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EFFECT OF THE GEOMETRIC CHARACTERISTICS OF A MULTIJET MIXING CHAMBER ON HIGH-TEMPERATURE HEAT EXCHANGE IN A CHANNEL

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The work entailed the experimental determination of the effect of the ratio of the diameters of the nozzles of electric-arc gas heaters to the channel diameter of a multijet mixing chamber on the heat exchange of a high-temperature air stream with the channel walls.

Multijet mixing chambers [1] are now widely used in installations for the investigation of the heat exchange of high-temperature heat carriers with channel walls [2, 3], and they are also used as the basic units of technological plasma apparatuses [4, 5]. These mixing chambers are short (1-2 bore diameters) water-cooled axisymmetric channels with circularly uniformly spaced holes for the inlet of several plasma jets from electric-arc gas heaters (EAGH). As a result of the collision of the jets at the center of the chamber, a high-temperature gas stream forms that moves into the channel, which is a continuation of the chamber.

The geometric characteristics of multijet mixing chambers and the methods of processing the experimental data in different investigations differ from each other. There is practically no information on the effect of the conditions of formation of the plasma stream in a multijet mixing chamber on its heat exchange with the channel walls. On the other hand, even for less complex conditions of formation of a high-temperature gas stream at the inlet to the channel, it was established that a change of the geometric characteristics at the initial section of the channel, in particular, of the inlet angle [6], leads to a change of the intensity of heat exchange between the gas and the channel walls. In connection with that, the present work investigates the effect of the slope of the plasma jet to the axis of the mixing chamber φ and the ratio of the diameters of the EAGH nozzles to the diameter of the mixing-chamber channel d/D on the high-temperature heat exchange.

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TABLE 1. Principal Experimental Characteristics of Channels

Parameter	Investigated variants			
	A	B	C	D
Diameter of reactor channel D, m	0,100	0,050	0,050	0,050
Diameter of EAGH nozzle d, m	0,010	0,010	0,019	0,0175
Slope of EAGH axes to the channel axis φ, deg	70	70	90	90
Specific enthalpy of air h_{g1}, 10^6 J/kg	7,3—11,3	7,4—9,7	11,6—15,8	5,9—9,9
Initial air temperature T_{g1}, 10^{6}°K	3,9—5,0	3,9—4,8	5,4—6,5	3,5—4,9
Total gas flow rate G_g, 10^{-3} kg/sec	4,9—7,8	5,9—7,7	4,0—7,7	4,9—7,5
Reynolds number at channel inlet Re_{D1}	450—935	1340—1800	690—1700	1220—1940
Enthalpy factor h_{g1}/h_w	23—26	23—30	22—44	7—12

The basic unit of the experimental installation was a plasma apparatus with a vertical cylindrical sectioned water-cooled channel, up to 9 bore diameters long. In the upper part of the apparatus, in a plane perpendicular to the axis of the channel, there were holes spaced at 120° for the inlet of three twisting plasma jets from the EAGH.

The power of the plasma apparatus in the inlet section of the channel was determined from the overall electric power of the EAGH and the heat losses to the EAGH electrodes. The heat losses to each channel section were also determined by calorimetry. The maximum error of determining the heat flux in the wall of a channel section was 7%. The temperature of the channel wall was determined from the heat flux density and checked by a thermocouple. As the initial channel section we took the plane passing through the centers of the holes for the intake of the plasma jets to the mixing chamber.

The principal geometric characteristics of the investigated channels and the parameters of the high-temperature air streams at the initial section are presented in Table 1.

The experiments were carried out with parameters of the high-temperature stream in the initial channel section corresponding to laminar flow ($Re_{D_1} < 2300$). According to the estimates of [2], the length of the initial section was greater than the length of the investigated channels but it was comparable with it. Subsequently, the results of the experiments were therefore compared with the theoretical dependence [3] for calculating the heat exchange at the initial section with laminar flow and variable thermophysical properties:

$$St_{01} = 0.364 Re_{x1}^{-0.5} Pr_1^{-0.67}. \tag{1}$$

This theoretical dependence was experimentally confirmed [3] for conditions of smooth entry of gas into a channel with 49.5 mm diameter at a temperature of argon plasma of up to 8000°K.

As an example of the effect of the geometric parameters on the intensity of heat exchange between high-temperature gas and channel walls, Fig. 1 presents experimental and theoretical data for channel variants A and B (see Table 1). It follows from them that under the conditions of formation of a high-temperature stream in the multijet mixing chamber, heat exchange of the gas with the wall is greatly intensified, especially at the first channel sections. With increasing distance from the initial section, the difference between the theoretical and experimental values of the heat flux density decreases, and at a channel length equal to 6 or 7 bore diameters it becomes practically equal to zero. An analogous nature of the change in heat flux density was also obtained longitudinally with other investigated variants of channels.

Generalization of the experimental data for the external problem was carried out by a method analogous to that of [3]. The heat-transfer coefficient was determined from the difference of specific enthalpies of the gas on the outer boundary of the thermal boundary layer, i.e., in the core of the stream, and at the temperature of the channel wall, the thermophysical properties of air were determined from the enthalpy in the core of the stream, which was taken to be equal to the mean mass enthalpy of air at the initial section of the channel.

From the experimental data for the variants of channels presented in Table 1, viz., A, B and C, D, the following generalizing dependences were obtained:

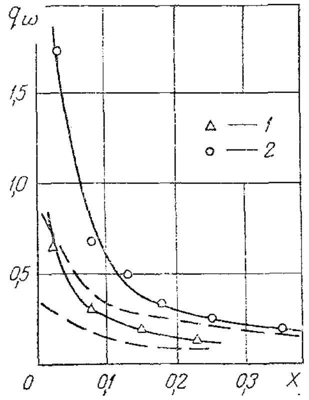

Fig. 1

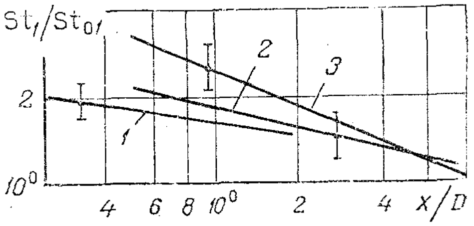

Fig. 2

Fig. 1. Change of heat flux density to the wall q_w (10^6 W/m^2) along the reactor channel X (m): 1) D = 100 mm, d = 10 mm, φ = 70°, T_{g1} = 3900°K, G_g = 7.82 kg/sec; 2) D = 50 mm, d = 10 mm, φ = 70°, T_{g1} = 3900°K, G_g = 7.94 kg/sec; dashed curves: theory, laminar flow [3].

Fig. 2. Effect of the ratio d/D on the heat exchange along the channel: 1) D = 100 mm, d/D = 0.10, φ = 70°, Re_{D1} = 450-935; 2) D = 50 mm, d/D = 0.20, φ = 70°, Re_{D1} = 1340-1800; 3) D = 50 mm, d/D = 0.35-0.38, φ = 90°, Re_{D1} = 690-1940.

$$\mathrm{St}_1 = 1.70\mathrm{Re}_{X1}^{-0.66}\mathrm{Pr}_1^{-0.67}, \tag{2}$$

$$\mathrm{St}_1 = 2{,}945\mathrm{Re}_{X1}^{-0.70}\mathrm{Pr}_1^{-0.67}, \tag{3}$$

$$\mathrm{St}_1 = 10.70\mathrm{Re}_{X1}^{-0.86}\mathrm{Pr}_1^{-0.67} \tag{4}$$

with the corresponding correlation coefficients 0.987, 0.966, and 0.932. In comparison with the theoretical values of (1), the change in heat-exchange intensity along the channels, in which the mixing chambers had a ratio d/D equal to 0.10, 0.20, and 0.35-0.38, is characterized by the dependences (Fig. 2) of the form

$$\mathrm{St}_1/\mathrm{St}_{01} = A\,(X/D)^{-n}, \tag{5}$$

for which A is equal to 1.67, 1.87, and 2.48, respectively, n = 0.14, 0.24, and 0.41, the maximum errors of approximation are 12, 22, and 18%, and the correlation coefficients are 0.863, 0.886, and 0.872, respectively. Introduction of the ratio of diameters d/D into the generalization made it possible to obtain a single dependence for all the experimental results:

$$\mathrm{St}_1 = \mathrm{St}_{01}\,(1.30 + 3.16d/D)\,(X/D)^{-(0.04+d/D)}, \tag{6}$$

generalizing 156 experimental points with maximum error of approximation amounting to 23%.

The possible effect of the slope of the plasma jet to the axis of the mixing chamber did not exceed the experimental error.

The fact that heat exchange in channels with multijet mixing chambers is more intense than under conditions of smooth inlet of heat carrier into the channel [3] may be explained by two factors. The principal factor is the experimentally established initial twisting of the gas stream in the peripheral region of the channel by the rotating plasma jets emerging from the EAGH. It is known [7] that local twisting of the gas at the channel inlet intensifies heat exchange in consequence of the rearrangement of the velocity and temperature profiles in the boundary layer. With increasing length of the channel, the tangential velocity component of the stream decreases on account of friction against the wall, and the effect of the twist of the stream on the heat exchange also decreases.

The second factor is the enforced turbulence of the stream at the channel inlet. It is caused by nonsteadiness of the burning of the electric arcs in the EAGH in consequence of shunting, as well as by the collision in the central channel region of the twisted plasma jets flowing out of the EAGH nozzles. Great viscosity of the plasma leads to rapid attenuation of the initial forced pulsations [8], and thus the effect of turbulence on the heat exchange of the gas with the walls diminishes along the channel.

It follows from an analysis of the experiments that if the ratio d/D increases from 0.10 to 0.35-0.38, the intensity of the heat exchange in the channel increases for the same Reynolds numbers. And the larger ratio d/D, the more intense the heat exchange at the front of the channel and the more rapid the decrease of the effect of the conditions of formation of the stream upon increase of the relative channel length. This nature of the effect of the ratio of diameters is due to the fact that with large d/D the twisted plasma jets act on a large cross-sectional area of the plasma stream forming in the channel, and thus impart to the gas layer at the channel wall a larger initial tangential velocity component. When the length of the channel increases, the relative decrease of the tangential velocity component is the greater, the higher the initial velocity is, and this also leads to rapid diminution of the intensity of heat exchange.

Thus, by changing the geometric characteristics of the mixing chambers of plasma apparatuses, particularly by changing the ratio of the nozzle diameters of the EAGH to the channel diameter of the apparatus, we can change the intensity of heat exchange of the high-temperature heat carrier with the channel walls, and thus also the efficiency of the plasma apparatus.

NOTATION

D, channel diameter, m; d, diameter of EAGH nozzle, m: G_g, total gas flow rate, kg/sec; q_w, heat flux density, $J/(m^2 \cdot sec)$; h_{g1}, h_w, specific enthalpy of air at the channel inlet and at wall temperature, respectively, J/kg; $Pr_1 = c_{p1}\mu_{g1}/\lambda_{g1}$, Prandtl number; $Re_{D1} = \rho_{g1}v_{g1}D/\mu_{g1}$, Reynolds number at the channel inlet; $Re_{X1} = \rho_{g1}v_{g1}X/\mu_{g1}$, Reynolds number on the longitudinal coordinate; $St_1 = q_w/(\rho_{g1}v_{g1}(h_{g1} - h_w))$, Stanton number; St_{01}, Stanton number for laminar flow; T_{g1}, air temperature at the channel inlet, °K; v_{g1}, air velocity, m/sec; X, longitudinal coordinate, m; λ_{g1}, thermal conductivity of air, $J/(m \cdot sec \cdot {}^\circ K)$; μ_{g1}, viscosity, $kg/(m \cdot sec)$; ρ_{g1}, density, kg/m^3; φ, slope of the axes of the EAGH to the axis of the channel, deg.

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