HEAT TRANSFER IN THE ELECTRICAL NEUTRAL CHANNEL OF AN ARC GAS HEATER

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Results are given from experiments on heat transfer in the motion of a high-enthalpy gas through a tube; the results are presented in the form of a general relationship St = f(Re, H /H_0, l/d).

In determining the thermal characteristics of a heater it is necessary to consider the heat-transfer coefficient in the flow of a high-enthalpy gas in the tube. The mean-mass temperature of the gas in a discharge chamber may be 5000-8000°K in the case of nitrogen or air in an eddy-type heater with a self-stabilizing arc length [1].

The following relationship has been recommended for calculations of the heat-transfer rate in the tube; it was derived for a steady-state flow with relatively cool gas (a few hundred degrees):

$$\mathrm{Nu}_{\mathrm{av}} = 0{,}024\ \mathrm{Re}_{\mathrm{av}}^{0{,}8}\,\mathrm{Pr}_{\mathrm{av}}^{0{,}4}\left(\frac{T_l}{T_{\mathrm{av}}}\right)^{0{,}8}. \tag{1}$$

Equation (1) applies for tubes with $l/d > 50$; for short tubes there is a correction dependent on Re and l/d.

The expression proposed in [1] contains the enthalpy ratio $(H_{wa}/H)^{0.18}$ rather than the temperature ratio of (1) and takes the wall temperature as the definitive temperature for the system.

Heat transfer in a gas heater is accompanied by dissociation and ionization of the gas, a marked dependence of the properties of the gas on temperature and pressure, and by twisting of the flow. The ratio of the channel to its diameter is usually quite small; the channel in a discharge chamber is the entrance part of the tube where the flow develops [3]. The gas flow in the channel and the heat transfer may be affected by adjacent elements in the discharge chamber.

The following equation has been used [4] to approximate the results of a calculation of the cooling of air flowing in a tube with a developed flow for a wall temperature of 300°K and a liquid temperature of 300-700°K:

$$\mathrm{Nu}_l = \frac{48}{11}\left[1 + 0.065\left(1 + \frac{T_{\mathrm{wa}}}{T_l}\right)\right]. \tag{2}$$

Calculations [4] show that the nature of the gas has little effect in such processing in terms of Nu.

An expression has also been derived [4] for the heat-transfer coefficient in the flow of an appropriately dissociated gas in a tube, the detailed results being for hydrogen with the dependence of Nu as a function of the properties of the gas at various wall and liquid temperatures.

Similar conditions apply for the use of (1) and (2), but they are difficult to compare, because in (2) we have no explicit entry for Re.

The conditions in an arc gas heater are such that these relationships cannot be used without a special test on the heat transfer in the mutual channel of the heater.

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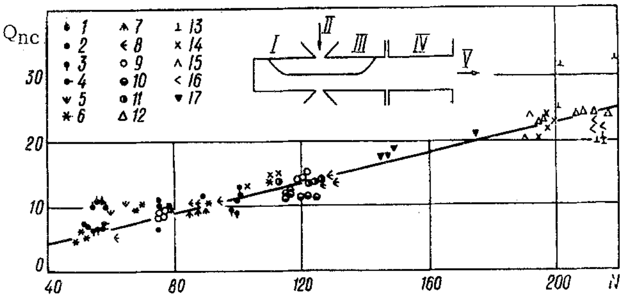

Fig. 1

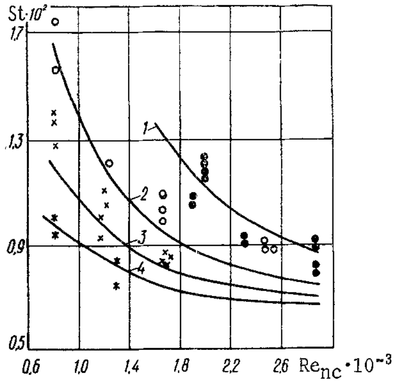

Fig. 2

Fig. 1. The dependence of the heat loss Q_{nc}, kW, in the neutral channel on the discharge power N, kW: 1–4) G = 2 g/sec; 5–8) 3; 9–11) 4; 12, 13) 5; 14–16) 6; 17) 7; 1, 5) l/d = 3, 33; 2, 6, 9, 12, 14, 17) 5; 8, 7, 10, 13, 15) 6, 67; 4, 8, 11, 16) 10. Scheme of discharge chamber: I) cathode; II) gas inlet; III) anode; IV) neutral channel; V) plasma jet.

Fig. 2. The dependence of St on Re_{nc}(d = 20 mm): 1–4) calculation from average relationships; Q_{nc} = f(N), Q_{dc} = f(I), Re_{nc} = f(G, d); 1) N = 207 kW; 2) 120; 3) 80; 4) 55; the points are experimental values.

Measurements have been made [5] on the heat transfer in the electrically insulated inserts between the electrodes, which serve to restrict the diameter of the arc in the heater, which have eddy stabilization of the arc.

The results were presented in the form

$$\mathrm{St} = A\left(\frac{N}{G}\right)^n, \tag{3}$$

where A and n are constants. The experimental points had a large spread, which for small N/G was 100%; in particular, for N/G of 2kJ/g, Equation (3) took the form

$$\mathrm{Nu} = 1.65\cdot 10^{-4}\mathrm{RePr}\,(N/G)^{0,34}. \tag{4}$$

The last factor in (4) characterizes the enthalpy of the hot gas.

Equation (4) [5] has a structure similar to that of (1) and can be used to calculate the heat transfer for a hot gas flowing in an insert in an eddy chamber with bilateral flow and stepwise change in channel diameter for the above range of gas-flow parameters.

A typical element in a discharge chamber is an electrically neutral channel placed at the exit from the arc heater and serving to stabilize the flow, to regulate the flow parameters, or to join the heater to other parts of the apparatus.

Here we consider the heat transfer in flow of a nitrogen plasma in such a channel.

The design of the discharge chamber and neutral channel is shown in Fig. 1; the internal diameter of the channel was varied from 10 to 30 mm and was always equal to the internal diameter of the anode; the channel length was 100 mm. An insert 1 mm thick was used for sealing at the point where the anode joined onto the neutral channel. The length of the anode was also 100 mm. See [6] for a more detailed description of the characteristics of the discharge chamber and the jet parameters.

The channel was a piece of thick-walled copper tube cooled on the outside by water; the heat flux to the channel wall was determined from the flow rate temperature rise of the water. The gas flow rate varied from 2 to 7 g/sec, while the power supplied to the discharge varied from 40 to 220 kW. These values corresponded to variation in Re_{nc} at the exit from the neutral channel from $0.5\cdot10^3$ to $4.5\cdot10^3$; the gas enthalpy at the entry to the neutral channel varied in the range 10,900–21,000 kJ/kg. The Re_{an} at the entry to the channel is related to Re_{nc} by Re_{nc} = 1.09 Re_{an}.

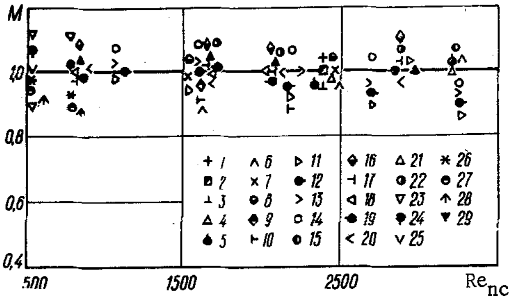

Fig. 3

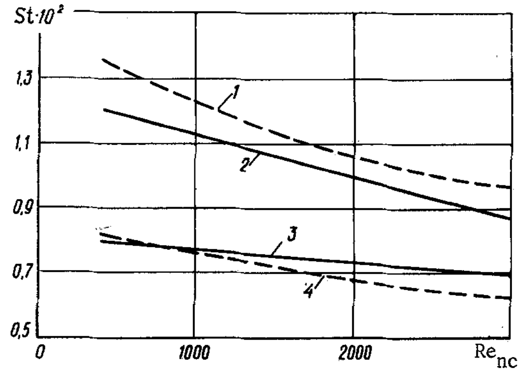

Fig. 4

Fig. 3. Dependence on Re_{nc} of the complex $M = St/[\exp(1.56 \cdot 10^{-2} H_{an}/H_0 - 5.3) - Re_{nc} \cdot \exp(4.02 \cdot 10^{-2} H_{an}/H_0 - 16)] \cdot [0.341 (d/l - 0.1)^{0.241} + 63]$: 1-8) d = 10 mm; 9-15) 15; 16-22) 20; 23-29) 30; 1) $H_{an} \cdot 10^{-3}$ = 8.4 kJ/kg; 2, 9, 16) 10; 3, 10, 17) 11.7; 4) 11, 18; 23) 13.4; 5, 12, 19, 24) 15; 6, 13, 20, 25) 16.7; 7, 14, 21, 26) 18.4; 8, 15, 22, 27) 20; 28) 21.7; 29) 23.5.

Fig. 4. Comparison of Eq. (7) with dependence from [1]: 1, 4) calculation according to [1]; 2, 3) according to (7); 1, 2) H = 19,200 kV/kg; 3,4) 10,000.

Measurements (Fig. 1) showed that in the range considered the heat loss in the neutral channel is dependent on the power in an approximately linear fashion.

Published evidence shows that the heat loss is due solely to convection.

The results were processed to obtain a generalized relationship by the method of [7]. Then Stanton's criterion is given by (5) as

$$St = \frac{q_{nc} \pi d^2}{(H - H_{wa}) 4G} = \frac{Q_{nc}}{4l/d\,(N - Q_{dc})}. \tag{5}$$

This expression applies when the gas enthalpy at the wall temperature is small relative to the mean-mass enthalpy of the hot gas; in our case, the former is only 5-10% of the latter and the loss in (5) refers to the mean-mass enthalpy at the entry to the channel. We deduced the Reynolds number Re from the gas flow rate, the nozzle diameter, and the viscosity $\bar{\mu}$ of nitrogen [8], all in relation to the mean-mass temperature: $Re = 4G/\pi d\bar{\mu}$.

We monitored the arc input power, the flow rate and temperature rise in the water cooling the anode and cathode, and the gas flow rate; these values enabled us to calculate St, Re, and the mean-mass enthalpy at the inlet and outlet of the neutral channel.

The dependence of Re_{nc} on G and d is approximated by

$$Re_{nc} = 8.13 \cdot 10^3 G/d. \tag{6}$$

We found on plotting St as a function of Re_{nc} for constant l/d that the points lie on distinct curves, the parameter of which is the arc input (Fig. 2); this separation was not observed [7] when data were processed for the anode in this way.

We found that the increase in St with H_{an} was just as pronounced as that of St on Re_{nc}; the former relationship was close to being linear, while the dependence of St on Re_{nc} and H_{an} is more complicated than that represented by (1). We found it impracticable to formulate St as the product of power functions of the independent variable.

The results for the various l/d showed that the parameter $P = St/[\exp(1.56 \cdot 10^{-2} H_{an}/H_0 - 5.3) - Re_{nc} \exp(4.02 \cdot 10^{-2} H_{an}/H_0 - 16)]$ is dependent only on l/d; more detailed examination revealed a certain spread in the points, which means that there is some dependence of P on the gas enthalpy, but this can be neglected in the range covered, which was 8400-25,000 kJ/kg.

The following is then the general relationship for the heat-transfer rate for a nitrogen plasma in a tube:

$$\mathrm{St} = \left[\exp\left(1.56\cdot10^{-2}\frac{H_{an}}{H_0} - 5.3\right) - \mathrm{Re}_{nc}\exp\left(4.02\cdot10^{-2}\frac{H_{an}}{H_0} - 16\right)\right]\left[0.341\left(\frac{d}{l} - 0.1\right)^{0.241} + 0.63\right].$$

This expression describes the values of Fig. 3 to 10-15%; we have stated above the range of variation of the parameters applicable to (7).

We see from (3) and (7) that St is affected by Re and l/d as well as by the gas enthalpy; the absolute values of the heat fluxes in our case were about twice those for identical values of the parameters in a neutral insert between the electrodes [5], which is ascribed to a cold layer of gas near the wall in the latter insert.

Figure 4 compares (7) with (1) in the form given in [1]. The results from the two formulas are similar in this range of parameters, but there is some difference in the dependence of St on the enthalpy and on Re_{nc} in these two cases.

NOTATION

T_l	is the mean-mass temperature of the liquid;
$T_{av} = (T_l + T_m)/2$;	
H	is the mean-mass enthalpy of the gas;
N	is the discharge power, kW;
G	is the gas flow rate, g/sec;
l	is the length of the neutral channel;
d	is the diameter of the neutral channel, mm;
Q_{nc}, Q_{dc}	are the heat losses in the neutral channel and the discharge chamber, respectively, kW;
H_{an}, H_{nc}	are the mean-mass enthalpy of the gas at the entrance to neutral channel (or anode exit) and at the exit from the neutral channel, respectively, kJ/kg;
H_0 = 335 kJ/kg	is the enthalpy of the cold gas;
Re_{nc}	is Reynold's number at the exit from the neutral channel.

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