A STUDY OF THE FLOW PATTERN ON THE WALL SIDE OF A TURBULENT BOUNDARY LAYER WITH INJECTION AND A POSITIVE PRESSURE GRADIENT

B. P. Mironov and P. P. Lugovskii

UDC 532.526.4

Results are shown of an experimental study dealing with the flow pattern on the wall side of a turbulent boundary layer with injection and a positive longitudinal pressure gradient.

In [1] the authors have derived a theoretical and an empirical relation between the critical value of the injection rate and the positive longitudinal pressure gradient. The theoretical relation is based on the premise that at some time $C_f = 0$, while b_{cr} is determined experimentally with an indicator instrument and a reading of the time at which the concentration of the injected liquid at the wall has almost reached 100%. According to these tests, an increase in the positive longitudinal pressure gradient leads to a prior concentrative displacement. On the other hand, special measurements under such conditions [2] have shown that the concentration profile of the displacement zone in a turbulent boundary layer does not depend on the pressure gradient. Only the injection rate affects the concentration profile. Thus, two contradictory trends are noted simultaneously. In order to explain this phenomenon, a special study was made of the flow pattern in a boundary layer with injection and a positive pressure gradient. The tests were performed in a hydraulic apparatus built with the same components as in [3]. The porous plate was wider than in [3], however, namely 200 × 15 mm in size. In order to lower the temperature level and to provide for a smoother regulation of the flow rate in the mainstream, water was pumped into the active zone from a constant-level tank through a large buffer chamber. The sublayer at the wall was observed with an indicator instrument and also visually by tracing a stream of fine aluminum particles of the 5-20 μ size. The flow pattern was photographed with a high-speed camera at 1000 frames per second. In addition, photographs were taken with a high-speed camera at 48 frames per second under continuous illumination, and also the velocity field was recorded using a model "Zenith-E" camera with a mirror-type view finder and a triple flash. Each frame yielded here some information about the flow pattern in the boundary layer.

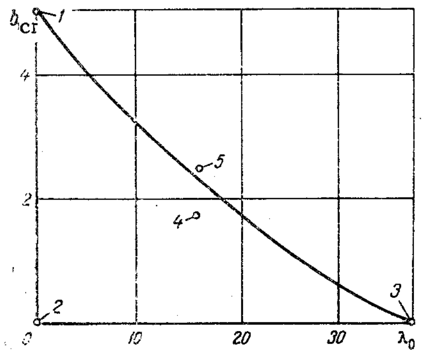

Fig. 1. Critical injection rate as a function of the positive longitudinal pressure gradient, for Re** = 4000: points 1-5 indicate the values of b and λ_0.

The critical value of the injection rate is shown in Fig. 1 as a function of the positive pressure gradient, according to [1]. Points 1-5 indicate the values of the injection rate and of the pressure gradient ($Re^{**} = 4 \cdot 10^3$) at which the flow pattern in the sublayer was studied.

Let us first examine the flow pattern in two extreme cases: 1) $b = b_{cr}$ and $\lambda_0 = 0$, and 2) $b = 0$ and $\lambda_0 = \lambda_{0,cr}$. For comparison, in Fig. 2a are shown photographs† depicting the $b = 0$ and $\lambda_0 = 0$ condition (item 2). According to Fig. 2b (item 1), during injection at the critical rate the streamlines bend strongly and transverse velocity fluctuations increase, but no backstream is noted in the boundary layer. The indicator method of testing [2] under the same conditions has revealed a thin layer of injected tracer liquid at the

---

†In Fig. 2 are shown the copies of negatives.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 25, No. 2, pp. 261-264, August, 1973. Original article submitted January 12, 1973.

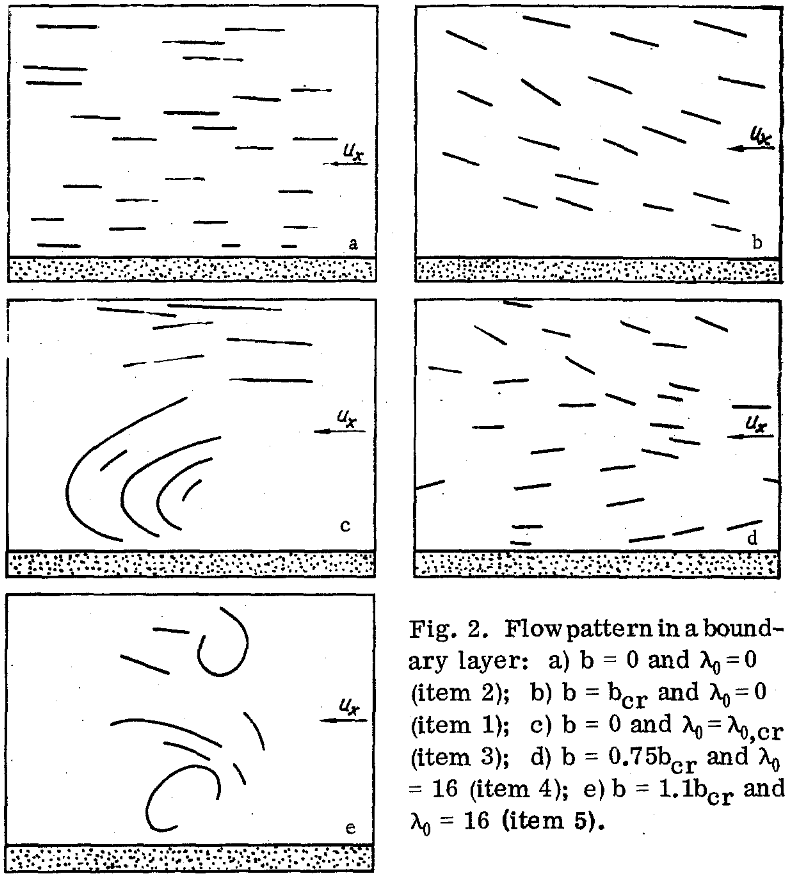

Fig. 2. Flow pattern in a boundary layer: a) $b = 0$ and $\lambda_0 = 0$ (item 2); b) $b = b_{cr}$ and $\lambda_0 = 0$ (item 1); c) $b = 0$ and $\lambda_0 = \lambda_{0,cr}$ (item 3); d) $b = 0.75b_{cr}$ and $\lambda_0 = 16$ (item 4); e) $b = 1.1b_{cr}$ and $\lambda_0 = 16$ (item 5).

surface of the porous plate, as evidence of an almost 100% concentration of injected liquid there. In Fig. 2c we see the flow pattern when $b = 0$ and $\lambda_0 = \lambda_{0,cr}$ (item 3). Eddies are distinctly noticeable here, characterizing the separation zone during diffusive flow. An analysis of the film strip shot with a high-speed camera* leads one to conclude that these eddies form in the immediate vicinity of the wall. This is evident in Fig. 2c.

Let us now examine the flow pattern within some intermediate range of λ_0 values. In Fig. 2d (item 4) we see that at $\lambda_0 = 16$ and $b = 0.75b_{cr}$ no backstream has yet appeared in the boundary layer.

A further increase in the injection rate to $b = 1.1b_{cr}$ (item 5) results in the appearance of regular backstreams in the boundary layer (Fig. 2e), typical of a flow near the separation point without injection. An analysis of our data for $b = 1.1b_{cr}$ and $\lambda_0 = 16$ has established that the backstreams cover an increasingly wider portion of the boundary layer. This is explained by the injection. An evidence of it is the thin layer of injected liquid which appears under these conditions at the surface of a porous plate and which has been recorded by the indicator method in [3]. All this confirms that the eddies generated under conditions of a positive pressure gradient and critical injection do not reach the wall, at least when the diffusion rate in the channel is very low. A similar pattern is noted when $\lambda_0 = 9$.

The presence of backstreams near a porous wall in a boundary layer with $b \approx b_{cr}$ and $\lambda_0 \neq \lambda_{0,cr}$ indicates that the gradient $\partial u_x/\partial y$ can become negative in the immediate vicinity of the wall. This, in turn, indicates that the instantaneous value of the friction coefficient may become zero. The flow pattern revealed here explains the causes of a prior concentrative displacement under a positive pressure gradient, as has been discussed earlier. The resulting dynamic displacement creates favorable conditions for a subsequent concentrative displacement.

NOTATION

C_f	is the friction coefficient;
$b = 2\rho_w w_w/\rho_0 u_0 C_{f0}$	is the wall permeability;

---

*This film strip was shown at the All-Union Conference on Heat and Mass Transfer in Minsk (1972).

ρ	is the density of the medium;
C_{f0}	is the friction coefficient at a plane plate in a homogeneous isothermal stream;
$\lambda_0 = -(2\delta/C_{f0}u_0)(du_0/dx)$	is the form factor referred to C_{f0}.

Subscripts

w	refers to the wall;
0	refers to the outer edge of the boundary layer or to "standard" conditions.

LITERATURE CITED

1. P. P. Lugovskii and B. P. Mironov, Inzh. Fiz. Zh., 13, No. 14 (1967).
2. P. P. Lugovskii and B. P. Mironov, "Some characteristics of a turbulent boundary layer with injection," in: Turbulent Flow [in Russian], Izd. Nauka (1970).
3. A. I. Leont'ev, B. P. Mironov, and P. P. Lugovskii, Inzh. Fiz. Zh., 10, No. 4 (1966).