EFFECT OF BLOWING AND SUCTION ON CHARACTERISTICS OF THE VISCOUS SUBLAYER IN A TURBULENT FLOW

V. M. Eroshenko, L. I. Zaichik,
A. A. Klimov, V. I. Kondrat'ev,
and V. A. Pershukov

UDC 532.526

The effect of blowing and suction on characteristics of a viscous sublayer is studied theoretically and experimentally.

Despite the element of arbitrariness in subdividing turbulent boundary-layer flow into a viscous sublayer and a turbulent core, such an approach is widely used within the framework of two-layer models of turbulence. To determine the effect of external perturbing factors (pressure gradient, blowing, suction) on characteristics of the viscous sublayer, investigators have proposed several hypotheses based on fixing various parameters at the boundary of the viscous sublayer: the Reynolds numbers Re_1 [1] and Re_2 [2], and the velocity $u_{\delta+}$ [1, 3, 4]. The hypotheses advanced in [5, 6] are equivalent to the condition $Re_2 = \text{const}$ [2]. In analyzing the effect of transverse mass flow on the viscous layer in [3, 7], it was held that suction must increase — and blowing must decrease — the stability of the laminar section near the wall. In connection with this assertion, the Reynolds number Re_1 should increase with suction and decrease with blowing. Such a character of dependence of the Reynolds number Re_1 on the rate of transverse mass flow Re_V is regarded in these studies as confirmation of the correctness of the chosen hypothesis for calculation of the characteristics of the viscous sublayer. To check the validity of different hypotheses, the present work theoretically and experimentally studies the effect of suction and blowing on the stability criterion Re_1 and other characteristics of the viscous sublayer.

1. As a model of flow in the viscous sublayer, we will use generalized Couette flow with a constant transverse velocity. The profile of axial velocity is described by the expression

$$\bar{u} = \frac{\exp(\mathrm{Re}_v \bar{y}) - 1}{\exp(\mathrm{Re}_v) - 1} \tag{1}$$

or, in universal coordinates, $u_+ = [\exp(V_+ y_+) - 1]/V_+$.

The parameters of the viscous sublayer δ and u_δ were found with the assumption that the number Re_1 is the maximum possible value of the Reynolds number at which monotonic damping of random perturbations can occur. Thus, Re_1 coincides with the critical Reynolds number Re_{1cr}, which can be determined from an energy analysis of flow stability [8].

The presence of transverse velocity in the flow does not affect the form of the equation for perturbations, which coincides with the usual Orr equation for plane-parallel flow [9]:

$$\left(\frac{d^2}{d\bar{y}^2} - k^2\right)\left[\frac{1}{\bar{u}'}\left(\frac{d^2}{d\bar{y}^2} - k^2\right)^2 \varphi + ik\,\mathrm{Re}_1 \cos\theta \left(\varphi' + \frac{\bar{u}''}{2\bar{u}'}\varphi\right)\right] + \frac{k^2 \mathrm{Re}_1^2 \sin^2\theta\, \bar{u}' \varphi}{4} = 0. \tag{2}$$

The boundary conditions for Eq. (2) were assigned in the form

$$\varphi = \varphi' = \varphi^{\mathrm{IV}} - 2k^2\varphi'' = 0 \text{ at } \bar{y} = 0.1. \tag{3}$$

The eigenvalue problem (2)-(3) was solved by the method of differential trial run [9]. The results of calculation of the critical energy Reynolds number Re_{1cr} in relation to the value of the blowing or suction parameter Re_V are shown in Fig. 1. Analysis of Eq. (2) with

---

G. M. Krizhizhanovskii State Energy Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 45, No. 2, pp. 209-213, August, 1983. Original article submitted April 5, 1982.

0022-0841/83/4502-0858$07.50

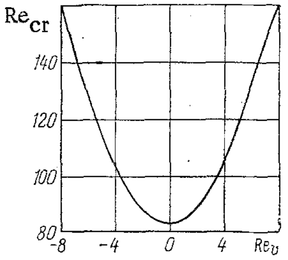

Fig. 1. Dependence of the critical energy Reynolds number on blowing (suction) intensity.

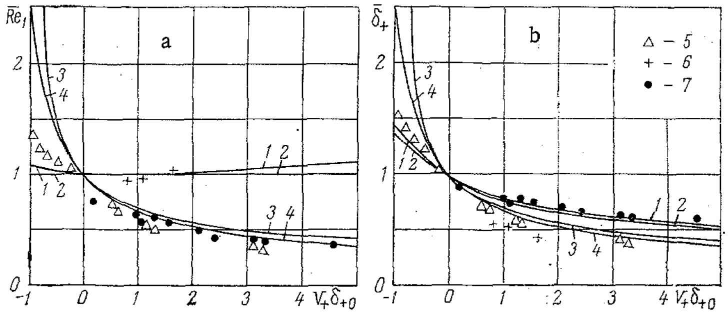

Fig. 2. Effect of blowing (suction) on the Reynolds number (a) and the thickness (b) of the viscous sublayer.

allowance for the velocity distribution (1) shows that the effect of transverse mass flow on stability proves to be symmetrical relative to the sign of Re_v. It can be seen from Fig. 1 that the value of Re_{1cr} increases with both blowing and suction.

Using the relation obtained $Re_{1cr}(Re_v)$ and the relations $Re_{1cr} = u_{\delta+}\delta_+$, $Re_v = V_+\delta_+$, $u_{\delta+} = [\exp(V_+\delta_+) - 1]/V_+$, we determined the effect of the parameter $V_+\delta_{+0}$ on the relative values of the Reynolds number of the viscous sublayer $\overline{Re}_1 = Re_1/Re_{10}$ and the thickness of the sublayer $\bar{\delta}_+ = \delta_+/\delta_{+0}$ (curves 1 in Fig. 2a and b), where Re_{10} and δ_{+0} are the corresponding values on an impermeable surface.

Figure 2 also shows calculated curves of $\overline{Re}_1$ and $\bar{\delta}_+$ obtained by using the hypothesis Re_1 = const (curves 2), Re_2 = const (3), and $u_{\delta+}$ = const (4). It should be noted that, in the chosen variables, the relations $\overline{Re}_1(V_+\delta_{+0})$ and $\bar{\delta}_+(V_+\delta_{+0})$ are not affected by the specific value of δ_{+0}, which is different in works by different authors. It can be seen from the figure that, despite the difference in the behavior of the dependence of the Reynolds number of the viscous sublayer on the intensity of the transverse mass flow, all of the hypotheses used give qualitatively the same results for the relative thickness of the viscous sublayer in blowing and lead to a decrease in $\bar{\delta}_+$. In the case of suction, it follows from all four hypotheses that $\bar{\delta}_+$ should increase. However, the hypothesis Re_2 = const is valid at $|V_+\delta_{+0}| < 0.733$, while the hypothesis $u\delta_+$ = const is valid at $|V_+\delta_{+0}| < 1$; given large values of the parameter $|V_+\delta_{+0}|$ neither hypothesis gives the actual value for the thickness of the viscous sublayer.

2. The experimental study of the turbulent boundary layer was conducted on a gasdynamic unit equipped with a hot-wire anemometer and an interferometer [10, 11]. The working section was a channel of square cross section. A plate with a porosity of ≈65-70% was installed in the lower wall of the channel. The experiment was conducted under isothermal conditions. The longitudinal pressure gradient created in the external flow by the blowing was eliminated by regulating the position of the flexible upper wall. The velocity distribution in the boundary layer was measured with the anemometer, and we took the effect of the wall on the anemometer readings in the boundary region into account.

The thickness of the viscous sublayer was determined as the distance from the wall at which the velocity distribution deviated 10% from exponential relation (1). As can be seen

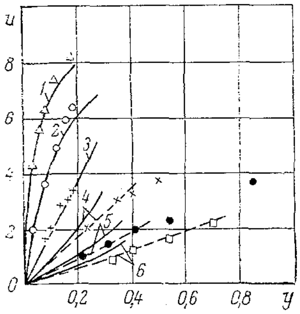

Fig. 3. Velocity distribution near the wall: 1) $(V/u_e)\cdot 10^2 = -2.6$; 2) -1.1; 3) 0; 4) 0.48; 5) 0.79; 6) 1.22. u, m/sec, y, $m \cdot 10^{-3}$.

from Fig. 3 (dashed lines), there is a linear velocity distribution at a sufficiently large distance from the wall in the case of blowing. The linear character of the velocity and concentration profiles in the boundary region in blowing was noted earlier in the works [7, 12].

Figure 2a and b shows the relative Reynolds numbers $\overline{Re}_1$ plotted from the empirically determined values of thickness and velocity at the boundary of the viscous sublayer. Also shown is the thickness of the viscous sublayer δ_+ (points 5). It can be seen that, in the case of suction, both the thickness of the viscous sublayer δ_+ and its Reynolds number Re_1 increase. The experimental data for suction agrees satisfactorily with the results of calculations obtained on the basis of energy analysis of the stability of the viscous sublayer. Figure 2 also shows experimental data for blowing obtained by the method of tracing a flow of particles [13] (points 6) and by the interferometric method [11] (7). The data shown does not allow a preference to be expressed for any one of the hypotheses examined for blowing.

NOTATION

δ, thickness of the viscous sublayer; u_δ, velocity at the boundary of the viscous sublayer; u_e, velocity at the boundary of the boundary layer; V, blowing or suction velocity ($V > 0$ in blowing); $u_* = \sqrt{\tau_w/\rho}$, dynamic velocity; τ, shear stress; k, wave number; θ, angle between flow velocity vector and wave vector. Dimensionless complexes: $\delta_+ = \delta u_*/\nu$; $u_{\delta+} = u_\delta/u_*$; $V_* = V/u_*$; $Re_1 = u_\delta\delta/\nu$; $Re_2 = \sqrt{\tau_{\delta+}\delta_+}$; $Re_V = V\delta/\nu$; $\bar{y} = y/\delta$; $\bar{u} = u_x/u_\delta$; $\overline{Re}_1 = Re_1/Re_{10}$; $\bar{\delta}_+ = \delta_+/\delta_{+0}$. Indices: +, w, δ, and 0, parameters in universal coordinates, on the wall, on the boundary of the viscous sublayer, and for an impermeable wall.

LITERATURE CITED

1. M. W. Rubesin, "An analytical estimation of the effect of transpiration cooling on the heat-transfer and skin-friction characteristics of a compressible turbulent boundary layer," NACA TN, No. 3341 (1954).
2. E. R. van Drist, "On the aerodynamic heating of blunt bodies," ZAMP, 9b, No. 5/6, 235-248 (1958).
3. V. P. Motulevich, "Turbulent heat- and mass-transfer on a plate in the porous suction and blowing of different gases," Inzh.-Fiz. Zh., 6, No. 1, 3-13 (1963).
4. W. H. Dorrans, "The effect of mass transfer on the compressible turbulent boundary-layer skin friction and heat transfer," J. Aeronaut. Sci., 23, No. 3, 283-284 (1956).
5. M. M. Gurfink. "Strong blowing into a turbulent boundary layer," Mekhanika, No. 5, 152-153 (1965).
6. I. P. Ginzburg and N. S. Krest'yaninova, "Turbulent boundary layer of an incompressible liquid on a plate with mass intake," Inzh.-Fiz. Zh., 9, No. 4, 444-450 (1965).
7. A. L. Ermakov, V. M. Eroshenko, Yu. N. Terent'ev, and L. S. Yanovskii, "Study of a laminar sublayer on permeable surfaces with blowing," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 5, 66-72 (1977).
8. S. S. Kutateladze, Boundary-layer Turbulence [in Russian], Novosibirsk, Nauka (1973).
9. M. A. Gol'dshtik and V. N. Shtern, Gasdynamic Stability and Turbulence [in Russian], Nauka, Novosibirsk (1977).
10. V. M. Eroshenko, M. G. Morozov, V. P. Motulevich, et al., "Gasdynamic unit with an IT-14 interferometer," in: Physical Gasdynamics [in Russian], Izd. Akad. Nauk SSSR, Moscow (1961), pp. 51-59.

11. V. M. Eroshenko, A. L. Ermakov, A. A. Klimov, and Yu. N. Terent'ev, "Interferometric and thermoanemometric methods of studying binary boundary layers," in: Thermophysical Properties and Gasdynamics of High-Temperature Media [in Russian], Nauka, Moscow (1972), pp. 70-84.
12. V. M. Polyaev, I. V. Bashmakov, D. I. Vlasov, and I. M. Gerasimov, "Effect of blowing on flow near the wall in a turbulent boundary layer on a porous plate," in: Heat- and Mass-Transfer [in Russian], Vol. 1, Pt. 2 (1972), pp. 92-100.
13. B. P. Mironov and P. P. Lugovskoi, "Study of flow in the boundary region of a turbulent boundary layer with blowing," Inzh.-Fiz. Zh., 22, No. 3, 460-465 (1972).

WAVE CHARACTERISTICS OF FALLING FILM FLOWS IN A CO-CURRENT GAS FLOW

M. N. Chepurnoi, V. É. Shnaider,
I. M. Fedotkin, and V. S. Lipsman

UDC 532.5.536.24

Data is presented from measurements of the frequencies, lengths, amplitudes, and phase velocities of waves in a falling annular flow of water and air in a pipe.

Film-type heat- and mass-transfer apparatus have come into wide use in different sectors of industry. The rate of production processes in such apparatus is determined to a large extent by the condition of the phase boundary. Studies of the structures of waves on the film surface [1-5] have shown that there are two classes of waves: large waves, which transport most of the liquid, and small waves, which overlay a thin layer of liquid (ripples). The wave parameters of two-phase film flows was studied in [1-5, 6, 7]. These studies pertain mainly to two-phase annular flows with thin films of liquids ($Re_q < 4000$) and high gas velocities ($v_g > 20$ m/sec), i.e., for flows in which drop removal from the surface of the liquid film is seen [2].

Presented below are results of experimental studies of the wave characteristics of liquid films flowing in a 30-mm-diameter pipe in a co-current gas flow. The flow-rate characteristics of the films were varied within the range $3500 < Re_q < 20{,}000$, while those of the gas were varied within the range $8000 < Re_g < 41{,}000$. The local characteristics of the film flow were measured by electrical methods [8, 9] and recorded in the form of oscillograms by recording devices. The length of the test section was 2400 mm. The measurements were made at five points of the test section. The length of travel of the film to the measurement points was 250, 500, 750, 1000, and 1625 mm. The velocity of the waves and the profile of the film surface were found from the known distance between the transducers and the time of passage of the waves over this distance. The experimental unit, measurement methodology, and method of analysis of the test data were detailed in [9].

The measurements showed that, as in [1, 3], the wave parameters of the liquid film are of a statistical nature, and the law of distribution of these quantities is close to a normal law. The thickness of the film and the frequency, for prescribed flow-rate characteristics, nearly stabilize by the time the flow travels 750 mm into the pipe, while the amplitude increases somewhat with an increase in the length of film travel. The mean values of wave frequency on the stabilized section are shown in Fig. 1 as a function of the rate parameters of the flow. Here, the dimensionless frequency of the waves

$$f^* = f\sigma(\rho_q g \nu_q)^{-1}. \tag{1}$$

It is apparent from the figure that the wave frequency is affected in almost equal measure by the rates of flow of the liquid and gas, with the liquid flow rate having the opposite effect. The latter is due to the fact that an increase in liquid flow rate is accompanied by an in-

---

Vinnitsa Polytechnic Institute. Kiev Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 45, No. 2, pp. 213-217, August, 1983. Original article submitted March 19, 1982.

0022-0841/83/4502-0861$07.50