HEAT TRANSFER CHARACTERISTICS IN THE CHANNEL OF A SEGMENTED ELECTRIC-ARC GAS HEATER

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An experimental investigation has been made of heat transfer in a segmented gas-stabilized electric-arc heater. It has been found that in the pressure range $4 \cdot 10^3 - 200 \cdot 10^3$ N/m^2, the heat transfer in the heater channel may be expressed in terms of the Knudsen number, and it is shown that the heat transfer decreases with increased expansion in the channel.

Gas-stabilized segmented electric-arc heaters are currently used extensively, both in technical processes and in physical research [1–3]. The stability of operation of these heaters, and the possibility of creating quite a long arc column hold out great promise for their application in different areas of technology.

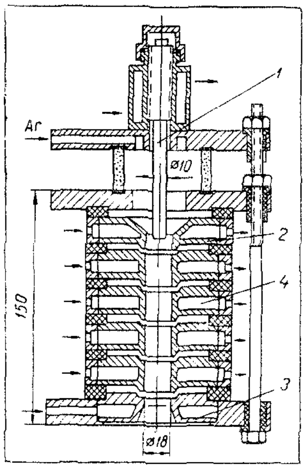

Fig. 1. Layout of the electric-arc heater: 1) tungsten cathode; 2) auxiliary copper anode; 3) main copper anode; 4) intermediate copper segments.

A heater of this type is shown in Fig. 1. The heater has a tungsten cathode of diameter 10 mm, auxiliary and main anodes, and intermediate segments with water cooling. The ratio of channel length to diameter in the given heater is 8. The heater operates at constant current, has a calculated power of up to 100 kW, the working gas being argon.

The efficiency of the heater depends on a number of factors, the most important being heat removal in the heater channel [4]. The conditions of heat removal in the various sections of the heater are different. The anode section, which completes the arc circuit, carries the greatest heat load, and the heat transfer there is determined by different relations, in comparison with the intermediate segments. The specific heat flux in the anode, as measurement shows, is very important in the total heat balance of the heater (30–40%).

One method of increasing the efficiency of the segmented heater is to increase the heat transfer through the walls of the segmented channel, which is possible in view of the nature of gas motion within the channel. It is known that the gas motion in the heater channel is laminar, because of the high temperature in the arc column, the Reynolds number not exceeding 2000. Radiative heat transfer of the ionized stream in the channel, at pressures equal to and less than atmospheric, may be neglected, according to a number of papers [2, 4], since it is not more than 10%.

One method of decreasing heat transfer from the arc column to the channel walls is transition from the continuous region of laminar gas flow to the slip regime, which may be achieved at reduced pressure in the system. Depending on the degree of expansion, there are three states of the gas: viscous, molecular-viscous, and molecular. These regimes are characterized by the ratio of the molecular mean free path to the characteristic body dimension. This ratio is known as the Knudsen number ($\mathrm{Kn} = \lambda/\delta$), and may be expressed in terms of the Reynolds and Mach numbers. For streams with comparatively low viscosity, i.e., with relatively large values of Reynolds number, when the characteristic dimension is the boundary layer thickness, the Knudsen number is $\mathrm{Kn} = \mathrm{M}/\sqrt{\mathrm{Re}}$. The slip regime lies in the range $10^{-2} < \mathrm{Kn} < 10^{-1}$.

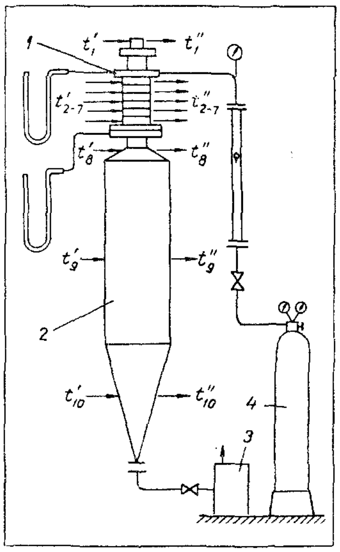

Fig. 2. Layout of the experimental equipment: 1) heater; 2) chamber of diameter 300 and height 1500 mm; 3) vacuum pump; 4) argon bottle.

Initial Conditions and Experimental Results

N, kW	I, A	U, V	G, g/sec	$P \cdot 10^{-3}$ N/m^2	T_{ga}, °K	v, m/sec	M	Re	Kn	With anode section			Without anode section		
										q,W	W/m^2 · · degree	St	q*, W	W/m^2 · · degree	St*
50.0	700	71.0	71.0	4.00	12000	1670	1.1	382	0.058	18800	1382	0.49	11300	1010	0.546
51.6	780	66.5	1.05	4.65	12600	1360	0.94	400	0.047	19850	1440	0.52	12320	1113	0.460
50.0	700	72.0	1.10	4.80	12700	1390	0.96	421	0.048	20300	1520	0.54	12800	1152	0.454
50.5	675	75.0	1.32	19.60	12000	762	0.52	506	0.023	20200	1545	0.51	12700	1140	0.374
50.2	710	70.5	1.29	27.60	12000	520	0.36	492	0.016	20000	1535	0.52	12450	1128	0.378
26.0	390	64.0	1.25	65.00	11000	263	0.18	534	0.008	13860	1070	0.37	8350	1025	0.360
25.4	420	60.5	1.29	30.00	11000	250	0.17	550	0.067	12000	768	0.258	7810	710	0.35
25.5	475	54.0	1.00	4.65	10600	1250	0.86	416	0.047	11160	884	0.348	7100	874	0.38
50.4	610	82.5	2.10	53.40	11000	238	0.164	800	0.005	23200	1904	0.376	15700	1480	0.29
50.6	550	92.0	2.31	63.50	11000	185	0.12	880	0.004	21800	1700	0.306	13600	1328	0.25
50.4	480	105.0	2.60	126.00	11000	101	0.07	1040	0.002	28700	2210	0.370	21200	2000	0.33
50.9	470	107.0	3.40	156.0	11000	132	0.092	1440	0.002	29400	2440	0.30	2185	2120	0.27
52.2	525	99.5	3.36	108. 2	11000	189	0.131	1430	0.0024	29400	1940	0.252	21850	2070	0.273

It is assumed [6] that in the slip regime the gas boundary layer moves away from the channel wall by the additional amount of the wall layer, equal to the molecular mean free path. This then creates an additional thermal resistance to heat transfer, because of which the heat given up to the wall decreases.

The dependence of heat transfer intensity on the hydrodynamic conditions is expressed by the parametric equation obtained from the original differential energy equation [5, 9]. Because of the weakness of the theoretical solution of the energy equation for our case of motion of a high-temperature gas in a channel, an attempt was made to determine experimentally the heat transfer coefficients as a function of the flow hydrodynamics.

The experimental equation is shown schematically in Fig. 2. It consisted of an arc gas heater, a chamber, a VN-2 vacuum pump, instruments to measure temperature and flow rate of water and argon, and to measure the static pressure of the gas at the entrance to and exit from the heater.

In the tests the heat balance of each section of the heater was plotted, the heat flux through it was determined, and the mean heat transfer coefficient in the channel was calculated.

The range of values investigated was as follows: argon flow rate 1–3.7 g/sec; pressure $4 \cdot 10^3$–$200 \cdot 10^3$ N/m^2; power 25–50 kW; current 300–700 A; voltage 70–120 V; gas temperature at channel exit 10 000–13 000° K.

The order of the calculations of heat transfer coefficient in the arc-heater channel was as follows. From the measured water temperature at the inlet and exit of each heater section, and the water flow rates, the heat flux through each section was calculated. By adding the heat fluxes over all the sections, we obtained the total amount of heat carried away by the water. The difference between the electrical energy supplied and the heat carried away gave the gas enthalpy at the heater channel exit. By calculating the specific gas enthalpy from tables and graphs [7, 8], we found the mean mass gas temperature at the channel exit. The characteristic temperature in the calculations was taken to be the mean of the gas temperatures at the channel inlet and exit. The calculation of heat transfer coefficients was performed according to the usual relation

$$\alpha = q/f\,\Delta t. \tag{1}$$

The temperature head was calculated as $\Delta t = (\Delta t_1 - \Delta t_2)/\ln(\Delta t_1/\Delta t_2)$, where $\Delta t_1 = T_{ge} - T_{w1}$, $\Delta t_2 = T_{ga} - T_{w2}$. The wall temperature was assumed to be equal to that of the water at the exit from the section. In view of the fact that the gas temperature was more than two orders larger than the wall temperature, this approximation is valid, since refinement of the wall temperature has little influence on the final result. The initial data and the experimental results are given in the table.

It may be seen from the table that for all the sections except one analysis of the dependence of heat transfer on pressure in the range $4 \cdot 10^3$–$200 \cdot 10^3$ N/m^2 reveals a tendency toward lower heat transfer at lower pressure. This allows us to suppose that in the range examined the slip regime is beginning to appear in the heater channel, while the heat flux in the anode section is practically independent of pressure, being determined by the electrical power supplied. Closure of the arc column at the anode section leads to a reduced mechanism of energy transfer, which may be likened to electron bombardment of the anode surface.

The table presents both the raw results of the tests (current, voltage, gas flow rate, heat fluxes, heat transfer coefficients) and results in the form of generalized groups—similarity parameters—by means of which we may better analyze the physics of the phenomenon examined, since the parameters are ratios of the competing quantities.

As these generalized parameters we chose the Stanton, Reynolds, Mach, and Knudsen numbers. Since the channel exit temperature in the tests lay in the range 10 000–13 000° K, the characteristic temperature was assumed to be of the order of 5000–6500° K, and the thermophysical properties of argon were referred to this temperature in calculating the parameters.

Since the present discussion relates only to the particular case of operation of a segmented electric-arc heater in argon, no wide generalization can be made. It may merely be noted that there is a dependence of heat transfer intensity on hydrodynamics at low pressure in the range of conditions examined.

From the experimental results we may obtain the expression

$$\mathrm{St} = 0.7\,\mathrm{Kn}^{0.25}, \tag{2}$$

$$300 < \mathrm{Re} < 1500;\ 0.002 < \mathrm{Kn} < 0.06;\ 0.1 < M < 1.0.$$

This expression may be used both for qualitative estimates of the influence of reduced pressure on heat transfer in electric-arc heaters with segmented channels, and for approximate quantitative evaluation of heat transfer in similar electric heaters when the pressure in the system is changed.

NOTATION

$\mathrm{Re} = G/0.785\,\mu g d$—Reynolds number; Kn—Knudsen number; $\mathrm{St} = \dfrac{\alpha}{Gc_p/f}$—Stanton number for whole channel; $\mathrm{St}^* = \dfrac{\alpha^*}{Gc_p/f}$—Stanton number, excluding anode section; M—Mach number; d—channel diameter, mm; f—channel surface area, m^2; G—flow rate of stabilizing argon, g/sec; I—current, A; U—voltage, V; P—pressure, N/m^2; v—mean gas velocity in channel, m/sec; q, q*—heat flux through channel walls with and without anode section, respectively, w; α, α^*—heat transfer coefficient in channel with and without anode section, $W/m^2 \cdot$ degree; T_{ge}, T_{ga}—gas temperature at heater inlet and outlet; T_{w1}, T_{w2}—temperatures of channel walls; λ—molecular mean free path; δ—characteristic body dimension; μ—dynamic viscosity, $N \cdot sec/m^2$; c_p—specific heat of gas, $J/kg \cdot$ degree; g—acceleration, m/sec^2.

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