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A Study of a Turbulent Boundary Layer Downstream of a Sudden Decrease in Wall Heat Flux

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SUMMARY Measurements are made of the mean and fluctuating temperature fields downstream of a sudden decrease in wall heat flux in a zero pressure gradient turbulent boundary layer. When the internal thermal layer thickness (δ_i) and maximum temperature difference across the layer are used as the normalising length scale and temperature scale respectively, mean, rms and higher order moments of the temperature are self-preserving, at least over the outer part of the internal layer. The temperature jump at the back of the large structure is observed across the major part of the boundary layer both upstream and downstream of the step.

1 INTRODUCTION

There have been several investigations of the turbulent boundary layer downstream of sudden changes in surface conditions (such as roughness or heat flux; these occurring either separately or in combination) primarily in view of their relevance to the atmospheric boundary layer. In the present investigation, the wall heat flux (Q_W) is constant upstream of the step. Downstream of the step the wall heat flux is zero and the wall temperature T_W is nominally equal to the free stream temperature T_1. Charnay et al (1977) measured the mean and fluctuating temperature fields downstream of a sudden decrease in wall temperature, but did not attempt to explain their results in the context of a self-preserving growth of the thermal disturbance introduced by the new boundary condition.

2 EXPERIMENTAL SETUP AND CONDITIONS

The boundary layer was developed, under zero pressure gradient, over the smooth wall of the working section (0.38 m × 0.23 m) of the wind tunnel. The first 3 m of the working section floor was heated while the last 1.83 m was unheated and constructed from an insulating material (0.025 m thick "Sindanyo" hard asbestos board with an epoxy coating) polished to a smooth flat surface. Immediately upstream of the step $T_W-T_1 \simeq 11°C$. The kinematic and the thermal boundary layers were fully developed at the step and the effect of buoyancy was negligible.

Mean (T) and rms temperature θ' measurements were made with a 0.6 μm Pt-Rh cold wire (temperature coefficient $1.5 \times 10^{-3}°C^{-1}$ operated by a constant current (50 μA) anemometer. Mean and rms voltages were measured with a DISA 55D31 digital voltmeter and a DISA 55D35 rms meter respectively. Higher order moments of temperature fluctuations θ, were obtained by digitising the signal recorded on a Hewlett-Packard FM3960A recorder at a sampling frequency of 4 kHz and then processing it on a PDP 11/20 computer. A preliminary investigation of the coherent structure of the boundary layer both upstream and downstream of the step has been made with a rake of 11 cold wire probes. In the construction of the rake, use was made of a double-sided printed circuit (p.c.) board which supports the probes. Each probe is made by soldering 0.5 mm dia. brass pins which form the prongs, to either side of a narrow (2 × 1 mm) strip of printed circuit board.

Experimental results were obtained at streamwise stations x_s/δ_0 of 0.19, 0.54, 1.69, 2.94, 5.73, 8.75, 12.83 and 20.17 (x_s is the streamwise distance from the step and δ_0 is the boundary layer thickness at the step = 63 mm) at a free stream velocity, U_1, of 14.5 ms^{-1}.

3 RESULTS AND DISCUSSION

Since (T_W-T_1) and Q_W are zero downstream of the step, the maximum of the mean temperature profile occurs at increasing values of y as x_s increases. Antonia & Luxton (1971, 1972) determined δ_i for a boundary layer subjected to a step change in surface roughness, by inferring the "merge" point between consecutive mean velocity profiles. A similar approach was used here to find δ_i for the internal layer. Due to experimental scatter in mean temperature profiles, only a rough estimate of δ_i was possible. A more satisfactory estimate of δ_i was inferred from merge points of rms temperature profiles with the upstream undisturbed profile, as shown in Fig. 1. The abscissa is normalised with the local kinematic boundary layer thickness (δ), to compensate for the small streamline displacement effect. δ_i is chosen as the point at which the slope of the θ' profile downstream of step matches that of the θ' profile at $x_s = -0.04$ m.

The experimental data for δ_i are shown in Fig. 2, with the fit $\delta_i \simeq 0.61\, x_s^{0.64}$. There is only moderate agreement between the present slope and that inferred from Charnat et al's four values of δ_i. Interestingly, Antonia et al (1977) obtained $\delta_\theta \propto x_s^{0.64}$, where δ_θ is the distance from the wall at which $\theta' = 0.01\,(T_W-T_1)$, for the growth of the internal layer downstream of a sudden increase in wall heat flux. The rate of propagation of the thermal disturbance seems to be independent of the nature of the change in boundary condition. This is at variance with observations downstream of a step change in roughness (Antonia & Luxton, 1971, 1972) where $\delta_i \propto x_s^{0.79}$ for a smooth to rough step and $\delta_i \propto x_s^{0.43}$ for a rough to smooth step. To obtain an analytical estimate of δ_i, Townsend's (1965) conditions for the self-preservation of the mean temperature cannot be used effectively in the present case as thermal equilibrium is not likely to be satisfied in the region close to the wall (both Q_W and $\partial T/\partial y$ are zero in this region). The calculation method of Bradshaw & Ferriss (1968) gives the equation for the outgoing characteristic from $x_s = 0$, provided advec-

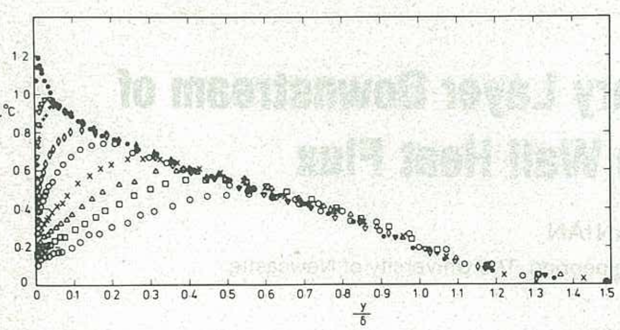

Figure 1 Rms temperature profile. •, x_s/δ_0 = -0.63; ∇, 0.19; +, 0.54; ◇, 1.69; ○, 2.94; x, 5.73; Δ, 8.75; □, 12.83; ⬡, 20.17

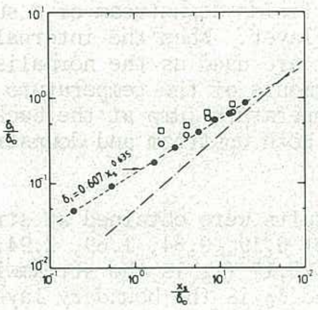

Figure 2 Growth of the interal layer δ_i. •, present data; values of Charnay et al's (1977) δ_i values: ○, from mean temperature profile; □, from rms temperature profile; -·-·-, Bradshaw & Ferris (1968) calculation

tion and diffusion of θ'^2 are negligible. These terms are small compared with production and dissipation in the outer region of the internal layer in the θ'^2 budget of Charnay et al (1977). Identifying the lateral position of the characteristic with δ_i this equation can be written as

$$\frac{d(\delta_i)}{dx} = \frac{(a_{1\theta}^{2}\ \tau)^{\frac{1}{2}}}{U} \tag{1}$$

where τ is the kinematic Reynolds shear stress $-\overline{uv}$ and $a_{1\theta}$ is a structure function parameter defined by

$$a_{1\theta} = \frac{\overline{v\theta}}{\theta'\tau^{\frac{1}{2}}} \tag{2}$$

with U given by

$$\frac{U}{U_\tau} = \frac{1}{\kappa}\ \ell n\ \frac{yU_\tau}{\nu} + c \tag{3}$$

Equation (1) can be integrated to give

$$\delta_i[\ell n(\delta_i/z_0) - 1] = \kappa\ a_{1\theta}\ x \tag{4}$$

where $z_0 = \nu\ e^{-\kappa c}/U_\tau$ is a "roughness parameter" and $\kappa \approx 0.41$ (ν is the kinematic viscosity). The distribution of $a_{1\theta}$ (Fig. 3) is shown for Charnay et al's data, using the self-preserving distribution of Klebanoff (1955). Although $a_{1\theta}$ is not constant, it is independent of x_s in the internal layer when plotted against y/δ_i. The calculated δ_i distribution (shown in Fig. 2) is obtained from equation (4) using $a_{1\theta}$ = 0.7 (i.e. the value at the experimentally inferred position of δ_i). The calculated growth rate of δ_i is appreciably larger than the experimental curve.

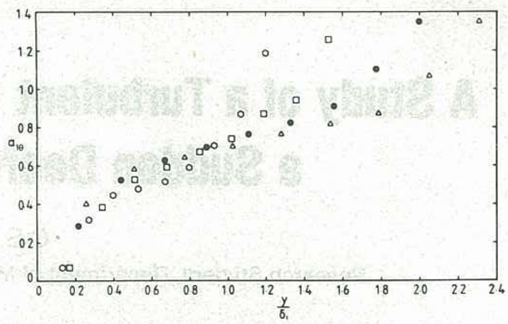

Figure 3 $a_{1\theta}$ distribution. Δ, x_s/δ_0 = 2.04; •, 4.08; □, 7.14; ⬡, 14.29

Mean temperature profiles downstream of the step in Fig. 4 show similarity in the region $0.05 < y/\delta_i < 0.6$, when δ_i is used as the relevant length scale and $(T-T_1)$ is normalised by (T_m-T_1), T_m being the local maximum temperature. The temperature profile has zero slope at $y/\delta_i \simeq 0.1$. For $y/\delta_i < 0.05$, profiles cannot be expected to be self preserving because the thermal production is very weak, and the flow there is far from local equilibrium as evidenced by Charnay et al's θ'^2 budget. Their mean temperature results at x_s = 0.35 m shows a peak at $y/\delta_i \simeq 0.25$ and the profile is rather steeper close to the wall, probably due to the fact that there was conduction across their downstream plate, maintained at about 3°C below their free stream temperature.

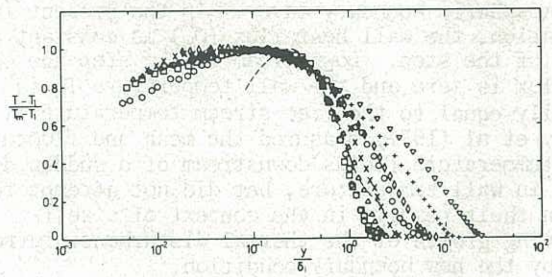

Figure 4 Normalised mean temperature profile. Symbols same as in Fig. 1. --- Charnay et al (1977) x_s = 0.35 m

The θ' (normalised by T_m-T_1) profiles (not shown here) downstream of the step exhibit reasonable similarity for $0.05 < y/\delta_i < 1.4$. The maximum value occurs at $y/\delta_i \approx 0.8$, which corresponds roughly to the location where the slope of the mean temperature profile is maximum. Charnay et al observed a second maximum in production close to the wall outside the viscous sublayer.

Since the signal to noise ratio of θ decreases with x_s, the internal layer interface could not be studied in detail and conditional measurements associated with this interface were not attempted. However a few normalised high order moments $\overline{\theta^n}/\theta'^n$ (n = 3 to 6) were evaluated at x_s/δ_0 = 12.83 and 20.17 (Fig. 5). The distributions of these moments are in good agreement at the two values of x_s for $y < \delta_i$. This supports previous evidence from the mean and rms temperature profiles for self-preservation of the internal layer. The skewness (n = 3) is positive in the region $y/\delta_i < 0.017$ presumably because of the arrival of hotter fluid from the outer part of the internal layer. The negative skewness in the region $0.017 < y/\delta_i < 0.8$ may reflect the arrival of the cold fluid from the wall region or from the outer part of the boundary layer. The distribution of $\overline{\theta^5}/\theta'^5$ is in qualitative agreement with the previous results. In the external part of the boundary layer both even and odd order

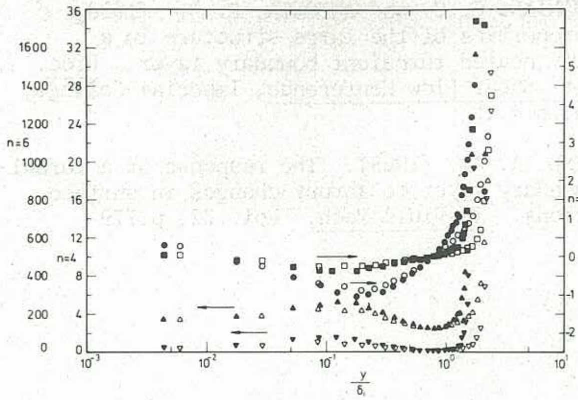

Figure 5 $\overline{\theta^n}/\theta'^n$ distribution. o, n = 3; Δ, 4; □, 5; ∇, 6; open symbols x_s/δ_0 = 8.75; closed symbols x_s/δ_0 = 20.17

moments increase rapidly as a result of outer layer intermittency. It is worth pointing out that the fourth and sixth order moments exhibit a minimum near $y = \delta_i$. At this location, the even order moments are approx. zero. It is also of interest to note that Antonia & Luxton (1974) observed peaks in the skewness and flatness factor of u at $y \approx \delta_i$ for a smooth to rough step change. No peaks were observed for a rough to smooth step near $y = \delta_i$, presumably because the statistics of u near the edge of the internal layer were dominated by the relatively high turbulence intensity of the upstream rough wall boundary layer.

The temperature traces (Figs. 6b, c) obtained with the rake downstream of the step show the same jumps (end of the ramp) at the back of the large structure that have been observed (e.g. Fig. 6a) in a continuously heated flow (e.g. Chen & Blackwelder, 1978; Subramanian & Antonia, 1979). Although the temperature at the wall is approximately equal to that in the free stream, the temperature jump occurs from hot to cold at the back of the large structure, in the layer near the wall as well as in the outer layers. Blackwelder & Chen (1978) have explained the temperature front as a demarcation line between the high speed fluid on the upstream side and the low speed fluid downstream. The temperature front provides a possible mechanism by which the large scale structure in the outer intermittent region is related to the bursting phenomenon near the wall. Charnay et al (1977, Fig. 22) showed simultaneous traces at the same x_s of u (in the outer part of the layer) and θ near the edge of the internal layer downstream of an increase in surface temperature. Both the turbulent/irrotational interface and internal interface register the presence of the back of the large structure. The relatively sudden increase in u precedes the sharp decrease in θ at the edge of the internal layer. In Fig. 6c, the sharp decrease in θ certainly penetrates the internal layer, as the mean edge of this layer is at $\delta_i \approx 0.67\ \delta$.

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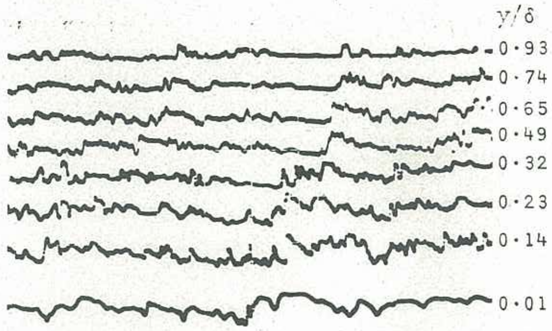

Figure 6 Typical temperature traces with the temperature rake. (a) x_s/δ_0 = -4.33, the bottom-most trace corresponds to $yU_\tau/\nu \approx 21$. Flow is left to right

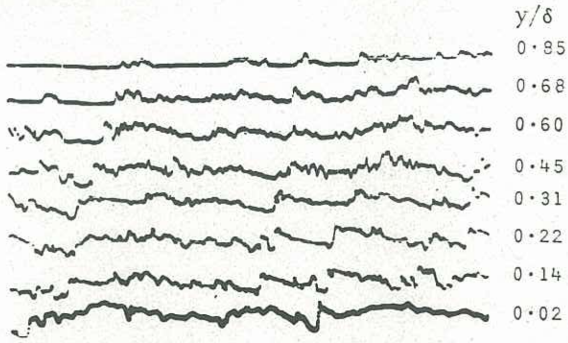

Figure 6 (b) x_s/δ_0 = 1.6, the bottom-most trace corresponds to $yU_\tau/\nu \approx 55$; $\delta_i/\delta \approx 0.17$

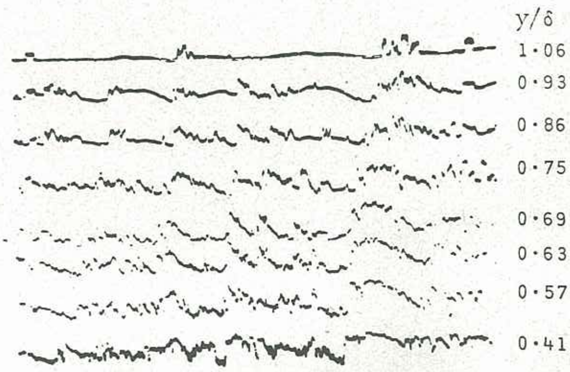

Figure 6 (c) $x_s/\delta_0 \approx 20.17$; $\delta_i/\delta \approx 0.67$

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