HEAT TRANSFER BETWEEN A PLASMA JET AND A HEMISPHERICAL WALL WITH INJECTION OF A GAS-COOLANT THROUGH CIRCULAR HOLES

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Using extensive information on the parameters of a gas flow in a boundary layer and the effect of the properties of injected gas on the heat transfer of permeable bluff bodies and plates, the authors of [1-6] were able to obtain the following approximate relative laws for heat and mass transfer:

$$\Psi = 1 - 0.67\left(\frac{M_1}{M_3}\right)^{0.25} B; \quad (1)$$

$$\Psi = 1 - \left(\frac{M_1}{M_3}\right)^{0.25} \exp\left[0.2303\left(-0.45 + 0.3B\right)\right]; \quad (2)$$

$$\Psi = 1 - 0.19\left(\frac{M_1}{M_3}\right)^{0.35} B; \quad (3)$$

$$\Psi = \exp\left[-0.37\left(\frac{M_3}{M_1}\right)^{0.7} B\right]; \quad (4)$$

$$\Psi = 1 - (2.33 - 4.384\,\varphi + 3.06\varphi^2)\exp\left[-(0.32 + 0.05\varphi)\left(\frac{M_1}{M_3}\right)^{0.7} B\right]; \quad (5)$$

$$\frac{\mathrm{St}}{\mathrm{St}_0} = \frac{M_3}{M_1}\frac{T_1}{T_a}\left(\frac{2}{\sqrt{\psi}+1}\right)^2\left(1 - \frac{B}{B_k}\right)^2, \quad (6)$$

where $\Psi = q/q_0$ is the ratio of the heat flux to a wall in the case of injection of coolant to the same without injection; $B = (\rho v)_3/(\alpha/c_p)_0$, injection parameter; $(\rho v)_3 = G_3/\pi r^2$; G_3, discharge of the injected gas; r, radius of the permeable section; α, local heat-transfer coefficient; c_p, isobaric heat capacity; M_1 and M_3, molecular weights of the incoming flow and the injected gas; φ, degree of perforation (the ratio of the total area of the holes to the area of the permeable section); St, Stanton number; the subscript 0 corresponds to values of the parameters without injection of coolant; $\mathrm{St} = \alpha/\rho_1 v_1 c_{p1}$; ρ_1, v_1, c_{p1}, density, velocity, and isobaric heat capacity of the incoming flow; T_1, temperature of the incoming flow; T_a, temperature of the adiabatic wall; $\psi = T_2/T_a$; T_2, temperature of the wall; $B_k = T_1[\arccos(2-\psi)/\psi]^2/T_a\,(\psi - 1)$. Equations (1) and (2) were obtained by the authors of [1, 2] for a laminar boundary layer formed in flow about the front critical point of a bluff body. Equation (5) was obtained for the flow of plasma jets about a bluff body [3], while Eqs. (3) and (4) were obtained for a turbulent boundary layer on a plate [4]. Gas-coolant is injected through the porous sections of a permeable surface for relatively low-temperature flows and for moderate values of the injection parameter B < 3 (except for [3]).

We should point out the limited number of studies which have dealt with the heat transfer of bodies in plasma jets in the presence of gas injection through circular holes [7-9]. Here, we study the local heat transfer of a hemispherical wall in a plasma air jet in the case where gas-coolant is injected through a system of circular holes and the process is strongly nonisothermal. There are several distinctive features to the process of heat transfer between a plasma jet and a wall. The most prominent feature is the turbulent character of flow along the entire jet at sufficiently low Reynolds numbers (Re ~ 10^2-10^3). Relatively rapid changes in the form and position of the plasma arc, fluctuations of current and voltage, and high temperature gradients all result in fluctuations of the flow parameters within a

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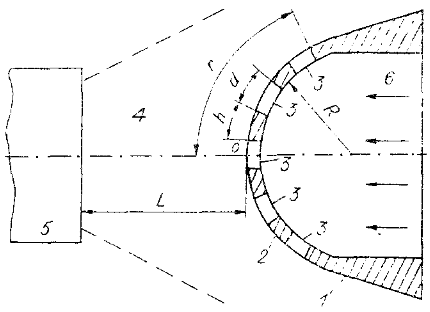

Fig. 1

fairly broad range of frequencies (10-100 kHz) [10]. Also, the injection of gas through a system of circular holes leads to additional agitation of the flow near the wall due to the interaction of elementary jets with one another and the incoming flow, the merging of these jets, and the formation of stagnant zones and large velocity gradients on the main sections of the elementary jets. Such a complex hydrodynamic pattern of flow is the main reason for the use of unusually large values of the injection parameter to achieve the same given thermal effect from injection q/q_0.

In generalized variables, the problem being considered is written in the form $q/q_0 = f(\varphi, r/R, d/r, B)$. The similarity number φ is obtained from the condition of replacement of the parameters of the injected gas by the equivalent parameters on the wall $G_3 \equiv \rho_3 v_3 \pi d^2 n/4 = (\rho v)_3 \pi r^2$, $\varphi \equiv \frac{d^2 n}{4r^2}$, where v_3 is the velocity of an elementary jet of the coolant.

Given the same discharge of the cooling gas (G_3 = idem), several different methods can be used to organize injection through circular holes: reduce the radius of the permeable section r while keeping the degree of perforation constant, i.e. localize the injection and obtain the similarity number r/R; with G_3 = idem, r/R = idem, and φ = idem, increase the number of holes n and simultaneously reduce their diameter d, in which case the total area of the outlet holes $\pi d^2 n/4$ remains constant and the similarity number d/r is obtained.

We studied models made of stainless steel Kh18N9T and having the form of a cone 1 with a hemispherical blunting 2 (Fig. 1). The thickness of the wall was $1 \cdot 10^{-3}$ m, while the fliud of the blunting R = $(5.0, 9.5, 19.0) \cdot 10^{-3}$ m. The hemispheroidal wall was made permeable by circular holes 3. The axes of the holes were directed along normals to the surface. The diameter of the holes d = $0.7 \cdot 10^{-3}$ or $1.0 \cdot 10^{-3}$ m. The dimensionless radius of the permeable region was varied within the range r/h = 0.31-0.69. All of the holes were spaced evenly on circles so that the distance between them h remained the same (up to 240 holes). The values of h and d were taken from the conditions

$$\varphi > \frac{\pi d^2}{4(d+h)^2} = 0.022; \tag{7}$$

$$\varphi > \frac{\pi d^2}{4(d+0.16R)^2}, \tag{8}$$

which were obtained from elementary geometric considerations (see Fig. 1): $k = 1, 2 \ldots, \varphi = \frac{d^2 n}{4r^2} = \frac{d^2[1+\pi(k+1)k]}{4k^2(d+h)^2} = \frac{\pi d^2}{4(d+h)^2}$, where k is the number of the circle on which the circular boles are located: k >> 1. Instead of the values of h and d, we took the upper values of the inequalities

$$h \leqslant 5\delta, \ d \leqslant \delta \tag{9}$$

(δ is the thickness of the boundary layer). With satisfaction of inequalities (9), the efficiency of injection of gas-coolant through circular holes is equivalent to the efficiency of cooling through porous materials [11].

Inequality (8) is a necessary condition for the joining of adjacent jets. Elementary jets of coolant will merge in the case of injection from a hemispherical surface if h <

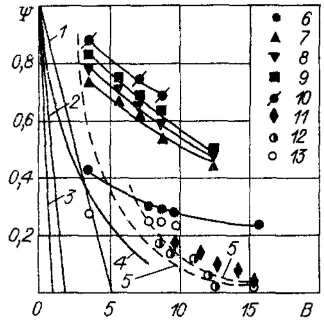

Fig. 2

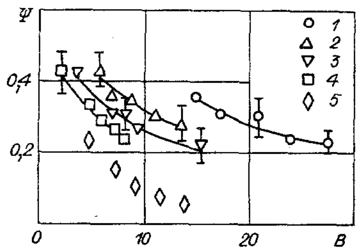

Fig. 3

$4\pi R\beta/360°$ (β is the angle reckoned from the normal of the hemispherical wall to the surface of tangential discontinuity of the jet parameters). The values of β vary only slightly for submerged jets, depending on the external conditions and the parameter of the jet: $\beta \approx 15°$ [12]. The degree of perforation was varied within the range φ = 0.025-0.121.

The models were placed in the working section of a jet 4 with $L = 4\cdot 10^2$ m (see Fig. 1). The jet was generated by an ÉDP-104A/50-5 plasmatron (designed by the Institute of Thermophysics of the Soviet Academy of Sciences, Siberian Department). The gas-coolant (nitrogen) 6 was delivered through the internal volume of the models and the holes of the permeable section counter to the plasma jet. The discharge of coolant was kept constant over the course of a given test.

The parameters of the plasma jet were measured during the experiments: mass-mean enthalpies H = 6100 kJ/kg, temperature T_1 = 3600 K, discharge of plasma-forming air $G_1 = 0.9\cdot 10^{-3}$ kg/sec; the parameters of the gas-coolant: discharge G_3 and temperature T_3; the temperature of the wall T_2 at the points 0, r/h = 0.5, and r/R = 0.87; heat flux q. The methods used to determine the heat and mass transfer characteristics were described in [7-9].

The radiative component of heat flux q_R was measured with an "Ikar-4" thermal radiation detector (developed at the ITTF of the Ukrainian Academy of Sciences) and was equal to $0.0042\cdot 10^6$ J/($m^2\cdot$sec). The value of q_R was also calculated from the with an error $\delta_{qR} \leq 9\%$. The value of q_R was also calculated from the formula $q_R = \varepsilon\sigma T_1^4$ for an effective emissivity $\epsilon = A\cdot 10^z$, an optical thickness $\ell = 10\cdot 10^{-2}$ m, $T_1 = 4\cdot 10^3$ K, A = 6.0, and z = 4. The data was taken from [13]. Here, $q_R = 0.0057\cdot 10^6$ J/($m^2\cdot$sec). The conductive component of the heat flux $q_\lambda \sim \lambda\Delta T/\Delta x \sim 10^4$ J/($m^2\cdot$sec) for $\Delta x \sim 1\cdot 10^{-2}$ and $\Delta T \sim 10^3$ K. Thus, the convective component of the flux ($q_\lambda \sim 0.02\ q_0,\ q_R \sim 0.0012\ q_0,\ q_0 = 4.5\cdot 10^6$ J/($m^2\cdot$sec)) plays the dominant role in the mechanism of heat transfer between the plasma jet and the wall.

Figure 2 shows the dependence of the relative heat transfer function Ψ on the injection parameter B. In this series of experiments, the injection parameter was changed by changing the discharge of coolant. The dimensionless radius of the model r/R = 0.59, $R = 19\cdot 10^{-3}$ m. Curves 1-5 were calculated from Eqs. (1)-(5), respectively, while points Ψ(B) found for models in which the 6-10 correspond to the values of Ψ(B) found for models in which the degree of perforation φ = 0.121, 0.051, 0.047, 0.043, 0.025. The solid lines were calculated from an approximate formula we obtained from the results of a complete two-factor experiment

$$\Psi = 1 - (4{,}59\varphi - 0{,}05)\exp[0{,}0025\varphi^{-1{,}25}B],$$

the error of the approximation not exceeding 3%.

It is evident from Fig. 2 that the results obtained here do not agree with the well-known data. Curves 1-4 were plotted for the boundary layer in the neighborhood of the critical point, coolant uniformly distributed over the injection surface, and injection through porous materials. To achieve the same thermal effect from injection through a perforated wall, it is necessary to increase coolant discharge by a factor of 3-5 compared to the injection of gas through porous materials [8]. This might explain the discrepancy between our findings and the well-known results.

A significant difference is seen when we compare the results of measurements of St/St_0 with results obtained from Eq. (6) in [5]. The results of the calculations with Eq. (6) are given by the points 13 in Fig. 2. The values of the temperature of the adiabatic wall T_a

used in the calculations were taken to be equal to the temperature of the gas-coolant T_3 [5]. Evidently, with flow over a hemispherical wall, the injection of gas through circular holes, and a strongly nonisothermal flow, the conditions necessary for the applicability of the asymptotic theory of a turbulent boundary layer – based on the use of integral relations at $x \to \infty$ – are not satisfied. However, in the region of the gas screen, there is satisfactory agreement between the experimental results in [7] and the theoretical findings in [5, 6].

Equation (5) was obtained by the author of [3] from the results of a two-factor experiment. The values of φ and B were varied (the effect of the molecular weight of the incoming flow and the injected coolant was not studied, although it figures in the formula). Tests were conducted under conditions similar to those present in our experiments. The difference between the results obtained here and in [3] is due to the different values of the radii of the model bluntings R. This was confirmed by measurements of $\Psi(B)$ obtained for models with $R = 9.5 \cdot 10^{-3}$ and $5.0 \cdot 10^{-3}$ m (points 11 and 12) ($\varphi = 0.12$, $r/R = 0.59$). With an increase in the blunting radius for the wall of the models, the experimental points approach the values calculated from Eq. (5). In Fig. 2, the results of calculation with Eq. (5) are shown by lines 5.

A combination system of thermal protection for the models consisted of regenerative cooling of the walls of the internal volume and the lateral surface of the holes and the cooling effect of injection. In the case of intensive injection, these effects were augmented by repulsion of the plasma jet. The sections of the surface in the region of the gas screen are cooled more poorly for models of large radius due to the greater expanse of the area to be cooled. In turn, overheating of the wall in the region of the gas screen adversely affects the regenerative cooling process and results in an increase in the temperature of the gas-coolant. The overall effect of these developments is to render the thermal protection afforded large-radius models less effective.

Figure 3 shows the relations $\Psi(B)$ for different dimensionless radii of the permeable section. Points 1-4 correspond to $r/R = 0.31, 0.52, 0.59, 0.69$ ($\varphi = 0.043$, $d = 1 \cdot 10^{-3}$ m). In this series of experiments, the injection parameter was changed by changing the discharge of the coolant and by varying the radius of the permeable section. The solid lines represent results calculated from an approximate formula we obtained from the two-factor experiment: $\Psi = 1 - \left(0.61 - 0.18\frac{r}{R}\right)\exp\left[0.105\left(\frac{r}{R}\right)^{2.04}B\right]$. The error of the approximation is no greater than 5%.

It is evident that the injection parameter B, changed by changing the radius of the permeable section r, does not generalize the relation $\Psi(B)$. Variation of B just by changing the coolant consumption G_3 made it possible to generalize the relation $\Psi(B)$ for the injection of gas through porous materials and circular holes [8]. Thus, for the injection of gas through circular holes, the condition of the replacement of the parameters of the injected gas by the equivalent parameters on the Hall is unacceptable. The jet character of the gas-coolant flow complicates the heat-transfer process and, as in the case of the flow of gas through porous materials, the pattern of flow of the gas in the neighborhood of the forward critical point is nonuniform. Also, by varying the radius of the permeable section during heat transfer, we also change the percentage of recuperative cooling of the wall. Thus, the injection parameter is not a similarity criterion in the problem being examined.

Points 5 in Fig. 3 correspond to the relations $\Psi(B)$ obtained for models with holes of the diameter $d = 0.7 \cdot 10^{-3}$ m and $n = 60$. We compared this relation with the experimental points 4, for which $d = 1.0 \cdot 10^{-3}$ m and $n = 30$ (for both relations, $\varphi = 0.043$, $r/h = 0.69$, $R = 19 \cdot 10^{-3}$ m). The comparison showed that an increase in the number of holes with a simultaneous decrease in their diameter improves the thermal protection provided the model. The distance between adjacent holes $h = 4.0 \cdot 10^{-3}$ m for the first case and $h = 5.3 \cdot 10^{-3}$ m for the second case. A reduction in the distance between adjacent holes leads to earlier merging of the elementary jets and to a reduction in heat flow to the wall. A similar situation occurs with an increase in the degree of perforation φ (see Fig. 2). The flow begins to lose its jet character in the neighborhood of the frontal point and the injection of gas from the surface becomes more uniform and approaches injection through porous materials.

In the case of intensive injections the merging of the elementary jets of coolant is a necessary condition for repulsion of the incoming flow, while a sufficient condition is ensuring the critical values of the injection parameter [5, 6].

It follows from analysis of the results obtained here that in the presence of the injection of a gas-coolant through circular holes, the process of heat transfer between a plasma jet and a hemispherical wall is not subject to the generalizations which are valid for pore cooling. An increase in the degree of perforation of the permeable section and in the number of holes leads to more uniform injection of the coolant, earlier merging of the elementary jets with one another, and, thus, a reduction in the thermal loads on the protected wall. A change in the area of the permeable section and the radius of the model changes the proportion of regenerative cooling which occurs during combination heat transfer between a plasma jet and a wall. This must be considered in establishing approximate laws of heat and mass transfer.

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