EXPERIMENTAL STUDY OF TEMPERATURE FIELDS AND HEAT FLUXES IN THE CHAMBER OF AN ELECTRIC ARC HEATER

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An experimental study is made of the distribution of temperatures and heat fluxes in the wall of the outer electrode of an electric arc gas heater with coaxially located electrodes.

Coaxial electric discharge plasmotrons, in which the gas is heated by a radial electric discharge rotating under the effect of an axial magnetic field in a circular interelectrode gap, have received wide distribution in different areas of technology. However, the thermal efficiency of such heaters is small and the life of their electrodes is often insufficient. The improvement of the characteristics of heaters is impossible without data on the distribution of heat losses between separate elements of the heater and in the elements themeselves and on the temperature fields in the walls of the construction as a function of the different parameters which determine the operation of the heater. A theoretical analysis of these effects is very complicated because of the abundance of factors acting on them, and the experimental data are incomplete. For example, the experimental studies whose results are presented in [1] showed that the greatest heat losses belong to the outer electrode (the chamber of the heater), with the distribution of heat

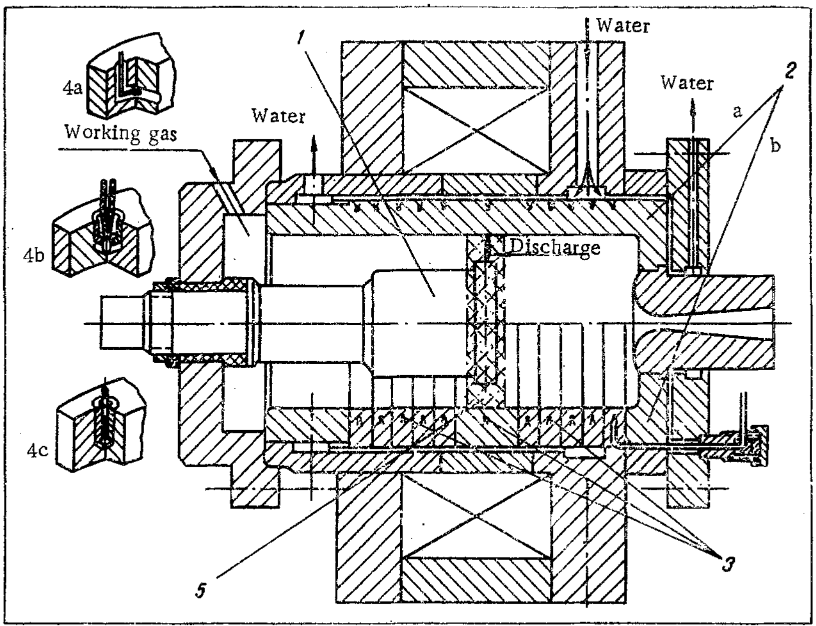

Fig. 1. Diagram of preparation of outer electrode with thermocouples: 1) Central electrode (anode); 2) outer electrode (cathode): a) one-piece, b) sectioned; 3) thermocouples; 4) means of mounting thermocouples: a) type I, b) type II, c) type III; 5) region of magnetic field maximum.

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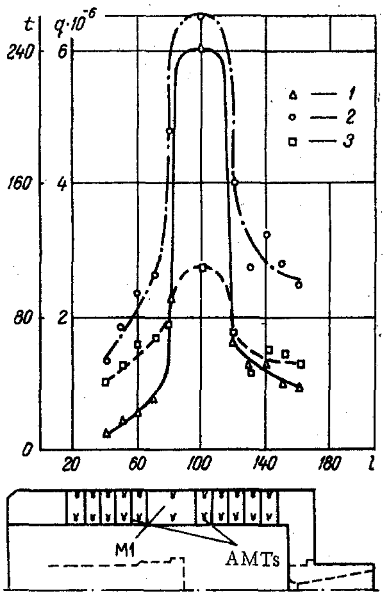

Fig. 2. Distribution of temperatures and heat fluxes in wall of outer electrode along chamber at I = 600 A, B = 0.7 T; P = $4.5 \cdot 10^5$ N/m^2: 1) specific heat flux; 2) temperature in wall on side of surface being heated; 3) temperature in wall on side of cooled surface. t, °C; q, W/m^2; l, mm.

losses over the heater chamber being very uneven, a sharply expressed maximum in the losses occurring in the discharge zone.

Articles have been published in which the dependence of the local heat fluxes in the heater chamber on the discharge current and electric power input was determined. However, these studies were conducted with atmospheric pressure in the heater chamber and in a narrow range of variation in the axial component of the magnetic induction. There are no experimental data in the literature on the temperature distribution in the walls of the heater elements as a function of the various factors affecting it (discharge current, magnetic induction, pressure in heater chamber, gas flow rate, wall material, cooling system, etc.).

In the present report we give the results of an experimental determination of the temperature fields in the chamber wall of a coaxial electric discharge heater and the dependence of the local heat losses to the wall for different values of the discharge current, magnetic induction, and pressure in the heater chamber.

Experimental Apparatus and Method of Conducting Experiment. The experiments were conducted on a coaxial electric discharge heater with stabilization of the discharge in the axial direction using a magnetic field with a sharply expressed maximum in the discharge region. A detailed description of the experimental apparatus is presented in [2]. The determination of the temperature fields and distribution of heat losses was accomplished in the outer electrode (cathode), with the central electrode (anode) having a diameter of 55 mm and the cathode having inner and outer diameters of 80 and 112 mm, respectively. Two types of outer electrode were used in the experiments (Fig. 1).

The first type consisted of a cylindrical bushing made of copper, the second was made up of rings, with a ring of copper 30 mm wide mounted in the discharge zone and rings 10 mm wide either of copper or of deeply anodized aluminum mounted in the other sections. There was an assured gap between the rings of the sectioned outer electrode which prevented the flow of heat along the electrode circuit, and the measured temperature field permitted the calculation of the local heat fluxes averaged over the width of a ring.

In addition, the sectioned outer electrode permitted the rather simple testing of different materials for the fabrication of the elements of the outer electrode and the selection of those whose use promotes an increase in the thermal efficiency of the heater and an increase in the life of the electrode.

The measurements of the temperature distribution in the wall of the outer electrode were made with Chromel–Copel thermocouples with thermoelectrode wires 0.3 mm in diameter. A diagram of the preparation of the thermocouples of the outer electrode is presented in Fig. 1. Two thermocouples were mounted in each section, one of them located near the outer surface of the electrode (2-3 mm) which was cooled by water, the other located near the surface subject to heating (2-3 mm). The thermocouple wires were run through the channels of the cooling system and protected with ED-5 epoxy resin. The lead out of the thermocouples was accomplished through resin packings located in the pipe connections. The temperatures were recorded on a type N-010 oscillograph.

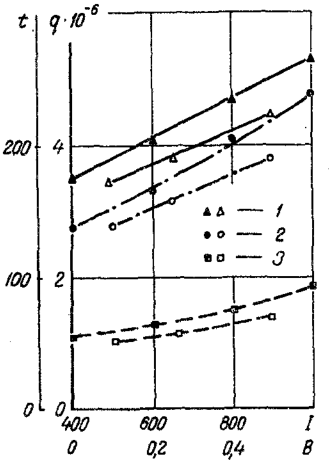

Fig. 3

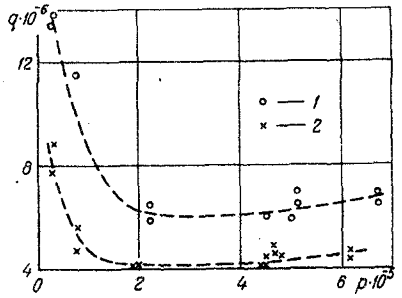

Fig. 4

Fig. 3. Dependence of temperatures and heat fluxes in wall of discharge zone on discharge current at $P = 5 \cdot 10^5$ N/m^2 and $B = 0.1$ T (dark points) and on magnetic induction at $I = 400$ A and $P = 4.5 \cdot 10^5$ N/m^2 (light points): 1) specific heat flux; 2) temperature in wall on side being heated; 3) temperature in wall on side of cooled surface. q, W/m^2; t, °C; I, A; B, T.

Fig. 4. Dependence of heat flux at wall of discharge zone on pressure at: 1) $I = 600$ A, $B = 0.7$ T; 2) $I = 400$ A, $B = 0.5$ T. q, W/m^2; P, N/m^2.

With the placement of the thermocouples in the electrode it was necessary to ascertain the effect of the electric discharge on the thermocouple readings and to resolve the question of the rational means for their mounting. When the thermocouples are mounted at a considerable depth in relatively narrow rings a significant disturbance occurs in the integrity of the wall material, resulting in distortion of the temperature field. In addition, the removal of heat from the junction through the thermoelectrodes can affect the thermocouple readings.

As the oscillogram recordings of the electrode wall temperatures, current, and discharge voltage at different times showed, the discharge does not affect the thermocouple readings.

The effect of the means of mounting the thermocouples on their readings was determined in preliminary experiments in which the two rings closest to the discharge zone were prepared by three different means (see Fig. 1). In the first of these the insert containing the thermocouple was placed in a ring-shaped channel whose entire interior was filled with fine filings of the ring material and flooded with heat-resistant cement. As shown in [3], the thermal conductivity of finely dispersed filings hardly differs from the therma conductivity of the material itself and consequently cannot affect the thermocouple readings. Moreover this means of sealing the thermocouples assures the location of a considerable length of the thermoelectrode wires (more than 50 diameters) at an isothermal surface, which prevents the removal of heat from the thermocouple junction through the thermoelectrode wires. However, the mounting of thermocouples by this method is possible only in the case of a sectioned electrode.

The second means is simpler in terms of execution. The thermocouple with the insert is lowered to the bottom of an opening drilled to the desired depth. However, the removal of heat along the thermoelectrode wires exists in this case and it is rather difficult to determine the exact position of the junction because of the possibility of short circuiting within the insert.

In the third means the welded thermocouple is covered by an insert made of the ring material, a section of thermocouple wires 15-20 diameters long adjoining the junction is twisted into a flat spiral, and then the insert containing the thermocouple is pressed into an opening drilled to the desired depth. Thus, the twisted section of wires is located in a plane close to an isothermal surface, which considerably decreases the removal of heat along the thermoelectrodes. The presence of the insert is necessary to prevent distortion of the temperature field due to drilling of the opening and to provide the necessary abutment of the thermocouple junction against the bottom of the opening.

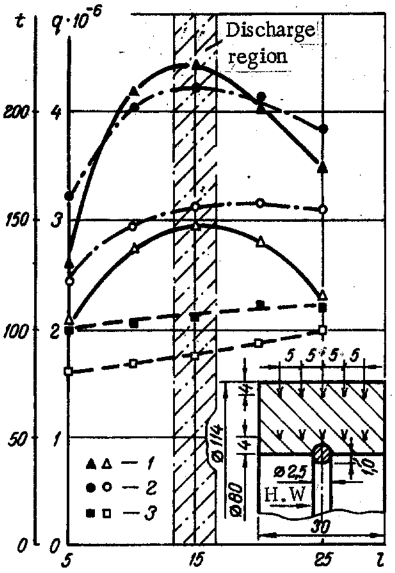

Fig. 5. Distribution of temperature field and heat flux in discharge ring of copper (dark points) and in ring of copper with hafnium insert at I = 400 A, B = 0.5 T, $P = 4.5 \cdot 10^5$ N/m^2 (light points): 1) specific heat flux; 2) temperature in wall on side being heated; 3) temperature in wall on side of cooled surface. t, °C; q, W/m^2; l, mm.

It was determined that the readings of thermocouples placed near the outer surface of the electrode are almost independent of the means of their mounting. The readings of thermocouples mounted near the inner surface differed markedly. The highest temperature was registered by thermocouples mounted by the first means. The second means of mounting the thermocouples reduced the readings by 35-40% and the third by 3-5% compared with the first.

Therefore in all subsequent experiments the thermocouples located near the outer surface were mounted by the second means and those near the inner surface by the third means; the constant measurement error connected with the means of mounting the thermocouple was allowed for in treating the experimental data.

It should be noted that the root-mean-square measurement error, including the accuracy in mounting the thermocouple, the class of precision of the recording instrument, and the accuracy in interpreting the oscillograms, is on the order of ±8%.

The studies were conducted on air with flow rates $G = (0.3\text{-}7) \cdot 10^{-3}$ kg/sec, pressures $P = (0.3\text{-}7) \cdot 10^5$ N/m^2, currents $I = 400\text{-}1000$ A, and magnetic induction $B = 0.1\text{-}1$ T.

The flow rate of the gas, the pressure in the forechamber, and the current and voltage of the discharge were measured during the experiment along with the temperature field in the wall of the outer electrode. The recording of the measured parameters was conducted on an N-010 oscillograph synchronously with the temperature recording.

Results of Experiment. An analysis of the data of the temperature recording showed that a stationary temperature mode is achieved in the investigated range of variation of the heater parameters. A typical temperature distribution in the wall of an outer electrode made up of rings, in a stationary mode with constant discharge current, magnetic induction, and pressure in the heater forechamber, is shown in Fig. 2. It is seen that in the region of the discharge there is a sharply expressed maximum in the temperatures of the electrode wall while the heat flux in this region is several times greater than the heat fluxes in the neighboring regions, the total heat losses in the narrow discharge zone being comparable to the losses in the rest of the chamber. Such a large difference in the local heat fluxes cannot be connected only with an increase in the heat losses in the discharge zone because of the drop in potential near the electrode, but is apparently connected to no less an extent with convective heat losses which depend both on the higher temperature drop between the gas and the wall and on the higher gas velocities in this region. A comparison of our results with the data of [1] shows that under the same experimental conditions the data obtained on the distribution of heat fluxes agree both in the nature of the distribution and in the magnitude.

The dependences of the temperatures and heat fluxes in the discharge zone on the magnetic induction, discharge current, and pressure in the forechamber are represented in Figs. 3 and 4. It is seen that the dependences of the temperatures and heat fluxes on the magnetic induction and discharge current are close to linear in the range of variation of the parameters studied.

The dependence of the heat fluxes in the discharge zone on the pressure at a constant current and magnetic induction has a minimum at the pressure $P = (1\text{-}2) \cdot 10^5$ N/m^2. The increase in heat fluxes at pressures less than atmospheric pressure is apparently explained by an increase in the rotation rate of the discharge and consequently of the gas stream, by an increase in the potential drops near the electrode because of the Hall effect, and by a decrease in the mass of the heat-absorbing gas. The increase in heat fluxes at pressures $P > 2 \cdot 10^5$ N/m^2 seems to be connected with an increase in convective heat losses because of the increase in gas density.

The dependences of the wall temperatures and heat fluxes on the magnetic induction, discharge current, and pressure in the other sections of the chamber have a nature similar to that examined.

An analysis of the results of temperature field measurements in the wall of the undivided electrode showed that under the same experimental conditions there is a marked difference in the temperature field only near the discharge zone.

The purpose of the subsequent experiments was to study the possibility of decreasing the heat losses through the use of different materials for the construction of the chamber elements, for which the chamber was divided into two regions, an extradischarge zone and a discharge zone 30 mm wide, which were examined separately.

The studies showed that the use of heat-resistant thermal insulation coatings can be quite effective. For example, replacing the copper rings in the extradischarge zone with rings of AMTs aluminum alloy with a heatproof coating of thickness $\delta = 70\ \mu$ obtained by the deep anodizing method permitted an increase in the heater efficiency from 18 to 28% at a discharge current $I = 600$ A, magnetic induction $B = 0.67$ T, and gas flow rate $G = 7 \cdot 10^{-3}$ kg/sec.

Similar results were obtained by the authors in a test of an outer electrode made of copper in which the extraelectrode zone was covered with a heatproof coating of aluminum oxide applied by spraying.

Temperature and heat flux distributions in a discharge ring in the middle part of which a ring of hafnium wire 2.5 mm in diameter is embedded in a ring-shaped channel are presented in Fig. 5. The temperature field and heat fluxes without the hafnium insert are also shown there for the same experimental conditions ($I = 400$ A, $B = 0.5$ T, and $G = 7 \cdot 10^{-3}$ kg/sec).

It is seen that in the case of shielding of the discharge part of the right with high-temperature heat-resistant material the temperature level in the wall is markedly reduced and the heat losses in this zone are decreased.

It should be mentioned that such heat shielding is also desirable on the central electrode (anode), although for the shielding of the discharge zone it is necessary to use high-temperature heat-resistant materials with low thermoelectron emission such as nickel or rhenium, and it is undesirable to have unshielded copper in the discharge region.

NOTATION

t	is the temperature, °C;
q	is the specific heat flux, W/m^2;
P	is the gas pressure, N/m^2;
G	is the mass flow rate of gas, kg/sec;
I	is the current, A;
B	is the magnetic induction, T;
δ	is the thickness, mm;
l	is the length, mm.

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