EXPERIMENTAL STUDY OF HEAT TRANSFER IN AN ELECTRIC ARC GAS HEATER WITH VORTEX STABILIZATION OF THE DISCHARGE

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The results of an experimental investigation into heat transfer in the discharge chamber of an electric-arc gas heater are presented. For the anode the resultant data are expressed in the form of generalized relationships $q_{an} = f(I, d)$, $St = f(l/d, Re, N/GH_0)$. The energy losses in the basic arc spot are estimated.

The parts of electric-arc gas heaters subjected to the most severe thermal conditions are undoubtedly the electrodes. The thermal flux reaching an electrode arises from a number of energy-transfer mechanisms. The chief of these in a heater with cooled metal electrodes operating at almost atmospheric pressure are convective heat transfer and the transfer of energy by charged particles in the region of the basic arc spot. With increasing temperature and pressure the proportion of the energy carried by radiation becomes greater.

The energy balance at the surface of the anode takes the form $Q_{an} = Q_c + Q_{el}$. The energy carried by convection Q_c is determined, for example, by Eq. (5.10) of [1]. The energy carried to the anode in the basic spot Q_{el} is made up of the thermal energy of the electrons, the kinetic energy which these acquire in the region of the anode potential drop, and the work function $Q_{el} = I((5/2e)K_B T_e + U_a + \varphi_a) = IU_2^{eff}$. The quantities entering into the electron component of the heat losses depend on the nature of the electrode material and the medium as well as the temperature, pressure, and current. For example, in the case of copper electrodes with a current of several amperes, operating in air or nitrogen at a pressure of 1 atm, the anode voltage drop U_a is 2-6 V and the work function $\varphi_a = 4.5$ V [3]. In the steady anode-operating condition, all the heat arriving at the electrode is taken off by the cooling water (Q_{an}).

The literature contains no reliable data regarding the quantities determining the heat losses in the neighborhood of the basic point under the conditions characteristic of electric-arc gas heaters.

Generalized relationships for the thermal losses at the electrode such as are required for the thermal calculation of a heater may be derived by the method employed earlier [4, 5].

Shorin [4] generalized experimental data relating to heat losses at the anode of a vortex electric-arc gas heater in the form

$$St = 0.95 Re^{-0.27} \left(\frac{l}{d}\right)^{-0.72}. \tag{1}$$

In this analysis St includes both the convective and the current loss components. The defining quantities in (1) were varied over the ranges $l/d = 1.53$-5, $Re = 5 \cdot 10^3$-$7 \cdot 10^4$. The St and Re numbers were found from the parameters measured experimentally in the following manner:

$$St = \frac{Q_{an}}{IU - Q_c} \cdot \frac{d}{4l}; \quad Re = \frac{4G}{\pi d \bar{\mu}}.$$

Kutateladze et al. [5] used an analogous method to correlate experimental data regarding the efficiency of a heater with a rod cathode and a cooled copper anode in the pressure range 760-32 mm Hg. Analysis of the data showed that the complex including the efficiency was proportional to $Re^{-0.5}$.

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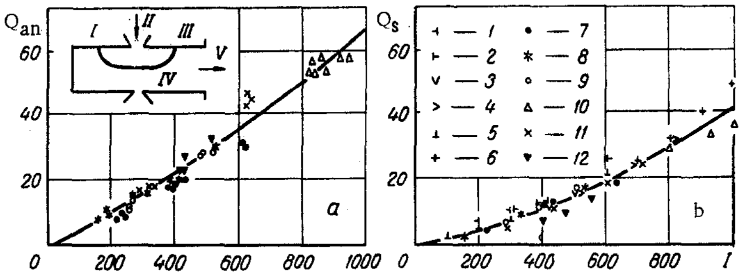

Fig. 1. Total heat losses at the anode (a) and energy losses in the basic spot of the arc (b) as functions of current: a) I, cathode; II, gas inlet; III, anode; IV, arc; V, plasma jet; b) 1) 4, d = 10 mm; 5, 6) 15; 7) 12, 20; 1, 5, 7) G = 2 g/sec, 2, 8) 3; 3, 9) 4; 6, 10) 5; 4, 11) 6; 12) 7.

This paper is devoted to a study of heat transfer in the discharge chamber of a widely-used form of heater (Fig. 1a) with a self-setting arc length and vortex stabilization of the discharge by nitrogen, using the method just indicated.

The electrodes were sections of copper tubes water cooled on the outside. Constructionally the cathode differed in no way from the anode. However, on the side opposite to the anode, the cathode was closed with a graphite stopper 20 mm long. The length of the electrode was 100 mm, the diameter of the anode 10, 15, 20, and 30 mm. The diameter of the cathode in the first three cases was 5 mm greater and in the last case equal to the diameter of the anode. The gap between the electrodes through which the gas (nitrogen) passed lay between 1.5 and 2.5 mm. Between the electrodes was an insulating ring with an internal diameter of 74 mm. The gas was fed along the tangent to the inner surface of the ring through two 4 mm diameter apertures. The graphite stopper and the gas ring, made of organic glass, underwent hardly any combustion and remained unchanged throughout the whole series of experiments.

During the experiment we used a loop oscillograph to measure the arc current and voltage, the gas flow, and the heating of the cooling water at the anode and cathode. Before the experiment we determined the rate of flow of the water. The parameters so measured enabled us to calculate the power evolved in the discharge chamber, the heat losses at the cathode and anode, the mass-average parameters of the heated gas, the St and Re numbers.

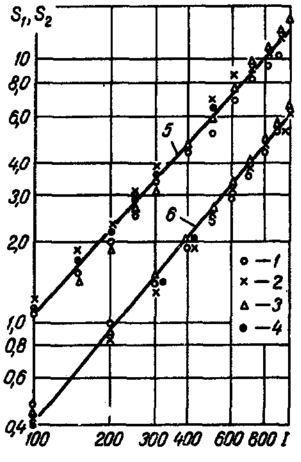

Fig. 2

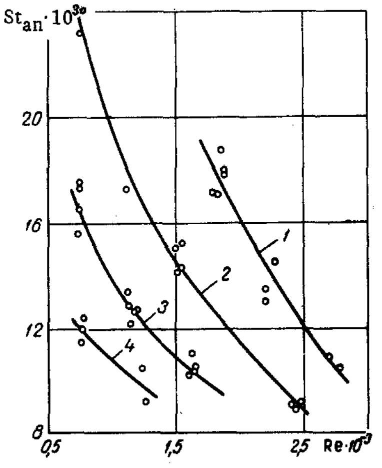

Fig. 3

Fig. 2. Dependence of the complexes $S_1 = q_{an} \cdot 10^{3.93d}$ and $S_2 = Q_{d.c}/0.933L \cdot 10^{0.17d}$ on the current I (A): 1) d = 10 mm; 2) 15; 3) 20; 4) 30; 5) S_2; 6) S_1.

Fig. 3. Dependence of the St number on Re for $l/d = 5$; 1) N = 207 kW; 2) 120; 3) 80; 4) 55.

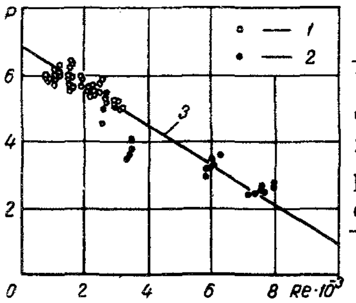

Fig. 4. Relation between the complex $P = \mathrm{St} \cdot 10^3/(3.4\ d/l + 0.32)\ \exp(0.923 \cdot 10^{-2} N/GH_0)$ and the Re number; d = 10-30 mm; N = 40-320 kW; G = 2-14 g/sec. 1) Electric-arc gas heater with two copper electrodes, l = 100 mm; 2) with a copper anode, l = 50 mm, d = 14 mm, and a rod-type graphite cathode; 3) calculation by Eq. (5).

Apart from the diameter of the electrodes, we varied the power of the arc over the range 40-220 kW, the current from 150 to 1000 A, and the gas flow from 2 to 7 g/sec. The range of variation of the enthalpy of the heated gas so achieved was 10000-22000 kJ/kg, and that of the Re number 700-3200.

In analyzing the data relating to the enthalpy of the heated gas we found that the relationship between the enthalpy and the power exhibited maxima for different gas flow rates. The existence of maxima on the curves may be attributed to the leading rise in losses as power increases. The maximum enthalpy values lie in the range 17000-21000 kJ/kg for the range of variation of the parameter N/G studied (30-55 kW · sec /g), and are determined by this parameter independently of the electrode diameter. The power corresponding to the enthalpy maximum is related to the gas flow rate for d = 10-30 mm by the equation $N_{H\,\max} = 31.6\ g + 33.8$.

On plotting the loss of heat at the anode and the total losses in the discharge chamber as functions of current, we obtain a single curve for a variety of gas flows (Fig. 1a); however, there is a slight separation of the curves for different anode diameters. This relationship may be attributed to the increase in the intensity of convective heat transfer which occurs, on increasing the enthalpy of the heated gas and the rate of flow, as a result of the increase in power and the reduction in the channel diameter. An increase in the rate of flow at constant power leads to a reduction in enthalpy and an increase in the velocity. As a result of this the losses diminish with increasing rate of flow at constant power. Furthermore, with increasing current the losses at the basic point of the arc become greater.

On plotting the relationship between the total losses per unit area of the heat-transfer surface of the anode and the current in logarithmic coordinates, we obtain a set of straight lines with parameter d. The generalized relationship for the specific thermal flux to the anode thus changes its form (Fig. 2):

$$q_{\mathrm{an}} = 0.4 I^{1.17}/10^{3.93d}. \tag{2}$$

An analogous consideration of data relating to the heat losses in the discharge chamber yields the following generalized relationship (Fig. 2):

$$\frac{Q_{\mathrm{d.c.}}}{L} = 0.933 \left(\frac{I}{100}\right)^{\left(\frac{d}{20} + 1.05\right)} \cdot 10^{-0.17d}. \tag{3}$$

The ratio of the heat losses at the anode to the heat losses in the discharge chamber for anode diameters of 10-30 mm is directly proportional to the current:

$$Q_{\mathrm{an}}/Q_{\mathrm{d.c.}} = 8 \cdot 10^{-5} I + 0.45 \tag{4}$$

or approximately equal to 0.5 as the current varies from 100 to 1000 A.

Using the foregoing method, we analyzed the resultant data in criterial form. An example of the relation between St and Re for $l/d = 5$ is presented in Fig. 3.

The points on the graph split up into individual curves, with a parameter given by the arc power.

This type of splitting remainded undetected earlier [4] on analyzing data relating to anode losses for argon. The generalized relationship there presented included only Re and l/d as defining parameters, not the parameter allowing for the enthalpy of the gas. This result may have been due to the use of a single level of power in the corresponding experiments.

After introducing the quantity N/GH_0 characterizing the enthalpy of the heated gas and also allowing for the parameter l/d, all the experimental data grouped themselves satisfactorily around a single curve (Fig. 4). The dependence of the normalized St number on Re may be approximated by the equation of a straight line. The generalized relationship for the heat losses at the anode in a heater with vortex stabilization of the discharge by the gas then takes the form

$$\mathrm{St} = (6.87 - 0.611 \cdot 10^{-3}\,\mathrm{Re})\left(3.4\,\frac{d}{l} + 0.32) \cdot 10^{-3} \exp(0.923 \cdot 10^{-2}\, N/GH_0\right). \tag{5}$$

The resultant relationship for the intensity of heat transfer at the anode was also compared with data relating to the losses at the anode of a slightly different arrangement of heater given in [6]. This paper [6] related to a determination of the mass-average enthalpy in terms of the arc power and rate of gas flow. The experiments were carried out in a heater with a cooled copper anode and a graphite rod cathode 20 mm in diameter. The diameter of the channel in the anode was 14 mm and the length of the anode 50 mm. The dimensions determining the tangential component of the gas flow rate in the anode channel differed considerably. The arc power varied from 120 to 320 kW and the nitrogen flow from 5 to 14 g/sec.

The results of the comparison (Fig. 4) indicate that Eq. (5) satisfactorily describes the heat losses in the copper anode of a heater with a rod cathode.

The range of parameters for which Eq. (5) was verified corresponds to $l/d = 3.5$–10; $\mathrm{Re} = 500$–8000; $N/GH_0 = 40$–165.

As already noted, the heat losses in the anode calculated from Eq. (5) are due to convective heat transfer and the transfer of energy in the basic spot of the arc.

Using experimental data obtained from [2], we estimated the extent of the losses in the basic spot of the arc. This calculation was necessarily rather approximate in view of the indeterminacy as regards the choice of enthalpy at the entrance into the channel.

The dependence of the heat losses in the spot on the current illustrated in Fig. 1b is described by the expression

$$Q_s = 1.25 \cdot 10^{-3}\, I^{1.51}. \tag{6}$$

It follows from the figure that the effective anode voltage drop varies from 22 V at $I = 200$ A to 42 V at $I = 100$ A. There have been various published values for the anode voltage drop in electric-arc gas heaters. According to some, this values is equal to 10 V and independent of current, according to others, it equals to 20 V for currents of the order of 200 A and falls with increasing current to 10 V at $I = 500$ A.

The estimation showed that the heat losses in the basic spot were, in our own case, approximately equal to the convective losses (Fig. 1). The relation between the losses due to the two basic mechanisms of energy transfer depends on the current flowing, the rate of gas flow, and the length and diameter of the electrodes. It is well known from the literature that the specific thermal flux in the basic spot of the arc is many times greater than the permissible thermal flux for a cooled copper wall. The motion of the basic spot over the surface of the electrode created by a gas vortex or eddy enables us to reduce the average specific thermal flux to values below the maximum permissible. The flux then becomes comparable with the specific thermal flux due to forced convection. It has sometimes been asserted in the literature that the heat losses in the electrodes of an electric-arc gas heater are determined by the electron transfer of energy in the basic arc spot. It follows from our present results that the proportion of heat losses due to convective heat transfer is very considerable for the usual arrangement of a heater in which the discharge is kept moving by vortex forces.

NOTATION

Q_{an}, Q_c, $Q_{d.c}$, P_s	are the heat losses in the anode, cathode, discharge chamber, and arc spot, kW;
l	is the length of anode;
d	is the diameter of anode, cm;
G	is the gas flow, g/sec;
N	is the arc power, kW;
$H_0 = 0.335$ kJ/g	are the enthalpy of the cold gas;
q	is the specific thermal flux, kW/cm^2;

L is the length of discharge chamber, cm;

μ is the viscosity of the gas found from the mass-average temperature of the heated gas.

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