DRAG OF A PLATE WITH SIMULTANEOUS UNEQUAL MASS BLOWING AND SUCTION

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This paper presents results of an investigation of friction on surfaces with simultaneous unequal blowing and suction of mass in a turbulent gas boundary layer.

The drag of a flat plate with simultaneous mass blowing and suction at the wall was measured in [1]. The present paper gives results of gasdynamic measurements on a perforated plate with unequal mass blowing and suction at the wall. The experiments were conducted over the range of variation of mass blowing and suction intensity of $j_+/j_- < 1.5$.

The layout of the experimental equipment is shown in Fig. 1. The main air stream was generated by a continuous subsonic wind tunnel with an open working section. The speed of the main stream was controlled in the range 13 to 30 m/sec, and the air temperature was 298°K.

The flat plate model with perforated surface 1 was mounted parallel to the main air stream in the zero-gradient flow region. At the front of the plate was a wire turbulence generator 2, so chosen as to produce a turbulent boundary layer over the entire plate. The model was made of textolite, of length 580 mm and width 200 mm. A part of the plate surface of dimension $220 \times 80\ \mathrm{mm}^2$ was perforated with apertures of diameter 1 mm on a pitch of 4 mm, so that the total area of the perforations was 5.2% of the entire surface. One series of apertures was connected with the blowing cavity, and the other with the suction cavity, as shown in Fig. 1, 1. The air blowing and suction was accomplished with separate fans 3 and 4, the output of which could be controlled by varying the current to the electric motors. The channels from the blowing and suction cavities and the fans were carefully sealed. The mass blowing and suction was varied by controlling the fan flow rates and the speed of the main air stream. During the experiments we measured the velocity distribution through the boundary layer at different distances from the plate leading edge, the flow rates of the air blowing and suction, and the air temperature. The longitudinal air velocity above the permeable surface was determined with a pitot tube rake with inlet aperture height of 0.2 mm and width 2 mm. The minimum distance from the center of the pitot tube to the plate surface was 0.2 mm. The difference between the total and the static pressure was measured by an inclined type MMI-240(5)11 micromanometer.

Theoretical Flow Model. In describing flow on a permeable surface with simultaneous blowing and suction of mass at the wall the authors of [1] used the suggested possibility of summing the friction forces on such a surface at the wall, for various levels of equal

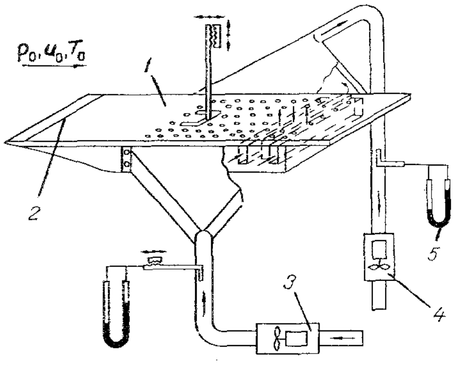

Fig. 1. Diagram of the experimental equipment: 1) flat plate model; 2) turbulence generator; 3, 4) fans for mass blowing and suction; 5) measuring probe.

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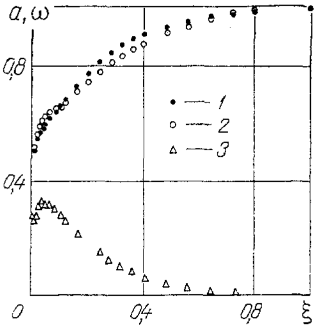

Fig. 2

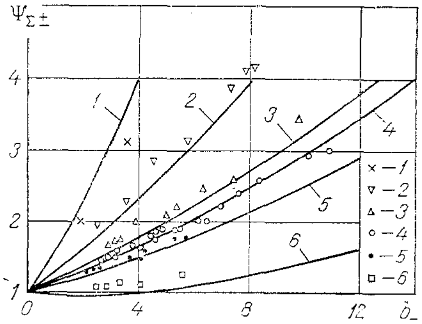

Fig. 3

Fig. 2. Comparison of the measured velocity profiles and variation of the coefficient a with mass blowing and suction at the wall: 1) velocity profiles with simultaneous identical mass blowing and suction at level $\bar{j}_+ = \bar{j}_- = 0.009$; 0.0063; 2) velocity profiles calculated from Eq. (4) for separate mass blowing and suction of the same level; 3) the coefficient a as calculated from Eq. (7).

Fig. 3. Variation of the relative friction coefficients on a plate with simultaneous mass supply and removal at the wall: 1) $j_+/j_- = 0$; 2) 0.57; 3) 0.92; 4) 1.0; 5) 1.1; 6) 1.37.

blowing and suction. However, this approach was not successful in describing the experimental data on surface friction with unequal mass blowing and suction. Moreover, there is poor agreement with test data that we obtained later with equal mass blowing and suction when the permeability parameter $b_\pm$ is greater than 5.3. Therefore, we shall use a somewhat different approach to obtain the laws of friction on the surfaces with simultaneous mass supply and removal at the wall.

We consider a smooth permeable surface on which uniform blowing and suction is accomplished through sequentially positioned infinitely small sections. To obtain the friction law for this surface we can use the limit integral obtained in [2]:

$$\sqrt{\Psi} = \int_0^1 \sqrt{\frac{\tilde{\tau}_0}{\tilde{\tau}}}\, d\omega. \tag{1}$$

To obtain from Eq. (1) the friction law on a permeable surface with mass blowing or suction one must know an approximation for the turbulent friction across the boundary layer as a function of the intensity of mass supply or removal. Unfortunately, the authors have not been able to measure the turbulent friction in the boundary layer with various levels of mass supply and removal at the wall. Therefore, we obtain approximate approximations. First we consider the case of identical mass supply and removal. The expressions proposed in [2] give quite good results for turbulent friction with separate mass blowing and suction:

$$\tau_+ = \tau_{w+} + j_+ u_+, \tag{2}$$

$$\tau_- = \tau_{w-} - j_- u_-. \tag{3}$$

It turned out that the velocity profiles with simultaneous identical mass blowing and suction can be expressed approximately by the formula

$$u = 0{,}5\,(u_+ + u_-). \tag{4}$$

Figure 2 compares Eq. (4) with the measured velocity profiles for equal simultaneous mass blowing and suction (u) and separate blowing (u_+) and suction (u_-) of the same intensity.

As a first approximation we shall assume that the turbulent friction and the friction force at the wall with equal simultaneous blowing and suction can be described in the form

$$\tau_\pm = 0{,}5\,(\tau_+ + \tau_-),\quad \tau_{w\pm} = 0{,}5\,(\tau_{w+} + \tau_{w-}). \tag{5}$$

Adding Eqs. (2) and (3) and taking account of Eqs. (4) and (5), we obtain an expression for the turbulent friction with the same mass blowing and suction at the wall

$$\tilde{\tau}_{\pm} = \frac{\tau_{\pm}}{\tau_{w\pm}} = 1 - ab_{1\pm}\omega, \tag{6}$$

where

$$a = 0.5\left(\frac{u_{-}}{u} - \frac{u_{+}}{u}\right). \tag{7}$$

Figure 2 shows the variation through the boundary layer of the experimental values of coefficient a. It can be seen from Fig. 2 that near the wall, where Eq. (6) is also valid, to a first approximation a can be assumed to be constant and equal to $a = 0.29$. With the approximation that the tangential stresses across the boundary layer vary as a cubic parabola, as proposed in [2], and allowing for the boundary conditions:

$$\text{for } \xi \to 0 \quad \tilde{\tau}_{\pm} \to 1 - 0.29\, b_{1\pm}\omega,$$

$$\text{for } \xi \to 1 \quad \tilde{\tau}_{\pm} \to 0, \; \frac{\partial \tilde{\tau}}{\partial \xi} \to 0$$

we obtain the formula

$$\frac{\tilde{\tau}_{\pm}}{\tilde{\tau}_0} = 1 - \frac{0.29\, b_{1\pm}\omega}{1 + 2\xi}, \tag{8}$$

where $\tilde{\tau}_0 = 1 - 3\xi^2 + 2\xi^3$.

Substituting Eq. (8) into Eq. (1), we obtain the following friction law for isothermal flow over a plate with identical mass blowing and suction ($2\xi + 1 \approx 1$):

$$\Psi_{\pm} = \frac{C_{f\pm}}{C_{f0}} = \left(1 + \frac{0{,}29\, b_{\pm}}{4}\right)^2. \tag{9}$$

It was shown earlier that with simultaneous action of several perturbing factors the relative friction law can be represented as the product of several friction laws accounting for each individual factor [2]. Therefore, with the same mass blowing and suction we can write the friction law in the form

$$\Psi_{\Sigma\pm} = \Psi_{\pm}\Psi_{b}, \tag{10}$$

where $\Psi_{\pm}$ is the friction law with the same mass blowing and suction, calculated according to Eq. (8) under the hypothesis $b_{\pm} = b_{+}$ for $j_{+}/j_{-} < 1$ and $b_{\pm} = b_{-}$ for $j_{+}/j_{-} > 1$; $\Psi_b = (1 + b_{-} - b_{+}/b_{cr})^2$, the friction law on a permeable surface [2]; and b_{cr}, critical permeability parameter. We account for the influence of the same level of mass blowing and suction on the critical blowing parameter to a first approximation from the analogy with the influence of the other factors [2] as $b_{cr} = b_{cr_0}\Psi_{\pm} = 4\Psi_{\pm}$. Then the friction law on a surface with different mass blowing and suction takes the form

$$\Psi_{\Sigma\pm} = \left(1 + \frac{0{,}29\, b_{\pm}}{4}\right)^2 \left(1 + \frac{b_{-} - b_{+}}{4\Psi_{\pm}}\right)^2. \tag{11}$$

Figure 3 shows our test data on the relative friction factor for the same values of Re** on a plate with simultaneous mass blowing and suction. The experiments were conducted at a variable suction level and at constant ratios of the levels of mass blowing and suction. The average friction factors were determined from the integral momentum relation for the case examined

$$C_{f\Sigma\pm} = 2\,\frac{\delta_2^{**} - \delta_1^{**}}{L} + \bar{j}_{+} - \bar{j}_{-}.$$

The momentum loss thickness values were determined by integrating the measured velocity profiles through the boundary layer thickness

$$\delta^{**} = \int_0^{\delta} \omega(1 - \omega)\, dy.$$

The average friction coefficient on an impermeable surface at the section L was calculated from the friction law of [2] $C_{f0} = 0.0256\ \mathrm{Re}^{**-0.25}$ using the formula

$$C_{f0} = \frac{0.0256\,(\mathrm{Re}_2^{**0.75} - \mathrm{Re}_1^{**0.75})}{0.75\,(\mathrm{Re}_2^{**} - \mathrm{Re}_1^{**})}.$$

The solid lines in Fig. 3 show the results of calculations from Eq. (11) for various values of j_+/j_-. It can be seen from Fig. 3 that there is satisfactory agreement between the relation obtained and the test data for simultaneous mass blowing and suction at the wall.

NOTATION

$\bar{j}_+$, $\bar{j}_-$, relative mass velocity of blowing and suction gas, respectively; δ_1^{**}, δ_2^{**}, momentum loss thickness at the start and the end of the perforated section, m; $\omega = u/u_0$, relative longitudinal flow velocity; C_{f0}, friction coefficient on an impermeable surface; $C_{f\pm}$, $C_{f\Sigma\pm}$, friction coefficient on a flat plate with simultaneous equal and unequal mass blowing and suction; $\Psi_\pm = C_{f\pm}/C_{f0}$, $\Psi_{\Sigma\pm} = C_{f\Sigma\pm}/C_{f0}$, relative friction law with equal and unequal mass blowing and suction; τ_+, τ_-, turbulent friction in a boundary layer with separate mass blowing and suction, respectively; $\mathrm{Re}_1^{**} = u_0\delta_1^{**}/\nu$, $\mathrm{Re}_2^{**} = u_0\delta_2^{**}/\nu$, Reynolds number at the start and the end of the perforated section; $b_+ = 2\bar{j}_+/C_{f0}$, $b_- = 2\bar{j}_-/C_{f0}$, $b_\pm = 2\bar{j}_\pm/C_{f0}$, permeability parameters.

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EXPERIMENTAL INVESTIGATION OF HEAT EXCHANGE IN A POROUS ANNULAR CHANNEL

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The problems connected with the intensification of heat exchange in an annular channel with a porous inner wall are considered. A method for calculating a "tube-in-tube" heat exchanger with a porous inner tube is described.

Various methods can be used for increasing the heat transfer coefficient and thereby intensifying the heat exchange. For instance, transverse flow of the heat-transfer agent through a porous wall can be provided. The transverse flow of the agent mass can be directed from the heated heat-transfer agent to the heating agent, and vice versa. For this, it is necessary to maintain a suitable pressure drop in the heat-transfer agents. In this case, the medium is drawn off continuously along the porous wall immersed in the flow on the part of one heat-transfer agent, while injection occurs on the part of the other agent. By

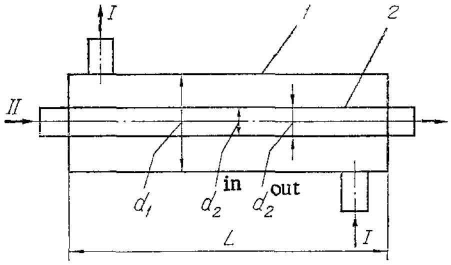

Fig. 1. Schematic diagram of the heat exchanger with an inner porous tube (I and II are the heated and the heating heat-transfer agents, respectively). 1) Outer tube; 2) inner porous tube.

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