HEAT TRANSFER IN A PLASMOTRON CHANNEL

A. M. Gonopol'skii, A. I. Dautov, R. Kh. Ismagilov, and F. A. Slobodkina

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The dependence of the heat-transfer coefficient in a plasmotron channel on gas flow rate, pressure, and electrical power is studied.

In connection with the intensive development of various forms of plasma technology (plasmochemical reactors, MHD generators, plasmotrons, etc.) and the introduction of new technical processes in which high-temperature gas flows are used, the problem of increasing plasmotron thermal efficiency, together with the accompanying problem of studying heat exchange between a high-temperature gas flow and the wall of an arc channel, is of practical interest. Study of the dependence of the heat-transfer coefficient on plasmotron energy parameters is of special importance. The present study is dedicated to this question. By processing experimental data on integral and local thermal fluxes in the channel walls the dependence of the heat-transfer coefficient on gas flow rate, pressure, and electrical power was obtained.

Considering the fact that the enthalpy, and not the braking temperature, is often the quantity measured experimentally in plasmotrons, it becomes desirable to use a coefficient analogous to the heat-liberation coefficient of [1], which considers not only convective, but other forms of heat transfer with the wall.

The experiments were performed with a plasmotron with a segmented interelectrode insert consisting of six sections and turbulent gas arc stabilization [2]. A schematic drawing of the plasmotron is shown in Fig. 1. The plasmotron anode and segments of the interelectrode insert are constructed of copper. The cathode is a hafnium bar pressed into a copper cathode holder. Interelectrode distance and channel diameter were $13 \cdot 10^{-2}$ and $1 \cdot 10^{-2}$ m, respectively, with an individual section length of $1.8 \cdot 10^{-2}$ m. Experiments were performed over a current range of 90-220 A, with flow rate of the plasma-forming gas — air — $G = (0.2\text{-}0.8) \cdot 10^{-3}$ kg$\cdot$sec^{-1} for atmospheric pressure at the output of the plasmotron nozzle-anode. During the experiments the following quantities were measured: arc current and voltage, section potentials, pressure at channel input, and flow rates of air and water used to cool plasmotron anode, cathode, and sections. The measured section potential value was assigned to the coordinate of the section midpoint. The measured quantities were used to calculate heat loss through individual plasmotron components, total thermal flux through unit channel length, electrical power, and mean-mass-flow braking-enthalpy distribution over channel length. The arc current and voltage were measured with type M 1106 meters (accuracy class 0.2), the section potentials by an S-50 static voltmeter (accuracy class 1.0), gas and water flow rates by RS-3, RS-5, and RS-7 rotameters, water temperature by mercury thermometers with 0.1° scale divisions, and channel pressure by a U-shaped manometer. Estimates of experimental accuracy with consideration of the accuracy of the instruments employed indicate that the relative error in thermal flux determination does not exceed 5%, that in mean mass enthalpy, 10%, and that in pressure, 5%.

In the data processing all experimentally measured quantities were referenced to their characteristic values. Thus, for example, braking enthalpy, calculated from the thermal balance equation, was referred for each of the six sections to the flow power in the initial

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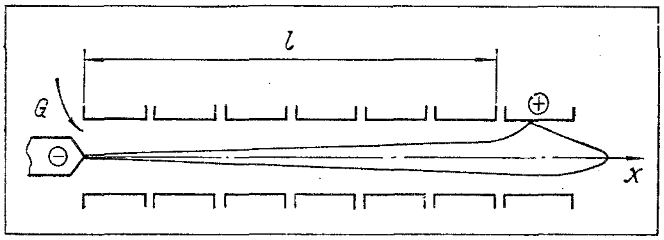

Fig. 1. Diagram of plasmotron channel.

channel section:

$$H = \frac{H^0}{\left(\frac{p^0F^0}{G^0}\right)^2}. \tag{1}$$

Here and below the superscript 0 indicates dimensionless quantities. The experimentally determined dependences for individual thermal fluxes into the wall per unit channel length were referenced to unit flow rate and transformed to dimensionless form:

$$q = \frac{q^0 l^0 G^0}{(p^0F^0)^2}. \tag{2}$$

In an analogous manner the dimensionless value of specific plasmotron power at unit flow rate was determined:

$$\eta = \frac{I^0 u^0 G^0}{(p^0F^0)^2}. \tag{3}$$

The dimensionless coordinate x is defined as $x = x^0/l^0$. In Eq. (1) the following dependence is assumed for convective thermal flux into the wall:

$$q = \alpha_1 (T - T_w).$$

The subcript w refers to parameter values at the wall. Since in the present study braking enthalpy and total thermal flux into the channel wall from all energy sources were measured, it is more convenient in computation to use a function of the form

$$q = \alpha (H - H_w).$$

Considering that $H_w \ll H$, we may write approximately

$$q \approx \alpha H. \tag{4}$$

Considering that q is the thermal flux through a unit length of channel wall, we will have

$$q(x) = \frac{dQ}{dx},$$

where Q is the integral thermal loss in the channel wall. Then with consideration of Eq. (4) we can write

$$Q = \int_0^1 \alpha H(x)\, dx. \tag{5}$$

As was demonstrated in [3], the length of the initial thermal stabilization segment in the Reynolds number range existing in the absence of an arc ($10^3 \leq Re \leq 6 \cdot 10^3$) does not exceed one or two channel diameters, i.e., is less than 20% of the total length. Then in the developed section the value of the heat-transfer coefficient changes only weakly over channel length. Based on this, we propose that the heat-transfer coefficient over channel length remains constant; i.e.,

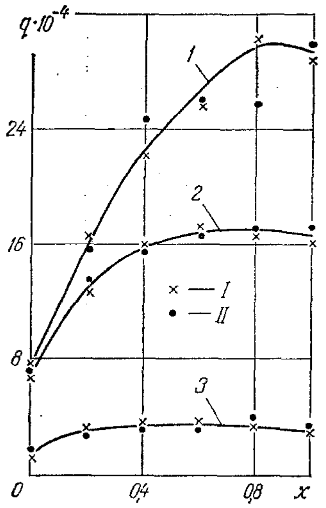

Fig. 2

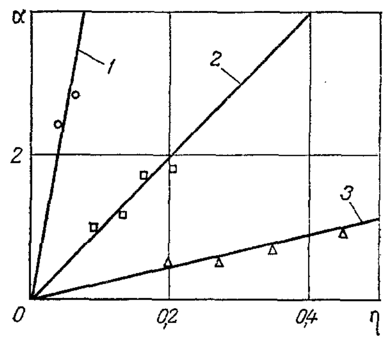

Fig. 3

Fig. 2. Comparison of calculated (I) and experimental (II) thermal fluxes along channel wall: 1) $G = 0.4 \cdot 10^{-3}$ kg/sec, I = 220 A; 2) $0.8 \cdot 10^{-3}$ kg/sec, I = 180 A; 3) $0.8 \cdot 10^{-3}$ kg/sec, I = 90 A; q, w/m^{-1}.

Fig. 3. Heat-transfer coefficient versus plasmotron electrical power and gas flow rate: 1) $G = 0.2 \cdot 10^{-3}$ kg/sec; 2) $0.4 \cdot 10^{-3}$; 3) $0.8 \cdot 10^{-3}$ kg/sec.

$$\alpha = \frac{Q}{\int_0^1 H(x)\,dx}\ .$$

The validity of this proposal is illustrated in Fig. 2, where experimental specific thermal fluxes into the channel wall are compared with the results of calculation by Eq. (4). Considering that the error in calculation of α from experimental data comprises ~15%, it can be maintained that over the parameter range studied the net heat-transfer coefficient varies only weakly over channel length.

The comparison of α values for various flow rates and powers presented in Fig. 3 demonstrates that for all flow rates G^0 the net heat-transfer coefficient depends linearly on the electrical power supplied to the plasmotron. With increase in flow rate the slope of the straight line decreases. By expanding the parameter variation range one can obtain a universal curve of the form $\alpha/\eta = f(G)$, which permits determination of losses into the plasmotron channel wall for a longitudinally drafted arc with sufficient accuracy.

The observed constancy of α over channel length evidently may indicate uniformity of the flow structure over the greater part of the channel length in the plasmotron configuration studied. This conclusion agrees with contemporary concepts of the behavior of an electric arc in a channel with a gas flow [4].

NOTATION

I, arc current, A; u, voltage across arc, V; p, pressure, $N \cdot m^{-2}$; G, gas flow rate; H, mean-mass braking enthalpy, $J \cdot kg^{-1}$; F, channel section area, m^2; l, channel length, m; q, thermal flux through unit channel wall length, $W \cdot m^{-1}$.

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GENERALIZATION OF TEST RESULTS ON HEAT TRANSFER IN FILM BOILING UNDER NATURAL CONVECTION CONDITIONS

É. K. Kalinin, I. I. Berlin, V. G. Karavaev, V. V. Kostyuk, and É. M. Nosova

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Experimental results on heat transfer during film boiling in a large volume are compared for 13 fluids and with the computational dependences of different authors.

A large quantity of experimental results on the heat transfer during film boiling in a large volume have been obtained up to now. Empirical and theoretical dependences for the computation of the heat transfer are proposed in a number of papers [1-6]. We have compared these dependences with each other and with test results obtained during film boiling on vertical surfaces as well as on horizontal cylinders and spheres of diameter $D \gg l_{cr}$.

A theoretical analysis of film boiling permits one to establish the dimensionless parameters governing the process and to obtain the structural form of the criterial formula for the heat transfer in the form $Nu = f(Ra, K_v)$. The formulas of different authors, which we have reduced to this form, are represented in Table 1.

Characteristics of the working sections and the range of variation of the governing parameters for the experiments included in the generalization are presented in Table 2.

TABLE 1. Theoretical and Empirical Dependences on Heat Transfer during Film Boiling

Author	Heating-surface geometry	Formula	
Labuntsov [1]	Vertical	$Nu = 0.25\, Ra^{1/3}$	(1)
Borishanskii, Fokin [2]	Vertical	$Nu = \begin{cases} 0.28 Ra^{1/3} Pr^{-1/3} & \text{for } \frac{\mu_l}{\mu_v}\frac{K_v}{Pr} < 63 \\ 0.0286 Ra^{1/3} Pr^{-1/3}\left(\frac{\mu_l}{\mu_v}\frac{K_v}{Pr}\right)^{0.55} & \text{for } \frac{\mu_l}{\mu_v}\frac{K_v}{Pr} > 63 \end{cases}$	(2)
Bulanova, Pron'ko [3]	Vertical and horizontal	$Nu = 0.134 Ra^{1/3}\left(\frac{1}{K_v}\right)^{1/3}$	(3)
Frederking, Clark [4]	Sphere ($D > l_{cr}$)	$Nu = 0.14 Ra^{1/3}\left(0.5 + \frac{1}{K_v}\right)^{1/4}$	(4)
Hendricks, Baumeister [5]	Sphere ($D > l_{cr}$)	$Nu = 0.35 Ra^{1/4}\left(0.5 + \frac{1}{K_v}\right)^{1/4}$	(5)
Breen, Westwater [6]	Horizontal cylinder ($D > l_{cr}$)	$Nu = 0.38 Ra^{1/4}\frac{\sqrt{1 + 0.34 K_v}}{K_v^{1/4}}$	(6)

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