EFFECT OF A PRE-ATTACHED DYNAMIC SECTION ON HEAT TRANSFER IN A TURBULENT BOUNDARY LAYER, WITH BLOWING

É. P. Volchkov, V. K. Koz'menko, and V. P. Lebedev

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This paper gives the results of an investigation of the effect of an initial dynamic section on heat transfer with blowing. The experimental data obtained show that the preattachment of a section can have a considerable effect on the heat transfer. A method is proposed based on the use of the relative laws of heat transfer; in this case, the effect of the initial section is taken into account in terms of the Stanton number at an impermeable surface. The calculation is in satisfactory agreement with the experimental data obtained, as well as with the experimental data of other authors.

An effective method for protecting surfaces from the action of high-temperature gas flows is blowing a cooling agent through a porous wall. The blowing may be carried out through the whole surface over which the hot gas flows, or only through one of its sectors. In practice, there is frequently a nonuniform distribution of the heat flux at the wall; therefore, the second case of feeding the cooling agent is the most probable. In this case, the blowing may be carried out through that section of the surface where there is the maximal heat flux (for example, in the critical cross section of a nozzle). In this case, ahead of the porous section there is installed an initial dynamic layer, which can have a considerable effect on heat transfer with blowing. The experimental data of various authors on heat transfer, when the blowing is carried out through the whole surface, diverge somewhat. One of the possible reasons for this lack of agreement may also be the presence of a pre-attached dynamic section, which is not taken into account in the analysis of the experimental data. In view of this there arises the question of investigation of the effect of an initial dynamic section on heat transfer in a turbulent boundary layer with blowing. Whitten et al.* and Sastri and Hartnett [1] discuss this question and note the substantial effect of a pre-attached section on heat transfer. However, the results of these authors are not in complete agreement and require further investigations.

The present article gives the results of an experimental investigation of heat transfer in a turbulent boundary layer at a porous plate, with an initial dynamic section. The blowing scheme is shown in Fig. 1. The tests were made in a subsonic aerodynamic tube. The working channel has the dimensions $110\times110\times1300$ mm^3. The air of the main flow is fed into the working channel through a shaped nozzle. The lower wall of the channel is porous, with sectionalized feed of the air blown. Each section is made of Textolite. The partitions separating the sections are also made of Textolite. The porous plates are made of stainless steel and have a thickness of 6 mm and a porosity of $\sim 70\%$. The experimentally determined total hemispherical degree of blackness $\varepsilon = 0.6$.

*D. G. Whitten, W. M. Kays, and R. J. Moffat, "The turbulent boundary layer on a porous plate: experimental heat transfer with variable suction, blowing, and surface temperature," Report No. HMT-3, Thermosciences Division, Department of Mechanical Engineering, Stanford University, December, 1967.

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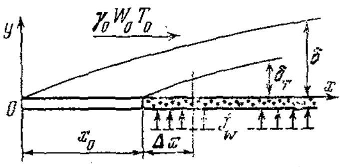

Fig. 1

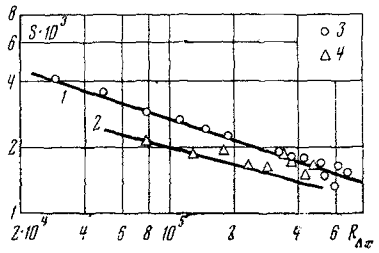

Fig. 2

The measurements of the permeability showed a good degree of uniformity of the blowing. The temperature of the porous wall was measured with Nichrome–constantan thermocouples made of wire with a diameter of 0.2 mm. The thermocouples were caulked into the outer surface of the porous plate. On the reverse side of the plate, the point of exit of the thermocouple wire was glued with an epoxy resin, to avoid direct incidence of the blown hot air on the thermocouple junction. The thermocouples were arranged along the surface of the porous wall on the central line. In certain sections, three thermocouples were glued over the width of the plate.

The mass flow rate of the air blown was monitored using reducers. The mass flow rate of the secondary air was measured using an RS-5 rotameter. During its passage along a system of conduits from the rotameters to the sections with the porous plates, the air was heated by special electric heaters. For more uniform distribution of the secondary air over the whole plate, a perforated distributor was installed inside each section. The temperature of the blown air was measured with a thermocouple ahead of the perforated distributor.

In this experimental unit, tests were first made on an impermeable plate (the results are given in [2]). In these tests, the dynamic characteristics of the gas flow and the heat transfer were confirmed by the presence of a fully developed turbulent boundary layer. The experimental values of the friction and heat-transfer coefficients corresponded to the generally accepted calculated values.

The first series of tests on a porous plate consisted in determining the heat-transfer coefficient in a turbulent boundary layer, when the blowing starts from the leading edge of the plate. Ten tests were made under quasi-isothermal conditions and with $\dot{J}_W = \mathrm{const}$. In this case, the initial blowing rate was varied from $1.2 \cdot 10^{-3}$ to $8.1 \cdot 10^{-3}$. The velocity of the main flow was 20–40 m/sec. The results of some of the heat-transfer tests are given in Fig. 2 with $\dot{J}_W/\gamma_0 W_0 = 2.9 \cdot 10^{-3}$ (experimental points 3), as well as in Fig. 3 (experimental points 3) and in Fig. 4 (experimental points 2 with $\dot{J}_W/\gamma_0 W_0 = 2.9 \cdot 10^{-3}$, $4.58 \cdot 10^{-3}$, $6.75 \cdot 10^{-3}$). All the experimental points are in satisfactory agreement with the limiting relative laws of heat transfer (curves 1), obtained under the condition $\dot{J}_W = \mathrm{const}$ [3, 4]:

$$\Psi_b' = \left(1 - \frac{b_T}{b_{T_*}}\right)^2 \left(1 + \frac{b_T}{b_{T_*}}\right)^{-0.2}, \quad \Psi_b' = \frac{S}{S_0}\frac{1}{\Psi_t^{0.8}}, \quad \Psi_t = \left(\frac{2}{\sqrt{\psi}+1}\right)^2 \tag{1}$$

Here S/S_0 is the ratio of the local Stanton number with blowing to the Stanton number at an impervious flat plate, around which is flowing a gradientless quasi-isothermal stream of gas (the ratio is taken at identical values of the R_x number); Ψ_1 takes account of nonisothermal heat transfer; $\psi = T_W/T_0$ is a temperature factor; $b_T = \dot{J}_W/\gamma_0 W_0 S_0$ is the parameter of the permeability of the wall (S_0 is taken at the same value of R_T^{**} as in the case with blowing); $\dot{J}_W = \gamma_W V_W$ is the mass rate of blowing of the gas through the wall.

The critical permeability of the wall, b_{T*}, calculated taking account of the nonisothermicity and of the finite nature of the Reynolds number, using the formula [4]

$$b_{T_*} = \frac{1}{\psi - 1}\left(\arccos\frac{2-\psi}{\psi}\right)^2 \left(1 + \frac{0.83}{R_T^{**0.14}}\right) \qquad (\psi > 1) \tag{2}$$

The values of S_0 were calculated using the formulas [2], obtained experimentally on an impermeable flat plate:

$$S_0 = 0.032 R_x^{-0.2} P^{-0.6} \tag{3}$$

$$S_0 = 0.0143 R_T^{**-0.25} P^{-0.75} \tag{4}$$

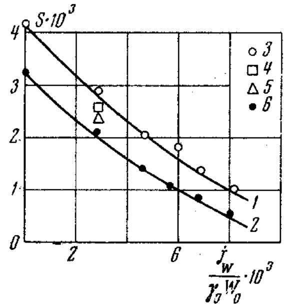

Fig. 3

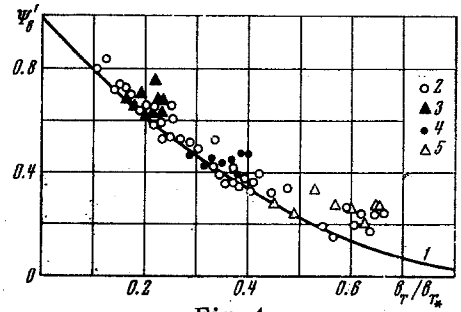

Fig. 4

The connection between R_T** and R_x needed in the calculation is obtained as follows. The integral relationship for the energy, with the quasi-isothermal flow of a gas along a porous surface, can be written in the form

$$\frac{d(R_T^{**}\Delta T)}{\Delta T dX} = \left(\frac{\dot{j}_w}{\gamma_0 W_0} + S\right) R_L \tag{5}$$

Here $\Delta T = T_W - T_0$, $X = x/L$, L is the characteristic linear dimension; R_L is the Reynolds number, constructed with respect to L; T_W is the temperature of the porous wall; T_0 is the temperature at the outer limit of the boundary layer.

Integrating Eq. (5), taking account of the fact that $\dot{j}_W$ = const and

$$S = \frac{q_w}{\gamma_0 W_0 c_{p_0}(T_w - T_0)} = \frac{\dot{j}_w(T_1 - T_w)}{\gamma_0 W_0 (T_w - T_0)} \tag{6}$$

we obtain

$$\frac{T_w - T_0}{T_1 - T_0} = \frac{\dot{j}_w}{\gamma_0 W_0} \frac{R_x}{R_T^{**}} \tag{7}$$

where T_1 is the temperature of the air blown. On the other hand, it is well known [4] that

$$\Psi_b = \frac{T_1 - T_w}{T_w - T_0} b_T \tag{8}$$

from which, after certain transformations, we obtain

$$\frac{T_w - T_0}{T_1 - T_0} = \frac{b_T}{b_T + \Psi_b} \tag{9}$$

Here

$$\Psi_b = \frac{S}{S_0} = \left(1 - \frac{b_T}{b_{T_*}}\right)^2 \tag{10}$$

$$b_T = \frac{\dot{j}_w}{\gamma_0 W_0 S_0} \tag{11}$$

Using relationships (7), (9), (10), (11), and (4), we obtain the final relatively simple expression for the connection between R_T** and R_x:

$$R_x = \frac{R_T^{**1.25} P^{0.75}}{0.0143\left[(1 - \alpha/b_{T_*})^2 + \alpha\right]} \qquad \left(\alpha = \frac{\dot{j}_w}{\gamma_0 W_0} \frac{R_T^{**0.25} P^{0.75}}{0.0143}\right) \tag{12}$$

In calibration experiments, measurements were also made of the velocity profiles; these are found to be in good agreement with calculation using the limiting dependence [5]

$$\omega \approx 1 - \sqrt{\Psi_b + b_T}(1 - \omega_0) + {}^1/_4 b_T (1 - \omega_0)^2 \tag{13}$$

Further experiments were carried out in an investigation of the effect of an initial dynamic section on heat transfer with blowing. In [6], based on the hypothesis of the conservative nature of heat transfer, an analysis was made of the effect of an initial adiabatic section on heat transfer on an impermeable plate. It was shown that this effect is expressed in terms of the ratio of the thickness of the loss of momentum to the thickness of the loss of energy in the cross section under consideration. In other words, taking ac-

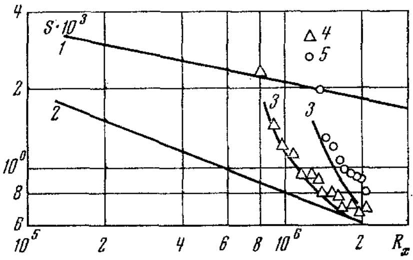

Fig. 5

count of this effect affects the value of the initial thickness of the loss of momentum in the cross section $x = x_0$

$$S_0^\circ = 0.032 R_{\Delta x}^{-0.2} P^{-0.6} \left[1 + \frac{R_0^{**1.25}}{A(m+1) R_{\Delta x}}\right]^{-0.086} \quad (A = 0.0143,\ m = 0.25) \qquad (14)$$

$$S_0^\circ = 0.0143 R_T^{**-0.25} P^{-0.75} \left[1 + \left(\frac{R_0^{**}}{R_T^{**}}\right)^{1.25}\right]^{-0.114} \qquad (15)$$

The validity of these formulas has been confirmed experimentally [2].

In the present experiments, a change in the initial thickness of the loss of momentum δ_0^{**} was achieved by varying the blowing of air, with a temperature equal to the temperature of the main flow, into the first section. As a result, the Reynolds number, constructed from the loss of momentum at the end of the pre-attached section, varied within the limits $R_0^{**} = 940$–3180. Fourteen experiments were carried out under quasi-isothermal conditions, with an initial section (see Fig. 1). The relative rate of blowing was varied from $2 \cdot 10^{-3}$ to $7.98 \cdot 10^{-3}$. The temperature of the air of the main flow was ~ 30°C, and that of the blown air was 110–115°C. The convective heat flux to the wall was determined from the energy balance at the surface of the porous plate. In this case, account was taken of the radiant heat flux, which amounted to ~ 10–20% of the convective flux. The experimental value of the Stanton number was determined from the relationship

$$S = \frac{\dot{J}_w c_{p_1} (T_1 - T_w) - q_1}{\gamma_0 W_0 c_{p_0} (T_w - T_0)} \qquad (16)$$

where q_1 is the radiant heat flux; $\gamma_0 c_{p0}$ are the specific weight and the specific heat capacity, with a constant pressure of the main flow; c_{p1} is the specific heat capacity of the blown gas.

The experimental Reynolds number, constructed from the thickness of the energy loss, was found from the integral relationship for the energy (at $\dot{J}_W = \text{const}$)

$$R_T^{**} = \frac{\dot{J}_w c_{p_1} (T_1 - T_0) - q_1}{g \mu c_{p_0} (T_w - T_0)} \Delta x \qquad (17)$$

Here Δx is the distance along the porous surface, calculated from the beginning of the thermal boundary layer; μ is the coefficient of dynamic viscosity.

The experiments carried out showed that the experimental values of S for the case of blowing, with an initial dynamic section, differ from the values of the Stanton number without an initial section, taken at the same values of $R_{\Delta x}$. Figure 2 gives a comparison between the experimental values of the Stanton number over the length of a porous plate for the case of heat transfer with an initial section (experimental points 4) and without an initial section (experimental points 3). Under these circumstances, the value of the initial blowing $\dot{J}_W/\gamma_0 W_0 = 2.9 \cdot 10^{-3}$, and $R_0^{**} = 3180$. The Reynolds number $R_{\Delta x}$ was constructed from Δx, calculated from the beginning of the thermal boundary layer. It is evident from the curve presented that an initial dynamic section has a considerable effect on the heat transfer. Figure 3 gives a comparison of the Stanton numbers with blowing, with an initial section (experimental points 4, 5, and 6) and without an initial section (experimental points 3), with different values of the relative blowing $\dot{J}_W/\gamma_0 W_0$. Under these conditions, the Reynolds number $R_0^{**} = 940$, 2460, and 3180 for experimental points 4, 5, and 6, respectively. The experimental S numbers were taken for values of $R_{\Delta x} = 7.1 \cdot 10^4$–$7.6 \cdot 10^4$. This curve shows that an effect of an initial dynamic section on the heat transfer exists at different blowing rates. In addition, it is obvious that the greater the value of R_0^{**} the stronger this effect.

In calculation of heat transfer at a permeable surface with an initial dynamic section, the limiting relative laws of heat transfer were used. However, everywhere in these relationships, instead of S_0 the Stanton number at an impermeable surface was used, with the same pre-attached section as in the above-considered case with blowing (i.e., formulas (14) and (15) were used). This means that the Stanton number is used to take account of an initial section in the calculation of heat transfer at a porous plate. As confirmation of the proposed method of calculation, we can adduce the fact that the effect of a pre-attached section does not enter into any of the quantities, except S_0, in the derivation of the limiting relative law of heat transfer.

In the given calculation the effect of an initial dynamic layer on the value of the critical parameter of the permeability of the wall was not taken into account, and b_{T*} was determined using formula (2). The calculated values of the Reynolds number $R_T{}^{**}$ were determined from the relationship (12); these values were obtained also for the case of blowing without an initial section, since the experimentally determined values of $R_T{}^{**}$ in the presence of a pre-attached section are in good agreement with the dependence (12).

A comparison between the results of calculation using the proposed method and experimentally obtained results is shown in Fig. 2 and Fig. 3. Here curves 2 represent calculation using formula (1), which was modified taking account of Eqs. (14) and (15). As can be seen from the curves, the calculation describes the experiments satisfactorily.

Figure 4, together with experimental data on heat transfer without an initial section, gives experimental data with the presence of a pre-attached section (experimental points 3, 4, 5) in the form of the dependence $\Psi_b{}' = f(b_T/b_{T*})$. The experiments were made with $R_0{}^{**} = 3180$ and with relative blowing rates of $2.8 \cdot 10^{-3}$, $4.58 \cdot 10^{-3}$, and $6.75 \cdot 10^{-3}$ for experimental points 3, 4, and 5, respectively. The experimental data were analyzed using the Stanton number at an impermeable plate, in the presence of an initial section. As is evident from the curve, with the proposed form of analysis, the experimental data, in the presence of a pre-attached section and without it, are in agreement between themselves and with the limiting dependence (1) (curve 1).

Figure 5 gives a comparison between the proposed method of calculation and the experimental data of the report (see footnote). Curves 1 and 2 represent calculation without an initial section for $\dot{J}_W/\gamma_0 W_0 = 0$ and $\dot{J}_W/\gamma_0 W_0 = 4 \cdot 10^{-3}$. The experimental points 4 and 5 correspond to Reynolds numbers $R_{x_0} = 8 \cdot 10^5$ and $R_{x_0} = 1.3 \cdot 10^6$. Curves 3 represent calculation using the proposed method. Good agreement between the calculation and the experiments can be noted.

As has been shown by the above analysis, a pre-attached dynamic section may exert a considerable effect on heat transfer with blowing. Under these circumstances, relative laws can be used for the calculation of heat transfer, if the Stanton number at an impermeable surface is used taking the pre-attached section into account.

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