EXPERIMENTAL DETERMINATION OF CRITICAL INJECTION ON A POROUS PLATE

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Experimental data are presented on determination of the critical injection parameter on a porous plate with turbulent boundary layer. The test results give satisfactory confirmation of the theoretical results of [1].

In wall boundary layers with transverse mass flow, e.g., in injection of gas through a porous wall, the situation may be encountered where the main fluid flow is pushed completely away from the wall. In this event friction at the wall falls to zero, heat transfer between the main stream and the wall becomes minimal, and the concentration of the injected fluid at the wall reaches 100%. For these reasons, at this critical injection rate we may achieve the most effective protection of the surface from an undesirable influence associated with the main stream.

The matter of critical injection is a fundamental one in boundary layer theory with cross mass flow, and the study of the conditions in which such injection appears is of great theoretical and practical interest. For a turbulent boundary layer the conditions for onset of critical injection were first obtained in asymptotic theory [1].

We shall examine the dynamic turbulent boundary layer. Existing test data on the influence of injection on friction confirm the theoretical conclusions of [1]. However, these tests were carried out, as a rule, at values of the injection parameter, b, appreciably less than critical [2–4]. The value of b is determined from the formula

$$b = \bar{j}_w \frac{2}{Cf_0}. \tag{1}$$

The friction coefficient for turbulent conditions is determined from the formula

$$\frac{Cf_0}{2} = \frac{B}{(Re^{**})^n} = \frac{0.0126}{(Re^{**})^{0.25}},$$

where $Re^{**} = W_0 \delta_1^{**}/\nu_0$; δ_1^{**} is the momentum thickness at the porous plate; ν_0 is the kinematic viscosity at the edge of the boundary layer.

Hacker [5] has measured the friction on the wall of a total pressure tube over a wide range of variation of mass flow rate of injected fluid. However, the negative values of friction coefficient that he obtained in the maximum air injection rate regime do not allow a reliable determination of the critical injection parameter.

In the present work an attempt has been made to evaluate experimentally the critical injection parameter on the basis of the following visual method. The basic flow liquid was a hydrochloric acid solution,

into which, through a porous plate, was injected a weak alkaline solution colored crimson with phenolphthalein. When critical injection was attained, a visible film of injected liquid was clearly seen on the porous plate. With injection parameters less than critical, the alkali was completely neutralized at the wall, and the injected liquid was decolorized. A diagrammatic layout of the equipment is shown in Fig. 1.

The porous surface was made up of 25 layers of Kapron [nylon] fabric, coiled into a tube 16 mm in diameter, with a longitudinal slit 180 mm long and 4 mm wide. The uniformity of injection was quite good. Ahead of the porous plate there was a fore-section 160 mm long. The working channel was of transparent plastic, and had a cross section of 30 × 30 mm. The flow was equilibrated by means of a convergent section at the inlet to the working section. The flow rates of injected liquid and main stream required to determine the injection parameter (1) were measured with calibrated measuring equipment. The fact that the main stream moved in a closed circuit enabled a constant concentration field to be maintained at the inlet to the working section.

The parameter b contains the friction coefficient Cf_0, which is a function of Re^{**}. To determine Re^{**} special measurements of velocity profile were conducted at distances $X_1 = 90$ and 130 mm from the front of the porous plate (250 and 290 mm from the beginning of the working section) at various Reynolds numbers and with and without injection.

The velocity was measured with a miniature Pitot tube with nose interior measuring 0.35×2 mm. Measurements on an impermeable plate showed that the values of momentum thickness δ^{**} agreed well with theoretical values (deviations of 2–3%) over the whole range of main stream velocity ($W_0 = 1.5$–2.2 m/sec). The theoretical value of δ^{**} was found from the momentum equation:

$$\frac{d\,Re^{**}}{d\,Re_{X_1}} = \frac{Cf_0}{2},$$

$$\delta^{**} = \frac{\nu_0}{W_0}[(1+m)\,B\,Re_{X_1} + (Re_0^{**})^{1+m}]^{\frac{1}{1+m}},$$

$$Re_{X_1} = \frac{W_0 X_1}{\nu_0}; \quad X_1 = 0.09 \text{ and } 0.130 \text{ m}. \tag{2}$$

The value of Re_0^{**} was found from the assumption that in the fore-section of length $X_0 = 160$ mm a laminar boundary layer develops. The butt joint between the porous plate and the fore-section acts as a turbulence generator, because of which a turbulent boundary layer is formed on the porous plate even at values
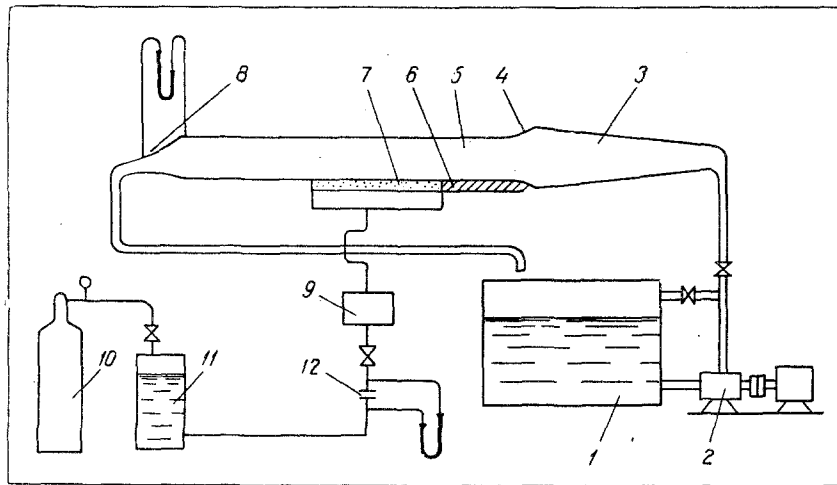
Fig. 1. Layout of test equipment: 1) tank with acid solution; 2) pump; 3) forechamber; 4) convergent section; 5) working section; 6) fore-section; 7) porous specimen; 8) measuring equipment for the main stream; 9) filter; 10) compressed air bottle; 11) tank with solution of alkali and phenolphthalein; 12) measuring equipment for the injected liquid.
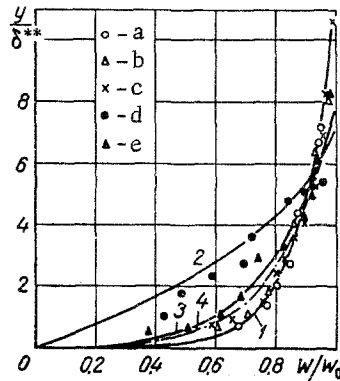

Fig. 2. Velocity profile in the boundary layer with no injection and in the turbulent regime [a) at $Re_X = 4.2 \cdot 10^5$, b) $5 \cdot 10^5$; c) $5.35 \cdot 10^5$; 1) according to the law $W/W_0 = (y/\delta)^{1/7}$], in the laminar regime [d) $Re_X = 1.5 \cdot 10^5$; 2) according to the law $W/W_0 = 2(y/\delta) - 2(y/\delta)^3 + (y/\delta)^4$], and in the presence of critical injection [e) $Re_1^{**} = 1320$, 3 and 4) according to Eq. (3) with $Re_1^{**} = 1300$ and 2600, respectively].
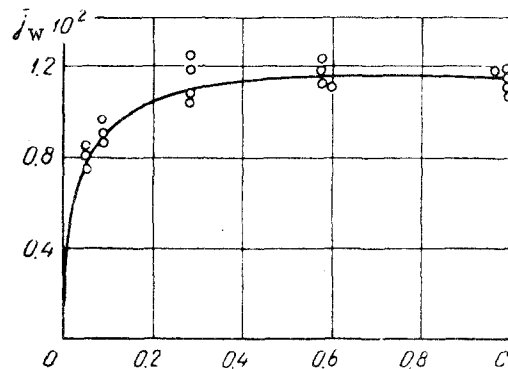

Fig. 3. Influence of acid concentration C (%) at constant alkali concentration on the conditions for appearance of a colored film at the porous surface.

Values of b_{cr} calculated from Re**

W_0, m/sec	1.68	1.84	1.95	2.1
$\bar{j}_W \cdot 10^2$	1.14	1.18	1.14	1.1
Re**	1300	1400	1450	1540
b_{cr}	5.5	5.7	5.6	5.5

of Re_{X_0} less than $3 \cdot 10^5$. This is confirmed by the velocity profile measurements, which are in good agreement with the theoretical "one seventh power law" distribution. It should be noted that the installation of a turbulence generator of height K at the entrance to the working section did not lead to a change in boundary layer thickness at the measured sections, since in our tests the condition [6]

$$KW_0/\nu_0 \geqslant 90$$

was satisfied.

In order to check that the agreement between the experimental and theoretical [according to Eq. (2)] values of δ^{**} did not result from fortuitous choice of the length X_0, supplementary tests were conducted with a laminar boundary layer in a fully laminar stream (Fig. 2).

It may be seen from the graph that the theoretical and experimental values of δ^{**} agreed for this case also. The velocity profiles were also measured with injection, where lift-off of the main stream from the wall was attained. The values of δ_f^{**} for these cases proved to be less than calculated by 30% on the average. At the same time, when expressed in relative coordinates W/W_0, y/δ^{**}, the test points satisfactorily confirmed the theoretical velocity distribution at the separation point, which is given, according to [2], by the formula

$$W/W_0 = \left(1 + 2.5 \sqrt{\frac{Cf_0}{2}} \ln y/\delta \right)^2. \quad (3)$$

Before determining the value of the critical injection parameter b_{cr}, it was necessary to find the ratio of concentrations of acid and alkali which would prove not to have an effect on the results obtained. Figure 3 gives the conditions at which the colored film on the porous plate appeared, for alkali concentration of 0.03%, as a function of acid concentration. For an acid concentration of 0.3% and above, the values of $\bar{j}_W$ remain unchanged. At small acid concentrations, the relation tends to zero, of course, since this corresponds to injection of dye into the boundary layer with neutral liquid. The method of determining the value of b_{cr} was as follows. We first determined the flow condition of the main stream at which the injected liquid was completely neutralized. Then, without changing the injection mass flow rate, the velocity of the main stream was decreased smoothly, until dye did not appear in the pores of the porous specimen. This moment was regarded as being the start of separation; it preceded critical injection, and from it values of $b_{cr\,min}$ were found. With further decrease in velocity of the main stream, a well-defined colored film appeared, having a visible thickness, in contrast

to the previous condition. Values of b_{cr} were also determined in this second regime. In spite of the fact that the accuracy of the results obtained depended appreciably on the experimenter, the difference between $b_{cr\,min}$ and b_{cr} was about 10% in all the tests.

The red film appeared practically at once along the whole length of the porous surface, its color being lighter at the front of the plate and darker at the rear. It was not possible to fix the time of onset of b_{cr} at any section of the plate. From the growth of intensity of film color toward the end of the plate, it may be concluded that the injection at the beginning of the porous section corresponded to the $b_{cr\,min}$ condition, while the injection was somewhat above critical at the end of the section. For this reason it was expedient to determine the b_{cr} values at Re** for the center of the plate, since the injection was closest to critical there. Here it is appropriate to remark that the values of Cf_0 varied insignificantly along the porous plate in our work. For example, the values of Cf_0, and of b_{cr} correspondingly, differed by roughly 15% between the end and the center of the plate.

The basic test data are presented in the table. The quantities b_{cr} were calculated from the test values of Re** at the center of the plate. The values of kinematic viscosity in these calculations were found from tables for aqueous solutions of acid and alkali. The viscosity of the solutions used was practically equal to that of water.

It may be seen from the table that the experimental values of b_{cr} do not differ appreciably. According to [2], the theoretical value of b_{cr}, allowing for finite Reynolds number, is 5.3 at Re** = 1300. In our tests we were not able to detect any influence of Re** on b_{cr}, since the range of variation of Re** was small.

From the above evidence the following main conclusions may be drawn. We have visually confirmed the existence of a flow regime with turbulent boundary layer and injection, where the main flow is almost completely separated from the wall. The concentration of injected liquid at the wall is then close to 100%. The evidence for this is the presence of a colored film on the porous surface at appreciably different concentrations of acid and alkali.

The experimental values of b_{cr} are in satisfactory agreement with theoretical values obtained in asymptotic turbulent boundary layer theory.

NOTATION

$b_{cr} = \bar{j}_W(2/Cf_0)$— critical injection parameter; $\bar{j}_W = \gamma_W W_W/\gamma_0 W_0$— relative mass flow rate of injected liquid; γ_W, γ_0—density of injected liquid and of main stream; W_W, W_0—velocity of injected liquid at wall and of main stream; Cf_0— friction coefficient; δ^{**}—momentum thickness; ν— kinematic viscosity; X_0—length of fore-section with laminar

boundary layer; X_1—abscissa, calculated from beginning of porous plate; K—height of turbulence generator; l—length of porous plate; Re^{**}, Re_{X_1}, Re_{X_0}—Reynolds numbers based on geometrical dimensions; ν—relative friction coefficient; $X = X_0 + X_1$; C—concentration.

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