A PLASMA SOURCE WITH A COMBINED CATHODE

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Results are presented of an experimental investigation of a plasma source the central electrode of which consists of a combination of a copper cylindrical cathode with a heated tungsten cathode at the end; the tests were conducted in argon and helium at currents of 0.4-3.0 kA.

Coaxial plasma sources with cooled copper electrodes and magnetic stabilization of the arc are widely used to heat gases, e.g., air [1], argon, helium [2]. The point of attachment of the arc to the central electrode can be displaced to the end in response to the gas flow; then the interaction of the arc with the external axial magnetic field is reduced, and the rate of arc wander is much lower. This may lead to electrode burnout at high currents.

An additional solenoid within the central electrode provides improved performance in a coaxial plasma source [3]. The internal magnetic field in this electrode provides for the movement of the point of attachment of the arc over the end surface, which eases considerably the operation of the electrode and reduces the comtamination of the gas flow by electrode material.

We have examined such a source having a central electrode containing two turns as a coil, these turns being connected in series with the power circuit, and the tests showed that the arc-burning voltage was higher than that for a simple electrode, especially at arc currents above 1.5 kA, but of course there was also a substantially increased heat loss to the external electrode.

We have examined the parameters of a plasma source the central electrode of which consisted of a cooled copper cylindrical cathode with a heated tungsten cathode at the end; depending on the gas flow rate

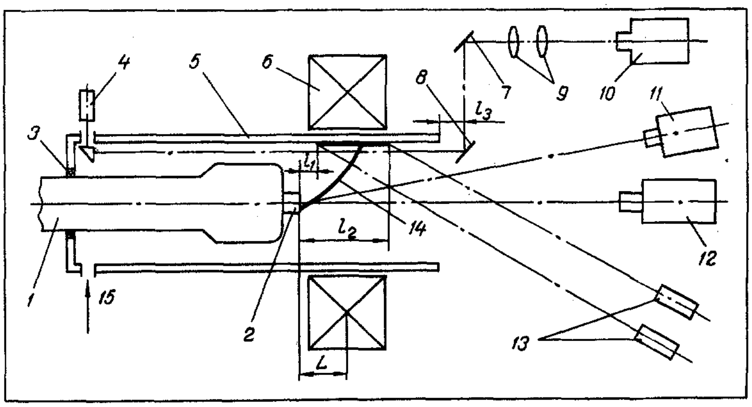

Fig.1. The apparatus: 1) copper cathode; 2) heated tungsten cathode; 3) insulator; 4) arc rotation transducer; 5) anode chamber; 6) solenoid; 7 and 8) mirrors; 9) lens; 10) spectrograph; 11) pyrometer; 12) cine camera; 13) arc length transducer; 14) arc; 15) gas inlet.

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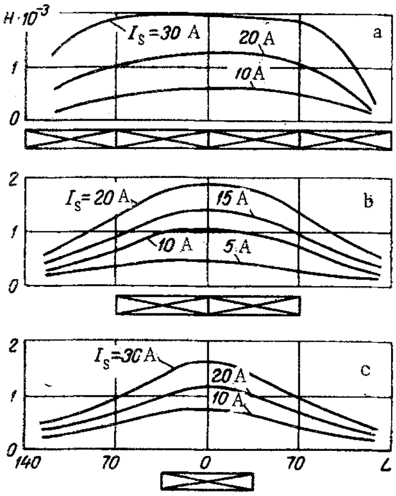

Fig. 2

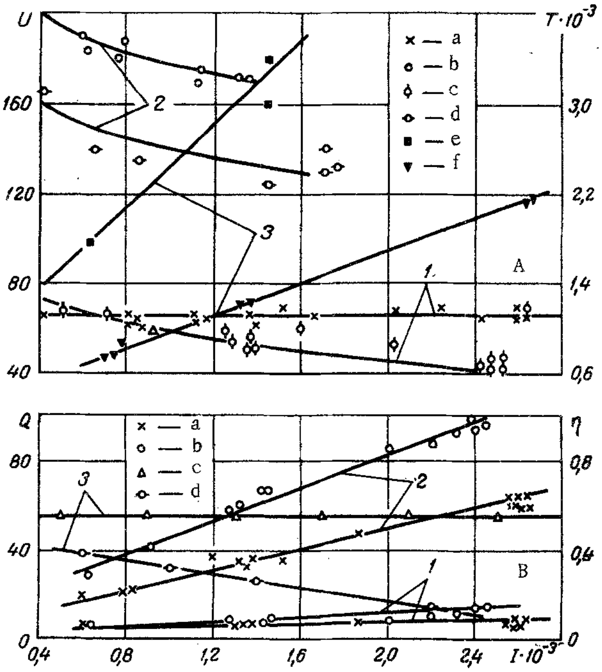

Fig. 3

Fig. 2. Axial fields in coils: a) four sections; b) two sections; c) one section. H, Oe; L, mm.

Fig. 3. A: 1, 2) Voltage–current curves; 3) temperature of gas at exit; B: heat losses at cathode (1) and anode (2) with heated cathode; 3) efficiency (argon, G = 30 g/sec; I_s = 10 A for argon, 30 A for helium). A: 1) argon, G = 30 g/sec; 2) helium, G = 10 g/sec; a, b) heated cathode; c, d) copper cathode; 3) heated cathode; e) helium, G = 10 g/sec; f) argon, G = 120 g/sec; B: a) argon, G = 120 g/sec; b) helium, G = 10 g/sec; c) heated cathode; d) copper cathode. Q, kW; U, V; I, A; T, °K.

and the strength and configuration of the external magnetic field, the arc could be struck between the copper electrodes (coaxial system) or between the tungsten cathode and the copper cylindrical anode (end-face system).

The apparatus is shown in Fig. 1. The arc discharge between the central electrode (cathode) 1 and the body (anode) 5 was struck by exploding a wire; the plasma source and the coil 6 were fed from separate power supplies. The internal diameter of the arc chamber was 70 mm, while the body of the cathode had a diameter of 40 mm. The heated cathode 2 consisted of lanthanum-treated tungsten in the form of a rod 10 mm in diameter.

The effects of the magnetic field on the operation were examined with various solenoids composed of identical sections, each section having 960 turns. The various forms of the external magnetic fields are shown in Fig. 2. We measured various parameters of the source during tests.

We measured the arc rotation speed with the photodiode system 4 (Fig. 1) having a narrow acceptance angle [4].

We measured the axial component of the arc length by means of two narrow-angle transducers 13 (DF-2), which were similar in design to the arc-rotation detector. During the measurements, the transducers were positioned on the wall of the arc chamber at distances l_1 and l_2 from the plane of the cathode.

We measured the temperature of the tungsten cathode by means of the specially developed BFÉP-1 fast photoelectric micropyrometer [5].

The sighting aperture of the pyrometer was 1 : 700, while the error of measurement was about ±1%; the instrument provided temperature recording with a delay of less than 10^{-3} sec in the range 1700-4300°K. We measured the radiation from an area 3 mm in diameter. The detector could also receive light from the arc column, which could lead to overestimation of the temperature.

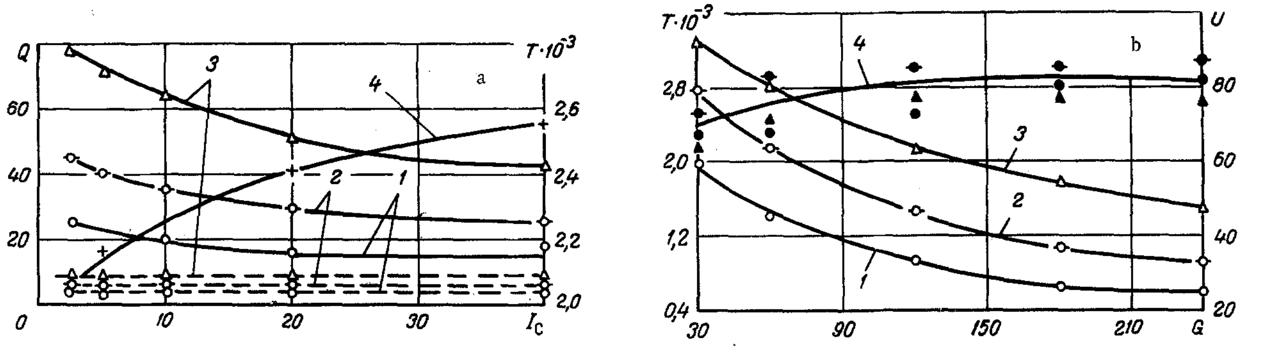

Fig. 4. a) Heat loss (1-3) and temperature of gas at exit (4) as functions of solenoid current (argon, G = 120 g/sec) for the following currents, A, in heated cathode: 1) 800; 2) 1300; 3) 2600; ——) loss in the anode; - - - -) loss in cathode; b) exit gas temperature (1-3) and voltage (4) as functions of argon flow rate (I_S = 10 A) for I, A: 1) 800; 2) 1300; 3) 2600. Q, kW; I, A; U, V; G, g/sec.

The electrode materials in the plasma were identified qualitatively by spectrographic examination of the rotating arc and the jet at the outlet by means of an ISP-30 spectrograph.

High-speed cinematography was used to deduce the arc structre, rotation speed, point of attachment, etc. We used a SKS-IM cine camera operating at $4 \cdot 10^3$ frames/sec with A-2 film and a blue filter.

The gas temperature distribution at the exit was measured with VR 5/20 thermocouples 0.34 mm in diameter; four or five such couples were set along a radius in the exit section.

In the first series of tests, we used a uniform axial magnetic field (Fig. 2a) to determine the operating capacity of the tungsten heated cathode and the stability of the device as a whole; the cathode was placed at the center of the solenoid (L = 0, Fig. 1). The tests were conducted with an argon flow rate of 30 g/sec and a helium flow rate of 5 g/sec.

We used arc currents of 0.6-2.5 kA and solenoid currents I_S = 10-40 A; in this range the discharge was unstable. Cinematography showed that the arc was attached to the end of the tungsten rod at its side surface, at the point abutting the copper body, or else to the cylindrical copper surface of the cathode body. If the brightly emitting region at the end is taken to be a cathode spot, the mean current density there was $0.5\text{-}1.0 \cdot 10^4$ A/cm^2.

Instability in the position of the cathode spot and change in arc length cause large variations in the plasma-source voltage; the value ranged from 70-80 V on attachment to the end of the heated cathode to 40-50 V on attachment to the cold copper rod, i.e., as in the case of a simple cathode [2].

The brightness temperature of the end of the heated cathode varied from 3300 to 1700°K with the arc burning voltage; the rate of change of temperature as recorded by the pyrometer was as high as 10^4 deg /sec. These results qualitatively reflect the change in the cathode temperature. Spectrographic studies on the exit jet showed that the lines of copper and tungsten were present.

With an argon flow G = 30 g/sec and I_S = 60 A, the arc burned stably between the copper electrodes, and the characteristics have already been reported [2].

Stable operation of the plasma source in argon with the arc attached to the heated cathode was achieved with a nonuniform axial magnetic field (Fig. 2c) and L = 120 mm. The photodiode transducers were sited at l_1 = 60 mm (DF-2a) and l_2 = 120 mm (DF-2b), these distances being measured from the cathode (Fig. 1).

With I_S = 10 A and G = 30 g/sec, the rate of rotation of the arc represented f = 200 Hz, and the arc burned stably with attachment to the heated cathode. The arc length then exceeded 60 mm (DF-2a), but was less than 120 mm (DF-2b). If I_S was raised to 40 A, the rate of rotation rose to 400 Hz and the arc was unstable, leaping from the heated cathode to the copper part and back again.

When this instability appeared, the voltage fell by 60-70%, while the current rose by 8-10%. The rate of rotation of the arc was reduced by a factor of 2-3. If the argon flow rate was greater than 30 g /sec, the arc burned stably with attachment to the heated cathode, no matter what the magnetic field strength.

Visual observations showed that the size of the exit jet was reduced as the solenoid current was increased, and the jet extended back into the arc chamber. Increase in discharge current at constant flow rate and constant magnetic field resulted in an increase in the arc length and improved stability of operation.

The pyrometer gave the temperature at the end of the tungsten rod as 4300–4800°K when the arc was stably attached there, as a result of a contribution from the radiation from the arc column. In this case, the exit jet did not show the lines of the electrode materials.

When helium was used, a stable condition was provided by a solenoid of two sections (Fig. 2b) with $I_s = 20$ A, $L = 90$ mm, and $G = 5$–10 g/sec. Spectrography showed only the lines of helium; the mean temperature in the arc column at $I_{ar} = 2.6$ kA and a flow rate of 10 g/sec was deduced from the He I 3888.65 Å and He I 3964.53 Å, the result being about $15 \cdot 10^3$°K. The physical constants of these lines were taken from [6].

Voltage–current curves of the source operating with argon and helium are shown in Fig. 3a together with results obtained using a copper central cathode and a uniform axial magnetic field [4]. In both cases the diameter of the arc chamber and the body of the cathode were the same as above, namely 70 and 40 mm.

At small currents, the arc current in argon was roughly the same in both modes of operation. However, when the arc was attached to the copper cathode, the voltage tended to fall as the current was increased, whereas when the arc was attached to the heated cathode, it remained constant. This is due in the first case to increase in the cross section of the arc column at constant length, and in the second to increase in the arc length.

If I_{ar} was 2–2.5 kA, the arc voltage and hence the dissipated power was increased for the heated cathodes relative to the copper wire by 65–70%; in the case of helium, the burning voltage was only 20–25% higher, while the voltage–current characteristic had a negative slope.

The heat losses in the electrodes increase linearly with the discharge current (Fig. 3b). The copper cathode had a current equivalent of the heat loss in helium of 20–30 V, or 15–20 V in argon [2], while the corresponding values for a tungsten heated cathode were 4–6 and 3.5–4 V, respectively. The heat losses to the arc chamber at $I_s = 10$ A were roughly the same in the two cases. The mean-mass temperature of the gas at the exit increased linearly with the current for the two gases (Fig. 3a).

If the heat loss in the electrode is linearly related to the current, the thermal efficiency of the source is

$$\eta = 1 - \frac{\Delta U_c + \Delta U_a}{U_{ar}}.$$

The arc burning voltage in argon with a heated cathode was largely independent of the current, so the thermal efficiency was also independent of the current; in the case of the copper cathode, the voltage decreased as the current rose, so η also fell (Fig. 3b). If $G = 30$ g/sec for argon with a discharge current of 2.5 kA, η with the heated cathode was twice the above value on account of the larger U_{ar} and the lower ΔU_c.

The heat losses in the central cathode were largely independent of the external magnetic field; the heat loss in the chamber tended to decrease as the external magnetic field was increased when a heated cathode was used, while the burning voltage did not alter, and the mean-mass gas temperature at the exit increased (Fig. 4a). The converse picture was observed for a copper cathode [2]. This was due to the different configurations of the arc column.

The argon flow rate affected the plasma parameters, which were examined at various fixed discharge currents (0.8, 1.3, and 2.6 kA) and external magnetic fields (Fig. 2c, $I_s = 10$ A). The argon flow rate varied from 30 to 240 g/sec.

The mean-mass gas temperature at the exit decreased as the flow rate was increased from 3200 to 600°K (Fig. 4b); the temperature distribution also tended to become flatter.

From measurements of the axial component of the arc length and the cine it was found that the increase in voltage was related to increase in arc length; at argon flow rates above 120 g/sec, the arc length remained unchanged, while the distance between the plane of the cathode and the point of attachment of the arc to the anode was 100–120 mm.

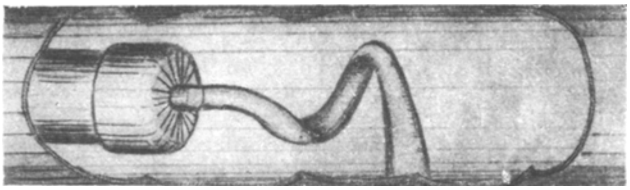

Fig. 5. Approximate configuration of arc column as indicated by high-speed cinematography.

distance between the plane of the cathode and the point of attachment of the arc to the anode was 100–120 mm.

High-speed cinematography showed that the arc column had a complex form, as shown in Fig. 5; near the cathode, there was a straight region along the axis, which then gave way to a turning and spiral form near the point of attachment to the anode. The diameter of the arc column in the linear part increased with the current and was 10–15 mm for I_{ar} = 2.6 kA; when the length l_{ar} = 8–10 cm, the mean electric field strength in the arc column was roughly 4–5 V/cm.

The cross section of the arc column increased with the current, while the electric field strength fell, but the increase in arc length caused the overall plasma voltage to remain practically unchanged.

When the arc was stably attached to the heated cathode, there was no appreciable size reduction over a total test period of 60 min (6 × 10 min) at 2–3 kA.

A combined cathode therefore permits the exit gas temperature to be regulated at constant flow rate by the use of an external magnetic field to change the cathode operating conditions. If the gas flow rate is small or zero, the source operates in the coaxial mode, while above a certain flow rate it operates in the end-face mode. The heated cathode roughly doubles the thermal efficiency of the plasma source relative to a copper cathode in the case of argon, and the gas at the exit is less contaminated with electrode material.

NOTATION

I_s, I_{ar}	are the solenoid and arc currents;
U_{ar}	is the arc voltage;
ΔU_c, ΔU_c	are the equivalents of the heat losses in the cathode and anode;
G, T	are the gas flow rate and the temperature at the exit from the plasma source;
Q	is the heat loss in the electrodes;
η	is the efficiency of the plasma source;
H	is the magnetic field of the solenoid.

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