HEAT TRANSFER BETWEEN THE ARC COLUMN AND THE DISCHARGE CHAMBER WALLS OF A VORTEX LINEAR PLASMA JET GENERATOR

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The heat losses in the insulated metal inserts of a two-sided plasma jet generator with vortex air arc stabilization have been investigated. The heat fluxes are generalized. It is shown that the development of turbulence is associated with degeneracy of the Reynolds number.

A considerable amount of material on the current-voltage characteristics of various types of plasma generators has now been accumulated and means of generalizing these characteristics by methods of approximate similarity have been proposed [1–4]. Much less information is available regarding heat-transfer processes in the discharge chambers of plasma jet generators and the generalization of their thermal characteristics.

This paper presents certain results of an investigation of the heat losses in the water-cooled cylindrical metal diaphragms used to limit the diameter of the arc column in powerful plasma generators with vortex gas stabilization. Usually, these diaphragms are also electrodes, but to separate the different processes in the electrodes and stabilizing diaphragms we investigated only nonconducting sections.

The experimental section is shown schematically in Fig. 1. The electric arc 1 burns in a longitudinal vortex gas flow 2 inside a metal diaphragm 3 cooled by water flowing through the gap 4 between the diaphragm and the outer shell 5. The gas enters the diaphragm at an axial velocity w_1 and temperature t_1 and leaves it with the parameters w_2 and t_2. The heat fluxes were determined from the rate of flow and temperature rise of the cooling water.

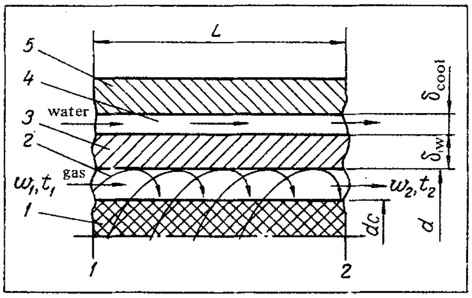

Fig. 1. Diagram of the experiment: 1) electric arc; 2) vortex gas flow; 3) inner wall of diaphragm; 4) cooling water; 5) outer shell.

The heat-transfer conditions are affected by the presence of a cold boundary layer created by the tangential gas vortex. The thickness of this layer and its velocity are not constant along the length and depend on many of the plasma generator parameters.

The experiments were performed on diaphragms with different geometries at gas flow rates from 50 to 250 g/sec and currents from 250 to 1200 A. We measured the arc voltage and the flow rate and temperature rise of the cooling water. The diaphragm dimensions were varied on the intervals: inside diameter—from 5 to 14 mm; length—from 25 to 100 mm. The maximum arc voltages were 1500 V, but in individual cases the specific heat flows into the cooled copper walls of the diaphragm increased to 3 kW/cm^2. As the experiments showed, for two-sided flow the heat losses are approximately the same on the cathode and anode sides of the diaphragm and amount to 5% of the generator power. They are considerably influenced by the diaphragm geometry. Increasing the length of the diaphragm at constant generator power and constant gas flow rate reduces the required value of the current, since the arc voltage increases. Consequently, the heat losses, which are directly related with the current, should also diminish. However, the increase in the surface of the diaphragm in the zone where the channel is more fully occupied by the high-temperature flow predominates and the net effect is an increase in the heat losses to the diaphragm. In the case of short diaphragms (up to 60 mm) because of the reduced occupation of the channel by the high-temperature flow and the presence of a not very turbulent cold boundary layer the heat losses at constant gas flow rate actually depend only slightly on the length. Lengthening the diaphragm beyond this limit increases the surface exposed to the high-temperature gas flow, and the increased occupation of the channel by this flow intensifies the turbulence in the boundary layer. As a result of the combination of these factors heat transfer between the arc column and the wall is intensified. The heat flux is also strongly affected by the variation in generator power at constant gas flow rate (Fig. 2a) caused by varying the current.

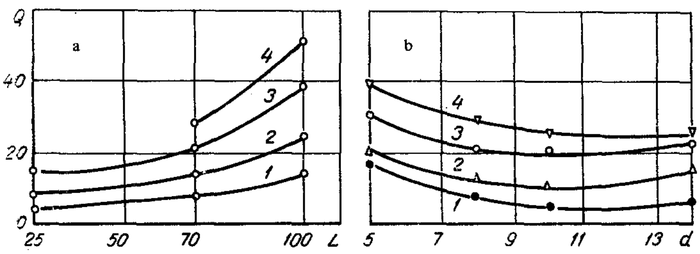

Fig. 2. Effect of length (a) and diameter (b) of diaphragm on heat fluxes at N = const and T = const (gas—air; Q, kW; I, A; N, kW; T, °K): a) G ' 50 g/sec; 1–N ' 300; 2–500; 3–700; 4–900; b) G = 25 g/sec; 1–N = 200, T = 2500; 2–300 and 3100; 3–400 and 3400; 4–500 and 3750.

An examination of the effect of the diaphragm diameter on the heat losses (Fig. 2b) indicates an intense increase in the specific and integral heat fluxes as the diameter decreases. Our investigations at constant generator power revealed a certain weakly expressed minimum of the heat losses at d = 10–12 mm. This minimum is attributable to the fact that at small diameters the heat-transfer coefficient varies more rapidly than the internal surface of the diaphragm. Reducing the diaphragm increases the heat-transfer coefficient owing to the increase in gas flow velocity and the increase in the radiative component of the specific heat flux with increase in the temperature and pressure in the discharge chamber. Under the given conditions at diaphragm diameters greater than 14 mm, the principal role begins to be played by the change in the surface area of the diaphragm exposed to the gas flow, and this factor has a weaker influence on the heat losses.

The practical application of the experimental data obtained in designing plasma generators requires their generalization. Generalized formulas of high-temperature heat- and mass-transfer processes are usually represented in the form of relations between the Nusselt or Stanton numbers and the Reynolds and Prandtl numbers and the temperature factor.

In convective heat transfer the Stanton number for a certain section of a tube is determined from the heat-balance equation

$$\pi dL\, \alpha (t_{\mathrm{ax}} - t_{\mathrm{w}}) = \frac{1}{4}\, \rho w c_p \pi d^2 (t_1 - t_2), \tag{1}$$

whence

$$\mathrm{St} = \frac{\mathrm{Nu}}{\mathrm{Re\,Pr}} = \frac{\alpha}{\rho w c_p} = \frac{t_1 - t_2}{t_{\mathrm{ax}} - t_{\mathrm{w}}}\, \frac{d}{4L}. \tag{2}$$

In our case, however, in constructing the loss balance it is necessary to take into account the nonuniformity of the temperature, velocity and physical properties over the length and cross section of the flow. Moreover, it is necessary to consider the heat release in the electric arc. Then instead of the temperatures it is more convenient to operate with the gas enthalpies. Thus, instead of (1) we have

$$2\pi R \int_{l_1}^{l_2} \alpha_h (h_{\mathrm{ax}} - h_{\mathrm{w}})\, dl = 2\pi \int_0^R (\rho_1 w_1 h_1 - \rho_2 w_2 h_2)\, r dr +$$

$$+\int_{l_1}^{l_2}\int_0^R 2\pi \frac{j^2(r,\,l)}{\sigma}\, r dr dl. \qquad (1')$$

Reducing Eq. (1') to dimensionless form and dividing it by the coefficients of the first term on the right-hand side, we obtain

$$\frac{2\pi R\,\alpha_{h_0} h_0 L}{2\pi R^2 \rho_0 w_0 h_0}\int_{l_1^*}^{l_2^*} \alpha_h^*(h_{ax}^* - h_w^*)\,dl^* = \int_0^1 (\rho_1^* w_1^* h_1^* -$$

$$-\rho_2^* w_2^* h_2^*)\, r^* dr^* + \frac{2\pi R^2 L j_0}{\sigma_0\, 2\pi R^2 \rho_0 w_0 h_0}\int_{l_1^*}^{l_2^*}\int_0^1 \frac{r^* j^{*2}}{\sigma^*}\, dl^* dr^*. \qquad (1'')$$

In this equation, the zero subscripts denote scale values, and the asterisks denote relative values ($\alpha^* = \alpha/\alpha_0$; $h^* = h/h_0$, etc.).

The dimensionless coefficient on the left-hand side of expression (1) can be represented in various forms. We first write it in the form

$$2\,\frac{\alpha h_0}{\rho_0 w_0}\,\frac{L}{d} = 2\,\mathrm{St}\,\frac{L}{d}.$$

The Stanton number is a generalized function, while the parametric criterion L/d takes into account the effect of the geometric configuration of the diaphragm on the heat-transfer process. Since in plasma generators $L/d < 50$, this effect may be present. However, the existence of a powerful turbulizing factor, the electric arc, considerably reduces the length of the transition section.

If as the scale value of the enthalpy we take its maximum value obtained as a result of the heating of the gas by the electric arc,

$$h_0 = h_{max} = \frac{N}{G}, \text{ and } G = \pi R^2 \rho_0 w_0,$$

then, referring the characteristic value α_0 to this value of the enthalpy and neglecting the value of the gas enthalpy at the wall, we transform the coefficient of the left-hand term of Eq. (1") to the form

$$\frac{1}{2}\,\frac{Q}{N} = \frac{1}{2}\,(1-\eta).$$

Taking as h_0 the starting value of the enthalpy of the heated gas $h_0 = h_{min}$, we can obtain the coefficient in yet another form. Multiplying the numerator and denominator by $h_{max} = N/G$, we represent the coefficient in the form

$$\frac{1}{2}\,\frac{Q}{Gh_{max}}\,\frac{h_{max}}{h_{min}}.$$

In this case, the ratio h_{min}/h_{max} is the enthalpy factor taking the temperature nonuniformity into account, while the number Q/Gh_{max} is a generalized function of the heat-transfer process.

Thus, we have

$$4\,\mathrm{St}\,\frac{L}{d} = \frac{Q}{N} = (1-\eta) = \frac{Q}{Gh_{max}}\,\frac{h_{max}}{h_{min}}. \qquad (3)$$

The choice of notation for the generalized functions depends on the conditions of the problem and the nature of the heat transfer. At large L/d, when the turbulence is highly developed and the specific heat flux is constant, it is convenient to use the Stanton number. In this case, however, to calculate the heat flux it is necessary to know the power released in the diaphragm. The power must also be known when the number Q/N and η are used, but it is possible to manage without it by writing the generalized function in the form Q/Gh_{max}, since, apart from the heat flux, it contains only known quantities.

Setting $G = \pi R^2 \rho_0 w_0$ and $I = \pi R^2 j_0$, we can represent the coefficient of the second term on the right-hand side of expression (1") in the form

$$\frac{4}{\pi}\frac{L}{d}\frac{I^2}{\sigma_0 h_0 G d}.$$

The latter multiplier is the known energy criterion [1]. In our case it is a generalized argument taking into account the effect of internal heat sources on the heat-transfer process.

Thus, we have established different ways of writing the generalized function and the principal generalized arguments L/d, h_{max}/h_{min} and $I^2\ Gd\sigma_0/h_0$. The generalized arguments should also include the Reynolds number, on which the heat-transfer processes depend. Experiments show that, in the presence of strong flow turbulence, there can occur a "degeneracy" of the Reynolds number, determined in generalizing the experimental data.

A considerable fraction of the heat losses in the diaphragm is due to the radiant flux. The established forms of the generalized function also make it possible to take the radiant flux into account. Presumably, however, a criterion reflecting the effect of the nature of the gas on the radiation intensity should be introduced into the generalized arguments. In our case, the experiments were performed only on one gas—air; therefore, there was no need for special criteria for taking the physical properties into account. It is also possible to disregard the slight changes in the temperature of the diaphragm wall and the fluctuations of the initial gas temperature. In this case, all the characteristic values of the physical properties remain constant and the generalization can be carried out in dimensional complexes corresponding to the dimensionless criteria.

The effect of the temperature nonuniformity is usually taken into account by means of a temperature factor, the ratio of the boundary temperatures given as part of the conditions of the problem. Unfortunately, the maximum temperature in the electric arc is not known in advance. It depends on other characteristic quantities. Therefore, the artificially constructed enthalpy factor h_{max}/h_{min}, must first be determined by measuring the power. It can also be computed from formulas obtained in connection with the generalization of the current-voltage characteristics [5–7]:

$$\frac{N}{Gh_0} = f\left(\frac{I^2}{Gd\,\sigma_0 h_0},\ \mathrm{Re},\ \frac{L}{d},\ \mathrm{Kn}\right). \qquad (4)$$

The generalized current-voltage characteristics show that in our case only three criteria are needed:

$$I^2/Gd\,\sigma_0 h_0,\ \mathrm{Re},\ L/d.$$

Since the same criteria enter into the heat-transfer equations, while the values of the physical properties remain constant, there is no need to simultaneously introduce an enthalpy factor and an energy criterion. It is sufficient to use use one or the other. Accordingly, in dimensional form for the generalization of the heat losses in the diaphragm we obtain the expression

$$\frac{Q}{G} = f\left(\frac{N}{G},\ \frac{G}{d},\ \frac{L}{d}\right). \qquad (5)$$

Instead of Q/G it is also possible to use one of the forms obtained above, and instead of the enthalpy factor the energy criterion.

At very large or, conversely, very small values of Re, when the friction forces become incommensurably small or large as compared with the inertia forces and the pressure forces, it degenerates and ceases to be one of the generalized arguments [8]. The electric arc has an important influence on the development of flow turbulence and the Reynolds number rapidly degenerates. This is clearly visible in Fig. 3, which shows the generalized heat flux as a function of the generalized power for various diaphragm geometries and Reynolds numbers. For a short diaphragm (L/d = 1.79) (Fig. 3) the relative heat flow to the diaphragm depends on the parameter G/d, whereas at L/d > 4.93 there is almost no dependence.

An analysis of the experimental data in form (5) shows that, in practice, the dependence of the parameter Q/G on G/d can be neglected when $L/d \geq 3$. Then the heat flow into the diaphragm is a function of the mean mass temperature and the geometric factor only. The dependence of the heat flow on the geometric factor can be assumed linear over the entire range of N/G investigated at L/d = 3–8.

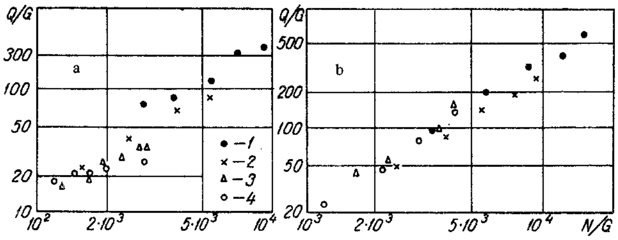

Fig. 3. Relative heat losses to diaphragm as a function of N/G, L/d, and G/d (gas—air): a) L/d = = 1.79; b) L/d = 4.93; 1–G/d = 17.8; 2–35.7; 3–71.4; 4–89.3.

In accordance with the above, Fig. 4 presents the dependence of F = (Q/G)/(L/d) on the parameter N/G.

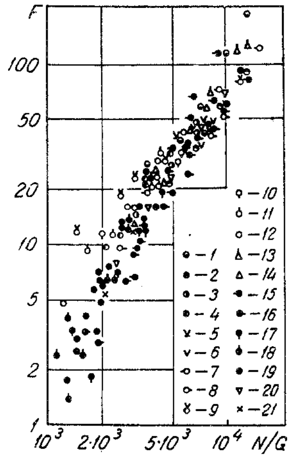

Fig. 4. Generalization of heat flows to diaphragms of a two-sided plasma generator with vortex air stabilization: F ' (Q/G)/(L/d) = f]N/G): L/d = 7.14; 1–G/d = 17.85; 2–35.7; 3–71.45; 4–89.3; L/d = 6; 5–G/d = 31.25; 6–62.5; L/d = 4.93; 7–G/d = 17.85; 8–35.7; 9–41; 10–53.5; 11–71.45; 12–89.3; L/d = = 3.75; 13–G/d = 31.25; 14–62.5; L/d = 3.57; 15–G/d = 17.85; 16–35.7; 17–53.5; 18–71.45; 19–89.3; L/d = 3; 20–G/d = 25; 21–50; Q/G, N/G, J/g.

The data show that at small specific powers the losses to the diaphragm increase rapidly with increase in power, but then the rate of increase slows. Consequently, the experimental curve can be approximated by two straight lines, which in linear coordinates correspond to different exponents:

a) for N/G > 2kJ/g and L/d = 3–8

$$Q/G = 6.6\cdot 10^{-4}\, L/d \left(\frac{N}{G}\right)^{1.34}; \qquad (6)$$

b) for N/G < 2 kJ/g and L/d = 3–8

$$\frac{Q}{G} = 12.4 \cdot 10^{-8} L/d \left(\frac{N}{G}\right)^{2.42}. \tag{6'}$$

The absence of a dependence of the heat flow on Reynolds number and its linear dependence on the length indicate the onset of steady-state developed turbulent flow in the diaphragm at $L/d > 3$. In this case as the generalized argument it is convenient to use the Stanton number. Then, instead of (6) and (6'), we obtain

a) at $N/G > 2$ kJ/g

$$\mathrm{St} = 1.65 \cdot 10^{-4} \left(\frac{N}{G}\right)^{0.34}, \tag{7}$$

b) and at $N/G < 2$ kJ/g

$$\mathrm{St} = 3.1 \cdot 10^{-8} \left(\frac{N}{G}\right)^{1.42}. \tag{7'}$$

The scatter of the experimental points in expressions (6) and (7) is ±50%. This not very high accuracy is due to the error in measuring the heat fluxes during the experiments, the inaccuracies of the approximation and the disregarding of a number of less important criteria. However, the formulas obtained can be used in calculating heat-transfer processes in the stabilizing diaphragms of electric-arc devices.

NOTATION

N is the power; I is the current, A; G is the gas flow rate, g/sec; R and d are the inside radius and diameter of the diaphragm, cm; r is the variable inside radius of diaphragm; L is the length of the diaphragm, cm; w is the velocity, cm/sec; T is the temperature, °K; t is the temperature, °C; h is the enthalpy, J/g; Q is the heat flux, kW; Nu is the Nusselt number; St is the Stanton number, Re is the Reynolds number; Kn is the Knudsen number; Pr is the Prandtl number; α is the heat-transfer coefficient, $W/cm^2 \cdot deg$; ρ is the density, g/cm^3; c_p is the specific heat at constant pressure, J/kg · deg; λ is the thermal conductivity, W/cm · deg; σ is the electrical conductivity; j is the current density; η is the efficiency. Subscripts: 0 denotes a characteristic quantity; 1 represents a parameter at the diaphragm inlet; 2—parameters at the diaphragm outlet; h—quantity referred to enthalpy; ax—parameters on jet axis; w—parameters at wall; mm—mean mass quantity; min—minimum; max—maximum.

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