rigidity of the elastoviscous skeleton on increasing the vibrational frequency. This model gives a good qualitative description of the motion and a reasonably complete quantitative description for n < 5-10; quantitative discrepancies occur for n > 10 on account of the gas compressibility, and Kroll has shown that this becomes more pronounced as the particle size decreases, while the model also becomes less strictly applicable.

NOTATION

A_V, vibration amplitude; d, particle diameter; f_V, vibration frequency; g, acceleration of gravity; H_p, height of dense bed; p, gas pressure; z, vertical coordinate; ε, porosity; μ_c, ν_c, dynamic and kinematic viscosities of gas; ρ_M, ρ_d, densities of material and of dense bed; σ_z, normal vertical stresses; Φ_M, particle shape factor; ω, angular frequency.

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EQUATIONS FOR THE HEAT FLUXES IN THE CATHODE AND ANODE SECTIONS OF A TWO-JET PLASMA SOURCE

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General relationships are derived for the heat fluxes at the cathode, anode, and nozzles of a two-jet plasma source working with air at atmospheric pressure.

A two-jet plasma source is an economical form of high-temperature open-arc source; engineering calculations require general relationships for volt—ampere characteristics, thermal efficiency, and heat fluxes at the electrodes. Equations for the voltages, currents, and efficiency have been given [1] for air at atmospheric pressure, but no values were given for the heat fluxes at the electrodes. These are very important, since a knowledge of these fluxes in terms of the other parameters is required in order to design a system with a higher thermal efficiency and better erosion resistance in the electrodes and nozzles.

The present study is a continuation of [1] and deals with the heat fluxes in the electrodes in such a source working in air at atmospheric pressure.

The apparatus, the arc-striking system, and the working parameters have previously been given [1]; the power supply was a dc source with an open-circuit voltage of 600 V. The arc current was varied over the range 80-250 A, while the power drawn did not exceed 90 kW. The air flow rate in each electrode unit varied over the range $0.3\text{-}1.5 \cdot 10^{-3}$ kg/sec.

The electrical parameters and the heat fluxes to the electrodes and nozzle were measured; the temperature of the cooling water was measured with a precalibrated differentiated six-junction Chromel—Copel thermocouple. The emfs were recorded with an N-700 loop oscilloscope. The water flow rate was measured with rotameters and measuring vessels. The error in determining the heat fluxes did not exceed ±15%.

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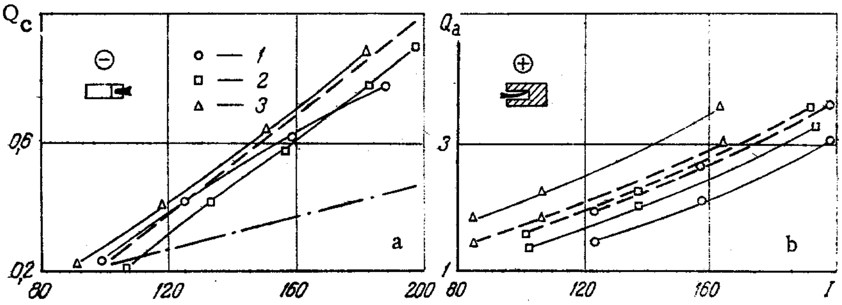

Fig. 1. Comparison of characteristic experimental heat fluxes (solid lines) and values calculated from (1), (2), and (8) (dashed lines) for the cathode (a) and anode (b) in a two-jet plasma source for the following air flow rates (10^3 kg/sec): 1) G_1 = 0.4; G_2 = 0.42; 2) G_1 = 0.69; G_2 = 0.74; 3) G_1 = 0.88; G_2 = 1.12. The dashed-dot line has been drawn up from (1); Q_c, kW; I, A.

The heat fluxes to the electrodes were determined as functions of the energy parameters, there being also some effect from the mutual disposition and geometry of the electrode units [1].

We now consider the heat flux in each unit.

Cathode. The cathode was of end-face type and made of water-cooled copper and zirconium; the diameter of the zirconium insert was 4 mm. Such a cathode receives energy on account of ions interacting with the surface [2], and it also receives heat from neutral particles on account of heat conduction, in addition to any radiation absorption. The heat flux into the body of the cathode is almost independent of the diameter of the copper sleeve and of that of the zirconium insert, as well as of the method of fitting the two together (although the latter may influence the working life), and there is also virtually no effect from the flow rate of the gas, the only relevant parameter for air at atmospheric pressure being the arc current [2-5]. Our results agreed with those of [2-5] within the error of measurement. However, the following formula is given in [5]:

$$Q_c = 2.34I \text{ W}, \tag{1}$$

but this proved unusable because the deviation from our measurements was very considerable. The following formula is applicable to within ±15% to our measurements for the current range 80-250 A:

$$Q_c = 7.5I - 500 \text{ W}. \tag{2}$$

The deviation of (2) from (1) occurs because (1) is for new or largely unused cathodes, whereas (2) is derived from long-term operation.

Figure 1a shows characteristic experimental values for the heat fluxes to the cathode for various air flow rates, together with theoretical curves from (1) and (2).

Anode. This was made of copper in hollow form and was water-cooled. The ratio of the length of the anode to the diameter was l_a/d_a = 2-6. The heat flux to the anode consists of heat deposited by the electric arc in the spot and of heat transferred by convection [6]. It has been found [7, 8] that the heat fluxes to the electrodes of a one-chamber air heater are dependent on the same quantities as are the volt—ampere characteristics and the thermal efficiency: I^2/Gd, G/d, pd, and l/d; for instance, the heat fluxes to the anode and cathode are defined, respectively, by the following formulas [7, 8]:

$$\frac{Q_a}{N} = 0.05\left(\frac{I^2}{Gd}\right)^{0.11}\left(\frac{G}{d}\right)^{-0.25}\left(\frac{l}{d}\right)^{0.17}, \tag{3}$$

$$\frac{Q_c}{N} = 0.141\left(\frac{I^2}{Gd}\right)^{0.06}. \tag{4}$$

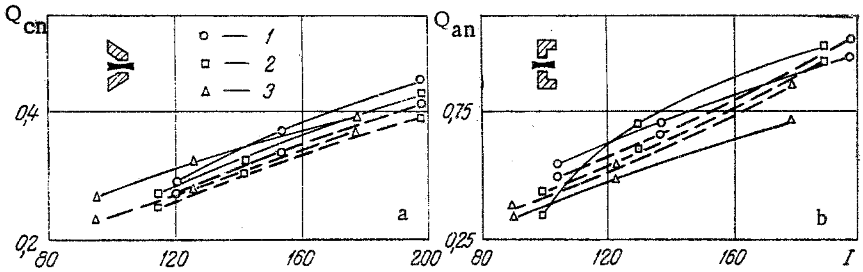

Fig. 2. Comparison of characteristic experimental heat fluxes (solid lines) and values calculated from (10) (dashed lines) for the nozzles in the cathode (a) and anode (b) parts of a two-jet plasma source working at the following air flow rates (10^3 kg/sec): 1) G_1 = 0.40; G_2 = 0.42; 2) G_1 = 0.69; G_2 = 0.74; 3) G_1 = 0.88; G_2 = 1.12.

However, the above formulas apply for the opposite polarity of the system (the hollow electrode is the cathode). In our case, the hollow electrode was the anode, which explains why G/d and l/d have negligible effects on the heat flux to the anode. For the same reason, the numerical coefficient and exponent are different. The heat flux to the anode may be approximated as follows:

$$\frac{Q_a}{N_2} = A\left(\frac{I^2}{Gd}\right)^{\alpha}. \tag{5}$$

Figure 1b shows characteristic experimental heat fluxes to the anode in this source.

We found that the measurements could be fitted to within ±20% by

$$\frac{Q_a}{N_2} = 20.9\cdot 10^{-4}\left(\frac{I^2}{G_2 d_{an}}\right)^{0.20}. \tag{6}$$

The electrical power in the anode unit is

$$N_2 = IU_2. \tag{7}$$

We substitute for U_2 from (8) of [1] into (6) to get the heat flux for this case as

$$Q_a = 1.5I\left(\frac{I^2}{G_2 d_{an}}\right)^{0.07}\left(\frac{G_2}{d_{an}}\right)^{0.12}(pd_{an})^{0.25}. \tag{8}$$

Nozzle. The nozzles in the two electrode units were similar in design and constituted electrically neutral stops. A nozzle receives heat by convective transfer from the heated gas and also by radiation from the arc [6]. The heat flux to a nozzle is dependent on the geometry and on the energy characteristics of the arc and plasma flux. In our experiments, the ratio of the nozzle length to the diameter varied within the following limits: cathode unit l_{cn}/d_{cn} = 0.75–3.75; anode unit l_{an}/d_{an} = 0.8–4.0.

Studies have been made [6, 8–10] of the heat fluxes to electrically neutral stops; those most similar to ours are found in [10], where power-law approximations were used. Therefore, the heat fluxes to the nozzles were approximated as

$$\frac{Q_n}{G_{el}} = A_{1.2}\frac{l_n}{d_n}\left(\frac{N_{el}}{G_{el}}\right)^{\alpha_{1.2}}. \tag{9}$$

Figure 2a,b shows the heat fluxes to the nozzles in this source.

We found that the heat fluxes to the nozzles were represented to within ±40% by

$$\frac{Q_n}{G_{el}} = A_{1.2}\frac{l_n}{d_n}\left(\frac{N_{an}}{G_{an}}\right)^{1.50}. \tag{10}$$

The result for the cathode was $A_1 = 15.8 \cdot 10^{-5}$, whereas that for the anode was $A_2 = 22 \cdot 10^{-5}$; the power deposited in each electrode unit was

$$N_1 = IU_1, \; N_2 = IU_2, \tag{11}$$

where U_1 and U_2 are defined by the following formulas [1]:

$$U_1 = 490 \left(\frac{I^2}{G_1 d_{\text{cn}}}\right)^{-0.10} \left(\frac{G_1}{d_{\text{cn}}}\right)^{0.25} (pd_{\text{cn}})^{0.25}, \tag{12}$$

$$U_2 = 715 \left(\frac{I^2}{G_2 d_{\text{an}}}\right)^{-0.13} \left(\frac{G_2}{d_{\text{an}}}\right)^{0.12} (pd_{\text{an}})^{0.25}. \tag{13}$$

Formula (1) agrees well with experiment and with the data of [10].

Figure 2a, b shows theoretical curves constructed from (10).

These expressions are sufficiently accurate for preliminary design calculations on the heat fluxes in the electrode units of such a device and also on the contributions from the geometrical and energy parameters to the fluxes.

NOTATION

I, current, A; U, voltage drop, V; N, power, kW; Q, heat flux, kW; G, air flow rate, kg/sec; p, pressure, N/m^2; l, channel length, m; d, channel diameter, m. Indices: 1, cathode; 2, anode; el, electrode unit; c, cathode; a, anode; n, nozzle; cn, cathode nozzle; an, anode nozzle.

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