

FRICITION AT THE SURFACE OF A PLATE WITH SIMULTANEOUS
INJECTION AND SUCTION OF GAS

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The results of measurements of friction at a surface with simultaneous mass injection and suction in the turbulent boundary layer are presented. Equations are proposed for calculations of the friction and velocity profiles under these conditions.

The friction at a perforated surface with simultaneous injection and suction of air in the turbulent boundary layer is studied in the present report. The air was injected and sucked through alternating openings located one after the other. The total area of the opening was 4.8%. The intensity of injection and the intensity of suction, normalized to the area of the entire perforated plate, were the same.

The experiments were conducted on a continuously operating subsonic wind tunnel with an open working section (Fig. 1).

The working section is 1 m long. The cross-sectional area of the outlet and inlet openings is 0.5 m^2 .

Parameters of the main stream are as follows: velocity, 27 m/sec; temperature, 298°K ; and Reynolds number (at 1 m), $1.8 \cdot 10^6$.

The model of a flat plate with a permeable surface 1 was mounted parallel to the main gas stream in the lower part of the working section of the tunnel in the region of zero-gradient flow.

The model consisted of a rectangular parallelepiped made of plastic, 480 mm long and 100 mm wide, containing two cavities isolated from each other. Both cavities had one common perforated wall in which openings were drilled so that one row of openings was connected with the injection cavity and another with the suction cavity (see Fig. 1). There were 24 openings in each row and 120 rows in all. The openings were arranged in straight-line order with a spacing of 4 mm.

The injection and suction of air was accomplished with one blower 2, which assured the equality of the flow rates of injected and sucked gas. The entire circuit from the injection cavity to the suction cavity, including the blower, was airtight. Variation in the injection-suction intensity (the flow rate of the simultaneously injected and sucked gas) was accomplished by varying the rotation rate of the blower.

The velocity distribution over the thickness of the boundary layer and the flow rate and temperature of the injected and sucked air were measured in the course of the experiment.

The longitudinal velocity above the permeable surface was determined with a velocity-head tube 3. The tube was shifted both along and perpendicular to the surface of the plate using a special coordinator with a step of 0.1 mm. The minimum distance from the center of the opening of the velocity-head tube to the surface of the plate was 0.2 mm.

The drop between the total and static pressures was measured with a micromanometer of brand MMI-240(5)11.

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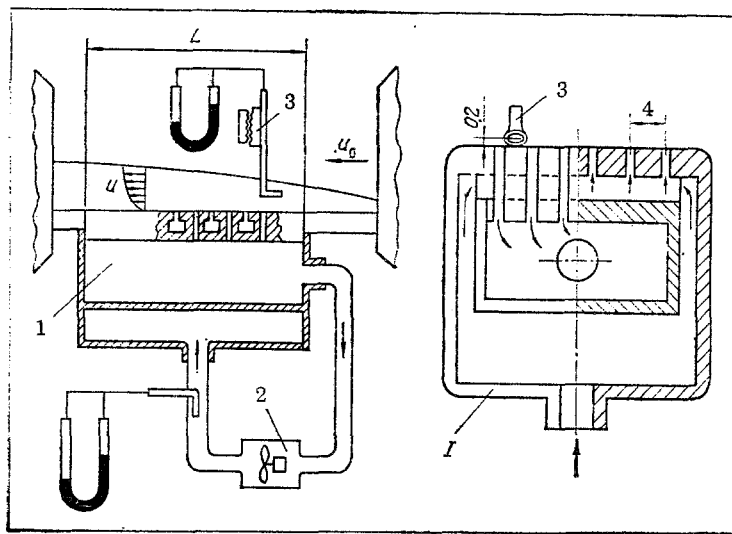


Fig. 1. Diagram of experimental installation: I) diagram of organization of simultaneous injection and suction; 1) permeable plate; 2) blower; 3) velocity-head tube.

The flow rate of injected and sucked air was determined with a velocity-head tube mounted in the injection circuit at a distance of $0.12d$ from the inner wall of the pipe.

The velocity distributions over the thickness of the boundary layer were measured along the axis of symmetry of the plate in several cross sections of the perforated section. According to [1], the location of the inlet opening of the velocity-head tube relative to the perforations in the presence of injection has little effect on the integral characteristics of the boundary layer. The experiments conducted in the present work also confirmed this fact for the case of simultaneous injection and suction.

The velocity profiles obtained for different injection-suction intensities are shown in Fig. 2. In the given case the injection-suction intensity was taken as the ratio of the mass velocity of air in the injection circuit to the mass velocity of the main stream:

$$\bar{j}_+ = \bar{j}_- = \frac{\rho_{st} V_{st}}{\rho_0 u_0}.$$

The thickness of momentum loss δ^{**} was determined from the experimental velocity profiles by the equation

$$\delta^{**} = \int_0^{\delta} \frac{u}{u_0} \left(1 - \frac{u}{u_0} \right) dy.$$

It is seen from Fig. 2 that with an increase in \bar{j} the velocity profiles become less full in comparison with the velocity profile at a smooth plate with zero-gradient flow. After a certain value of the parameter $\bar{j} = \bar{j}_{cr}$ is reached the velocity profile remains unchanged with a further increase in \bar{j} .

The average values of the coefficient of friction at the perforated plate with simultaneous injection-suction are shown in Fig. 3. The average coefficient of friction was determined from the integral momentum equation for the entire perforated plate. For the experimental conditions with equality of the injected and sucked gas it has the form

$$\frac{c_f}{2} = \frac{d\delta^{**}}{dx},$$

from which

$$\frac{c_f}{2} = \frac{\delta_2^{**} - \delta_1^{**}}{L}.$$

It is seen from Fig. 3 that the coefficient of friction becomes constant after the critical values of the injection-suction intensity are reached.

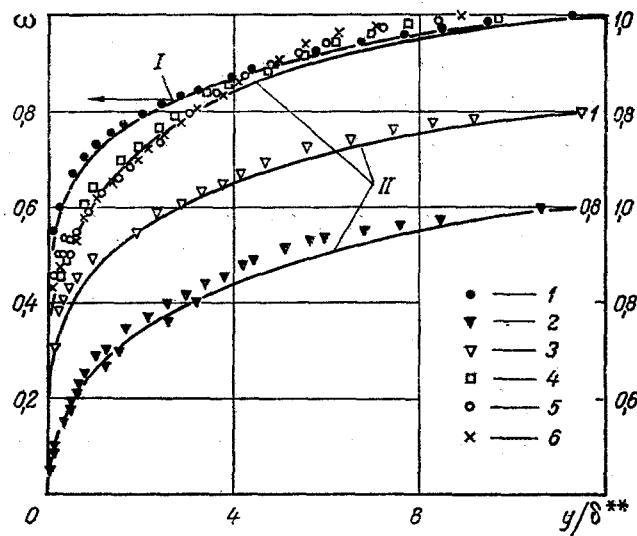


Fig. 2. Velocity profiles in the turbulent boundary layer at a plate with simultaneous injection and suction of air: I) calculation by the equation $\omega_0 = 0.716(y/\delta^{**})^{1/7}$; II) calculation by Eq. (11); 1) $\bar{j} = 0$; 2) 0.0034; 3) 0.00575; 4) 0.00735; 5) 0.008; 6) 0.0108.

The dependence of the relative coefficients of friction on the permeability coefficient b is shown in Fig. 4.

The permeability parameter was determined from the formula

$$b_+ = b_- = \bar{j} \frac{2}{\bar{c}_{f_0}}$$

The average coefficient of friction \bar{c}_{f_0} was calculated from the friction law $c_{f_0} = 0.0256 \cdot Re^{** - 0.25}$ for the case of isothermal zero-gradient flow of an incompressible gas [2]:

$$\frac{\bar{c}_{f_0}}{2} = \frac{0.0128(Re_2^{**0.75} - Re_1^{**0.75})}{0.75(Re_2^{**} - Re_1^{**})}$$

As seen from Fig. 4, with an increase in the injection-suction intensity the law of friction at the surface of such a plate grows, and after the parameter b reaches the critical value ($b_{cr} = 5.1$) it remains constant.

Theoretical Model of Flow. Theoretical studies made on perforated injection [1] showed that the velocity profiles, total friction, and heat exchange at such a plate differ little from their values at a fully permeable surface if the degree of perforation is greater than 1%.

Therefore, for the case when the area of the injection openings and the area of the suction openings in the plate are separately greater than 1% one can assume in a first approximation that injection and suction of gas exist simultaneously over the entire surface.

Then the total friction at such a plate can be written in the form

$$\tau_{\pm}(F_+ + F_-) = \tau_+ F_+ + \tau_- F_- \quad (1)$$

$$\tau_{\pm} = \frac{\tau_+ F_+ + \tau_- F_-}{F_+ + F_-} \quad (2)$$

When the areas of injection and suction are equal, we obtain

$$\tau_{\pm} = \frac{\tau_+ + \tau_-}{2} \quad (3)$$

or (3) can be rewritten as

$$\bar{c}_{f_{\pm}} = \frac{1}{2}(\bar{c}_{f_+} + \bar{c}_{f_-}) \quad (4)$$

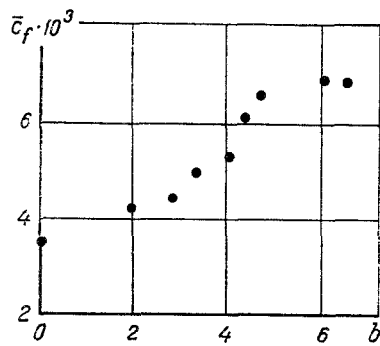


Fig. 3

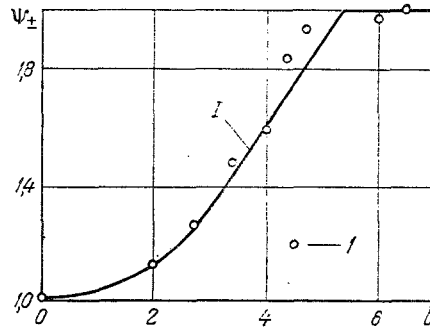


Fig. 4

Fig. 3. Average coefficients of friction at plate with simultaneous injection and suction of air.

Fig. 4. Relative coefficients of friction at plate with simultaneous injection and suction of air: I) calculation by Eq. (7); 1) experimental results.

Dividing the left and right sides of (4) by \bar{c}_{f_0} , we obtain

$$\Psi_{\pm} = \frac{\Psi_+ + \Psi_-}{2}, \quad (5)$$

where \bar{c}_{f_0} is the coefficient of friction at an impermeable plate.

We make the assumption that the friction laws Ψ_+ and Ψ_- at a plate with simultaneous injection and suction remain the same as with only injection and only suction separately. Using the equations from [2] for the determination of Ψ_+ and Ψ_- with separate uniform injection and suction,

$$\Psi_+ = \left(1 - \frac{b}{b_{cr}}\right)^2, \quad \Psi_- = \left(1 + \frac{b}{b_{cr}}\right)^2, \quad (6)$$

one can reduce (5) to the form (for $b_+ = b_-$)

$$\Psi_{\pm} = 1 + \left(\frac{b}{b_{cr}}\right)^2. \quad (7)$$

The curve based on Eq. (7) is plotted with a solid line in Fig. 4. In our case $b_{cr} = 5.1$ [2]. It is seen from Fig. 4 that the experiment satisfactorily confirms the correctness of the use of Eq. (7) for calculating the friction at a surface with simultaneous injection and suction.

In a first approximation we will assume that the velocity profile at a plate with injection-suction can be represented as the half-sum of the profiles at this plate with separate injection and suction:

$$\omega_{\pm} = \frac{\omega_+ + \omega_-}{2}. \quad (8)$$

Equations for the velocity profiles with separate uniform injection and suction at a plate are obtained in [2]:

with injection

$$\omega_+ = \left(1 - \frac{b_+}{b_{cr}}\right) \omega_0 + \frac{b_+}{b_{cr}} \omega_0^2, \quad (9)$$

with suction

$$\omega_- = \left(1 + \frac{b_-}{b_{cr}}\right) \omega_0 - \frac{b_-}{b_{cr}} \omega_0^2. \quad (10)$$

Here ω_0 is the velocity profile at an impermeable plate.

With simultaneous injection-suction of gas at the surface of the plate one can take the profile at an impermeable plate (ω_0) as the initial profile for the injection of gas. Then for the simultaneous suction of gas the initial profile, in all probability, can be identified with the profile which is obtained with the injection of gas ($\omega_{0-} = \omega_+$).

With allowance for these assumptions we obtain the following equation for the velocity profile at the surface of a plate with simultaneous injection-suction of gas:

$$\omega_{\pm} = \frac{1}{2} \left[\left(1 - \frac{b}{b_{cr}} \right) \omega_0 + \frac{b}{b_{cr}} \omega_0^2 \right] \left[2 + \frac{b}{b_{cr}} - \frac{b}{b_{cr}} \left(1 - \frac{b}{b_{cr}} \right) \omega_0 - \left(\frac{b}{b_{cr}} \right)^2 \omega_0^2 \right]. \quad (11)$$

For critical injection-suction, when $b = b_{cr}$, we obtain

$$\omega_{\pm cr} = \frac{3\omega_0^2 - \omega_0^4}{2} \quad (12)$$

Equations (11) and (12) are compared with experimental data in Fig. 2. One can note that there is satisfactory correspondence between the calculated profiles and the experimental data. Some divergence of the profiles is observed at the outer limit of the boundary layer.

NOTATION

\bar{j}_+ , \bar{j}_- , relative mass velocities of injected and sucked gas, respectively; δ_1^{**} , δ_2^{**} , thicknesses of momentum loss at start and end of perforated section, respectively, m; u , stream velocity, m/sec; \bar{c}_f , average coefficient of friction; b_+ , b_- , permeability parameters for injection and suction, respectively; $Re_1^{**} = u_0 \delta_1^{**} / \nu$, $Re_2^{**} = u_0 \delta_2^{**} / \nu$, Reynolds numbers at start and end of perforated section, respectively; $\Psi_+ = c_{f+} / c_{f_0}$, $\Psi_- = c_{f-} / c_{f_0}$, relative friction laws with injection and suction; $\omega = u / u_0$, relative velocity.

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INVESTIGATION OF THE HYDRODYNAMIC CONDITIONS OF JET HEAT TRANSFER

B. P. Zhilkin and N. I. Syromyatnikov

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An impact jet model that can be used to explain the regularities of heat transfer is proposed.

The impact jet model which can best be used to analyze heat transfer to the real stress structure is apparently that in [1]. Three characteristic domains are isolated in this model: potential flow, external viscous mixing, and near-wall boundary layer of the obstacle. The authors did not determine the neighborhood of the stagnation point with a ratio between the radius r starting therefrom and the hole diameter d varying within the range $0 \leq r/d \leq 0.18$. The presence of a local maximum heat-emission coefficient at $r/d = 2.5$ is explained within the framework of this model by the highest turbulence level in this zone due to emergence of the viscous mixing domain on the obstacle surface; then the heat-transfer intensity drops because of the growth of the turbulent boundary layer and the diminution in the flow velocity of the gas film because of spreading.

However, it was not taken into account in the model [1] that centrifugal force, whose effect under definite conditions can result in the formation of spiral vortices [2, 3], i.e.,

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