Technical Notes

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Turbulent Spot Growth in Favorable Pressure Gradients

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Introduction

THE key variable in describing a boundary layer during transition from laminar to turbulent flow is the intermittency. Observed intermittency distributions in a zero pressure gradient boundary layer can be explained on the basis of the theory of turbulent spots,[1,2] with the additional hypothesis of concentrated breakdown.[2] The application of the theory is particularly simple if the spots can be assumed to grow linearly, as they are known to in two-dimensional, zero pressure gradient flow.[3] In other cases, lack of adequate experimental data on spot parameters has often led to ad hoc assumptions, e.g., that the spot grows at a constant angle with the local streamline, irrespective of pressure gradient and streamline divergence.[4] Much interesting work on the structure of turbulent spots in zero pressure gradient flow has been reported[5-7] in recent years, with some data on the effect of Reynolds number and of a mildly favorable pressure gradient.[6] In the present Note, we report experimental results on the *lateral* growth of spots in an extensive series of favorable pressure gradient flows.

Experiments

All experiments were made in a 0.6 m × 0.6 m low-turbulence wind tunnel, on a flat plate mounted horizontally between the top and bottom walls of the tunnel. Pressure gradients were imposed by installing appropriate liners on the top wall. Hot wire measurements were made with a constant temperature set, using 5μm diam. Pt-Rh probes. Mean velocities could also be measured with a flattened pitot of 0.55 mm height. Probes could be traversed both along and across the stream.

Isolated spots could be generated by striking a spark across a 2 mm gap aligned perpendicular to the flow direction, both electrodes being flush with the plate surface. The gap was mounted in a special plug which could be located at any one of 13 sites along the centerline of the 2.13-m long plate. The spark was fired through an induction coil controlled by a Morse key. Studies were also made of turbulent wedges behind an isolated roughness element; this was a 0.5 mm diam pin projecting 3 mm above the surface, with a round head 1.25 mm in diameter

Two pressure gradient liners, designated F1 and F2, respectively, were used; their leading edges were located 26.5 and 45.5 cm, respectively, downstream of the leading edge of the plate. Both liners were such that the freestream velocity varied from a constant value U_1 upstream to a (higher) constant value U_2 downstream. In each case, experiments were made at several tunnel speeds; the corresponding freestream velocity distributions $U(x)$ are shown, along with the results, in Figs. 1 and 2.

Results

Data on the turbulent wedge behind a pin, and the envelope of spot positions from the spark experiments, are collected and presented in Figs. 1 and 2. (The half-width shown in these figures is the average of values on either side.) Both pin and spark data were obtained in the flows F1a, F2a, and F2c. It is seen that in general the wedge is slightly wider than the spot envelope, but the eventual *rate* of growth, as measured by the half-angle α, does not appear to be significantly different whether the agent is a pin or a spark. This conclusion extends earlier results[3,7] on zero pressure gradient flows.

It is also clearly seen from Figs. 1 and 2 that a favorable pressure gradient inhibits spot growth; Wygnanski[6] also reported a low spread angle, $\alpha = 5$ deg, in his single pressure gradient flow, corresponding to a Falkner-Skan parameter $\beta = 0.12$. However, the present data show that the resulting turbulent wedge is not necessarily linear in general, but as pressure gradients decrease downstream the wedge grows rapidly, and tends to become linear again.

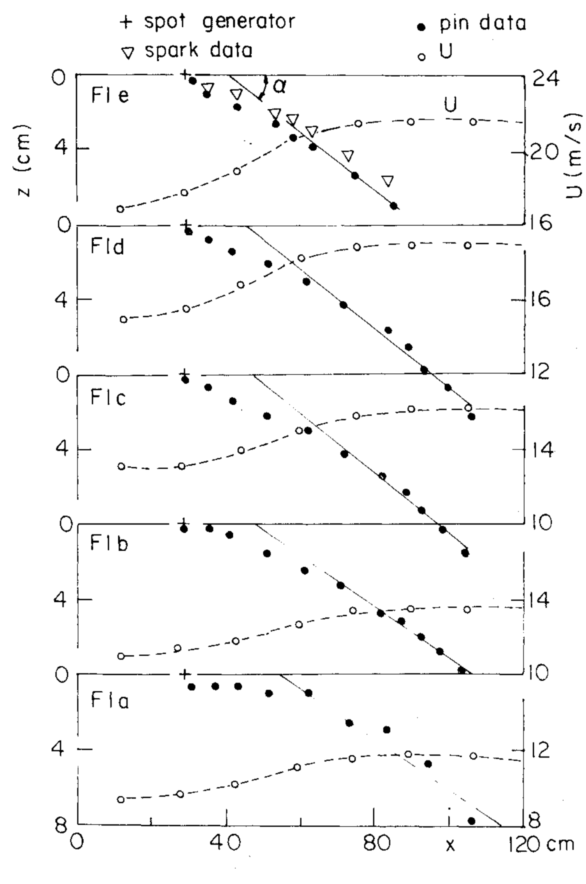

Fig. 1 Spot growth in the flow series F1.

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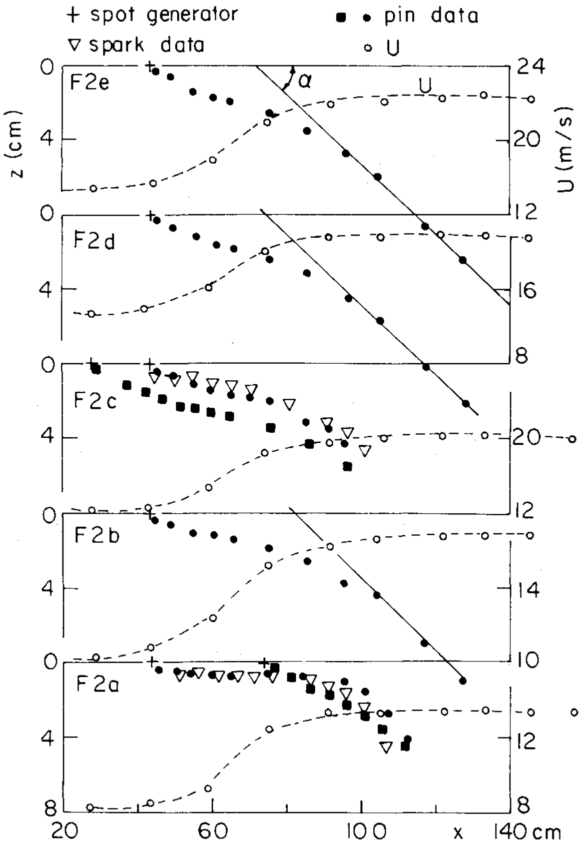

Fig. 2 Spot growth in the flow series F2.

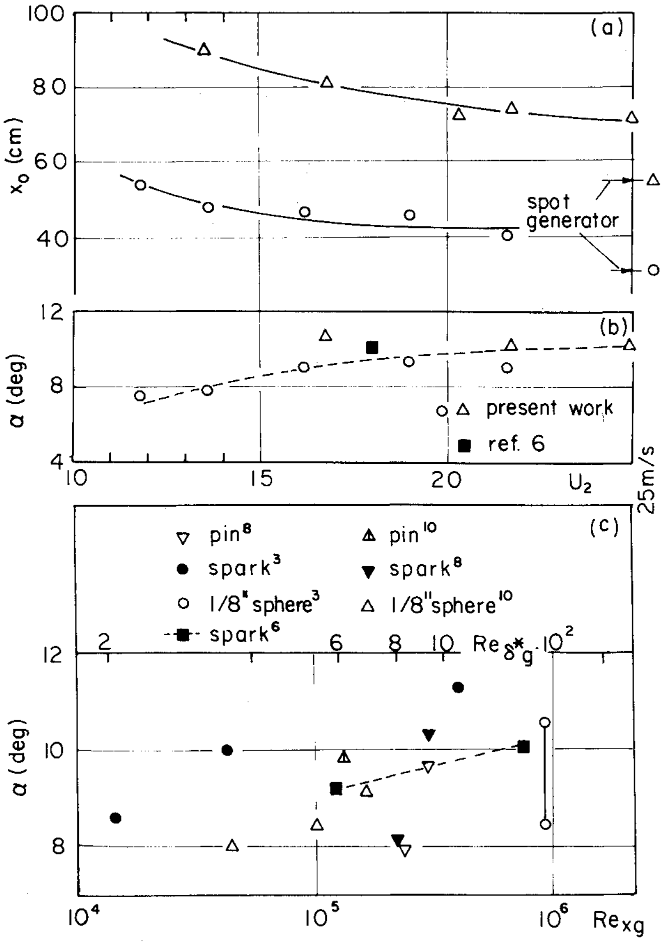

Fig. 3 Spot growth parameters in flow series (a) F1, (b) F2, and (c) constant pressure boundary layer flow. Re_{xg} is Reynolds number based on location of spot generator.

Figure 3 shows the effective origin x_0 from which linear growth occurs, as a function of the final freestream velocity U_2, as well as the semiangle α in the linear stage. It is clear that x_0 moves slowly upstream as U_2 increases, but the Reynolds number $U_2 x_0/\nu$ also increases. It is, therefore, not a simple matter of reaching a critical Reynolds number based on x_0. The slow increase of α with U_2 is consistent with observation in zero pressure gradient flow, also summarized in Fig. 3 as a function of Reynolds number. These data, some taken many years ago,[8,10] are seen to be in excellent agreement with those of Ref. 6 over the smaller range of Reynolds number covered in the latter.

A possible explanation of the favorable gradient observations is provided by the following stability argument. In flow F2c, Fig. 4 compares the observed boundary-layer Reynolds number Re_θ (based on the momentum thickness θ) with theoretical estimates of both Re_θ itself and its critical value. Re_θ is computed using the Thwaites method; the critical value is obtained from a correlation with the Thwaites pressure gradient parameter.[9] Observed and calculated Re_θ are clearly in excellent agreement; note in particular how theory predicts the dip in Re_θ (due to acceleration) around the streamwise station $x \simeq 60$ cm. The theoretical estimates of $Re_{\theta cr}$ show first a steep rise in the favorable pressure gradient region (thus rendering the flow subcritical), followed by an equally steep fall as the gradient diminishes. The point where the spot growth tends to become linear again is seen to be close to the point where flow ceases to be subcritical.

In the favorable pressure gradient flow reported by Wygnanski,[6] the displacement thickness δ^* was constant at 2.34 mm; this gives the highest Reynolds number Re_{δ^*} in his flow as of the order of 800, compared to an estimated $Re_{\delta^*_{cr}}$ of 1500 at $\beta = 0.12$. Therefore this flow is always subcritical, and the observed slow growth is consistent with the stability explanation offered above.

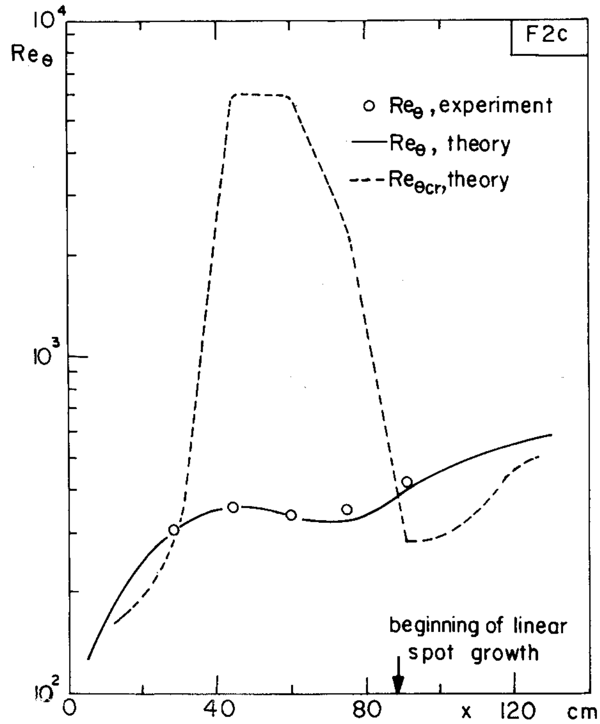

Fig. 4 Measurements of boundary layer Reynolds number, compared with the laminar theory of Thwaites and the critical Reynolds number for instability.

Conclusions

Present experiments, extending earlier data in constant pressure flows, show that the wedge angle increases slowly with Reynolds number. A favorable pressure gradient, presumably because of its stabilizing effect, inhibits the growth of turbulent spots, and, in general, results in a nonlinear turbulent wedge. However, as soon as the pressure gradient diminishes to the point where the flow becomes supercritical, spot growth picks up rapidly and the associated turbulent wedge becomes linear.

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Injection into a Turbulent Boundary Layer Through Different Porous Surfaces

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Nomenclature

C_f	= skin friction coefficient
Re_L	= Reynolds number based on length
U	= local mean velocity
U_e, UE	= edge velocity
U_*	$= \sqrt{\tau_w / \rho}$
U^+	$= U/U_*$
$\sqrt{\overline{u'^2}}/U_e$; U'/UE	= axial turbulence intensity
$\sqrt{\overline{v'^2}}/U_e$; V'/UE	= normal turbulence intensity
$\overline{U'V'}/U_*^2$	= Reynolds stress
V_0	= injection velocity
V_0^+	$= V_0/U_*$
Y	= vertical distance from wall
Y^+	$= YU_*/\nu$
τ_w	= wall shear
ρ	= density
ν	= laminar kinematic viscosity

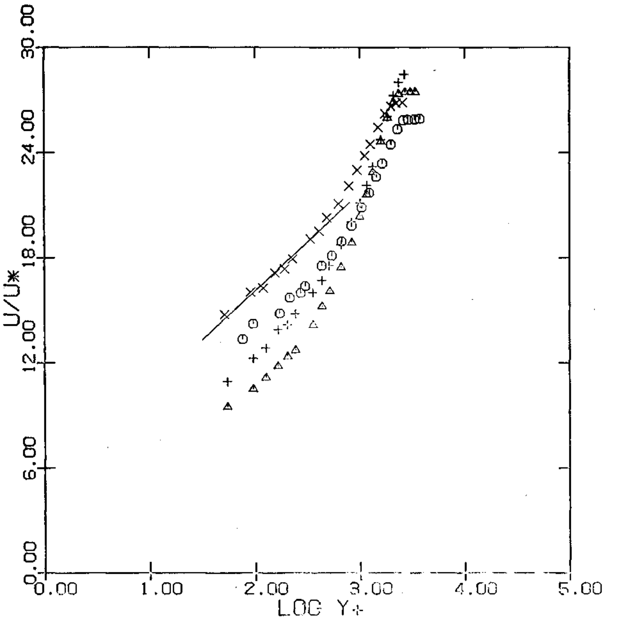

Fig. 1 Law of the wall profiles. Perforated titanium wall at $Re_L = 4.96 \times 10^6$: ○, $V_0^+ = 0.14$; Δ, $V_0^+ = 0.19$. Porous, sintered wall at $Re_L = 5.76 \times 10^6$ (Ref. 9): +, $V_0^+ = 0.10$. Smooth, solid wall at $Re_L = 4.96 \times 10^6$: ×. Calculated from Clauser for a smooth, solid wall:———.

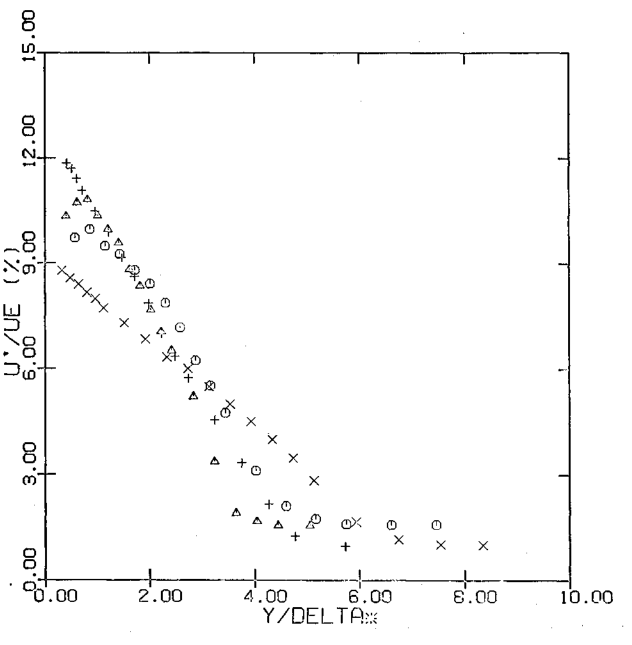

Fig. 2 Axial turbulence intensity profiles. Perforated titanium wall at $Re_L = 4.96 \times 10^6$: ○, $V_0^+ = 0.14$; Δ, $V_0^+ = 0.19$. Porous, sintered wall at $Re_L = 5.76 \times 10^6$ (Ref. 9): +, $V_0^+ = 0.10$. Smooth, solid wall at $Re_L = 4.96 \times 10^6$ (Ref. 9): ×.

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