HEAT TRANSFER IN A CONVERGENT CHANNEL WITH A PERMEABLE WALL

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The effect of a negative longitudinal pressure gradient and a transverse flow of material on the process of heat transfer in an axisymmetric channel is studied.

The experimental studies [1, 2] which have been performed up to now on the heat transfer in axisymmetric channels of the convergent type have not revealed any appreciable effect of the negative longitudinal pressure gradient on the Stanton number. In the given case the conservative nature of the effect is evidently explained to a certain extent by the weak deformation of the fluid-mechanical pattern of flow relative to the case of nongradient flow over an impermeable surface. The flows encountered in practice are often complicated by the presence of a transverse flow of material. Injection leads to the fact that the profiles of velocity and temperature become less full [3]. However, a similar pattern clearly develops only with external flow over bodies. Under the conditions of the internal problem the effect of injection is manifested in two ways. On the one hand, the transverse flow results in the velocity profile becoming less full and consequently leads to an increase in the displacement and momentum thicknesses. On the other hand, the increase in the integral characteristics leads to a more rapid increase in the velocity in the potential section of flow. The positive velocity gradient which develops in this case produces the opposite effect, leading to greater fullness of the velocity profile. Thus, the formation of the fluid-mechanical pattern of flow takes place with the harmony and opposition of the two indicated effects — the transverse flow of material and the positive velocity gradient. And a natural question is how does the heat transfer behave under these conditions? Is it only a function of the fluid-mechanical and thermal states of the system or are there also factors which affect the variation in the coefficient of heat transfer — the Stanton number.

The present report is devoted to an experimental study of this question with the turbulent flow of air in an axisymmetric convergent channel with a permeable wall.

The installation consists of a wind tunnel of the open type with plasma heating of the working substance. The principal elements of the installation are as follows: the test section, the system for supply of the working substance, the system for supply of the injected substance, the electric-arc heater, the forechamber, and the measurement system.

The test section consists of a porous convergent channel located in an injection chamber. The porous convergent channel was made by the method of hydrostatic molding from noncorroding powder with a particle size of 0.06 mm. The length of the convergent channel is 203 mm, the inlet diameter is 34.4 mm, the angle of convergence is 4°, and the wall thickness is 1.5 mm.

The temperature of the inner wall of the porous convergent channel was measured with 14 Chromel—Alumel thermocouples of $d = 0.2$ mm. The thermocouple beads were caulked into the wall of the convergent channel along two diametrically opposite generatrices at seven equally spaced cross sections at a depth of 1.3 ± 0.1 mm.

The following parameters were measured during the experiment: the stagnation temperature and pressure at the entrance to the test section, the flow rates of the principal and the injected air, the pressure and temperature of the gas in the injection chamber, the temperature of the inner wall of the porous convergent channel, and the distributions of static and stagnation pressures along the length of the channel. The parameters were recorded after the system had entered a steady thermal mode.

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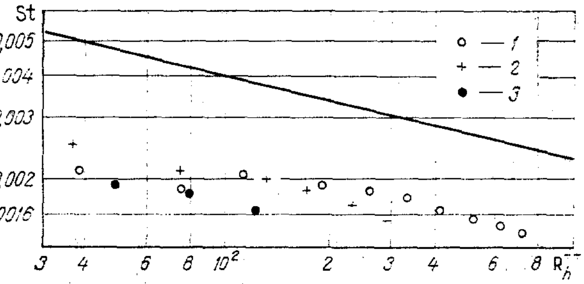

Fig. 1. Dependence of actual values of Stanton number on Reynolds number R_h^{++}: 1) $R_1 = 0.416 \cdot 10^5$, $(\psi_h)_{av} = 0.605$, $(\rho_w w_w)_{av}/\rho_{01} w_{01} = 0.0213$; 2) $R_1 = 0.386 \cdot 10^5$, $(\psi_h)_{av} = 0.51$, $(\rho_w w_w)_{av}/\rho_{01} w_{01} = 0.0218$; 3) $R_1 = 0.247 \cdot 10^5$, $(\psi_h)_{av} = 0.45$, $(\rho_w w_w)_{av}/\rho_{01} w_{01} = 0.0282$. Curve: calculation from Eq. (4).

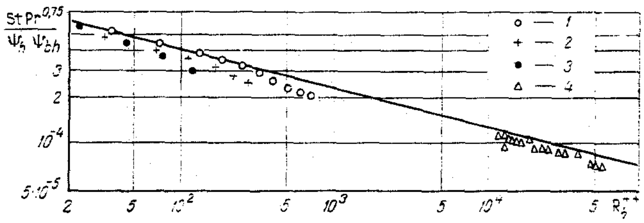

Fig. 2. Results of generalization of experimental data on heat transfer with allowance for factors of nonisothermicity and injection. Designations of experimental points same as in Fig. 1; 4) experimental data of Back and Cuffel [2] for $b_h = 0$.

The method of determination of the heat-transfer coefficient discussed in the present article is based on the method of local modeling [3].

The Reynolds number, constructed from the thickness of energy loss, was determined from the dependence

$$R_h^{++} = \frac{\int\limits_0^x q_w dx}{\rho_0 c_{p0} v_0 (T_0^* - T_w)}, \quad q_w = (\rho w)_w (h_w - h_x), \tag{1}$$

while the parameter of the longitudinal pressure gradient was determined from the equation

$$f = \frac{\delta^{**}}{w_0} \frac{dw_0}{dx}. \tag{2}$$

The experimental data were analyzed on a computer. The experimental data on heat transfer were analyzed in the form of the dependence

$$St = \varphi(R_h^{++}). \tag{3}$$

The relative density $(\rho w)_w/\rho_{01} w_{01}$ of the transverse flow of material was varied from 0.0205 to 0.0296 in the tests; the temperature T_0^* of the principal flow was varied from 499 to 727°K, while the wall temperature T_w was varied from 297 to 346°K. The Reynolds number R_1 of the principal flow at the entrance to the test section was varied from $0.247 \cdot 10^5$ to $0.416 \cdot 10^5$.

The distribution of the actual values of the Stanton number as a function of the Reynolds number calculated from the thickness of energy loss is shown in Fig. 1. The curve shows the dependence of the heat-transfer coefficient under standard conditions, corresponding to the equation

$$St_0 \doteq \frac{0.0128}{R_h^{++0.25} Pr_0^{0.75}}. \tag{4}$$

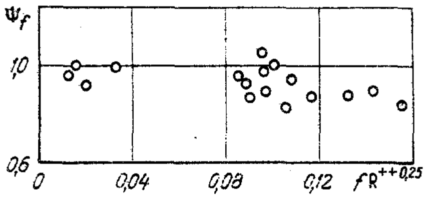

Fig. 3. Effect of negative longitudinal pressure gradient on heat transfer. Points: authors' experiments.

A generalization of the experimental data on heat transfer through the reduction of the values of St observed in the experiments to standard conditions is presented in Fig. 2. They were reduced to standard conditions by the elimination of the disturbing factors occurring in the experiment through the equation

$$\mathrm{St}_0 = \frac{\mathrm{St}}{\Psi_h \Psi_{bh}}, \tag{5}$$

where

$$\Psi_h = \left(\frac{2}{\sqrt{\psi_h}+1}\right)^2, \quad \Psi_{bh} = \left(1 - \frac{b_h}{b_{\mathrm{cr.h}}}\right), \tag{6}$$

$$b_h = \frac{(\rho w)_w}{\rho_0 w_0 \mathrm{St}_0}, \quad b_{\mathrm{cr.h}} = \frac{1}{1-\psi_h}\left(\ln \frac{1+\sqrt{1-\psi_h}}{1-\sqrt{1-\psi_h}}\right)\left(1+\frac{0{,}83}{R_h^{++0,14}}\right).$$

It is seen from the graph that the experimental points reduced to standard conditions are grouped along the curve corresponding to the dependence (4) with a maximum relative error not exceeding 15%.

The experimental data of Back and Cuffel [2], obtained under the conditions of the absence of injection but with the same enthalpy factor, are presented in the same figure. Sufficiently satisfactory agreement of the experimental data is observed.

In Fig. 3 the experimental data on heat transfer, reduced to relative form, are presented as a function of the negative longitudinal pressure gradient. It is seen that all the points are grouped near unity within the limits of the experimental accuracy.

Thus, one can conclude that the negative longitudinal pressure gradient does not have an appreciable effect on the heat-transfer coefficient for nonisothermal flow over a permeable surface. The distribution of the heat flux as a function of the longitudinal coordinate is determined by the fluid-mechanical pattern of flow.

NOTATION

R_h^{++}, thermal Reynolds number, constructed from thickness of energy loss; q, specific convective heat flux; c_p, specific heat capacity at constant pressure; ν, coefficient of kinematic viscosity; ρ, flow density; w, velocity; h, enthalpy; T, temperature; δ^{++}, thickness of momentum loss; St, Stanton number; Pr, Prandtl number; Ψ, relative heat-transfer law; ψ_h, enthalpy factor; b, permeability parameter. Indices: 0, parameter in potential core; w, parameter at wall; cr, critical parameter; x, parameter at supply temperature; 1, parameter at inlet; av, average value of parameter.

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