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THE TURBULENT BOUNDARY LAYER OVER A FLAT PLATE WITH STRONG STEPWISE HEATING

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The turbulent boundary layer over a flat plate with stepwise heating causes expansion of the boundary layer, but the effects of heating on the mean and RMS velocities are small. The Reynolds stress near the surface is reduced due to the density decrease. The most important effect of the strong stepwise temperature rise is to change the turbulent kinetic energy diffusion pattern. Significant streamwise diffusion of kinetic energy is induced near the leading edge of the heating section, suggesting that in modeling this flow a modification of the boundary layer assumption would be required in this region.

1. INTRODUCTION

The turbulent boundary layer over a flat plate with a stepwise change in surface temperature is a basic non-isothermal fluid mechanical
problem of practical importance to many engineering applications. The majority of the studies on this problem to date have been focused on cases with small wall temperature rise so that the dynamic properties of the isothermal flow are unaffected. Some examples of such studies are the works by Johnson and Whippany, Johnson, Blom, and Antonia et al. These workers examined the statistical behaviors of the velocity and thermal fields and found that the temperature fluctuation was intermittent well within the fully turbulent region of the velocity boundary layer, and that the turbulent Prandtl number was not constant.

One of the more thoroughly studied boundary layer flows in which the density effects are significant is the compressible boundary layer. Most of the works on this subject are concentrated on fully developed boundary layer with different wall temperature and free stream Mach numbers. In general, many of the turbulence parameters measured in the compressible boundary layer are similar to incompressible data both in trends and magnitude, indicating a Mach number independence.

The study of the turbulent boundary layer over a strongly stepwise heated surface in which the dynamical effects of the density gradient become important has not been very extensive. Rotta studied the boundary layer over a flat plate with strong surface heating, with the thermal and velocity boundary layer having effectively the same origin. Based on semi-empirical analysis, he derived the friction coefficient and the Stanton number from the mean velocity and temperature profiles. Nicholl examined the dynamical effects of a sudden increase of up to 100°C in boundary temperature on fully turbulent boundary layers on the floor and the roof of a wind tunnel. He found that buoyancy effects of the density gradient on the floor generated a local wall jet downstream of the temperature discontinuity. On the roof, the density gradient had a stabilizing effect and the turbulence was suppressed.

The objective of the present study was to investigate the turbulent boundary layer over a flat plate with strong stepwise wall temperature rise. Thermal structures in the heated boundary layer were observed using high-speed schlieren cine. Mean and root-mean-square (rms) density distributions were obtained from Rayleigh scattering intensity measurements. Velocity statistics were provided by a single-component laser Doppler velocimetry (LDV) system. Mean and rms velocity profiles, the Reynolds stress, and the turbulent kinetic energy diffusion were derived.

2. EXPERIMENTAL SET-UP AND DATA REDUCTION

Details of the experimental set-up and data reduction procedure are available in Ng. The boundary layer flow was developed over the floor of a 75 cm long, 10 cm wide channel made up of three equal length segments. The first floor segment was lined with sand paper to trip the boundary layer. The second segment was water-cooled to maintain it at room temperature. The third segment was a heating section made up of nine heating strips stretched spanwise across a ceramic block, and was left opened for measurement accessibility.
A 4-watt argon-ion laser was used as the light source with the 488 nm line used for the schlieren system and Rayleigh scattering measurements, and the 514.5 nm line for the LDV system. The schlieren system incorporated an 18 mm and two 1.0 m focal length lenses and a knife edge to form schlieren images which were filmed with a Fastax WF-17 16 mm high-speed camera operating at about 3000 frames/sec.

The basic operating principles of LDV are described in many references (e.g., Durst et al., Stevenson). The dual beam, real fringes system used in our experiment consisted of a 51 mm separation beam splitter and a 600 mm focal length lens with the collecting optics in the forward scattering direction. Aluminum oxide powder of 0.30 m nominal diameter was used as seed particles.

The basic principle of deducing density information from Rayleigh scattering intensity measurements is described by Pitz et al. and Rambach et al. In our system, an 18 mm focal length and a 120 mm local length lens were combined to form a lens system to focus the laser beam to a waist diameter of about 100 m. Light scattered from the 1 mm long section centered about the beam waist was collected with the collecting optics at 90° to the beam path.

Data from the LDV and Rayleigh scattering were collected by a computer-based data acquisition and control system shown schematically in Fig. 1. The statistical quantities derived from the measurements are: the mean and rms density, and the mean and rms velocities, and in the streamwise (x) and cross-stream (y) direction respectively; the Reynolds stress, the streamwise and cross-stream turbulent kinetic energy diffusion, and the probability density function and the skewness and flatness factors of the density and velocity measurements; and the velocity and density spectrum. Procedures to obtain these quantities are described in Ng.

3. RESULTS AND DISCUSSIONS

The free stream velocity for both the isothermal and heated flows was set at 10.5 m/s, and the wall temperature of the heated flow at 1250°C, as measured by an optical pyrometer. Two-dimensionality of the flow was checked by inspecting velocity profiles in the horizontal cross-stream direction. At x = 150 mm (the origin is at the midspan point of the leading edge of the heating section), the flow remains fairly uniform at ± 25 mm from the center.

Data were taken at six streamwise stations (Table I). Measurements in the heated flow were made after a "warm-up" period of about one hour to allow the heated surface to reach the steady state. The LDV data validation rate ranged from 12000/sec in the free stream to about 6000/sec near the surface. Data from either the LDV or the Rayleigh scattering system were digitized and recorded by the computer at a rate of 2500/sec and 8192 samples were taken at each location.

Schlieren Photographs

Schlieren photographs of the heated boundary layer are shown in Fig. 2. Existence of identifiable large scale structures, indicated
by dark arrows on the picture, is not apparent until the thermal boundary layer attains sufficient thickness at about $x = 25$ mm. The overall shape of the thermal structures is similar to typical turbulent structures in a boundary layer such as Head and Bandyopadhyay's (16) case of an isothermal boundary layer flow with similar Reynolds number. This indicates that the turbulent structures in a boundary layer are not significantly affected by severe wall heating, except perhaps in regions near the thermal discontinuity.

**Mean and RMS Density and Velocity Profiles**

Detailed analysis of the mean and rms velocity and density profiles of a flow similar to the present experiment have been reported by Cheng and Ng (17); hence only a brief discussion will be presented here. The effect of severe wall heating on the mean streamwise velocity is limited to a slight deceleration near the surface. This agrees with results reported by Nicholl for regions sufficiently far downstream from the temperature discontinuity. The local wall jet reported by Nicholl in regions close to the discontinuity was not observed in our experiment. Rather, volumetric expansion of the fluid causes the expansion of the boundary layer, resulting in increases of the boundary layer thickness, $\delta$, displacement thickness, $\delta_1$, and the momentum thickness, $\delta_m$ (Table I). For the heated boundary layer, the density fluctuation reaches a peak at $y/\delta_T = 0.2$, where $\delta_T$ is the thermal boundary layer thickness, and then drops off near the surface. This is quite different from the results of Johnson (2) and Sreenivasan and Antonia (18) for the case of a small stepwise temperature rise. In Johnson's results, the temperature fluctuation reaches a peak at $y/\delta_T = 0.05$. Sreenivasan and Antonia's results do not show any drop-off in the rms temperature down to $y/\delta_T = 0.1$.

Typical rms velocity profiles, $\hat{u}$ and $\hat{v}$, are shown in Fig. 3. It can be seen that the profiles are quite similar to those measured by Corrsin and Kistler (from Hinze (19)) for a rough surface. Severe heating does not have a significant effect on the rms velocities. The value of $\hat{u}$ is increased slightly very close to the surface. The Richardson number of the flow is estimated to be in the order of 0.01, indicating that turbulence generation by buoyancy effect is not important.

**Reynolds Stress**

Strong heating reduces the Reynolds stress, $-\rho \overline{u'v'}$, near the surface. This is due mainly to the reduction in fluid density. The value of $u'v'$ is essentially not affected. The mixing length, defined as

$$1_m = \left[ - \overline{u'v'} / \left| \frac{\partial \overline{u}}{\partial y} \right| \frac{\partial \overline{v}}{\partial y} \right]^{1/2}$$

for station 5 is plotted in Fig. 4. Both the isothermal and heated case compare well with the Escudier formula (Launder and Spalding (20)) for boundary layer flow.

**Turbulent Kinetic Energy Production and Diffusion**

The production of turbulent kinetic energy by turbulent stress, $-\rho \overline{u'v'} \partial \overline{\delta} / \partial y$, is reduced near the surface by strong wall heating. There is, however, no reduction in the turbulent kinetic...
energy level as indicated by the rms velocities. This suggests that either the dissipation rate has to decrease, which seems unlikely, or other production terms, like the pressure fluctuation-velocity fluctuation interaction, in the kinetic energy balance may be important.

The streamwise turbulent kinetic energy diffusion, $\overline{u'k}$, is shown in Fig. 5 in non-dimensional form. A peak is induced near the surface by strong wall heating. The change in the $\overline{u'k}$ profile is quite rapid near the temperature discontinuity, indicating that significant streamwise kinetic energy diffusion is induced in this region. This probably is a result of the volumetric expansion of the fluid close to the surface.

Some typical cross-stream kinetic energy diffusion profiles, $\overline{v'k}$, are shown in Fig. 6 in non-dimensional form. The effect of volumetric expansion of the fluid on the cross-stream diffusion pattern is also apparent. A second peak in the $\overline{v'k}$ profile is induced near the surface by wall heating, indicating changes in the cross-stream diffusion direction near the surface.

Spectrum

Some typical power spectra of the streamwise velocity are shown in Fig. 7. It can be seen that wall heating has little effect on the general spectral distribution. One interesting observation is that the length scale, obtained by extrapolating the spectrum of the low wave number end, seems to be decreased by strong heating near the surface.

4. SUMMARY AND CONCLUSIONS

The development of the turbulent boundary layer over a flat plate with strong stepwise heating was studied using schlieren photography, Rayleigh scattering measurements, and LDV. The overall shape of the thermal structures observed in the schlieren pictures of the heated boundary layer is similar to that of the large-scale turbulent structures in an isothermal turbulent boundary layer.

Wall heating causes only a small change in the mean velocity profile. No local fluid acceleration due to dilatation is observed. The boundary layer thickness, the displacement thickness, and the momentum thickness are all increased by wall heating. The value of $\overline{u}$ is increased slightly near the surface while $\overline{v}$ remains essentially unchanged.

The Reynolds stress near the surface is reduced by wall heating due to the decrease in fluid density. The production of turbulent kinetic energy is also reduced modestly near the surface.

The major effect of strong stepwise heating on the turbulent boundary layer is the change in the turbulent kinetic energy diffusion pattern. Near the temperature discontinuity, a rapid change in the $\overline{u'k}$ profile occurs, indicating that significant streamwise turbulent kinetic energy diffusion is induced. This suggests that in modeling this flow a modification of the boundary layer assumption would be required near the discontinuity. The cross-stream diffusion pattern is also altered by fluid expansion, with changes of the diffusion direction in parts of the boundary layer. No significant change due to heating is observed in the
velocity spectrum.

ACKNOWLEDGEMENT

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REFERENCES

Table I  Boundary layer thicknesses, displacement thicknesses, and momentum thicknesses of the isothermal and heated boundary layers

<table>
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<th></th>
<th></th>
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<td></td>
<td>x</td>
<td>( \delta_{(.995)} )</td>
<td>( \delta_1 )</td>
<td>( \delta_2 )</td>
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<td>( \delta_{(.995)} )</td>
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Fig. 1  The computer-based data acquisition and control system for Rayleigh scattering and LID measurements
Fig. 2  Schlieren records of the heated boundary layer

Fig. 3  Rms Velocities of the isothermal and the heated boundary at station 6
Escudier Formula:
\[
y/\delta < \gamma/\kappa, \quad l_m/\delta = \gamma y/\delta
\]
\[
y/\delta > \gamma/\kappa, \quad l_m/\delta = \gamma
\]
\[
\gamma = 0.09
\]
\[
\kappa = 0.41
\]

Fig. 4 Mixing lengths of the isothermal and heated boundary layer at station 5
Fig. 5  Streamwise turbulent kinetic energy diffusion at various stations
Fig. 6. Cross-stream turbulent kinetic energy diffusion at various stations.
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