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On the criteria for reverse transition in a two-dimensional boundary layer flow

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Experiments on reverse transition were conducted in two-dimensional accelerated incompressible turbulent boundary layers. Mean velocity profiles, longitudinal velocity fluctuations $\tilde{u}'(=(\overline{u'^2})^{\frac{1}{2}})$ and the wall-shearing stress (τ_w) were measured. The mean velocity profiles show that the wall region adjusts itself to laminar conditions earlier than the outer region. During the reverse transition process, increases in the shape parameter (H) are accompanied by a decrease in the skin friction coefficient (C_f). Profiles of turbulent intensity ($\overline{u'^2}$) exhibit near similarity in the turbulence decay region. The breakdown of the law of the wall is characterized by the parameter

$$\Delta_p(=\nu[dP/dx]/\rho U^{*3}) = -0{\cdot}02,$$

where U^* is the friction velocity. Downstream of this region the decay of $\tilde{u}'$ fluctuations occurred when the momentum thickness Reynolds number (R) decreased roughly below 400.

1. Introduction

Even though the phenomenon of reverse transition in boundary-layer flows was observed several years ago by Sternberg (1954) and Sergienko & Gretsov (1959) at supersonic speeds, detailed investigations have been carried out only recently, after finding it possible to obtain relaminarizing boundary layers even at low speeds. At these speeds not only are compressible effects negligible but also quantitative measurements of some of the fluctuating velocities are possible which are of great help in understanding the basic physics of the problem. The work done by Launder (1964), Moretti & Kays (1965), Schraub & Kline (1965) and Patel (1965) has revealed many interesting features regarding accelerated relaminarizing turbulent boundary layers in general. Moretti & Kays found that during acceleration the turbulent heat transfer rate near the wall decreased appreciably and they suspected this decrease to be due to reverse transition. Their analysis indicated that the drop in the heat transfer rate occurred consistently when the parameter $K=\nu/U_\infty^2(dU_\infty/dx)$ (where dU_∞/dx is the gradient of the free-stream velocity along the flow direction and ν is the kinematic viscosity) reached a value of about $3{\cdot}5\times10^{-6}$. A somewhat similar trend has been noticed by Schraub & Kline in their water-channel experiments; they observed that the burst rate of the large turbulent eddies near the wall tended to zero at $K \simeq 3{\cdot}5 \times 10^{-6}$.

Certain dimensional arguments have been offered, purporting to show that the relevant parameter is of the form K/C_f^n, where n is a constant and lies in between 0·5 and 1·5. The variation of C_f being small compared to that of K in the experiments the effect of C_f can be neglected as a first-order approximation. It will be generally conceded that in all the experiments so far conducted no accurate evaluation of C_f has been made and hence it is difficult to determine the exact value of the index n. The analysis by Back, Massier & Gier (1964) also supports this view. Patel, Launder and the present authors have noticed that, during acceleration the inner log law (namely $U/U^* = A \log yU^*/\nu + B$, where U^* is the friction velocity) breaks down; and according to Patel this happens when the value of $\Delta_p\,(= \nu[dP/dx]/\rho U^{*3})$ is roughly equal to $-0{\cdot}02$. In fact, this parameter Δ_p is simply $-2{\cdot}8K/C_f^{\frac{3}{2}}$. Patel has suggested that this breakdown of the law of the wall may be associated with relaminarization and he has taken this breakdown as defining the onset of reverse transition. This parameter Δ_p has the special significance that it is based only on variables directly affecting the wall region of the flow (i.e. it is independent of the stream velocity and over-all properties of the layer). In a very recent paper, Patel & Head (1968) have shown that it is more appropriate to use a shear stress gradient parameter $\Delta_\tau\,(= \nu\alpha/\rho U^{*3}$, where α is a function of dP/dx) instead of Δ_p. According to them the law of the wall breaks down at $\Delta_\tau \simeq -0{\cdot}009$ for boundary layer, channel and pipe flows. Evaluation of all these parameters such as Δ_p, Δ_τ, etc. calls for accurate measurement of wall shear stress which is difficult in accelerated boundary layers which are thin and quasi-turbulent.

Launder (1964) has investigated the problem of boundary-layer reverse transition in somewhat greater detail by measuring some of the turbulent quantities. His investigations are geared more towards the understanding of the basic physics of the problem. The results obtained by Launder, and those from certain preliminary experimental investigations by the authors, indicate vaguely that the problem is associated with low Reynolds numbers. The part played by the pressure gradient on the decay of non-isotropic turbulence is not yet clear. Since the physics of the problem is not yet completely understood, a valid theoretical approach to this subject does not exist yet. There is also a possibility that the decay of turbulence is mainly a Reynolds number effect and the part played by the favourable pressure gradient is just to reduce the Reynolds number. With these ideas in mind, the present investigation was started to probe somewhat deeper into the problem and also to trace step by step the relaminarizing process experimentally and to isolate the effect of the pressure gradient from that of viscosity if possible.

Mention should be made of the work done on relaminarizing duct flows by Sibulkin (1962), Laufer (1962, pp. 166–174) and Badri Narayanan (1968). In duct flows the decay of turbulence is brought about mainly by viscous effects and during the reversion process $\overline{u'^2}$ and $\overline{v'^2}$ decay exponentially, whereas the Reynolds stress decays much earlier. In pipe and channel flows, during reverse transition, the mean velocity profiles first approach that of laminar flow in the wall region. The $\overline{u'^2}$ profiles exhibit near similarity during the decay process if the maximum value of $\overline{u'^2}$ and the distance from the surface at which it occurs are taken as the appropriate velocity and length scales. The spectrum of $\overline{u'^2}$ also exhibits similarity. The results of the present investigation reveal that there exist some common features in the decay of turbulence in duct and boundary layer flows, indicating that the decay of non-isotropic turbulence seems to follow some definite and basic trends irrespective of the type of flows.

As stated in the previous paragraph, there exists diversity in view in defining the onset of reverse transition, such as the breakdown of the law of the wall and the reduction in the turbulent heat transfer rate, etc., but none of them has taken into account the exact decrease in turbulence level. The authors feel that the relaminarizing condition should be represented in addition by a decrease in turbulent fluctuations, otherwise there is a possibility that the observations may pertain only to the phenomena of accelerated flows without necessarily including relaminarization. With this aim in view, experiments were conducted under seven different experimental situations and the measurements consisted of (*a*) mean velocity profiles, (*b*) longitudinal velocity fluctuations ($\tilde{u}'$), and (*c*) wall shear stress. The results of these investigations indicate certain definite trends and throw some light on the basic features of the phenomenon of reverse transition in general.

2. Experimental set-up

The experiments were conducted in a 1 ft. × 1 ft. low-speed wind tunnel at the Department of Aeronautical Engineering, Indian Institute of Science, Bangalore. The free-stream turbulence in the tunnel was 0·3 % of the free-stream velocity. The acceleration of the flow was obtained by using suitably shaped wedges (figure 1). Seven sets of experiments were conducted with various initial Reynolds numbers and free-stream velocities. The boundary layer profiles were measured on the smooth top wall except in the case of exps. 2 and 3 where a separate flat plate was used to obtain low initial Reynolds numbers. Static pressure holes of 0·25 mm were drilled at suitable intervals all along the central line of the top wall and plates. In addition, holes of $\frac{1}{2}$ in. diameter were also drilled for the insertion of surface heat transfer gauges to measure skin friction.

The mean velocities, as well as the longitudinal velocity fluctuations in the boundary layer, were measured with a 0·0001 in. diameter, 1 mm long Pt–Rh hot wire. A pitot tube with a 0·30 mm opening was also used to measure the mean velocities wherever possible as an additional check for the hot-wire measurements. A constant current hot-wire anemometer system was employed for turbulence measurements. The surface heat transfer gauge was made by embedding a 0·0006 in. diameter platinum wire $\frac{1}{4}$ in. long on the surface of a Perspex plug. The gauge was calibrated in a large aspect ratio two-dimensional channel flow where the wall shear stress was estimated from pressure gradient measurements. In this particular investigation, the boundary layer thickness being small, special care was taken to see that the heat from the wire did not appreciably alter the boundary layer itself. For this purpose, the wall shear stress on the plate was measured at various wire temperatures and it was observed that the shear stress values obtained were almost the same, provided that the wire overheat did not exceed 60 °C. The calibration was independent of the type of flow whether laminar or turbulent, and this fact was of great importance since both types of flows featured during reverse transition. The skin friction measured in exps. 2 and 3, using the surface heat transfer gauge, agrees well ($\pm 5\%$) with that obtained

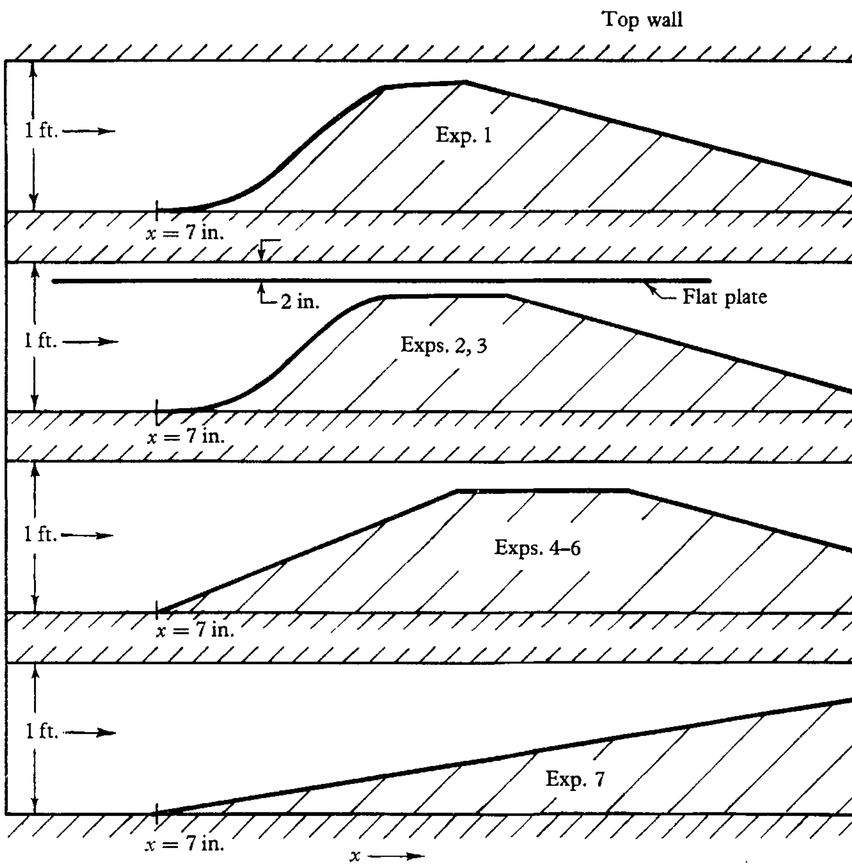

FIGURE 1. The experimental set-up for various pressure gradients. The boundary-layer measurements were made on the top wall of the wind tunnel except in exps. 2 and 3.

by Preston tube in the fully turbulent region. In the region where $dP/dx = 0$ ($x = 20$ in. in exp. 2) the skin friction coefficient evaluated by the heat transfer gauge again agrees with the theoretical laminar flat plate value. Hence it is assumed that the surface heat transfer gauge is capable of measuring the correct wall shear stress all along the pressure gradient region, irrespective of the type of flow and pressure gradients. In fact Liepmann & Skinner (1954) have shown that the effect of the pressure gradient is negligible if it is a favourable one. But the use of this instrument is cumbersome and calls for very steady temperature conditions and in this investigation these measurements were restricted to exps. 2 and 3. The surface heat transfer gauge, though not a very sensitive instrument for measuring wall shear stress (heat transfer rate $\propto 3\sqrt{}$(wall shear stress)), seems to be the only instrument that can be used with some reliability in an environment where both laminar and turbulent flows occur in large pressure gradients. A 1 mm diameter Preston tube was also employed for measuring the wall shear stress in the fully developed turbulent flow region as a check of the results obtained from the heat transfer gauge.

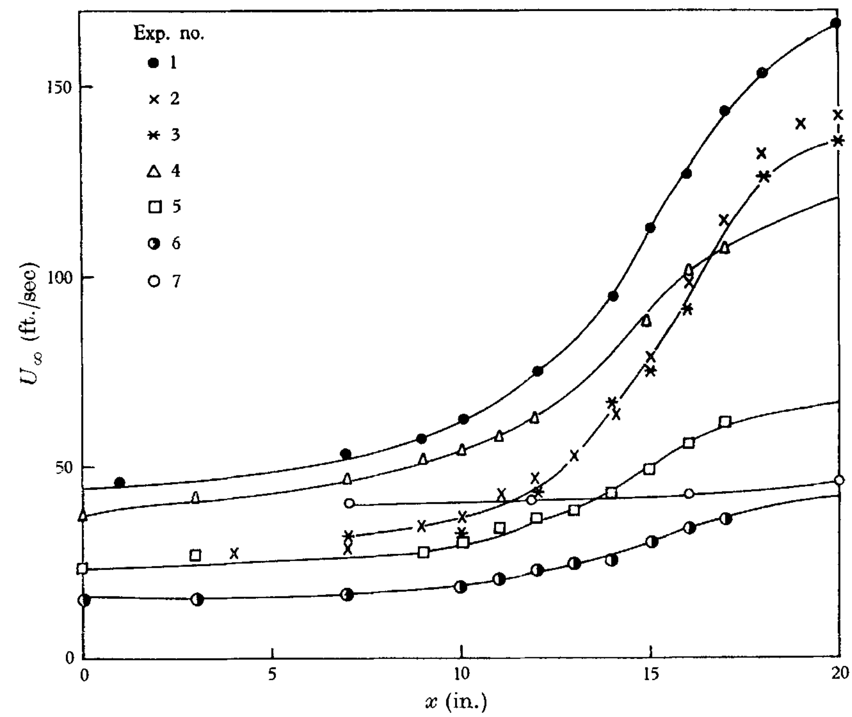

FIGURE 2. Variation of free-stream velocity with x.

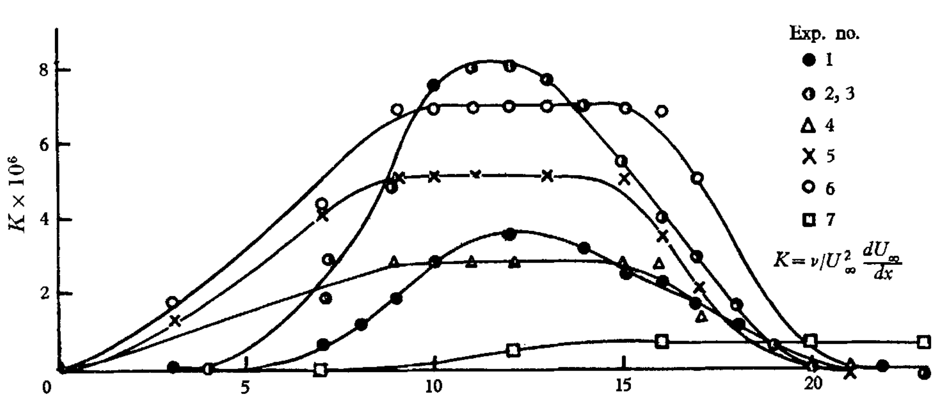

FIGURE 3. Variation of K with x.

3. Experimental results

Pressure gradient

In the first three cases the velocities varied exponentially with distance and in the other four cases the reciprocal of the free-stream velocity varied linearly with x. Experiments 4–6 were conducted with a 40° wedge and in the last case a 9° wedge was employed. The variation of the free-stream velocity and that of the pressure gradient parameter K along x are shown in figures 2 and 3. Reverse

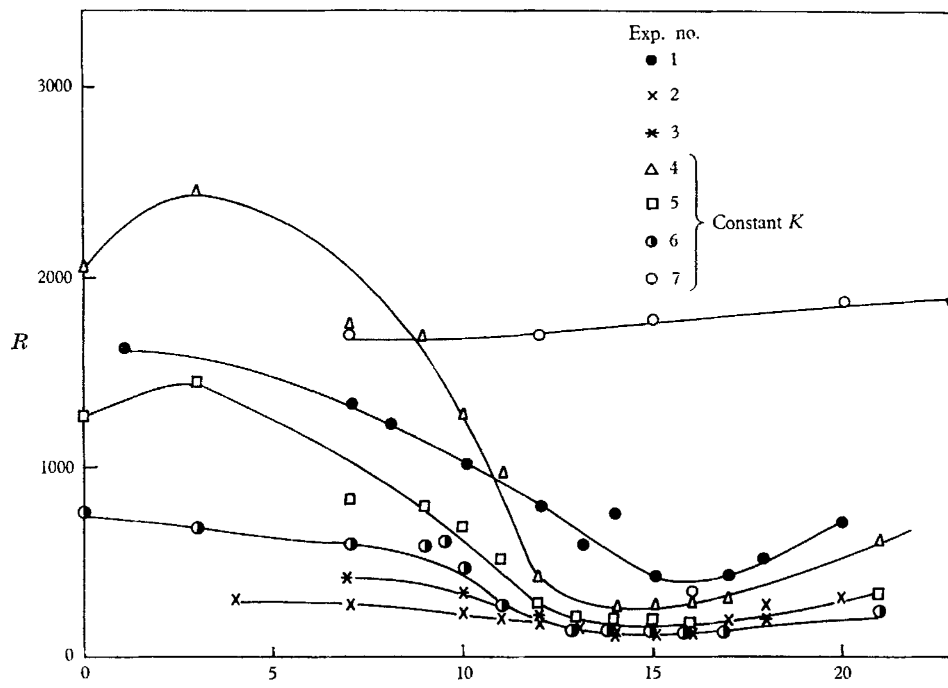

FIGURE 4. Variation of Reynolds number with x.

transition occurred in the first six cases, whereas in the seventh experiment an equilibrium turbulent boundary layer was maintained all along the pressure gradient region. A study of this equilibrium case is necessary to distinguish relaminarizing flow from the non-relaminarizing ones.

Mean velocity profiles and other boundary layer parameters

In all the cases the initial boundary layers were fully turbulent and the mean velocity profiles when plotted in the universal logarithmic plot exhibit a definite logarithmic region. The variation of Reynolds number (R) for all the cases are shown in figure 4. Except for exp. 7, the R drops appreciably around $x = 12$ in. irrespective of the initial value. Figure 5 shows the variation of the shape parameter (H) with x. Initially there is a decrease in H followed by an appreciable increase as the flow moves downstream. The maximum value of H is around two

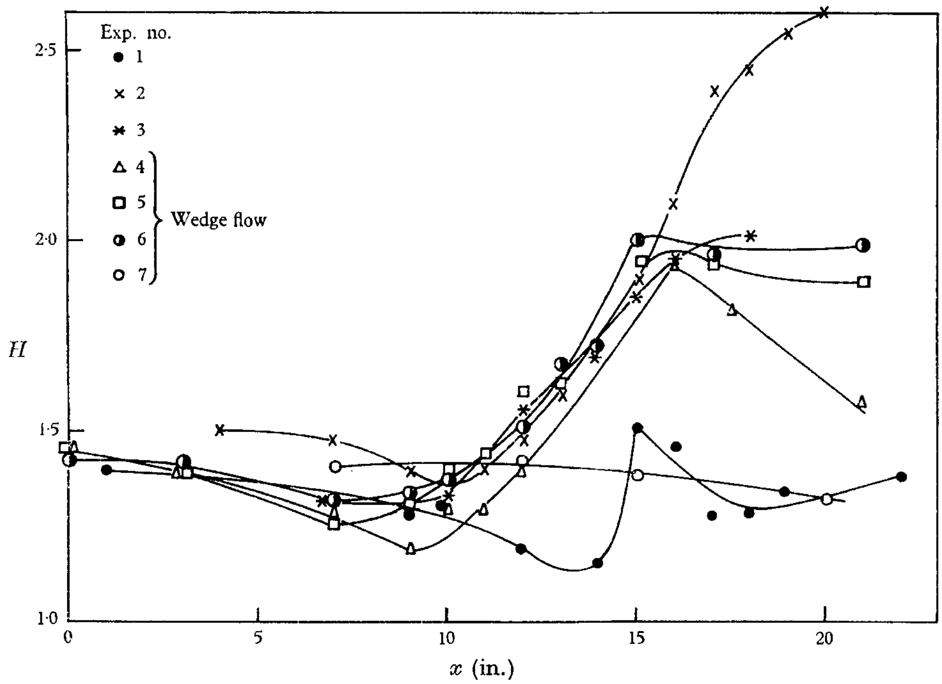

FIGURE 5. Variation of shape parameter with x.

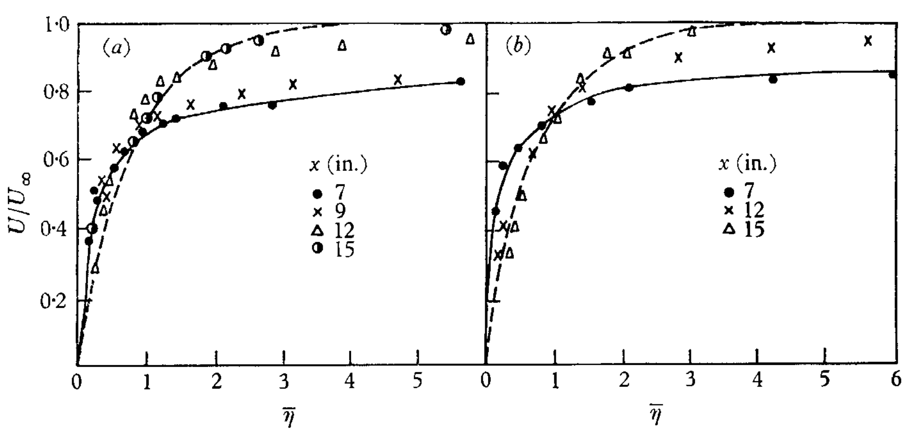

FIGURE 6. Mean velocity profiles (wedge flow). — —, laminar flow. (a) Exp. no. 4. (b) Exp. no. 5. $\overline{\eta} = (yU_\infty/\nu)\sqrt{K}$.

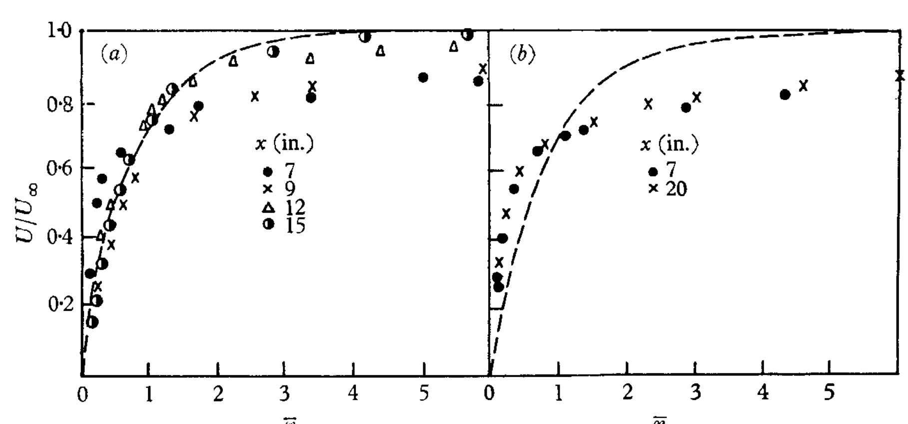

FIGURE 7. Mean velocity profiles (wedge flow). — —, laminar flow. (a) Exp. no. 6. (b) Exp. no. 7. $\overline{\eta} = (yU_\infty/\nu)\sqrt{K}$.

for cases 3–6 and much more for exp. 2. For case 1, the increase is not so predominant while in the equilibrium case it is almost constant.

The mean velocity profiles for the straight wedge flows (exps. 4–7) are shown in figures 6 and 7 in the form U/U_∞ versus $\bar{\eta}$ where $\bar{\eta} = (yU_\infty/\nu)\sqrt{K}$. In the case of wedge flows a unique laminar solution (Launder & Stinchcombe 1967) exists. The laminar boundary layer profiles that occur between two converging planes are given by the relation $U/U_\infty = 3\tanh^2[\bar{\eta}/\sqrt{(2)} + 1{\cdot}146] - 2$, where $\bar{\eta} = (yU_\infty/\nu)\sqrt{K}$

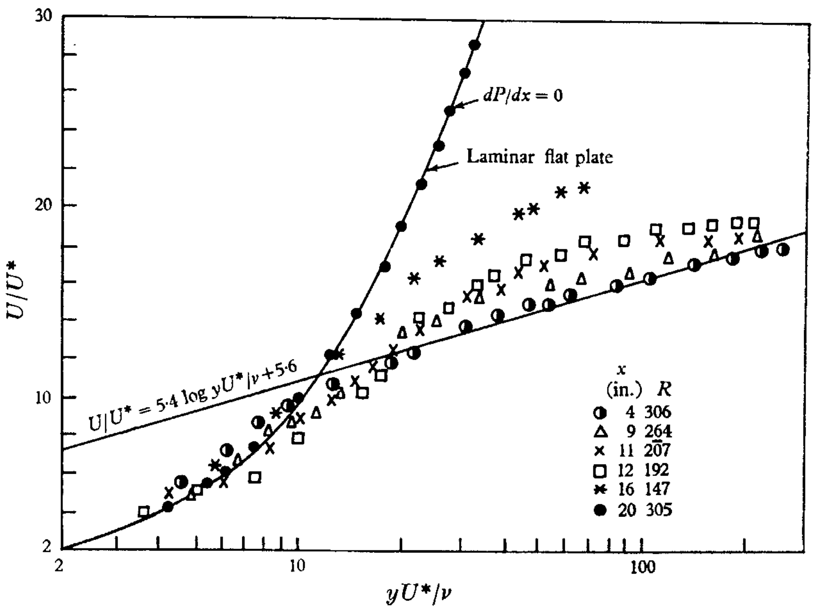

FIGURE 8. Universal logarithmic plot of the mean velocity profiles. Exp. no. 2.

and $C_f = 2{\cdot}31\sqrt{K}$ and the value of H is constant and equal to 2·07 irrespective of the value of K. In this case, it is easy to compare the measured relaminarizing profiles with the fully laminar one. In the other cases (1, 2, 3) the situation is more complicated and computation of the laminar profiles is rather involved. Figures 6 and 7 show that the mean velocity profiles approach that of laminar condition during reverse transition. It can also be noticed that the profiles become laminar at first near the wall and gradually approach the outer region as the flow moves downstream. In exp. 7, equilibrium condition being maintained, the mean velocity profiles do not show any tendency to become laminar. The mean velocity profiles obtained in exp. 2 are plotted in figure 8 in the logarithmic form using the skin friction values as measured by the heat transfer gauge.

Wall shear stress

The surface heat transfer gauge was used to measure the wall shear stress in exps. 2 and 3. In exps. 4–6 the wall shear stress was estimated only in the turbulent region using the Preston tube as well as Clauser's method, and no attempt was made to measure C_f in the reverse transition region using the heat transfer gauge. Figure 10 shows the mean velocity profiles plotted in the Clauser

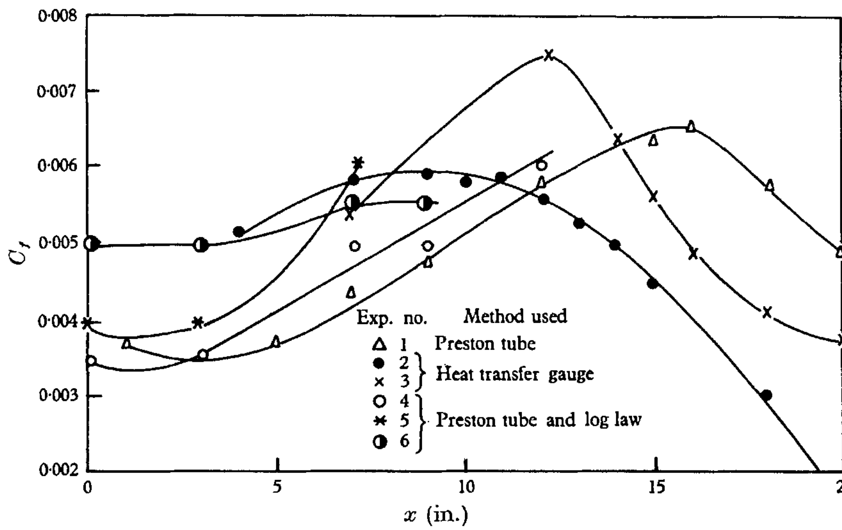

FIGURE 9. Variation of skin friction coefficient with x.

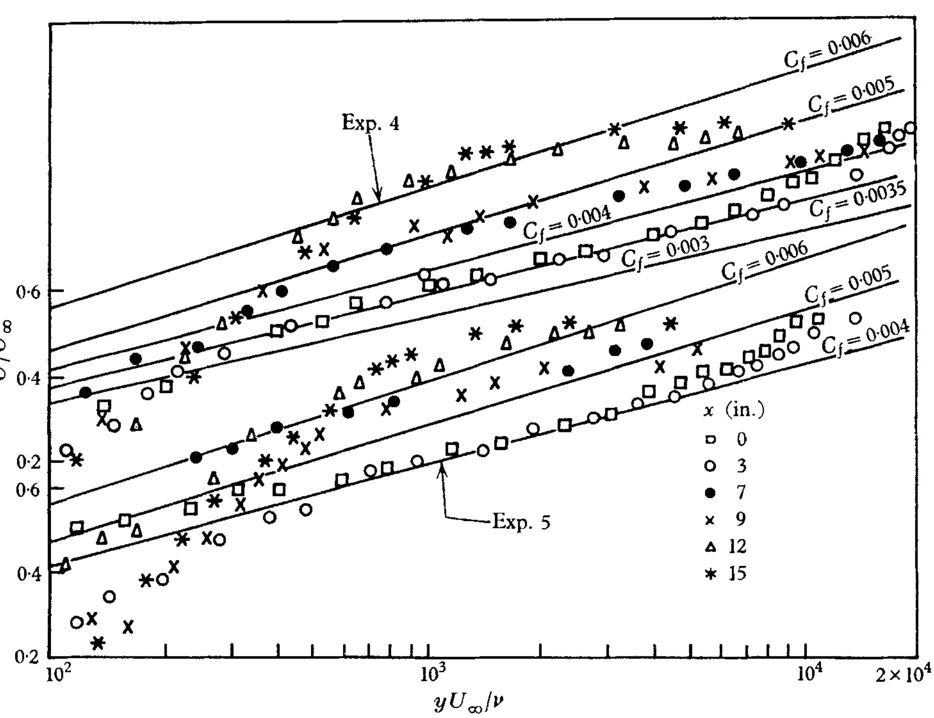

FIGURE 10. U/U_∞ versus $(yU_\infty/\nu).(U/U^*) = 5{\cdot}4 \log yU^*/\nu + 5{\cdot}6$.

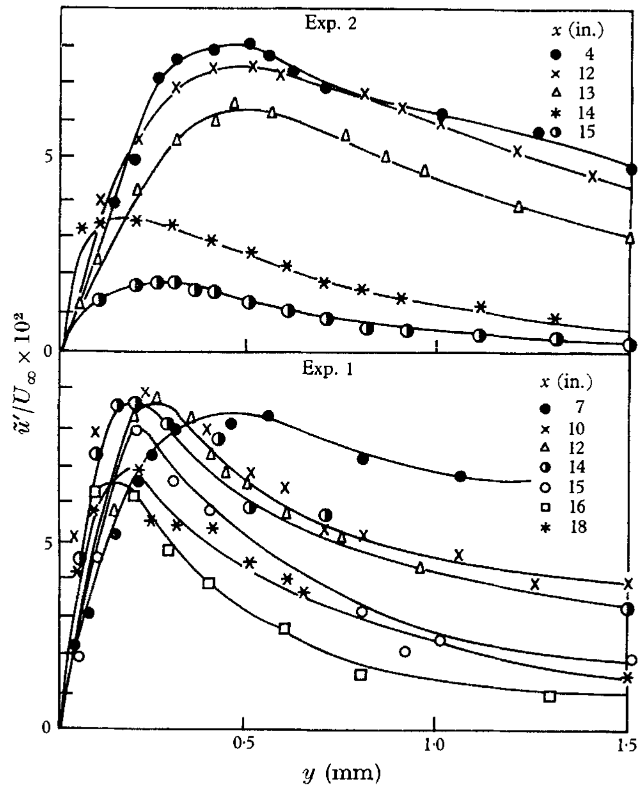

FIGURE 11. $\tilde{u}'$ fluctuations in the wall region.

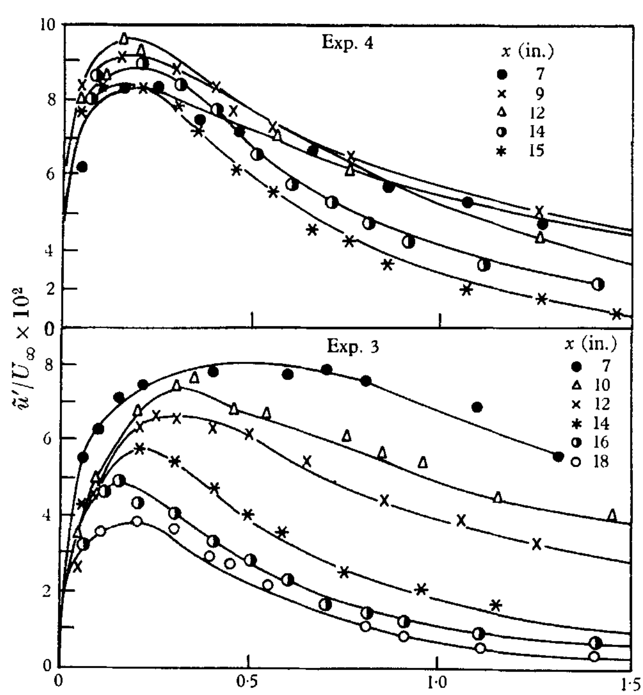

FIGURE 12. $\tilde{u}'$ fluctuations in the wall region.

form, namely U/U_∞ versus yU_∞/ν with C_f as a parameter. In exps. 1 and 7, the Preston tube was used. The final results of the skin friction measurements are plotted in figure 9.

Turbulent velocity fluctuations

In this investigation the turbulence measurements were restricted to the root mean square longitudinal velocity fluctuations ($\tilde{u}'$) only. No attempts were made

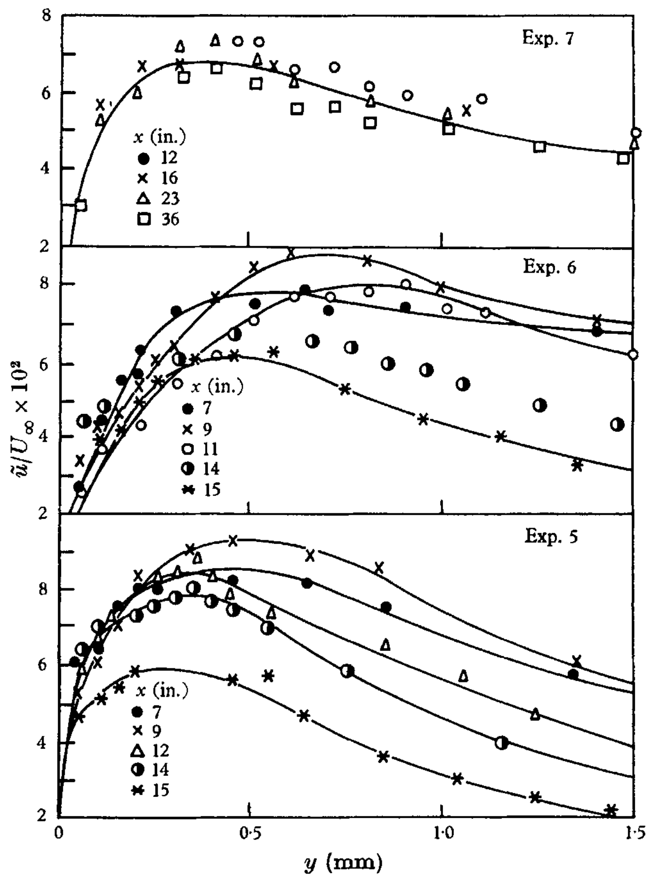

FIGURE 13. $\tilde{u}'$ fluctuations in the wall region.

to measure the other fluctuating quantities such as $\overline{u'v'}$ and $\tilde{v}'$ because of the very small boundary layer thickness occurring during the reverse transition. The $\tilde{u}'$ profiles near the wall region are shown in figures 11–13 for all the cases. It can be seen that, especially in the case of the wedge flows, the $\tilde{u}'$ increases in the beginning and then decreases as the flow moves downstream indicating decay of turbulence during reverse transition. In exp. 7 equilibrium in turbulent quantities ($\overline{u'v'}$ and $\tilde{v}'$ were also measured) was achieved only beyond $x = 20$ in. Marked decrease in $\tilde{u}'$ can be noticed in exps. 2 and 3 probably due to the low Reynolds numbers and the comparatively large accelerations involved in these flows.

4. Discussion

Flow ahead of the pressure gradient region

The experiments were carried out with initial Reynolds numbers (R) ranging from 300 to 2000. Rough sand paper trips were used far ahead of the wedges to hasten and fix transition. The $\tilde{u}'$ distribution and the mean velocity profile plotted in the universal logarithmic form indicated that fully developed turbulent conditions were achieved before the flow was subjected to acceleration. The mean velocity profiles showed a definite positive wake component which disappeared even in small favourable pressure gradients. In all the seven cases studied the boundary layer in this region was fairly thick and it varied from 8 to 26 mm.

Mean velocity profiles and wall shear stress

In exp. 2 at $x = 20$ in. where dP/dx has become zero the mean velocity profile is the same as that of the laminar flat plate (Blasius profile) indicating that the mean velocity profile has become completely laminarized, but the exact location of the start of this process is rather difficult to judge. A study of the measured mean velocity profiles (exps. 4–6) indicates that in the straight wedge flows the flow tends to become laminar (figures 6, 7), but this process is somewhat gradual. In all these cases at $x = 7$ in., the profile is far away from the theoretical laminar shape for a wedge flow. The rate of change to laminar condition is faster in exp. 6 than in exp. 4, perhaps due to the low Reynolds numbers involved. Similar situations have been noticed in the case of reverse transition in pipe and channel flows (Sibulkin 1962; Badri Narayanan 1968). In exp. 7, the mean velocity profile maintains similarity from $x = 7$ in. to 20 in. and there is no relaminarization at all. In exps. 4–6, it can be seen that the changeover to the laminar condition is very gradual. The velocity profile near the wall region adjusts to the laminar condition earlier than the outer region, again as in duct flows. The present measurements indicate that relaminarization in the wall region begins at $x = 12$ in., 10 in. and 9 in. for exps. 4–6 respectively, and at $x = 15$ in. the mean velocity profiles have almost reached fully laminar conditions in all these cases.

When the mean velocity profiles are plotted in the universal logarithmic form (figures 8 and 10) the law of the wall seems to break down apparently because of a thickening of the viscous sublayer around $x = 10$ in., 9 in. and 7 in. for exps. 2, 4 and 5 respectively. It is interesting to note that the minimum value of H also occurs at the same locations and this suggests that the breakdown of the law of the wall is associated with the minimum value of H in favourable pressure gradients (Fiedler & Head (1966) have indicated that in a similar environment intermittency extended right through the boundary layer when H was minimum). Similar trend has also been noticed by Patel & Head (1968) in their experiments. The values of the pressure gradient parameter (Δ_P) in the region where the law of the wall breaks down are tabulated (table 1) for all the six cases. According to Patel & Head, the breakdown occurs when Δ_P is roughly equal to $-0{\cdot}02$. The stress gradient parameter Δ_τ could not be estimated for want of sufficient data.

Since some allowance has to be made for the errors involved in the measurement of C_f it is not unreasonable to assume that the critical value of Δ_P is around 0·02 as suggested by Patel.

In the present investigation the breakdown of the law of the wall occurs somewhat earlier than the relaminarization of the mean velocity profile at the wall region. According to Bradshaw† what happens in real relaminarization is that the edge of the sublayer overlaps the 'outer' region. In the inner region the only length scale that matters is the distance from the surface; the eddies are unaffected by the outer layer since the backflow from the outgoing 'mixing jet' large eddies extends down only to $y/\delta \simeq 0{\cdot}2$ (δ is the boundary layer thickness). As soon as the sublayer gets to $y/\delta \simeq 0{\cdot}2$ the backflow (which does not carry much turbulent energy) can join up with the low-energy viscous region between the 'bursts' near the wall and so the intermittency extends down to the surface.

Exp. no.	x in. (at breakdown of the law of the wall)	c_f (at breakdown of the law of the wall)	Δ_P (at breakdown of the law of the wall)	x in. at $\tilde{u}'_{max}$	$K \times 10^6$ at breakdown
1	13	0·0058	−0·023	14	3·6
2	9	0·0060	−0·030	11	5·0
3	7	0·006	−0·196	10	3·0
4	9	0·005	−0·0226	12	2·8
5	7	0·0060	−0·0253	9	4·2
6	7	0·0060	−0·0258	9	4·3

TABLE 1

The Reynolds number R decreases below 400 in all the experiments (except exp. 7), irrespective of the initial values. In all these cases R decreases consistently in the increasing pressure gradient region and then increases again as the gradient is removed. Hence the minimum value of R, unlike that of H, does not seem to signify anything special except that its location coincides with that of the maximum value of dP/dx in the present experiments. But the large decrease in R in all the first six experiments makes one suspect that reverse transition may be a Reynolds number effect. Similar trends can be seen in Launder's (1963) results also. In the equilibrium case, R is practically constant from $x = 7$ in. to 29 in. (figure 4).

The longitudinal velocity fluctuations

The decay of turbulent fluctuations can also be considered as one of the features of reverse transition. It can be seen that in exps. 1–6 (figures 11–13) a marked decrease in the values of $\tilde{u}'/U_\infty$ occurs. In the last three experiments (4, 5, 6), there is really an increase in the $\tilde{u}'$ values in the beginning of the pressure gradient region, followed by decay. In these cases, it is somewhat easy to pinpoint the location of the decay region. It has been found that when the $\overline{u'^2}$ profiles are plotted in the non-dimensional form using the maximum value of $\overline{u'^2}$ at each station and its distance from the wall as the appropriate velocity and length

† Personal communication from Peter Bradshaw of N.P.L., England.

scales, all the profiles during the decay process exhibit an approximate similarity (figure 14). Badri Narayanan (1968) has shown that this near similarity is observed in the case of relaminarizing channel flows also. Laufer's (1962) measurements in pipe flows and Launder's (1964) data in boundary layer flows also show the same trend. Since $\overline{u'^2}$ distribution is nearly similar during the turbulence decay, it is sufficient if only the maximum value of $\overline{u'^2}$ at each station is con-

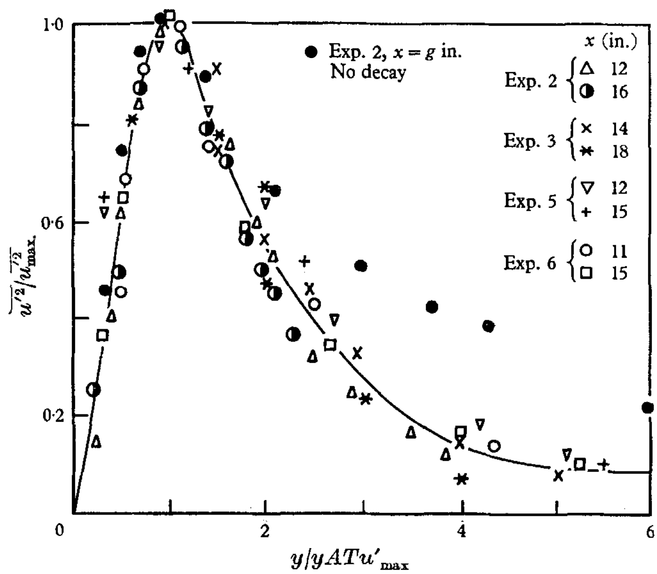

FIGURE 14. Near similarity in $\overline{u'^2}$ profiles during reverse transition.

sidered for reference purposes. When the $\tilde{u}'_{\max}/U_\infty$ is plotted versus x (figure 15) it is possible to locate within experimental error the stations (x) where the decay of $\tilde{u}'_{\max}/U_\infty$ begins. According to figure 15, the peak value of $\tilde{u}'/U_\infty$ occurs at $x = 14$, 11, 10, 12, 9 and 9 in. in exps. 1–6 respectively. These x locations are somewhat downstream of the region where the breakdown of the law of the wall occurs. It is possible that $\tilde{u}'$ fluctuations alone may not be sufficient to characterize the beginning of decay of turbulence since the other turbulent quantities such as $\tilde{v}'$ and Reynolds stresses may behave in a different way, but the results obtained from relaminarizing channel flow suggest that the decay of all the turbulent fluctuations starts simultaneously.

When the $\tilde{u}'_{\max}/U_\infty$ is plotted versus R (figure 16) decay seems to start only when R is reduced below 400. Some of Launder's results are also plotted in the same figure. The drop is gradual when R is between 400 and 300, but in the case of Launder's (1964) experiments the drop is steep and this may be due to the initially large turbulent intensity levels in his experiments. Below $R = 300$, the drop of $\tilde{u}'_{\max}/U_\infty$ is sudden. It is difficult to predict when $\tilde{u}'_{\max}/U_\infty$ will approach zero. Since during reverse transition the fluctuations become irrotational (see channel flow), the extrapolation of the curve in figure 16 is not desirable. The present results indicate the possibility of a critical Reynolds number for $\overline{u'^2}$ decay and according to figure 16, this value seems to be $R = 300 \pm 100$. The values of K

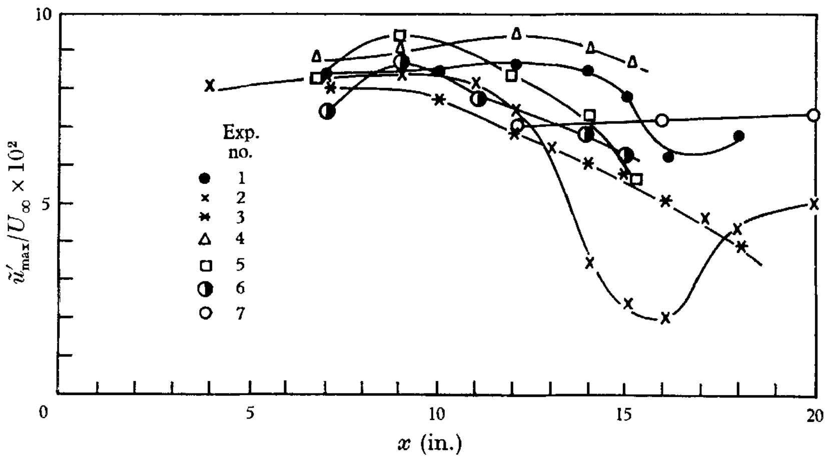

FIGURE 15. $\tilde{u}'_{max}$ versus x.

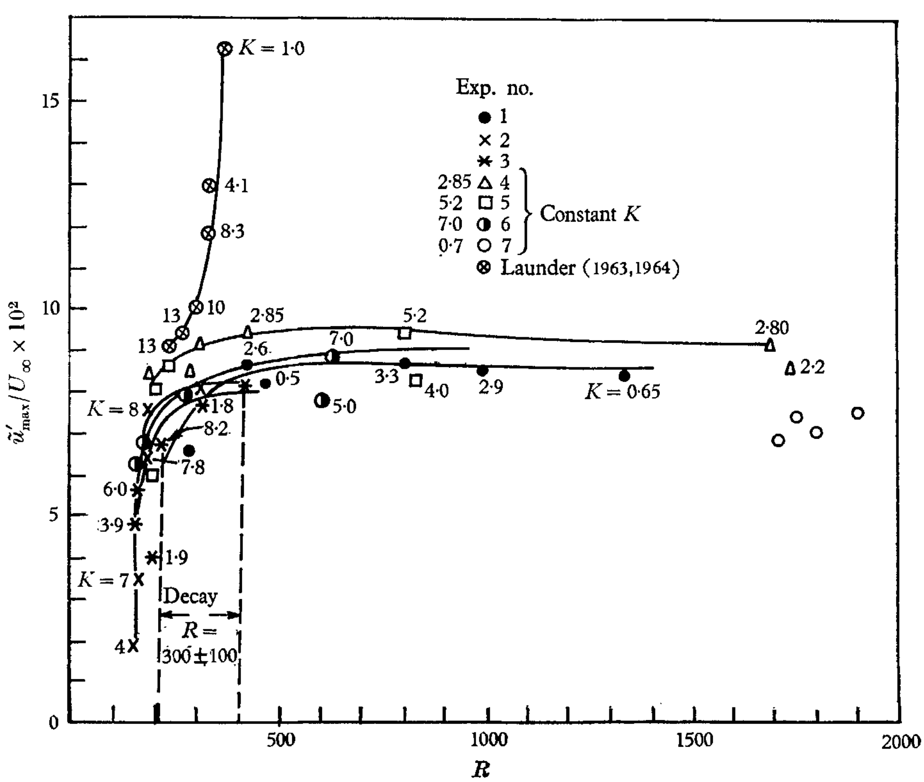

FIGURE 16. Variation of $\tilde{u}'_{max}$ with Reynolds number.

are also indicated in the same figure for each experimental point. It looks as though the parameter K is not a relevant one to define the onset of the decay process.

When $\overline{u'^2_{max}}/U^2_\infty$ is plotted versus t (figure 17) where t is the time taken by any fluid particle in the free-stream to travel a distance x from the beginning of the favourable pressure gradient region, there is a slight increase in the beginning

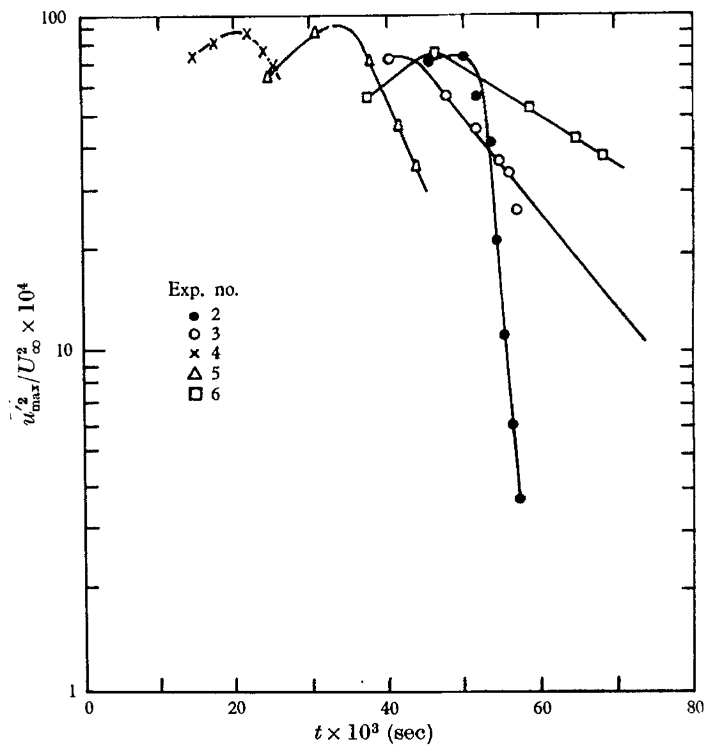

FIGURE 17. Exponential decay of $\overline{u'^2_{max}}$.

and then an exponential decrease during the decay process. Similar trend has been observed in relaminarizing pipe and channel flows, indicating that the decay of non-isotropic turbulence is basically exponential with respect to time, irrespective of the type of flow.

The criterion for reverse transition

The present investigation as well as those of others (Launder 1963, 1964; Patel & Head 1968; Schraub & Kline 1965) indicate that reverse transition in a two-dimensional boundary layer occurs in three different stages. During the reverse transition process the following events occur consecutively: (i) disappearance of the large eddy structure (turbulent bursts according to Schraub & Kline) near the wall, (ii) breakdown of the law of the wall, and finally (iii) the decay of turbulent intensity. These events are characterized by the parameters namely K, Δ_p (or Δ_τ) and R respectively.

A study of the mean velocity profiles (figures 6, 7) also shows that relaminarization of the mean velocity near the wall begins at the same position where the turbulent intensity also decreases, i.e. at $x = 14$, 11, 10, 12, 9 and 9 in. for exps. 1–6 respectively.

5. Conclusions

Reverse transition in a two-dimensional boundary layer occurs in three consecutive stages: (i) the disappearance of the turbulent bursts near the wall at $K \simeq 3 \times 10^{-6}$; (ii) the breakdown of the law of the wall when $\Delta_P \simeq -0{\cdot}02$—the minimum value of shape parameter (H) also seems to occur at this region; (iii) around a Reynolds number (R) equal to 300 the turbulent intensity shows a tendency to decay.

The profiles exhibit near similarity during the turbulence decay process, when plotted using the maximum value of $\overline{u'^2}$ and its location from the wall as the appropriate velocity and length scales respectively.

$\overline{u'^2_{\max}}/U^2_\infty$ decays exponentially when plotted against t where t is the time taken by a fluid particle in the free-stream to travel a distance x from the beginning of the favourable pressure gradient region.

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