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ELECTRIC-FIELD STRENGTH IN A CASCADE ARGON ARC

V. G. Karolinskii,[a] M. I. Sazonov,[a] E. I. Yurinok[b], and O. I. Yas'ko[b *)]

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An experimental investigation of the electric-field strength along the length of a cascade argon at a pressure lower than atmospheric pressure has been performed. The influence of different processes on the formation of the voltage-current and E–I characteristics of the arc was considered. It is shown that the processes of heat transfer are of primary importance; however, in the region of mixing of the cathode jet with the heated gas the Reynolds number has a marked influence. The generalized characteristics of the voltage across the arc, of the near-electrode voltage drop, and of the electric field strength averaged over the length are presented.

Introduction. Plasma torches (plasma generators) with a cascade electric arc find application in different high-temperature technological processes, especially in those cases where high-enthalpy plasma flows are required at low flow rates of the working gas (plasma processing of toxic and radioactive wastes, applying of special coatings, and so on). They can work both at atmospheric and lowered pressure in the discharge chamber.

To design plasma generators and to make good use of them under certain conditions, it is necessary to know the characteristics of the arc discharge. The most important of them is the volt-ampere characteristic. It characterizes the plasma generator as a circuit load and as a converter of electric energy into heat energy. On it the working plasma-flow parameters that determine the conditions of conducting the technological process are also dependent. The formation of the volt-ampere characteristic is determined by the processes occurring in the discharge chamber. The character of these mechanisms can change along the length of the channel as the working gas heats up. This reflects on both the parameters of the plasma flow and the local value of the electric-field strength. Accordingly, there is a certain relationship between the electric-field strength and the effects in the discharge chamber of the plasma generator. The features of the dominant factors can be elucidated by regression-analysis methods in the course of the processing of experimental data on the dependence of the field strength on the discharge current (*E–I* characteristics).

In this work, we have performed an analysis of the processes in a plasma generator with a cascade argon arc, designed for production of a plasma flow that is used for applying diamond-like coatings in vacuum. In this case, the pressure held in the discharge chamber of the plasma generator is somewhat lower than atmospheric pressure.

Experimental Setup and Method of Investigation. The schematic of the discharge chamber of a plasma generator with a cascade arc is shown in Fig. 1. The arc 1 burns in the channel between the hot pivotal cathode 2 and the cold cylindrical anode 3. The channel consists of units 4 made in the form of cooled copper washers 4 mm in thickness and insulated from each other with spacers 1.25 mm in thickness. The inside diameter of the washers was varied from 4 to 10 mm. The washers and anode were cooled by the water 5. This

*) Deceased

[a]Brest Polytechnic Institute, Brest, Belarus; [b]Academic Scientific Complex "A. V. Luikov Institute of Heat and Mass Transfer," National Academy of Sciences of Belarus, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 73, No. 5, pp. 973-978, September–October, 2000. Original article submitted December 10, 1999.

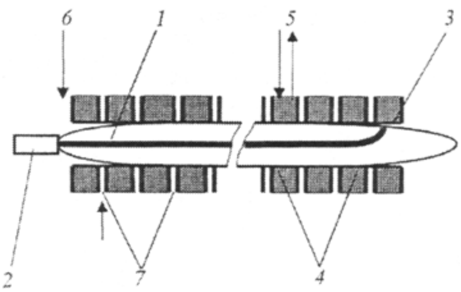

Fig. 1. Schematic of the discharge chamber of a plasma generator with a cascade arc: 1) arc; 2) cathode; 3) anode; 4) units of the discharge chamber; 5) water supply; 6) main blow of the gas; 7) distributed blow of the gas between the units.

plasma generator can work reliably if the voltage drop across the arc length within the limits of the isolated washer does not exceed the breakdown value. The main flow rate of argon changed from 0.14 to 0.45 g/sec. Besides the main blow of the gas 6, we used the distributed blow 7 between the washers, and the total flow rate of the gas was 0.168–0.584 g/sec. The strength of current was varied from 25 to 70 A, and the diameter of the discharge channel was formed by washers 4, 6, 8, and 10 mm in diameter. In the experiment, we measured the current, the flow rate of the gas, and the voltage between the cathode and the anode as well as between the cathode and each washer. The number of the latter was changed from 3 to 11. The pressure in the discharge chamber varied from $2.4 \cdot 10^4$ to $8.3 \cdot 10^4$ Pa.

To elucidate the features of the dominant processes influencing the volt-ampere characteristics, we represented them in generalized form where the similarity numbers were used as variables. The dependent variables were formed as the total or local generalized resistances of the arc discharge $\pi_{\mathrm{dep.total}} = Ud\sigma_0/I$ and $\pi_{\mathrm{dep.}i} = E_i d^2 \sigma_0/I$, where U, E_i, d, and I denote the voltage across the arc, the local value of the electric field strength, the diameter of the discharge channel, and the current, respectively. The parameter σ_0 is the characteristic value of the electrical conductivity of the arc plasma. This parameter, as were other basic parameters reflecting plasma properties, was determined by a method that allowed for the dependence of the properties on temperature [1]. Each of the independent variables characterizes a definite process.

The characteristics were represented in the form of power expressions:

$$\frac{Ud\sigma_0}{I} = C \prod_k \pi_{\mathrm{dep.}\,k}^{B_k}, \tag{1}$$

$$\frac{E_i d^2 \sigma_0}{I} = C_i \prod_{ik} \pi_{\mathrm{dep.}\,ik}^{B_{ik}}. \tag{2}$$

The selection of the dominant variables was performed by the "forward" stepwise method. In this case we used multiple linear regressions: an ordinary and a ridge regression. The latter provides a lower accuracy; however, we were forced to resort to it to elucidate the relative role of individual processes in the case of a strong correlation between the independent variables. The linearization of expressions (1) and (2) was performed by taking the logarithm (in natural logarithms). The dominant independent variables were selected from the initial set that incorporated the similarity numbers reflecting the convective, conductive, radiant, and turbulent heat transfer. Gasdynamic processes were represented by the Reynolds numbers. These dimensionless variables were based on the diameter of the channel as well as on its length. In analyzing the field strength, we considered both the local values determined from the change of voltage between the washers and the averaged values calculated from the voltage between a given washer and the cathode and by the corresponding length. This length was also used in the corresponding independent variables. For the Reynolds number and convective

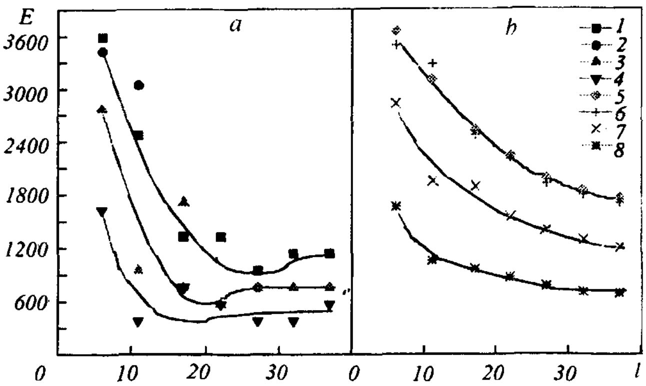

Fig. 2. Change in the values of the electric-field strength [a) local; b) average] along the length of the discharge channel: 1, 5) $G_{\text{main}} = 0.14$ g/sec, $G_{\text{blow}} = 0.028$ g/sec, $D = 0.004$ m; 2, 6) 0.26, 0.042, and 0.004; 3, 7) 0.31, 0.073, and 0.006; 4, 8) 0.31, 0.073, and 0.010; 1, 5) $I = 55$ A; 2, 6) 30; 3, 7) 50; 4, 8) 70. E, V/m; l, mm.

heat transfer we individually formed the similarity numbers for the main flow rate of the gas and for the distributed blow of the gas.

Independent similarity numbers that are based on the diameter of the channel have the following form: $\sigma_0 h_0 G_i d/I^2$ for the convective heat transfer; $\sigma_0 \lambda_0 T_0 d^2/I^2$ for the conductive heat transfer; $\sigma_0 Q_0 d^4/I^2$ for the radiant heat transfer; $\sigma_0 \rho_0 h_0^{1.5} d^3/I^2$ for the turbulent heat transfer; $G_i/\eta_0 d$ for the Reynolds quantity.

The characteristic parameters of the plasma h_0, λ_0, ρ_0, and Q_0 denote enthalpy, heat conduction, density, and losses by radiation in a unit volume, whereas T_0 is the characteristic temperature of the arc. The data on the parameters are taken from [2-4]. The symbol G_i denotes the flow rate of the gas for the main or distributed gas blows. The numbers that are based on the length of the channel have the same form; however, in them the total or local values of the length l_i are used instead of the diameter d.

From the indicated set of initial similarity numbers the program selects only those whose influence is beyond the limits of error. The relative role of individual selected variables (and, consequently, of processes corresponding to them) is determined from the standardized coefficients of regression β_{ik}, while the natural coefficients B_{ik}, along with the constant sets C_i, are used for construction of the characteristics of the arc.

When an ordinary regression is used, the program selects only the most important variables. In this case, the index of their relative role also reflects the influence of those processes that correlate strongly with the chosen variables and are outside the dominant processes. The characteristics obtained in this case are more compact and accurate as compared with the ridge regression.

Processes in the Discharge Channel. An electric arc is a very complex phenomenon in which a great number of processes occur, and the dominant role of some of them depends on the discharge conditions. Evidently, the conditions must change along the discharge chamber as the working gas heats up and the dimensions of the arc channel change. This reflects on the electric field strength as a function of the distance from the cathode.

Figure 2 shows some examples of this dependence for the local values of the field strength and for the field-strength values averaged over the length. The first values were determined from the potential difference between the individual units of the discharge chamber, and the second ones were found from the voltage between the considered unit and the cathode, divided into the corresponding length. The figure shows that the field strength depends weakly on the flow rate of the gas but decreases with increase in the diameter of the channel. Near the cathode, the local strength has a maximum value that then sharply decreases at a distance of ~20 mm from the cathode. From this point on it increases somewhat and then takes on an approximately constant value. In the region of the minimum there is a marked dispersion of the experimental points. The aver-

TABLE 1. Values of the Standardized Coefficients of Ridge Regression β for Dominant Independent Variables. The Dependent Variable Is Based on the Local Value of the Electric-Field Strength

Form of the variable	Unit number						
	1	2	3	4	5	6	7
$\pi_{\text{cond }d}$	0.367	–	–	–	–	–	0.449
$\pi_{\text{conv }d}$	–	–	–	0.463	–	–	–
$\pi_{\text{turb }d}$	0.255	–	–	–	0.673	–	–
$\pi_{\text{rad }d}$	0.313	–	0.388	0.289	–	0.719	–
$\pi_{\text{conv }d\text{.blow}}$	–	–	–	–	–	–	0.474
$\pi_{\text{rad }l}$	–	–	–	–	–	–	–
$\pi_{\text{cond }l}$	–	0.584	–	–	–	–	–
$\pi_{\text{Re }d}$	–	0.231	–	–	–	–	–
$\pi_{\text{Re }l}$	–	–	0.337	–	–	–	–

aged values of the strength decrease along the channel fairly smoothly. Its magnitude increases with distance from the cathode as compared with the local value, since it also includes the increased value near the cathode.

To reveal the interrelation between the local field strength and the character of the processes occurring in the arc column, we found the generalized E–I characteristics in the form of expression (2) for each of the units of the discharge channel. The relative role of individual mechanisms was estimated by the value of the standardized regression coefficients β (Table 1).

In the region of the first unit nearest to the cathode where the local electric field strength has a maximum value, it was revealed by the methods of ridge regression that the greatest influence on the considered characteristic is exerted by the conductive heat transfer, which is dependent significantly on the diameter of the discharge chamber. Among the dominant similarity numbers were also the heat transfer by radiation and the turbulent energy transfer. Despite the fact that at a lowered pressure the emissive power of argon decreases significantly, the appearance of a marked radiant component can be due to the impurities of the electrode material in the cathode jet. The same jet can be a source of turbulization. However, the latter assumption is not indisputable, because there is a strong correlation between the individual processes of energy transfer. The most significant correlation was observed between the turbulent and radiant energy transfer. This can be seen from the data of Table 2 for the fourth unit of the channel. The correlation coefficient between $\pi_{\text{rad}.d}$ and $\pi_{\text{turb}.d}$ is close to unity ($K = 0.99$). This value is also observed for the remaining units. Therefore, it is not inconceivable that the computational program can point toward turbulent transfer in place of radiant transfer and conversely. In the case of the first unit, the relative values of the standardized coefficients β for radiative and turbulent heat transfer disagree somewhat with the coefficients of correlation between the dependent and the corresponding independent variables. For $\pi_{\text{conv}.\,d}$ $K = 0.80$, for $\pi_{\text{rad}.\,d}$ $K = 0.91$, and for $\pi_{\text{turb}.d}$ $K = 0.92$. However, it is precisely these correlation coefficients that markedly exceed the other values.

In the region of the second unit, along with conduction, convective processes play a marked role, which manifests itself as the appearance of the Reynolds number. Apparently, the convective heat transfer is outside the dominant processes because of the strong correlation with the conductive heat transfer ($K = 0.79$); however, the marked role of the processes of mixing of the cathode jet with the cold gas, which occurs in this unit, manifested itself as the appearance of a weaker Reynolds number among the dominant ones. Convective processes are also of considerable importance in the regions of the third and fourth units (the region of the minimum of the E–I characteristics), and, as the strength in the fifth unit increases, turbulence has a dominant role. Evidently, turbulent energy transfer also dominates in the sixth unit; however, as the channel is being filled with discharge, the characteristic begins to flatten out in the asymptotic regime, where of first importance are conduction and convection.

Averaged Characteristics. The local E–I characteristics depend on the change in the dominant processes along the discharge channel. They are suitable for the analysis of these processes. At the same time, in

TABLE 2. Correlation Matrix for Variables of the Generalized *E–I* Characteristic in the Region of the Fourth Unit

Variables	Correlation coefficient								
	$\pi_{\mathrm{conv}\,d}$	$\pi_{\mathrm{cond}\,d}$	$\pi_{\mathrm{cond}\,l}$	$\pi_{\mathrm{turb}\,d}$	$\pi_{\mathrm{rad}\,d}$	Re_d	Re_l	$\pi_{\mathrm{conv}\,d,\mathrm{blow}}$	$\pi_{\mathrm{dep}\,d}$
$\pi_{\mathrm{conv}\,d}$	1.00	0.90	0.49	0.87	0.81	0.25	0.64	0.85	0.74
$\pi_{\mathrm{cond}\,d}$	0.90	1.00	0.48	0.90	0.87	–0.20	0.38	0.82	0.68
$\pi_{\mathrm{cond}\,l}$	0.49	0.18	1.00	0.12	0.02	0.04	–0.26	0.49	0.25
$\pi_{\mathrm{turb}\,d}$	0.89	0.90	0.12	1.00	0.99	–0.05	0.68	0.77	0.72
$\pi_{\mathrm{rad}\,d}$	0.81	0.87	0.02	0.99	1.00	–0.11	0.67	0.71	0.69
Re_d	0.25	–0.20	0.04	–0.05	–0.11	1.00	0.60	–0.13	0.15
Re_l	0.64	0.38	–0.26	0.68	0.67	0.60	1.00	0.27	0.55
$\pi_{\mathrm{conv}\,d,\mathrm{blow}}$	0.75	0.82	0.49	0.77	0.71	–0.13	0.27	1.00	0.59
$\pi_{\mathrm{dep}\,d}$	0.74	0.68	0.25	0.72	0.69	0.15	0.55	0.59	1.00

designing a plasma apparatus the averaged *E–I* characteristics and the volt-ampere characteristics of the arc discharge are more convenient. If, in addition to these data, the generalized dependences for the near-electrode drops ΔU of voltage that includes the voltage across the radial anode region of the arc column are available, the length of the discharge channel can be calculated as well.

For this purpose, the characteristics obtained by the ordinary (not ridge) regression can be simpler and more accurate. In this case, it is well to bear in mind that the chosen dominant similarity numbers can represent not only the process that they reflect in their form, but also other mechanisms strongly correlated with this process. Below are the generalized characteristics obtained by the indicated method in static processing of the experimental data described above:

$$\frac{E_{\mathrm{av}} d^2 \sigma_0}{I} = 0.448 \left(\frac{\sigma_0 \lambda_0 T_0 d^2}{I}\right)^{0.378} \left(\frac{G_{\mathrm{main}}}{\eta_0 l}\right)^{0.361} \left(\frac{G_{\mathrm{blow}}}{\eta_0 l}\right)^{0.089}, \tag{3}$$

$$\frac{\Delta U d \sigma_0}{I} = 3.346 \left(\frac{\sigma_0 \lambda_0 T_0 d^2}{I^2}\right)^{0.375} \left(\frac{\sigma_0 \lambda_0 T_0 l^2}{I^2}\right)^{0.202}, \tag{4}$$

$$\frac{U d \sigma_0}{I} = 7.543 \left(\frac{G_{\mathrm{main}}\, l \sigma_0 h_0}{I^2}\right)^{0.190} \left(\frac{G_{\mathrm{blow}} d \sigma_0 h_0}{I^2}\right)^{0.043} \times$$

$$\times \left(\frac{\sigma_0 \lambda_0 T_0 d^2}{I^2}\right)^{0.041} \left(\frac{\sigma_0 \lambda_0 T_0 l^2}{I^2}\right)^{0.128}. \tag{5}$$

The standard error for the natural algorithms of these expressions is $SE_{(3)} = 0.070$; $SE_{(4)} = 0.282$; $SE_{(5)} = 0.047$.

The characteristic values of the parameters and temperature of the plasma were taken from [1].

CONCLUSIONS

1. By the data of measurements of the local values of the electric-field strength in a cascade argon arc at a lowered pressure ($P = 2.4 \cdot 10^4$–$8.3 \cdot 10^4$ Pa) we have determined the dominant mechanisms that exert an influence on the formation of the *E–I* characteristics. It is shown that they change along the length of the discharge channel. Near the cathode, the main influence is exerted by the conductive and radiative transfer; then, in the zone of mixing of the heated gas, the role of convection and of the Reynolds number increases. In

this region, the value of the field strength is minimum. The increase in the strength further downstream is due to the action of turbulent energy transfer; however, in the asymptotic zone of discharge stabilization, the main role is played by convection and conduction.

2. The electric-field strength averaged over the length of the channel decreases with distance from the cathode. It depends on conductive heat removal and the Reynolds number, which are based on the length of the channel for the main flow rate of the gas and for the additional blow of the gas distributed along the arc. The effective value of the near-electrode voltage drop depends on conductive heat transfer and increases with increase in both the diameter and length of the discharge channel. The total voltage across the arc is formed predominantly under the action of convective and conductive heat transfer.

NOTATION

I, current; U, voltage across the arc; E_i, local value of the electric-field strength; G, flow rate of the gas; T, temperature; Q, emissive power of the plasma; d, diameter of the discharge channel; h, enthalpy; η, coefficient of dynamic viscosity; λ, coefficient of thermal conductivity; π, similarity number; σ, coefficient of electrical conductivity. Subscripts: 0, characteristic value.

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