdot 10^{-3}$, $G_0 = 1.0 \cdot 10^{-3}$, $G_i = 0.4 \cdot 10^{-3}$ kg · sec^{-1}.

Fig. 4. Dependence of η for a plasmotron on current: 1) $G_1 = 0.8 \cdot 10^{-3}$, $G_0 = 0.5 \cdot 10^{-3}$, $G_i = 0.06 \cdot 10^{-3}$ kg · sec^{-1}; 2) $G_1 = 0.8 \cdot 10^{-3}$, $G_0 = 0.4 \cdot 10^{-3}$, $G_i = 0.08 \cdot 10^{-3}$ kg · sec^{-1}; 3) $G_1 = 2.0 \cdot 10^{-3}$, $G_0 = 1.2 \cdot 10^{-3}$, $G_i = 0.16 \cdot 10^{-3}$ kg · sec^{-1}; 4) $G_1 = 2.0 \cdot 10^{-3}$, $G_0 = 1.0 \cdot 10^{-3}$, $G_i = 0.2 \cdot 10^{-3}$ kg · sec^{-1}; 5) $G_1 = 3.0 \cdot 10^{-3}$, $G_0 = 0.8 \cdot 10^{-3}$, $G_i = 0.44 \cdot 10^{-3}$ kg · sec^{-1}. I, A.

η^*_{in} only very slightly. The local heating efficiency in the outlet section of the channel, η^*_{out}, is determined mainly by the mass quantity of the injected gas G_i. For example, curves 1 and 3 in Fig. 3 were obtained for different values of G_1 and G_0, but for identical values of G_i. It can be seen that in both cases η^* tends to one and the same value. With increase of G_i, the quantity η^*_{out} increases, but the relation $\eta^*_{out}(G_i)$ is not linear, which can be seen from Fig. 3. If an increase of Gi from $0.16 \cdot 10^{-3}$ to $0.2 \cdot 10^{-3}$ kg · sec^{-1} leads to an increase of η^*_{out} by almost 10% (curves 2 and 1), then an increase of G_i from $0.2 \cdot 10^{-3}$ to $0.4 \cdot 10^{-3}$ kg · sec^{-1} increases η^*_{out} by very little (curves 3 and 4). It is obvious that with sufficiently high values of G_i the reduced increase of η^*_{out} with increase of G_i is explained by the additional heat losses through the turbulence created by the injected gas. A change of arc current does not violate the nature of the $\eta^*(z)$ distribution described above; however, the plasmotron efficiency decreases with increase of current. This can be seen from Fig. 4, where for all values of I the plasmotron efficiency depends on the total flow rate of the gas G_1 and with increase of G_1 it is reduced, but the numerical value of η for a given value of G_1 depends significantly on the distribution of the flow rate along the arc chamber.

The experiments showed that in the range of parameters given above the mean-mass stagnation enthalpy of the gas increases continuously in the direction of flow. This is assisted by convergence of the channel and, to a significant degree, by the high value of the local thermal efficiency achieved by injection in the entire extent of the channel. Over the range of variation of I and G investigated, with fixed values of G_0 and G_i, the mean-mass enthalpy at the plasmotron outlet increases linearly with increase of I. In the case G = const and I = const, the quantities h_m and η depend on the ratio of the flow rates G_0 and G_i, which can be seen from Fig. 5. The presence of a maximum of the curves $h_m(G_i)$ and $\eta(G_i)$ is related directly with the special features shown above of the distributions $q(z)$, $\eta^*(z)$, and $E(z)$. If the main part of the flow is supplied to the channel in its initial section and only a small part of the mass of the gas is distributed over the length of the arc chamber, then because of inadequately enclosed cooling of the walls η and h_m have low values. With small values of G_0, in consequence of the considerable heat loss in the initial section of the channel, and the strong cooling of the positive column by the injected gas, h_m and η will also be low. Analysis of the available data in [1,3] and the results of this work has shown that for plasmotrons with the optimum geometry derived in [1,3] and here, from the point of view of increasing η and h_m, there appears to be a distribution of the gas flow for which $G_0 = 0.3$ to $0.5 \cdot 10^{-3}$ kg · sec^{-1}.

Thus, the use of a distributed gas injection and profiling of the arc chamber make it possible to optimize the integral characteristics of plasmotrons for a specified current, air flow, and other fixed parameters. The results presented here can be used for the development of optimal plasmotrons.

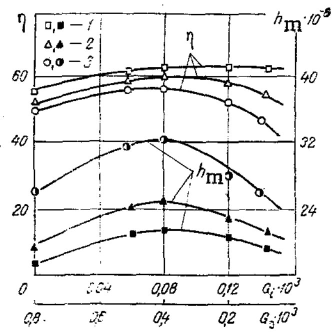

Fig. 5. Dependence of h_m and η on G_i and G_0 when $G_1 = 0.8 \cdot 10^{-3}$ kg·sec^{-1}. Points 1, 2, and 3 correspond to values of I equal to 100, 125, and 175 A. h_c, J/kg; G_i and G_0, kg·sec^{-1}.

NOTATION

I, current, A; E, electric field strength, V·m^{-1}; h, stagnation enthalpy, J·kg^{-1}; η, η^*, thermal efficiency of plasmotron and local heating efficiency; q, heat flow through the channel wall, W·m^{-1}; G, mass flow rate of gas, kg·sec^{-1}; G_i, flow rate of gas injected between sections, kg·sec^{-1}; R, L, radius and length of arc chamber, m; z, coordinate referred to L; l_a, l, lengths of anode and section, m; δ, distance between sections, m. Indices: in, out, quantities in the initial inlet and final outlet sections of the channel; m, mean-mass value of quantities; 0, 1, quantities when z = 0 and z = 1.

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