FRICTION ON A PLATE IN THE NEIGHBORHOOD OF THE STAGNATION LINE OF A PLANE TURBULENT JET

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Results are presented of an investigation and comparison of local values of the surface friction coefficient for the interaction of a plane turbulent jet and a plate.

A numerical analysis of the flow near the stagnation point by using modern turbulence models shows [1-3] that the growth of free-stream turbulence results in significant intensification of the heat transfer and, to a lesser degree, exerts influence on the surface friction stress. This result is confirmed well by measurements of local heat-elimination coefficients [4]. Existing test data on friction are limited and do not permit giving a quantitative estimate of the influence of turbulence on friction [5, 6]. Moreover, the admissibility of using thermal friction stress sensors under conditions where the analogy between the transport of heat transfer and friction is not satisfied [6] raises doubts.

It follows from the Blasius solution for a longitudinally streamlined plate ($\varphi=0°$) that the local tangential friction stress is [7]

$$\tau_w = F''(0)\mu W_m \sqrt{\frac{W_m}{\nu x}} = a\mu W_m \sqrt{\frac{W_m}{\nu x}}, \tag{1}$$

where $F''(0) = a = 0.332$. Transforming (1), we have

$$c_f' = \frac{\tau_w}{\frac{\rho W_m^2}{2}} = 2a\,\mathrm{Re}_x^{-0.5}. \tag{2}$$

From the Howarth solution for plane laminar flow near the stagnation line ($\varphi=90°$) the coefficient $F''(0) = a$ in (1) and (2) equals $a = 1.233$ when the influence of the pressure gradient is taken into account.

The Reynolds numbers are small in the neighborhood of the leakage line of a plane turbulent jet, the pressure gradient is negative, and, consequently, it can be expected that the near-wall boundary layer is almost laminar here. The number Re_x (2) can be represented in the form

$$\mathrm{Re}_x = \frac{W_m}{W_\mathrm{B}}\frac{x}{\mathrm{B}}\mathrm{Re}_\mathrm{B}. \tag{3}$$

in the case of a plane turbulent jet impinging on a plate.

Substituting (3) into (2) results in the following dependence for the local friction coefficient:

$$c_f' = \frac{2\tau_w}{\rho W_m^2} = 2a\left(\frac{W_m}{W_\mathrm{B}}\right)^{-0.5}\left(\frac{x}{\mathrm{B}}\right)^{-0.5}\mathrm{Re}_\mathrm{B}^{-0.5}. \tag{4}$$

If τ_w in (4) is referred to the kinetic energy of the jet at the nozzle exit $\rho W_\mathrm{B}^2/2$, we obtain

$$c_f = \frac{2\tau_w}{\rho W_\mathrm{B}^2} = 2a\left(\frac{W_m}{W_\mathrm{B}}\right)^{1.5}\left(\frac{x}{\mathrm{B}}\right)^{-0.5}\mathrm{Re}_\mathrm{B}^{-0.5}. \tag{5}$$

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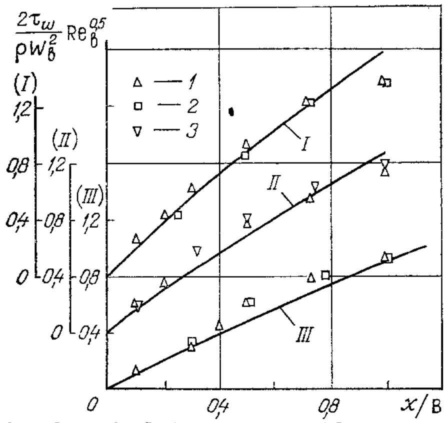

Fig. 1. Change in the local friction coefficients on a wall in the domain of plane turbulent jet interaction with a plate located normally at different distances from the nozzle exit: curves I ($\bar{h}$ = 4), II ($\bar{h}$ = 8), III ($\bar{h}$ = 10) are a computation by means of (5); points are experiment; B = 10 mm; 1) Re_B = 12,000; 2) 18,000; 3) 33,000.

Equations (4) and (5) are valid for 0 < x/B < 1.2. The coefficient a in (4) and (5) takes account of the joint influence of the pressure gradient and the jet turbulence in this case, where they are, in turn, functions of the distance between the nozzle and the plate surface. The dependences to determine a are obtained from an analysis of the test data and have the following form:

for $1.5 < \bar{h} \leqslant 6$

$$a = 0.974\bar{h}^{0.38}, \tag{6}$$

for $\bar{h} > 6$

$$a = 2. \tag{7}$$

The velocity on the outer boundary of the near-wall boundary layer (4), (5) is determined from the following equations [4]:

for $1.5 < \bar{h} \leqslant 6$

$$\frac{W_m}{W_B} = 0.882\bar{h}^{-0.2}\left(\frac{x}{B}\right) - 0.102\,\bar{h}^{-0.4}\left(\frac{x}{B}\right)^3, \tag{8}$$

for $\bar{h} > 6$

$$\frac{W_m}{W_B} = 5.95\bar{h}^{-1.2}\left(\frac{x}{B}\right) - 5.9\bar{h}^{-2.6}\left(\frac{x}{B}\right)^3. \tag{9}$$

A comparison of the results of computing the friction coefficient by means of (5) with test data is performed in Fig. 1. The agreement is satisfactory.

The dependence of the friction coefficient c_f' on the Reynolds number Re_x [7] is represented in Fig. 2. Curve 1 is from Blasius theory for the case of laminar longitudinal flow around a flat plate:

$$\frac{c_f'}{2} = \frac{\tau_w}{\rho W_m^2} = 0.332\mathrm{Re}_x^{-0.5}, \tag{10}$$

curve 2 is from the Prandtl theory for longitudinal turbulent flow around a flat plate:

$$\frac{c_f'}{2} = \frac{\tau_w}{\rho W_m^2} = 0.0296\mathrm{Re}_x^{-0.2}, \tag{11}$$

curve 3 is from Howarth theory for plane flow near the stagnation line at normal impingement of a laminar stream on the plate:

$$\frac{c_f'}{2} = \frac{\tau_w}{\rho W_m^2} = 1.233\mathrm{Re}_x^{-0.5},$$

and the curves 4 ($\bar{h}$ = 4) and 5 ($\bar{h}$ = 8 and 10) are a computation for the case of flow in the neighborhood of the leakage line (0 < x/B < 1.2) of a plane turbulent jet:

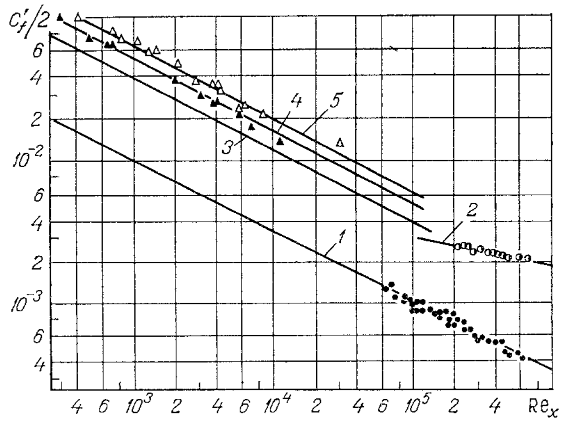

Fig. 2. Surface friction for different plate streamlining conditions: 1, 2) longitudinal laminar (10) and turbulent (11); points are experiment [7]; 3 (12) is normal laminar; 4 (13) and 5 (14) are normal to a plane turbulent jet; points are experiment; B = 10 mm, $Re_B = (1.2\text{–}3.3)\cdot 10^4$.

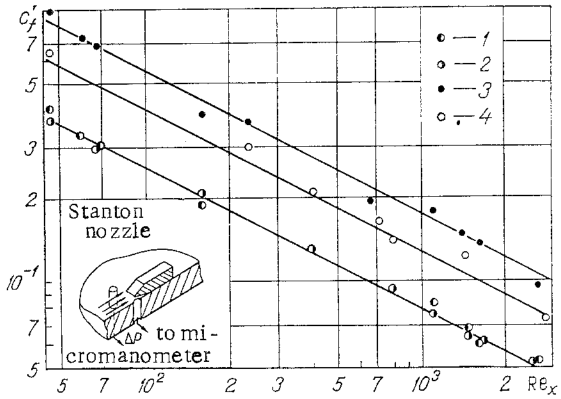

Fig. 3. Comparison between experimental values of the friction coefficient on a plate: $\bar{h} = 8$; $Re_B = (1.2\text{–}3.3)\cdot 10^4$; $Pr \simeq 0.71$; 1, 2, 3) computation using (15), (12), and (16), respectively; 4) measured values.

$$\frac{c_f'}{2} = \frac{\tau_w}{\rho W_m^2} = 1.65 Re_x^{-0.5}, \ \bar{h} = 4, \tag{13}$$

$$\frac{c_f'}{2} = \frac{\tau_w}{\rho W_m^2} = 2 Re_x^{-0.5}, \quad \bar{h} > 6. \tag{14}$$

It follows from an analysis of Fig. 2 that the turbulence of a jet impinging on a plate results in an increase of approximately 30-40% on the local friction coefficient (curve 5).

The surface friction stresses were measured with a Stanton baffle plate (Fig. 3). A baffle plate of the size 2.5 × 2.5 × 0.08 mm, fabricated from a safety razor blade, was mounted with the cutting edge toward the flow above one of the holes (d = 0.3 mm) in the plate. The other hole, at a range of 3 mm from the first, was the static pressure receiver. The dynamic pressure was measured by a Stanton nozzle and recorded by a micromanometer. The tangential friction stresses at the wall were computed by means of the calibrating dependence [8]

$$y_* = -0.23 + 0.618 x_* + 0.0165 x_*^2,$$

where

$$y_* = \lg\left(\frac{\tau_w H^2}{\rho \nu^2}\right); \ x_* = \lg\left(\frac{\Delta P H^2}{\rho \nu^2}\right);$$

H is the height of the baffle plate, which equals half the thickness of the blade, m; $\Delta P = \Delta P' - \Delta P_{st}$; $\Delta P'$ is the pressure drop measured by the Stanton nozzle; and ΔP_{st} is the static pressure drop between the holes.

A nozzle of width B = 10 mm was used in the tests. The Reynolds number compiled from parameters at the nozzle exit is $Re_B = (1.2\text{-}3.3)\cdot 10^4$. The spacing between the obstacle and the nozzle exit varied within $\bar{h}$ = 2-10 limits.

If the surface friction is determined for jet impingement on the plate from the heat flux distribution (Fig. 3, points 1) as

$$\frac{c_f'}{2} = St_x Pr^{2/3}, \tag{15}$$

or from (12) by substitution of the value of the Reynolds number Re_x computed from the near-wall boundary layer parameters for a plane jet (2) impinging on a plate, we obtain lowered values of the friction coefficients as compared with the measured values (4).

If c_f' is determined from the formula

$$\frac{c_f'}{2} = 2.163 St_x Pr^{0.6}, \tag{16}$$

we obtain elevated values of the friction coefficients (points 3). Formula (16) is obtained by substituting the equation

$$St_x = 0.57 Re_x^{-0.5} Pr^{-0.6}$$

into (2).

In conclusion, it can be noted that the Reynolds analogy is not satisfied in the gradient (accelerated) flow domain for turbulent jet interactions with obstacles.

NOTATION

x, longitudinal coordinate; B, nozzle width; h, spacing between the nozzle and the plate; $\bar{h} = h/B$, same unit in dimensionless form; W_m, the velocity on the outer boundary of the near-wall boundary layer; W_B, velocity at the nozzle exit; c_f, surface friction coefficient; τ_w, tangential stress at the wall; $Re_x = W_m x/\nu$, $Re_B = W_B B/\nu$, Reynolds numbers; $St_x = \alpha/c_p \rho W_m$, Stanton number; Pr, Prandtl numer; ρ, density; c_p, specific heat; ν, kinematic viscosity.

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