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LDV Measurements of Turbulent Baroclinic Boundary Layers

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Abstract. Described here are shock tube experiments of nonsteady, turbulent boundary layers with large density variations. A dense-gas layer was created by injecting Freon through the porous floor of the shock tube. As the shock front propagated along the layer, vorticity was created at the air-Freon interface by an inviscid, baroclinic mechanism. Shadow-schlieren photography was used to visualize the turbulent mixing in this baroclinic boundary layer. Laser-Doppler-Velocimetry (LDV) was used to measure the streamwise velocity histories at 14 heights. After transition, the boundary layer profiles may be approximated by a power-law function $u \sim u^a$ where $a \simeq 3/8$. This value lies between the clean flat plate value ($a = 1/7$) and the dusty boundary layer value ($a \simeq 0.7$), and is controlled by the gas density near the wall.

Key words: LDV measurements, turbulent boundary layer profiles, baroclinic effects

1. Introduction

At the last symposium a new class of boundary layers was introduced (Kuhl et al., 1992) — baroclinic boundary layers — created by normal shock propagation along a dense-gas layer located on the floor of the shock tube test section. Vorticity was deposited at the layer interface by a baroclinic mechanism $\nabla \rho \times \nabla p$. Wave reflections within the dense (Freon) layer strongly perturbed the vorticity layer, which rolled up into a turbulent boundary layer.

This is not surprising, e.g., the interface is first subjected to shock accelerations, and is thus susceptible to Richtmyer-Meshkov instabilities (Richtmyer 1960, Meshkov 1969). Later, it can be viewed as a Kelvin-Helmholtz mixing layer with strong density effects. In this respect, it can be viewed as a boundary layer version of the Brown and Roshko free shear problem (1974), but is also related to dusty boundary layers.

This class of problems has the advantage that it allows one to study the evolution of a turbulent boundary layer that is created and dominated by inviscid (baroclinic) effects. In particular, detailed measurements are needed to check direct numerical simulations of such boundary layers (e.g., Greenough et al., 1993).

Described here are the results of shock tube experiments performed at the EMI. The diagnostics included LDV measurements of streamwise velocity histories in the boundary layer, and companion shadow photography of the development of the mixing layer. The experiments are described in the next section.

2. Experiment Description

A schematic of the shock tubes test section is shown in Figure 1. A fixture was used that consisted of a narrow plenum chamber covered by a porous surface forming the floor of the test section. Through this floor Freon gas was injected at constant pressure into the shock tube that was initially filled with ambient air. The injection duration and the diaphragm rupture delay were computer controlled.

A differential laser interferometer was used to visualize the pre-shock density gradient normal to the floor. Repeated tests showed that the computer controlled injection procedure led to very reproducible preshock density profiles. The leading edge of the Freon layer was approximately

Fig. 1. Schematic of the test section (lengths in mm)

Fig. 2. Pre-shock density profile of the Freon layer

1000 mm ahead the center of the test section; the actual preshock density profile is shown in Figure 2; for numerical simulations it can be modelled as tanh-profile:

$$\rho/\rho_{air} = 2.8 - 1.8 \tanh [(y - y_c)/h] \quad \text{where } y_c = 6.5 \text{ mm and } h = 9 \text{ mm.} \quad (1)$$

Shadow photographs from the 24-spark Craz-Schardin high speed camera made visible the essential features of the shock-induced flow and the turbulent mixing processes.

The primary diagnostic consisted of a dual-beam Laser-Doppler-Velocimeter (LDV) in combination with 100-MHz transient recorders that eliminate the need for real-time signal processing and make it possible to perform Doppler burst spectrum analysis in a post-processing mode. The LDV system allows one to simultaneously measure the streamwise velocity component at four different heights. The probe volumes — about 125 μm in diameter and 1.2 mm in spanwise extension — were located in the center of both the streamwise and spanwise width of the test section. The characteristics of the spectrum analysis were a compromise between accuracy and data rate. The average data rate was of the order of 180 kHz. The accuracy of the velocity measurements can only be estimated to be around 2 % (because it depends significantly on the signal-to-noise ratio of the optical signal, which can vary over a wide range). Besides this, one must remember that the collected data represent the velocity of tracer particles; thus the accuracy of velocity fluctuations depends upon the frequency response of the particles.

The velocity measurements were accompanied by pressure measurements at the roof of the test section. In addition pressure histories at different heights were obtained with pressure gauges mounted flush into an aluminium plate that was substituted for one of the test section windows in some experiments.

3. Flow Visualization

of a $M_S = 1.4$ shock

The first frames in Figure 3 show the initial interaction with the dense-gas layer and the deposition of vorticity at the interface. The shock front is curved (i.e., retarded) near the wall because of the smaller sound speed in the Freon layer that causes a slower propagation of the shock front. The periodic deformation of the interface observed in the first frames of the shadowgraphs can be explained as follows: the dense gas layer acts like waveguide, whereby the shock reflects between the wall and the interface, and sets up a series of compression and expansion waves that radiate from the layer. The smooth undulated surface of the interface layer is soon broken up into regions characterized by small scale structures in the shadowgraphs; they rapidly spread over the whole interface, indicating the transition to turbulent boundary layer flow.

The second set of frames in Figure 4 show the evolution of the turbulent shear flow. The layer interface is no longer undulated; small scale structures become predominant and first spread from the interface into the boundary layer and at later times also into the freestream region.

Fig. 3. Shadow photography of the flow

Fig. 4. Shadow photography of the evolution of the turbulent boundary layer

4. Streamwise Velocity Histories

Figure 5 shows five sample histories of the streamwise velocity. The height $y = 45$ mm corresponds to the freestream condition; at $y = 30$ mm the probe is located in the transition region, while probes at $y = 20$ mm, 10 mm and 4 mm are in the boundary layer.

The pressure and LDV measurements suggest that there are two characteristic regimes in the development of the shear flow:

1. A periodic regime ($\Delta t \leq 0.75$ ms) — distinguished by large oscillations of the pressure due to the wave reflections in the Freon layer. Corresponding oscillations of the streamwise velocity indicate strong perturbations of the shear layer (e.g., as much as 100 % in the interface region).
2. A shear flow regime ($\Delta t > 0.75$ ms) — where the streamwise velocity $u(y, t)$ varies with y similar to boundary layer flows. Near the wall u increases with time, as the shear layer acquires momentum from the freestream flow through turbulent mixing. The thickness δ_{S_t} of the sublayer (where one could expect a loss of momentum due to viscous drag arising at the wall) grows like $4\sqrt{\nu t}$, and is smaller than 0.3 mm in Freon for times less than 2 ms. Thus the main part of the boundary layer is not influenced by wall drag.

The streamwise velocity fluctuations u' are comparatively weak ($\pm 5\%$). Though the LDV system might be inappropriate to give exact quantitative information on the turbulence in this nonsteady flow, it tends to overestimate fluctuations rather than to underestimate — at least for the frequencies below 20 kHz.

The weak fluctuations can be interpreted in combination with the shadowgraphs that show very-fine-scale structures (i.e., smaller than 1 mm) are immediately present. Contrary to previous numerical simulations, no predominant 2-D rotational structures were observed. This suggests

Fig. 5. Streamwise velocity at different heights

that: (i) the complete 3-D turbulence spectrum — including Kolmogorov scales — is setup immediately after transition, (ii) dissipation acts immediately to keep u' small; and (iii) it probably takes more time for large-scale structures to grow.

5. Evolution of the Velocity Profiles

Figure 6 shows the evolution of the velocity profiles during the periodic regime for the first four cycles. During each cycle three times are depicted: – the instant of peak velocities (t_1, t_4, t_7, t_{10}), – the mid-point of each cycle (t_2, t_5, t_8, t_{11}), – and the instant of minimum velocities (t_3, t_6, t_9, t_{12}). Also a curve from a previous numerical simulation is shown (Kuhl et al., 1992), averaged during the same time period (0 to 1 ms). This calculated curve is most similar to the profiles at the minimum fluctuation times.

Figure 7 presents a semi-logarithmic plot of the velocity profiles: in (a) the evolution of the mid-cycle values during the periodic regime, which converge at later times, in (b) four instantaneous profiles in the shear flow regime, which show a logarithmic law behaviour in the range from $y = 4$ mm to $y = 20$ mm. The profiles may be fit with a logarithmic function:

$$u/U_\infty = 1 + b \log y/y_0 \quad (2)$$

where the constants are listed in Table 1. At late times, the logarithmic slope converges to a value of $b \simeq 0.45$, similar to other turbulent boundary layers.

Time	b	y_0 [mm]
t_{13}	0.58	19.6
t_{14}	0.48	16.9
t_{15}	0.44	18.7
t_{16}	0.45	17.5

Table 1.

6. Boundary Layer Profiles

In the shear flow regime, it is useful to scale the experimental data — in order to facilitate comparisons with other boundary layer flows. In Figure 8 we have plotted the boundary layer profiles

$$u/U_\infty = f(\eta) \quad (3)$$

where $U_\infty \simeq 230$ m/s, $\eta = y/\delta$ and $\delta = y$, where $u/U_\infty = 0.98$.

Fig. 6. Instantaneous streamwise velocity profiles during the periodic regime: (a) first cycle; (b) second cycle; (c) third cycle; (d) fourth cycle. Solid lines without symbols from the numerical simulation (Kuhl et al., 1992).

Fig. 7. Semi-logarithmic profiles of streamwise velocity: (a) evolution of mid-cycle values; (b) shear flow regime.

Approximating the profiles by a power law function

$$u/U_{\infty} = \eta^{\alpha} \quad (4)$$

yields exponents α between $2/8$ and $3/8$. The baroclinic boundary layer profiles are thus midway between a clean flat plate ($\alpha = 1/7$) and a dusty boundary layer behind a normal shock. This illustrates that there are density effects (i.e., the profiles are lower than clean flat plate case), though less than in the dusty boundary layer. The density profile tends to control the shear flow profile $u(y)$: Specifically the density ratios of the different cases: (e.g. $\bar{\rho}/\rho_{air} \approx 10$ for the normal shock over a dust bed, $\bar{\rho}/\rho_{air} \approx 4$ for the Freon layer, and $\rho/\rho_{air} = 1$ for the clean flat plate) explain why the present results are mid-way between the flat plate and the dusty boundary layer case.

Fig. 8. Boundary layer profiles

7. Conclusions

Two characteristic regimes were observed in the boundary layer evolution: an initial periodic regime that was dominated by wave reflections within the Freon layer, and later, a turbulent shear flow regime. Near the wall, the boundary layer profiles exhibited a logarithmic law-of-the-wall region $u/U_\infty = 1 + 0.45 \log y/y_0$ similar to viscous turbulent boundary layers. Away from the wall, the profiles had a power-law character: $u/U_\infty = \eta^\alpha$ where $2/8 \leq \alpha \leq 3/8$. These values lie between the clean flat plate value of $\alpha = 1/7$ and the dusty flow value of $\alpha \simeq 0.7$. The velocity profiles are controlled by the gas density near the wall.

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