Freestream Turbulence Effects on Attached Subsonic Turbulent Boundary Layers

S. Raghunathan* and R.J.W. McAdam†
Queen's University of Belfast, Northern Ireland

Experimental data on the influence of freestream turbulence in the range 0.3-6% on an attached turbulent boundary layer at zero pressure gradient, at a Mach number of 0.8 and at a momentum thickness Reynolds number of 10^4 are presented. Correlations with the low speed data indicate that there is no influence of Reynolds number on the freestream turbulence/boundary-layer interaction. The skin friction coefficient shows nonlinear effects at low turbulence levels and correlates well with the wall turbulence. The boundary-layer momentum thickness shows an initial increase followed by a decrease in its levels with the increase in turbulence.

Nomenclature

C_f = skin friction coefficient
C_{f0} = skin friction coefficient at zero turbulence
D = rod diameter of turbulence grids
$\tilde{e}_f$ = rms voltage at frequency f
f = frequency
G = Clauser shape parameter
H = shape factor = δ^*/θ
L_ϵ = dissipation length parameter (from Bradshaw[7])
M_∞ = freestream Mach number
$\tilde{p}$ = rms pressure fluctuation
q_∞ = wind tunnel kinetic pressure in the freestream
R_θ, R_δ = Reynolds number based on θ and δ, respectively
Tu = turbulence level = $\tilde{u}/u_\infty$
u = mean velocity
$\tilde{u}$ = rms velocity fluctuation
u_∞ = freestream mean velocity
u_T = friction velocity
y = vertical ordinate
β = nondimensional pressure gradient parameter = $(\delta^*/\tau_w)(dp/dx)$
δ = boundary-layer thickness (at $u/u_\infty = 0.995$)
δ^* = displacement thickness
θ = momentum thickness
ν = kinematic viscosity
π = wake profile parameter
ρ = density
τ_w = shear stress at the wall

Subscripts

∞ = conditions in freestream
w = conditions at wall
0 = conditions at zero turbulence
$(\tilde{\ })$ = rms value

Introduction

THE freestream turbulence levels encountered in practical fluid flow problems can vary over a wide range. For example, the turbulence levels in free flight are very much less than 1% whereas the flow in turbomachines may have turbulence levels of more than 1%. The turbulence in the latter case, however, may include flow unsteadiness which is not isotropic and therefore is not turbulence as it is understood. Turbulence levels in the wind tunnels are relatively higher than the free-flight conditions but lower than those in turbomachines. An understanding of the influence of freestream turbulence on the behavior of turbulent boundary layer is essential in using wind tunnel data for predictions.

For the freestream turbulence whose scale is much larger than that of a turbulent shear layer, the effect of freestream turbulence on the shear layer is very small and the shear layer will obey the same laws as that for a steady flow. Turbulence whose scale is much smaller than that of a shear layer decays rapidly and has no practical relevance. Only turbulence whose scale is of the same order as the thickness of the shear layer is found to have significant effect on the mean properties of the shear layer. Investigations by Kline et al.,[1] Charney et al.,[2] Huffman et al.,[3] Robertson and Holt,[4] Evans,[5] Green,[6] Bradshaw,[7] and Meir and Kreplin[8] have shown that the boundary-layer skin friction and the integral properties of the boundary layer are very sensitive to the freestream turbulence level. However, the freestream turbulence effects may not be very strong at low intensities of turbulence. All of the investigations to date were performed on a low-speed boundary layer and at a low value of momentum thickness Reynolds number, and the influence of compressibility and Reynolds number on the above interaction is not yet understood. This is particularly important in view of the high Reynolds number test facilities already built or being built. This paper presents experimental data on the influence of freestream turbulence on an attached turbulent boundary layer at a high subsonic Mach number of 0.80 and boundary-layer momentum thickness Reynolds number of 10^4. The results are correlated with the low-speed data.

Experimental Program

The experiments were performed in a 10 cm^2 suck-down transonic tunnel which had a running time of 12 s. Only the floor of the test section was slotted. The porosity of the tunnel based on all the four walls was 2.4%. The turbulence in the test section was varied by monoplane grids placed upstream of the test section as shown in Fig. 1. The blockage at this section was kept constant for all the test conditions. The test section Mach number was set by wedge-shaped chokes placed downstream of the test section.

The turbulence boundary layer on the top wall was chosen as the model boundary layer. There was no slot between the end of the wind-tunnel construction, and the top wall of the test section and the boundary layer was fully turbulent from the station where the turbulence grids were introduced. Most of the tests were performed at station 1 (Fig. 1), a distance 750 mm from the turbulence grids. Some tests were performed at station 0 330 mm from the turbulence grids. Earlier experiments have shown that $R_\theta \approx 10^4$ is obtainable at station 1. The freestream Mach number during the tests was 0.80. The

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*Lecturer, Department of Aeronautical Engineering. Member AIAA.
†Research Student, Department of Aeronautical Engineering.

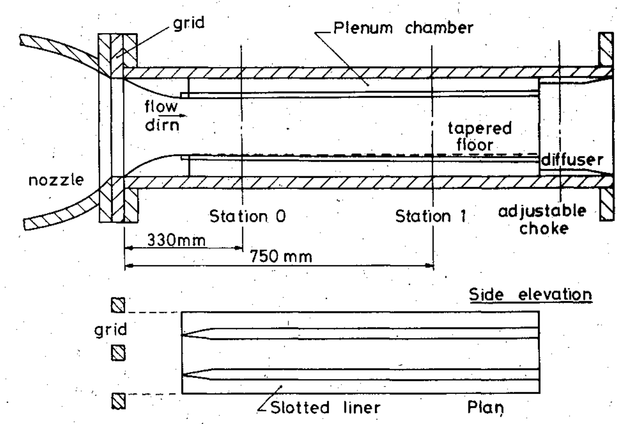

Fig. 1 Position of turbulence grid relative to test section.

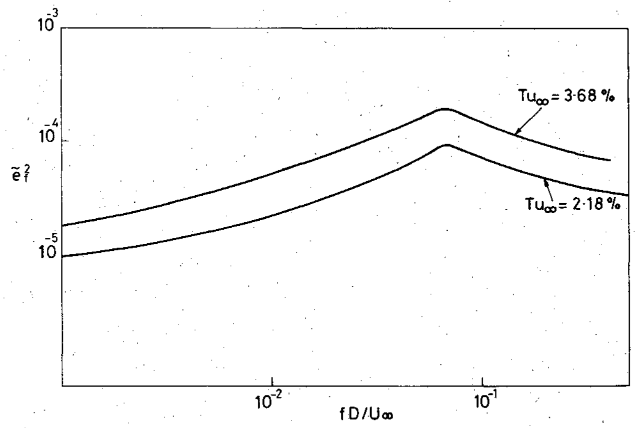

Fig. 2 Spectra of freestream turbulence with Strouhal number based on grid bar diameter.

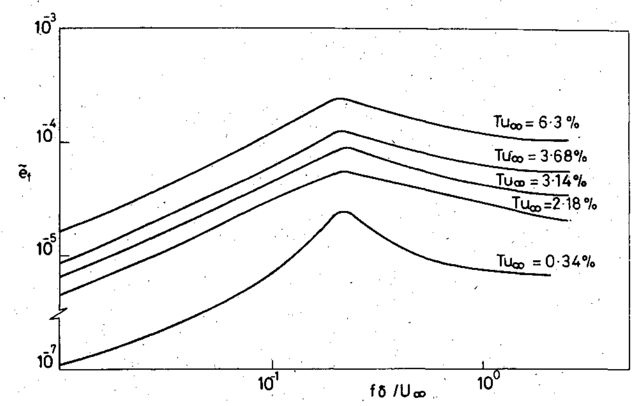

Fig. 3 Spectra of freestream turbulence with Strouhal number based on boundary-layer thickness.

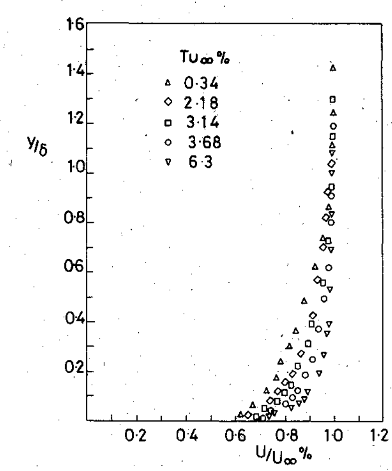

Fig. 4 Nondimensional velocity profiles.

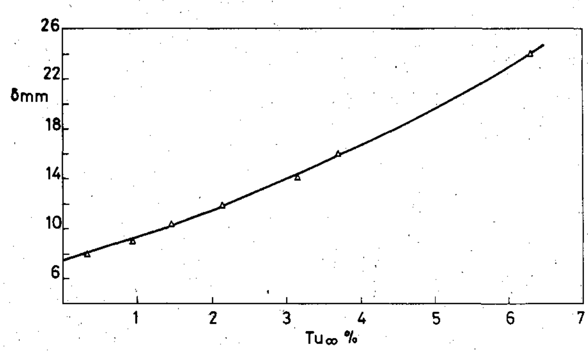

Fig. 5 Variation of boundary-layer thickness with freestream turbulence.

intensity of freestream turbulence at station 1 was varied 0.0034-0.063. However, the turbulence levels of 5% or more may not have been isotropic. The nondimensional pressure gradient parameter was $< \pm 0.2$.

Measurements were made of velocity and turbulence profiles for various freestream turbulence levels, using a pitot tube and DISA constant temperature hot-wire anemometer, respectively. Measurements were also made of pressure fluctuations on the surface by flush-mounted Kistler-type 6031 transducers. Boundary-layer skin friction was measured by a Preston tube.

Results and Discussions

The hot-wire spectra of freestream turbulence at station 0 correlated with the Strouhal number based on the width of the turbulence promoting rods are shown in Fig. 2. For clarity only the cases for the low and high turbulence levels are shown here. The strong correlation at station 0 indicates the presence of vortices shed by the rods. At station 1, however, the correlation was poor and therefore the hot wire was measuring the turbulence rather than the vortex motion. In fact, as shown in Fig. 3 the hot-wire spectra correlate well with the Strouhal number based on the boundary-layer thickness δ for all values of the freestream turbulence. It has been suggested that some of the previous investigations with monoplane grids could have included the effect of vortex shedding.

Approximate estimation of the dissipation length parameter L_ϵ,[7] based on the longitudinal level of turbulence alone, revealed that L_ϵ/δ is within a range of 1-7, which is comparable to the L_ϵ/δ values of the other investigations. The influence of freestream turbulence is not expected to depend critically on the scale of turbulence when L_ϵ is of the same order as δ.

The nondimensional velocity profiles for various levels of turbulence are shown in Fig. 4. Increase in the freestream turbulence results in flatter velocity profiles, implying an increase in the momentum transport across the boundary layer with the increase in the freestream turbulence.

In Fig. 5 is shown the strong influence of Tu on δ. Typically the value of δ is larger by 10% at $Tu = 0.01$ when compared with δ_0, the value of δ as $Tu_\infty \rightarrow 0$. The variation of δ with Tu_∞ is nonlinear.

The combined effect of the flattening of the velocity profiles and the increase in δ results in significant changes in the nondimensional integral properties of the boundary layer, δ^*/δ, θ/δ, and H as shown in Fig. 6. The trends are similar to those obtained in low-speed flows and at low R_θ values.

The law of the wall plots are shown in Fig. 7. The skin friction values for these plots are based on Preston tube

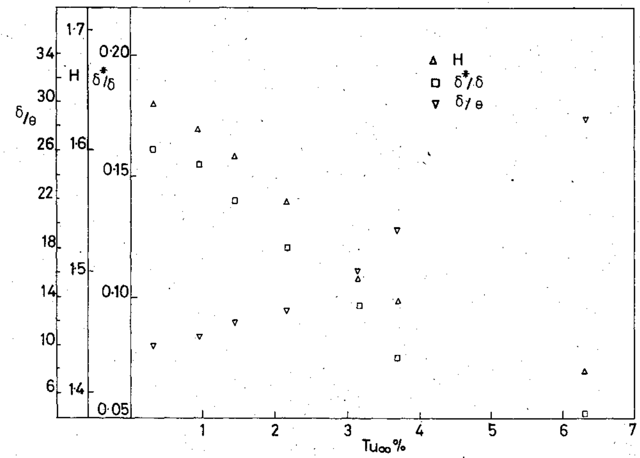

Fig. 6 Variation in nondimensional integral properties of the boundary layer.

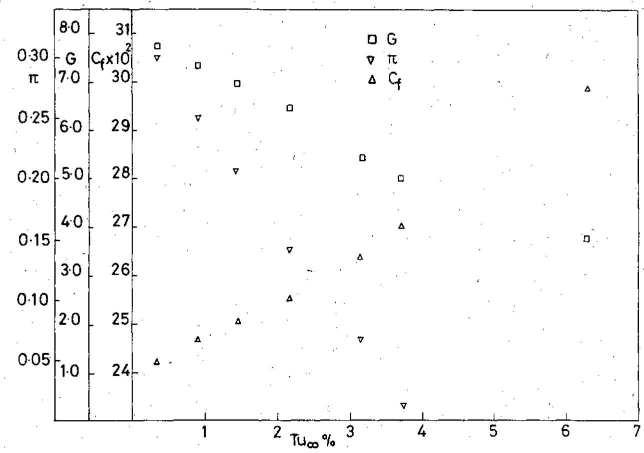

Fig. 8 The influence of freestream turbulence on skin friction, wake profile parameter, and Clauser shape.

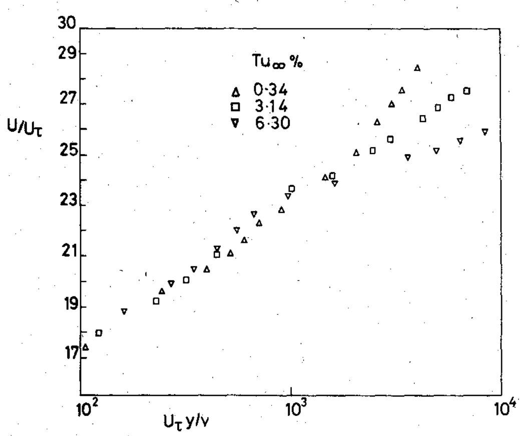

Fig. 7 Variation in law of the wall plots.

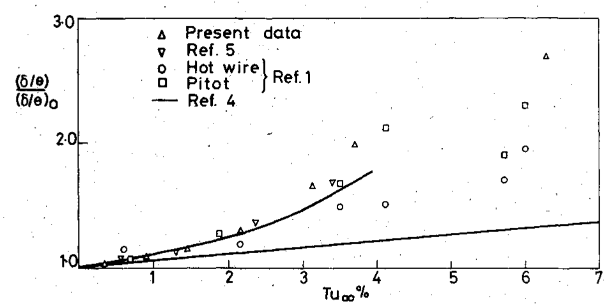

Fig. 9 Variation of ratios of boundary-layer and momentum thickness with freestream turbulence.

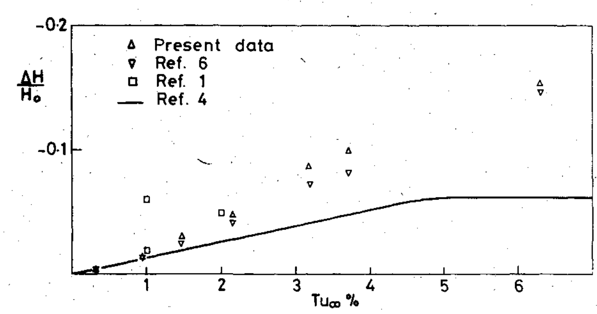

Fig. 10 Influence of freestream turbulence on the shape factor.

measurements. These plots show that the law of the wall of the form

$$u/u_\tau = A + B \log (u_\tau y/\nu) \quad (1)$$

holds good for all the values of Tu, confirming that the law of the wall is unaffected by the changes in Tu_∞. A close look at these plots indicates that the values of A and B may be dependent on Tu_∞, which is contradictory to what is generally understood. The outer layer, however, is very sensitive to Tu_∞.

The influence of Tu_∞ on C_f, π, and G are shown in Fig. 8. The increase in Tu_∞ results in an increase in C_f and decreases in π and G. π and G are calculated from the expressions given in Ref. 9.

The variation of $(\delta/\theta)/(\delta/\theta)_0$ with Tu_∞ is shown in Fig. 9. Also shown in the figure are the results of Robertson and Holt,[4] Evans,[5] and Kline et al.[1] The Robertson and Holt results show a linear relationship

$$(\delta/\theta)/(\delta/\theta)_0 = 1 + 5Tu_\infty \quad (2)$$

This linear prediction appears to be accurate only up to $Tu_\infty = 0.01$, beyond which it underestimates the effect of Tu_∞. The present results agree well with those of Evans[5] and Kline et al.[1] up to $Tu_\infty \simeq 0.04$. For $0.040 < Tu_\infty < 0.06$ the present results show a larger variation of $(\delta/\theta)/(\delta/\theta)_0$ with Tu_∞ when compared with the rest of the data. A curve fit of the form

$$(\delta/\theta)/(\delta/\theta)_0 = 1 + 500\, Tu_\infty^2 \quad (3)$$

is a reasonably good representation of data for $0 < Tu_\infty < 0.04$. Within the scatter of the data the influence, if any, of R_θ is not noticeable.

The influence of Tu_∞ on $\Delta H/H_0$ is shown in Fig. 10. The present results are in close agreement with those of Green[6] and Kline et al.[1] The Robertson and Holt[4] data underestimate the freestream turbulence effects on $\Delta G/H_0$. Green's[6] prediction of

$$\Delta H/H_0 = -2Tu_\infty \quad (4)$$

seems to be an adequate fit for $0 < Tu_\infty < 0.06$. Once again there is no noticeable effect of R_θ on these results.

Figure 11 shows a plot of $\Delta G/G_0$ with $\tilde{u}/u_\tau$. The present results are in close agreement with the rest of the data.[2,3,5,6] The variation of $\Delta G/G_0$ with $\tilde{u}/u_\tau$ is linear and Green's[6] prediction of

$$\Delta G/G_0 = -1/3(\tilde{u}/u_\tau) \quad (5)$$

is a good representation of data.

The variation of $\Delta\pi/\pi_0$ with $\tilde{u}/u_\tau$ is shown in Fig. 12. The present results agree well with those of Charney et al.[2] The

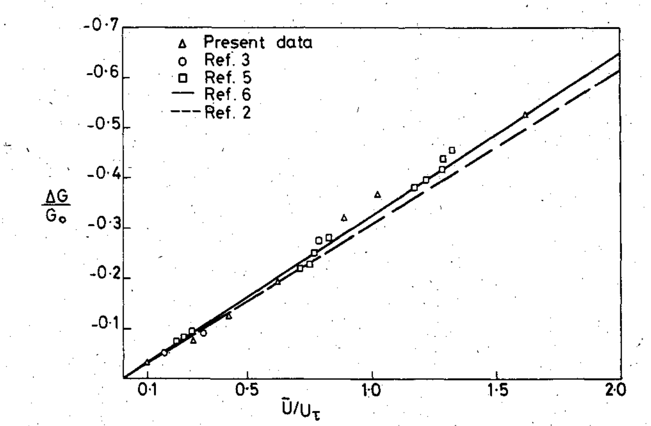

Fig. 11 Correlation of variations in Clauser shape parameter with u/u_τ.

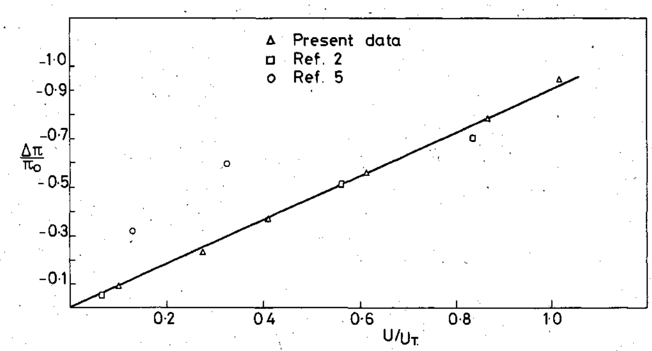

Fig. 12 Correlation of variations in wake profile parameter with u/u_τ.

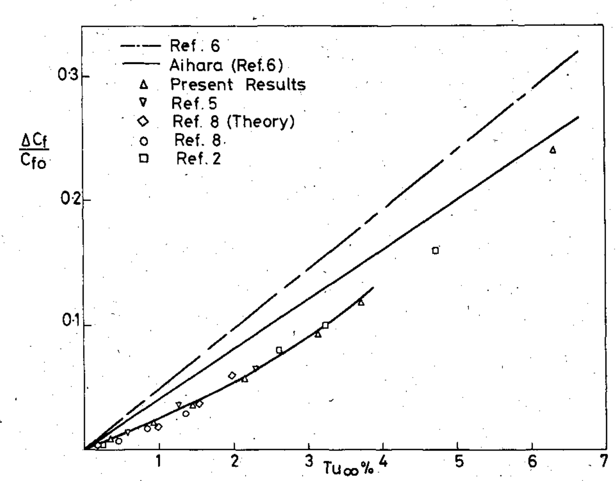

Fig. 13 Variation of skin friction with freestream turbulence.

limited data for Evans[5] show a larger influence of $\bar{u}/u_\tau$. The data can be represented by a straight line fit

$$\Delta\pi/\pi_0 = 0.9\bar{u}/u_\tau \tag{6}$$

and from Green[6] and Charney[2]

$$\Delta\pi/\pi_0 = -2.7\Delta G/G_0 \tag{7}$$

The influence of Tu_∞ on $\Delta C_f/C_{f0}$ can be observed from Fig. 13. All of the experimental data show a unique relationship. The predictions of Green[6] and Aihara[12] considerably overestimate the skin friction changes. The data also show nonlinear effects at low turbulence levels. It has been suggested by Bradshaw[7] that at low turbulence levels the

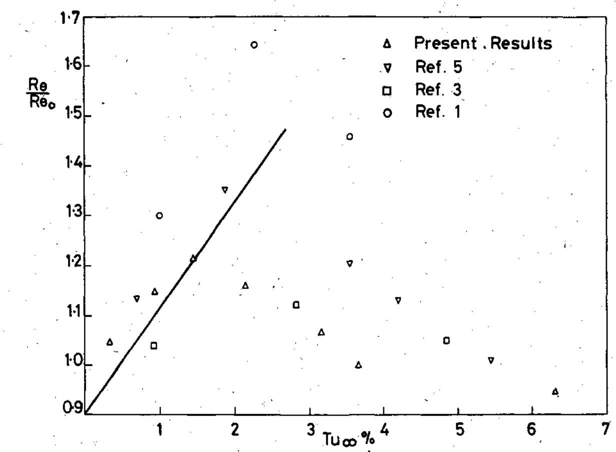

Fig. 14 Variation of Reynolds number based on momentum thickness with freestream turbulence at fixed location.

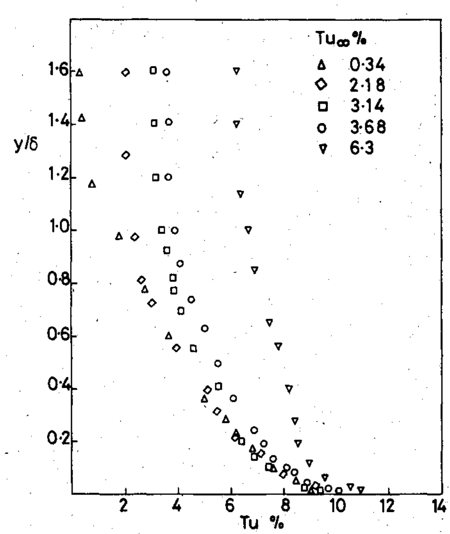

Fig. 15 Distribution of turbulence within the boundary layer for different freestream levels.

freestream turbulence does not correlate with the boundary-layer eddies producing this nonlinear effect. All the experimental data can be represented by a curve fit

$$\Delta C_f/C_{f0} = 12.6Tu_\infty^{1.4} \tag{8}$$

for $0 < Tu_\infty < 0.04$. There is no noticeable influence of R_θ in the range 3×10^3-10^4 on this plot. Hancock[11] refers to the influence of Tu_∞ on $\Delta C_f/C_{f0}$ as a nonlinear relationship not only for $Tu_\infty < 1\%$ but also for $Tu_\infty > 1\%$, his proposed skin friction correlation agrees with Eq. (8) for $L_\epsilon/\delta \approx 1.5$. An approximate linear relationship can be

$$\Delta C_f/C_{f0} \approx 2.5Tu_\infty \tag{9}$$

for $0 < Tu_\infty < 0.02$.

Bradshaw[7] gives an expression

$$\Delta C_f/C_{f0} = 3.2Tu_\infty \tag{10}$$

The momentum thickness Reynolds number is very sensitive to turbulence as seen from Fig. 14. One of the reasons for the scatter in data for $\Delta R_\theta/R_{\theta 0}$ is due to the limitation of the available data and therefore the inaccuracies in estimating $R_{\theta 0}$. The general trend is an initial increase in $R_{\theta 0}$ up to $Tu_\infty \approx 0.02$ and then a decrease in R_θ. This trend is due to a combined effect of the thickening of and flattening of the

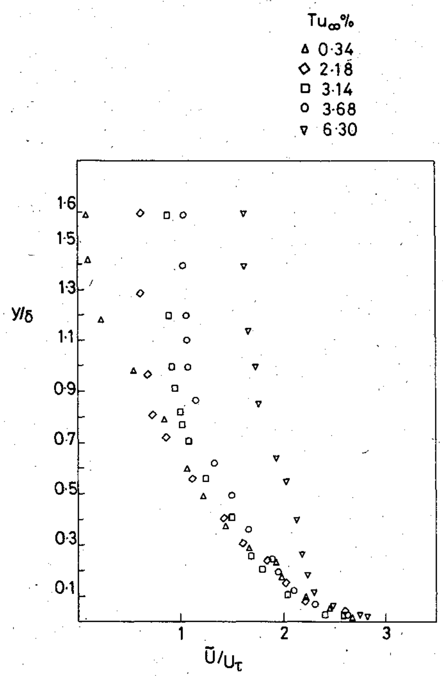

Fig. 16 Variation of $\tilde{u}/u_\tau$ in boundary layer for different freestream turbulence levels.

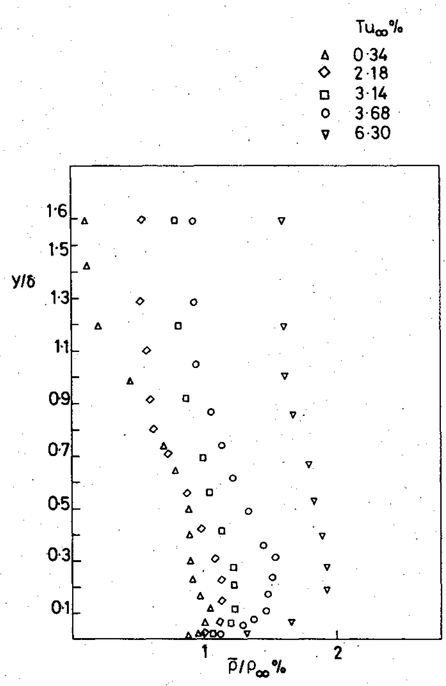

Fig. 17 Variation of density fluctuations in boundary layer for different freestream turbulence levels.

boundary layer with the increase in Tu_∞.

Using the relationship of the form

$$\sqrt{2/C_f}=A_l \ln R_\theta + B_l \tag{11}$$

Green[6] has shown that

$$\Delta R_e/R_\theta = 0.27/C_f - 0.97\sqrt{2/C_f}\,Tu_\infty \tag{12}$$

which is a function of C_f and Tu_∞ and results in a decrease in R_θ with an increase in Tu_∞. The experimental data are in disagreement with this trend for $0<Tu_\infty<0.02$. However it must be mentioned that Green's analysis is for constant value of H, whereas the value of H was a variable in this plot. Neglecting the data of Kline et al.[1] which show large variations in $\Delta R_\theta/R_{\theta 0}$, the influence of Tu_∞ on R_θ can be approximately expressed as

$$\Delta R_\theta/R_\theta \approx 15 Tu_\infty \tag{13}$$

for $0<Tu_\infty<0.02$.

The distributions of turbulence within the boundary layer for the various levels of freestream turbulence are shown in Fig. 15. The turbulence levels in the outer layer are sensitive to the freestream turbulence, whereas the turbulence levels near the wall do not change appreciably with the changes in the freestream turbulence. A plot of $\tilde{u}/u_\tau$ with y/δ as shown in Fig. 16 indicate that near the wall the value of $\tilde{u}/u_\tau$ tends to a constant value

$$(\tilde{u}/u_\tau)_w \approx 2.8 \tag{14}$$

which agrees closely with the results of Charney et al.[2]

This gives a value of

$$C_f = \tfrac{1}{4} Tu_w^2 \tag{15}$$

where $Tu_w = (\tilde{u}/u_\infty)_w$.

This shows that the skin friction coefficient varies as the square of the turbulence level near the wall.

The density fluctuations within the boundary layer interpreted from hot-wire measurements are shown in Fig. 17. As the changes in density fluctuation levels cannot be associated with the changes in turbulence (vorticity), they must arise due to the changes in entropy or noise levels in the tunnel. Pressure fluctuation measurements with a flush-mounted transducer on the wall at station 1 showed a change in $\tilde{p}/q_\infty$ from 0.65 to 2.05% when Tu_∞ is changed from 0.0034 to 0.063, showing a change in tunnel noise levels with the change in the turbulence grid. This was confirmed by pressure fluctuation level measurements in the settling chamber which varied with the changes in Tu_∞. Obviously, the noise is due to the vortex shedding at the grid. Earlier experiments,[10] however, have shown that the influence of noise on the boundary layer is negligible, in the range $0.006<\tilde{p}/q<0.015$.

Conclusions

Experimental investigations on a zero pressure gradient boundary layer at $M_\infty=0.8$ and $R_\theta \approx 10^4$ have shown that there is no Reynolds number or Mach number effect on the freestream turbulence/boundary-layer interaction. The skin friction coefficient showed nonlinear effects at low freestream turbulence levels and correlated very well with the turbulence level near the wall. These nonlinear effects were also observed by Hancock. The influence of the increase of freestream turbulence on the momentum thickness Reynolds number is to produce an initial increase in the latter up to a turbulence level of 2% followed by a decrease.

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