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Experimental Study on the Evolution of a Wall Layer from a Wake

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Experiments are conducted on the development of the turbulent boundary layer on a flat plate located in the wake of another flat plate. The mean velocity field and the Reynolds stresses of the evolving layer are measured in six cases involving different wake conditions. The study is on the evolution of the wall layer developing under zero pressure gradient. The results indicate significant influence of the wake on the evolving layer. The perturbed wall layer has a low shape factor accompanied by lower Reynolds shear stress. The perturbation intensity falls by a factor of 2 over a distance of 50–100 momentum thicknesses. The data analysis reveal multilayered structure and growth of an internal layer. The applicability of some simple correlations and turbulence models for these complex flows are also examined.

Nomenclature

C_f = coefficient of skin friction = $2\tau_w/(\rho U_e)^2$
G = Clauser shape parameter, $1/\Delta\int_0^\infty (U_e - U)/U_\tau)^2\, dy$
g = gap between the plates, m
H = shape factor, δ^*/θ
l = chord of the flat plate, m
R_θ = $U\theta/\nu$
R_{uv} = shear stress correlation coefficient, $uv/\langle u\rangle\langle v\rangle$
TKE = turbulent kinetic energy, 0.5 $(u^2 + v^2 + w^2)$
U = mean velocity, m/s
U^+ = U/U_τ
U_τ = friction velocity, m/s, $\sqrt{\tau_w/\rho}$
u = instantaneous streamwise velocity fluctuation, m/s
$\overline{uv}$ = Reynolds shear stress
v = instantaneous normal velocity fluctuation, m/s
x = streamwise distance, m
y^+ = yU_τ/ν
y = normal distance, m
δ = distance from the wall, mm, at which $U/U_e = 0.995$
δ^* = displacement thickness, mm, $\int_0^\infty [1 - (U/U_e)]\, dy$
Δ = Clauser thickness, mm, $\int_0^\infty [(U_e - U/U_\tau)]\, dy$
Π = Coles' wake profile parameter
ρ = density of air, kg/m^3
θ = momentum thickness, mm, $\int_0^\infty [U/U_e(1 - U/U_e)]\, dy$
τ_w = wall shear stress, N/m^2
ν = kinematic viscosity, m^2/s

Subscripts

∞ = value at infinity
e = value at boundary-layer edge
— = time average
$\langle\ \rangle$ = root-mean-square value

Introduction

TURBULENT shear flows are commonly classified into wall flow and free flows. The presence of the wall in one case and the inflection point in the mean velocity profile in the other result in different mechanisms of the production of turbulent energy. Consequently, the structures of large scale motions and the dynamics of their evolution are very different. The change on one type of turbulent flow into another provides a setting for studying how structures of one kind are generated in the background of structures created earlier that are qualitatively different. Thus, it provides a way of understanding the process of generation and evolution of structures of turbulent motion in an environment that can be regarded as highly disturbed.

The change of wall flow into free flow, for example, in jets and wakes, has been studied extensively and is well documented in the literature. However, there are few studies on the change of a free turbulent flow into a wall turbulent flow. The present study is concerned with the evolution of the wall layer from the wake under zero pressure gradient. These studies are important in several problems, such as those in turbomachinery, where the turbulent wake of a stator row can influence to a significant extent the development of the boundary layer on the downstream rotor row. Here we consider the development of a boundary layer on a body placed in the wake of another body. The oncoming wake can be viewed as a perturbation of classical initial conditions. Also, the persistence of turbulent shear flow outside the wall layer constitutes a perturbation of the boundary condition at the outer edge. The upstream body is selected to be a flat plate since its wake provides the most basic prototype of wakes, which is very well understood. The second body is also selected as a flat plate.

Although no earlier investigation of this type is reported in literature, a review of related studies is given to facilitate interpretation of the results. Extensive experimental investigations on the evolution of a free shear layer from a wall layer like the formation of a jet (Weir et al.[1]) and a wake (Anderopolous and Bradshaw[2]) have been reported in the literature. Studies of the interaction of shear layers in a duct by Dean and Bradshaw[3] and wake/boundary-layer interaction studies by Pot,[4] Sundaram and Yajnik,[5] Nakayama et al.,[6] and Kreplin et al.[7] also fall into the class of complex flows. Several studies are reported on the wall layer development under a homogeneous, nearly isotropic turbulent freestream. The major contributions are from the work reported by Evans,[8] Bradshaw,[9] Hancock and Bradshaw,[10] Blair,[11] and Castro.[12] Their studies showed the significant effects of the freestream turbulence on the outer layer and on the skin friction of the developing wall layer.

Investigations on the wall layer development under external uniform mean shear were first reported by Rose[13] and later by Champagne et al.[14] The studies by Mulhearn and Luxton[15] and Ahmed et al.[16] covered the effects of both weak and strong external uniform mean shear on the mean flow and turbulence

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characteristics of the wall layer. In the present study the wall layer is subjected to nonuniform external mean shear and anistropic turbulence fields due to the presence of the upstream wake. The aforementioned studies reported in the literature formed the basis for the present study. The conventional methods of measuring quantities such as the mean velocity, Reynolds stresses, and spectra, which give only gross features of the flow, are the simplest approaches in situations where the studies are first of its kind or where significant data describing the flow are not available from previous studies. Since the present study is believed to be the first of its kind on the evolution of the boundary layer when a wake is present in the oncoming flow, it is considered desirable to begin with conventional measurements.

Experimental Setup and Measurement Techniques

The experiments were conducted in the 0.3×1.5 m low-speed tunnel at the National Aeronautical Laboratory. This blower-driven tunnel is designed for studies on turbulent boundary layers. The test section has an adjustable length up to a maximum of 9.6 m. The air speed in the test section can be varied continuously up to a maximum of 50 m/s. The flow is uniform within $\pm 0.5\%$ over 85% of the test section area, and the turbulence level is $< 0.1\%$ in the range of measurements. The unit Reynolds number for the present study is 1.6 million/m, and the freestream speed is 30 m/s.

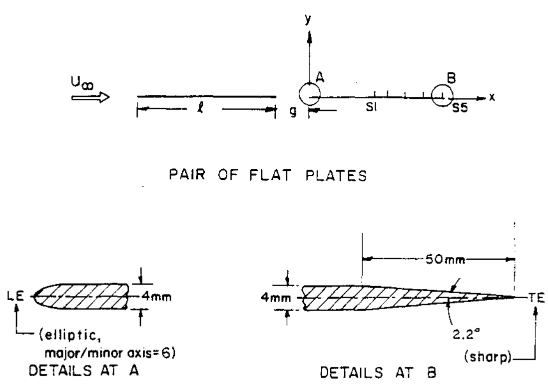
Two 4-mm-thick machined steel flat plates having 450 mm chord and 300 mm span were used for the present study. Each plate had an elliptic leading edge (major/minor axis = 6) and a sharp trailing edge. The plates were arranged in tandem fashion (Fig. 1) in the mid-vertical plane of the test section. The upstream plate was the wake generator, and the wall layer on the downstream plate was studied. Based on several previous studies on turbulent bounday layers in the tunnel, transition trips consisting of 10-mm-wide, thin strips of sandpaper (grade 50) were pasted at 10% chord from the leading edge on both sides of each plate. This transition was used to generate normal turbulent wakes. Two configurations were studied, with spacing between plates at one-fourth and one-half times chord (cases 2 and 3). In the second part of the study the wake was thickened by increasing the roughness on the plate using grade 24 sandpaper. The sandpaper covering the first 30% of chord was found to give the required result. This resulted in the momentum thickness being approximately twice the momentum thickness of the normal wake. The variation of parameters such as wake width and momentum defect indicated the approach to an asymptotic state for both of the cases. Three configurations were studied, with spacing between the plates at one-fourth, one-half, and one times the chord (cases 4, 5 and 6, respectively).

For the given freestream velocity two parameters are needed to describe the fully developed wake of the first plates as seen by the second plate. The momentum thickness at the leading edge of the second plate can be chosen as one such parameter, since it represents the momentum defect of the wake at the beginning of its influence on the wall layer development. The distance between the plates indicates indirectly the extent of diffusion of momentum at the leading edge of the second plate and can be used as another parameter. The relevant values of $g/2\theta_{LE}$ used for describing the configurations are given in Table 1. It is easily seen that the parameter $g/2\theta_{LE}$ represents the configurations in terms of the evolution of the layer from the near wake and intermediate wake.

The mean velocity field was measured using a standard conventional boundary-layer probe and digital micromanometer. The wall shear stress was determined from the mean velocity profiles using Bradshaw's[17] method and was also counterchecked by the Clauser[18] chart method. The values obtained by these methods were within $\pm 2\%$ for all of the cases studied. The turbulence measurements were made with 5μm tungsten wire in an x-array configuration. The active wire length of the sensors gave a length-to-diameter ratio of ~ 160, and spacing between the cross wires was ~ 50 in wall units. Two-channel, constant-temperature anemometers (DISA 55M01) were used with accessories including signal conditioners (DISA 55D26). The anemometers were operated at an overheat ratio of 1.8 with a frequency response of 55 kHz (as determined by the square-wave test). A typical estimate of the error in the measurement of turbulence intensity is $\pm 3\%$. Two-dimensionality was also checked. The profiles of mean velocity and Reynolds stresses at three locations covering 66% span were in agreement within ± 1 and $\pm 2\%$, respectively. Further details of the experimental setup can be found elsewhere (Sundaram[19]).

Results and Discussions

The mean velocity distribution in the inner layer for all six cases studied are shown in Fig. 2a. They indicate wall similarity and the applicability of the universal wall law with coefficients as recommended by Coles.[20] The values of U/U_τ at $Y^+ < 100$ are a little higher than the log law values, unlike the lower values generally found when the oncoming flow is freestream. Examination of u vs y close to the wall at a given station indicates hardly any difference in all the six cases. This difference is due to the reduced value of U_τ. It can also be seen that the range of validity of the wall law is shifted to higher values of Y^+ in the evolved layer, which is largely due to the thickening of the layer. The range of validity also appears to be smaller for these layers. Similar results are reported by Ahmedis group and also by Charnay et al.[21] It is further seen that the wake strength of the layer is significantly reduced. The wake component almost disappears for the cases where the layer evolves from the intermediate wake (cases 3 and 6). The reduction in Π can be attributed to the increase in the turbulence in the outer region of the evolving layer. The wake strength is a strong function of the Reynolds number based on momentum thickness of the layer (Cebeci and Smith[22]), as indicated in Fig. 2b. The figure clearly indicates that the evolved layer, despite being at higher R_θ compared to



STATION	S1	S2	S3	S4	S5
x/ℓ	0.47	0.6	0.73	0.86	0.99

$\ell = 450$ mm, $U_\infty = 30$ m/s

$g = 0.25\ell,\ 0.5\ell,\ 1.0\ell$

Fig. 1 Definition sketch.

Table 1 Configuration parameters ($\beta = 0$)

	Case 2[a]	Case 3	Case 4	Case 5	Case 6
$g/1$	0.25	0.50	0.25	0.50	1.00
$\theta_t/1 \times 10^3$	3.93	3.93	7.86	7.86	7.86
$\theta_{LE}/1 \times 10^3$	4.51	4.16	8.42	7.96	7.90
$g/2\theta_{LE}$	26.0	60.0	15.0	32.0	64.0

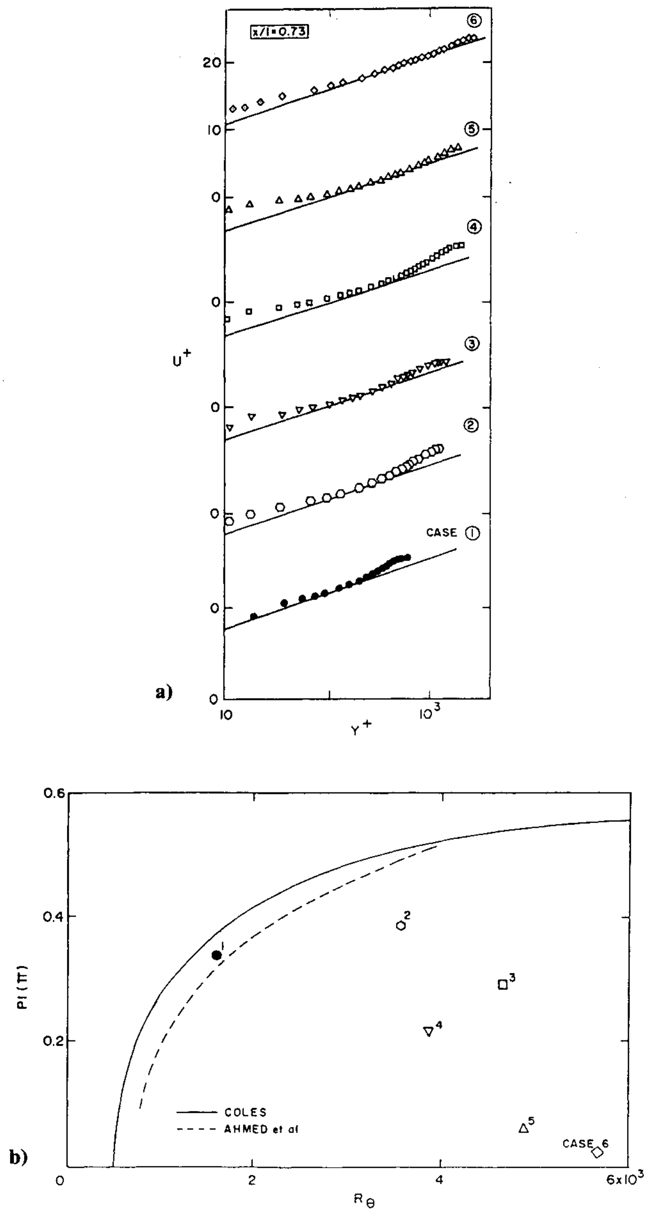


Fig. 2 Effect of wake on the inner layer.

the layer developing under freestream (case 1), has very low values of Π. A reduction of 80% in Π is reported by Kline[23] for a freestream turbulence level of 6.4%. The reduction in wake strength due to external mean shear is only marginal, as reported in literature. The large reduction in Π in the present study can be attributed to turbulence field rather than mean shear. The evolving layer has a higher turbulence level in the outer layer due to intense mixing promoted by the wake, which results in the significant reduction in the wake strength of the layer. Since Π is an outer layer parameter, very low values of Π also reflect structural changes in the outer layer.

The mean velocity distribution in the outer layer in the form of velocity defect in the usual coordinates following Clauser is shown in Fig. 3 for all of the six cases. The defect profiles appear to be similar to a good approximation in all of the cases. Although the shape of the defect profiles for case 1 agrees well with the defect profile for the standard turbulent boundary layer, there are definite deviations in all other cases studied. From the figure it is clear that the evolving layer for cases 2 and 4 has a mean velocity distribution only slightly different from that of the standard turbulent boundary layer. However, for the evolution of the wall layer for cases 3, 5, and 6, the departures are significant.

From Table 1 it is clear that the values of $g/2\theta_{LE}$ are <30 for cases 2 and 4 and are between 30 and 100 for cases 3, 5, and 6. Hence, cases 2 and 4 and cases 3, 5, and 6 represent the evolution of the wall layer from the near and intermediate regions of the wake. This can also be inferred from the results discussed in terms of the mean velocity distribution in the inner and outer layer, which indicate that cases 2 and 4 are one type and cases 3, 5, and 6 are another type. For cases 3, 5, and 6 the distance between the plates is larger compared to that for the case 2 and 4, the wall layer evolves from the slowly developing intermediate wake, which is characterized by the onset of the large-scale mixing between the outer regions of the upstream boundary layers. This mixing causes the velocity profiles to be fuller than the layer from the near wake. The fullness of the profile leads to a lower velocity defect in the overlap region of the evolving layer.

The variation of shape factor H along the second plate for all the cases showed that H was generally lower for the wall layer evolving from the wake. The value of H was $\sim 10\%$ lower than the equilibrium value for a given R_θ of the layer evolving from the intermediate wake. The trend of H showed a rather slow approach to equilibrium. A similar reduction was also observed in values of G. The reduction was primarily due to the increase in the momentum thickness for the evolving layer compared to the equilibrium layer. Blair also reports a similar reduction in the integral parameters for the wall layer developing under a turbulent freestream.

The variation of C_f on the second plate with R_θ is shown in Fig. 4. Generally the trend is close to the relation given by Coles for all of the six cases. It is evident from the figure that the layer evolving from the near wake has C_f marginally lower than the reduction as a consequence of the increase in the value of R_θ due to the thickening of the layer. However, the values of C_f for the layer evolving from intermediate wake are slightly higher than the values at the same R_θ compared to the equilibrium layer. The marginal increase in C_f for these cases is partly due to higher wake turbulence as a consequence of intense mixing promoted by the intermediate wake.

For cases 2 and 4, where the layer evolves from a near wake, the streamwise turbulence intensity distribution is observed to be only marginally altered from the distribution for the equilibrium layer. For cases 3, 5, and 6, where the layer evolves from an intermediate wake, a significant influence of the wake in the region $y > 0.2\Delta$ is observed. This distribution is like that

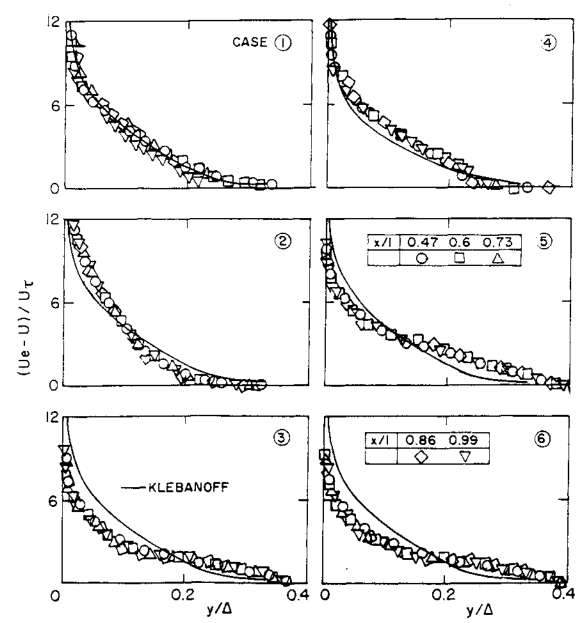


Fig. 3 Velocity defect profiles.

of the wake beyond $y > 0.16\Delta$. The normal turbulence intensities are observed to be reduced by $\sim 50\%$ for case 6 in the region $0.1\Delta < y < 0.3\Delta$. The sudden change in the distribution at $y = 0.16\Delta$ indicates the dominance of the wall ($y < 0.16\Delta$) and of the wake ($y > 0.16\Delta$).

The significant deviations in the Reynolds stress distribution (Fig. 5) are observed for the evolving layer, compared to the distribution of the equilibrium layer. For cases of the layer evolving from the intermediate wake (cases 3, 5, and 6), the stresses are generally very low (as much as 50%, for case 6) in the region $0.1\Delta < y < 0.3\Delta$. The stresses are marginally higher in the region near the edge of the layer because of the earlier turbulence of the upstream wake. The distribution also shows a critical distance $y/\Delta \simeq 0.16$ in the evolving layer which divides the layer into wall-dominant and wake-dominant zones. The profiles are approximately similar. The distribution of normal intensity across the layer showed almost identical features like those of Reynolds stresses. Since the contribution of the large-scale motion to the normal intensity is the result of the efficient turbulent mixing, the low Reynolds stresses indicate very poor efficiency of turbulent mixing across the layer, illustrating lack of coherence of turbulent eddies.

The analysis of the data from the present study, similar to the analysis reported recently by Kiske et al.,[24] attempts to fit the data of both the mean velocity and Reynolds stresses to a framework based on similarity laws. The evolving layer has characteristics of both wake-type and boundary-layer-type regions, and this emerges after a comparison of the profiles of mean velocity (velocity defect) with the distributions of the corresponding quantity in the wake and the constant-pressure boundary layer. The function f representing the mean velocity defect nondimensionalized with appropriate shear velocity shown in Fig. 6 is as follows:

$$f = (U_e - U)/(\tau_{\max}/\rho)^{0.5}$$

for far wake, and

$$f = (U_e - U)/(\tau_w/\rho)^{0.5}$$

for constant-pressure boundary layer, excluding the region close to the wall. Approximate analytical representation for these functions are

$$f = 4.76[1 - (y/\delta)^2]^3$$

for wake and

$$f = -1/k\ \ln(y/\delta) + (0.55/k)\ [2 - 2\sin^2(\Pi y/2\delta)]$$

for the constant boundary layer. Both the mean velocity and the shear stress are referred to the same set of length and velocity scales. Each of these quantities collapses to the universal curve of its own when viewed in terms of these variables, a feature that, as can be observed, is not present anywhere in this strict form in the evolving layer. The length and velocity scales for the wake are (δ_N, U_N), and for the constant-pressure boundary layer they are (δ_W, U_τ). The first set of reference quantities demonstrates the extent of similarity of the evolving layer with the wake. The second set collapses part of the profiles of the evolving layer to the universal curve for the constant-pressure boundary layer. The comparisons were made for both mean velocity and Reynolds stresses measured at five measuring stations for all of the cases studied. In brief, only one sample distribution is given in Fig. 6.

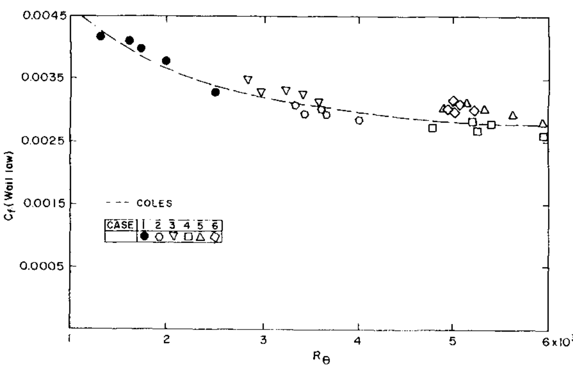


Fig. 4 Skin-friction variation.

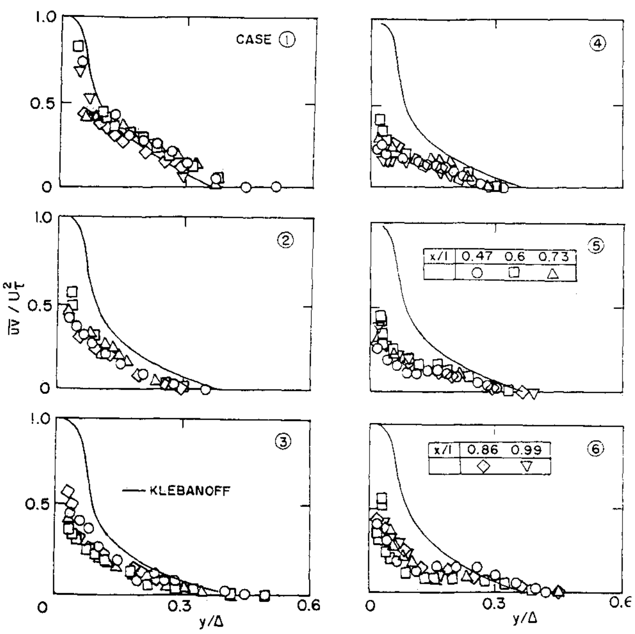


Fig. 5 Reynolds shear stress distribution.

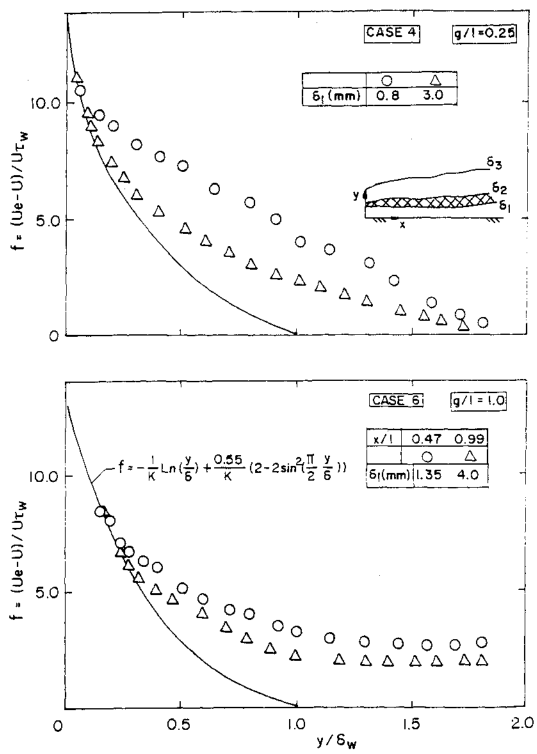


Fig. 6 Defect profiles in boundary-layer variables.

The mean velocity defect profiles for two typical configurations (cases 4 and 6) at two streamwise locations on the plate ($x/l = 0.47, 0.99$) in the boundary-layer variables (δ_w, u_{τ_w}) are shown in Fig. 6. The deviations are visible from the similarity profile. The thickness of the layer δ_1 is estimated from the value of y/δ_w at which these deviations begin to occur. The symbol δ_1 represents the boundary-layer type region ($0 < y < \delta_1$), with its own charactersitic length and velocity scales (δ_w, u_{τ_w}), which are different from those for similarity laws. Similar plots with wake variables give the thickness δ_2, which distinguishes the region $\delta_3 > y > \delta_2$ as the wake-type region, where δ_3 is the full thickness of the layer. Hence, an internal layer ($\delta_1 < y < \delta_2$), which joins the aforementioned regions, is indicated for two cases in Fig. 7, where its growth can be observed. It shows that substantial part of the evolving layer is of the wake type. This is similar to the flows in turbomachinery, where the typical wave lengths of the wake turbulence of the stator row, as seen by the boundary layers of the downstream rotor row, are indeed large due to small local boundary-layer thickness compared to the thickness of the wake.

In the present investigation it was found that both the mean velocity and Reynolds stress profiles showed approximate similarity for all of the cases. Two approaches were attempted for the interpretation of the observed similarity in these evolving shear layers: 1) the straightforward interpretation that, for the given parameters describing the outer flow and the wall conditions, the solution of the governing equation for equilibrium wall layers is not unique, and 2) the possibility of a slowly varying but not so small perturbation on the equilibrium profile. It is well known that the relaxation length for turbulent boundary layers is of the order of 10^3 times the momentum thickness. Since the length of the plate in the present study is of the order of 10^2 times the momentum thickness of the layer, one may anticipate deviations from true similarity. The profiles of $(U_e - U)/U_\tau$, $\overline{uv}/u_\tau^2$ vs y/Δ can be represented in the following form:

$$f(x,y,\alpha) = f_0(\eta,\alpha) + f(\eta,\alpha,x); \quad \eta = y/\Delta = (yu_\tau)/(U_e \cdot \delta^*) \tag{1}$$

where α is the set of parameters describing the oncoming wake.

If we consider large x expansions of the turbulent boundary-layer quantities, studies on the laminar boundary layer suggest that the quantities referred to earlier have the following type of expansions:

$$f(x,y,\alpha) = f_0(\eta,\alpha) + \sum_{i=1} g_i(x,\alpha) f_i(\eta) \tag{2}$$

where $g_{i+1}/g_i \longrightarrow 0$ as $x \longrightarrow \infty$.

If only the first term dominates, we have

$$f(x,y,\alpha) = f_0(\eta,\alpha) + g_i(x,\alpha) \cdot f_i(\eta) \tag{3}$$

On the basis of studies on laminar boundary layers, one would expect g_1 to vary exponentially with x. To examine the possibility of a slowly varying perturbation on an equilibrium profile, an integral parameter Δf is introduced to measure the strength of the perturbation. It is given by

$$\Delta f = \int_0^\infty [f(x,\eta) - f_0(\eta)]^2 \, d\eta \tag{4}$$

where $f(x,\eta)$ is the quantity (e.g., mean velocity) in similarity variables, and $f_0(\eta)$ is the quantity in the similarity profile.

From Eq. (3),

$$\Delta f = g_1(x,\alpha) \int_0^\infty [f_1(\eta)]^2 \, d\eta \tag{5}$$

If g_1 behaves exponentially with x, Δf has to behave like

$$\Delta f = a \exp(-bx/\theta)$$

where θ can be taken as the average momentum thickness or local momentum thickness.

Figures 8 show that $\ln(\Delta f)$ varies linearly with the x/θ to a good approximation. Figure 8a represents the velocity defect profiles, and Fig. 8b represents the turbulence intensity profiles for the six cases. It is clear from the figures that the perturbation decay for the turbulence intensity profiles of the evolved layer is slower than that for the mean velocity defect profiles. The perturbation of the intermediate wake on the layer is much larger than that due to near wake. Also, the wall layer evolving from the intermediate wake (cases 5 and 6) relaxes faster than the layer evolving from near wake (cases 3 and 4). It is also estimated that the half-life distance of the perturbation for the layer is between 50 and 100 times the local momentum thickness.

The distribution of the shear stress correlation coefficient (R_{uv}) across the layer for all of the cases is shown in Fig. 9. Control case 1 has values close to 0.45, which is the normal value for zero pressure gradient layer (Klebanoff[25]). Whereas in all other cases where the wall layer evolves from the upstream wake, the correlation coefficient has qualitatively the same trend as the equilibrium layer but the values are closer to 0.3, except for case 6, which has a value close to 0.4. This reduction of 25–30% from the value for the equilibrium layer is due to low Reynolds shear stress across the layer. Low values of R_{uv} indirectly indicates poor efficiency of the turbulent mixing in the transverse direction, although the mixing is generally enhanced in the evolving layer.

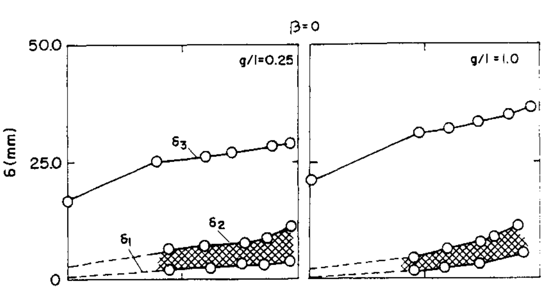


Fig. 7 Growth of internal layer.

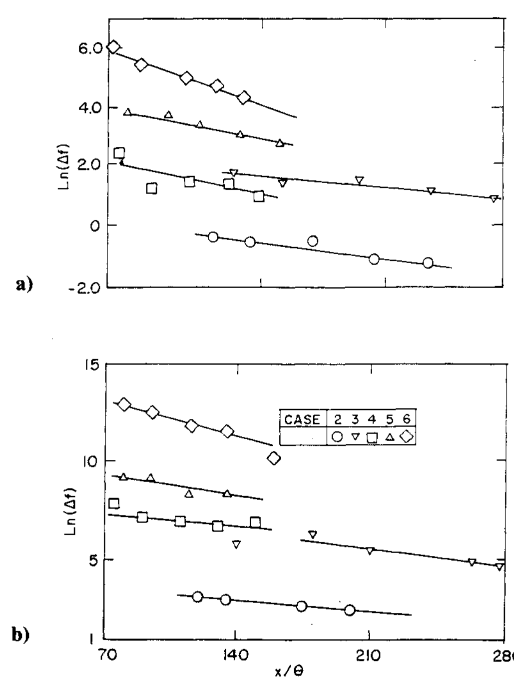


Fig. 8 Perturbation decay rate.

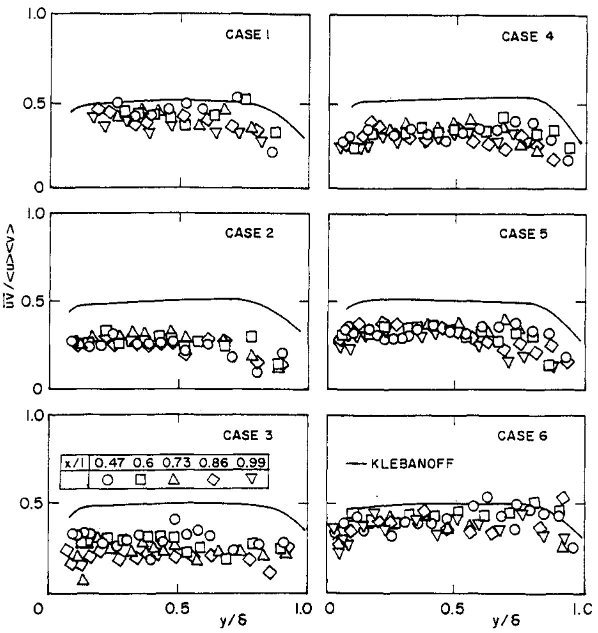


Fig. 9 Variation of shear stress correlation coefficient.

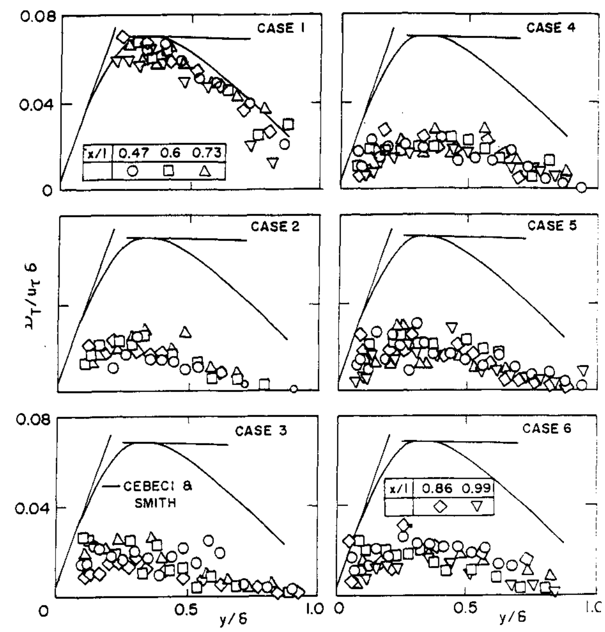


Fig. 10 Eddy viscosity distribution.

The distribution of eddy viscosity in the wall layer is shown in Fig. 10. The popular eddy viscosity model, where the eddy viscosity is scaled with the normal thickness and the friction velocity, fits the observations for the case 1 rather well. It generally gives considerably higher values of eddy viscosity for cases where the layer evolves from the upstream wake, although the observed data seem to have qualitatively similar trends.

Conclusions

An examination of the mean velocity and Reynolds stress data for the six cases studied with the oncoming flow being either freestream or freestream with the flat-plate wake indicate the following features: 1) The wall law is applicable even in these complex flow conditions. 2) A significant influence of the wake is observed in the outer layer. The low wake strength of the evolving wall layer, despite being at higher R_θ, is an indication of subtle changes in the turbulent structures. 3) The evolving layer has a low shape factor accompanied by lower Reynolds shear stress across the layer, indicating enhanced mixing across the layer, although the efficiency of the turbulent mixing is poor in the transverse direction. 4) The layer evolving from the intermediate wake relaxes faster from its perturbed state than the layer evolving from the near wake. 5) The simple correlations and turbulence models with optimized coefficients for application to equilibrium flows need modification for application to complex flows even for this simple configuration.

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