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MEASUREMENT OF WALL SHEAR STRESS IN TURBULENT BOUNDARY LAYERS USING AN OPTICAL INTERFEROMETRY METHOD

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ABSTRACT

A new laser interferometry skin friction meter was built and was used to measure skin friction in a series of turbulent boundary layer flows. This method has the advantage of providing a direct measure of skin friction through thin film lubrication theory. It does not rely on the existence of a law of the wall or a logarithmic mean flow region in the flow such as that assumed by the more conventional techniques such as Preston tube and the Clauser chart.

The measurements made with the laser interferometer were compared with Preston tube and Clauser chart measurements in zero, favourable and adverse pressure gradient flows. Although the interferometer results show some scatter, the agreement is seen to be satisfactory and suggests that the law of the wall based techniques are valid in the range of parameters investigated here.

INTRODUCTION

The determination of wall shear stress τ_0 is vital in any description of wall bounded shear flows. It is often represented in the form of a wall shear velocity, $U_\tau = \sqrt{(\tau_0/\rho)}$ where ρ is fluid density, which is commonly accepted as the relevant scaling velocity for turbulent boundary layers.

Unfortunately, direct measurement of skin friction is not straight forward. The Preston tube (Preston 1953) is one of the simplest and most popular methods. The wall shear stress is calculated by measuring the velocity from a Pitot tube fixed on the wall and a wall pressure tapping. The calculation assumes that the universal law of the wall holds for fully developed turbulent boundary layers. A calibration chart is required and the most commonly used is that of Patel (1965) where extensive measurements where conducted in fully developed pipe flow where the skin friction is known as a function of pressure drop in the pipe. Another commonly used technique is the Clauser chart (Clauser 1954). This method also assumes the universal law of the wall and further assumes the existence of a logarithmic law of the wall

$$\frac{U}{U_\tau} = \frac{1}{\kappa}\ln(\frac{yU_\tau}{\nu}) + A \tag{1}$$

for flow above the viscous buffer zone ($yU_\tau/\nu > 100$, say). Here U is mean velocity, y is the wall-normal distance, ν is kinematic viscosity and κ and A are universal constants. Patel (1965) confirmed that the Preston tube measurements agree with (1).

The existence of a logarithmic law of the wall has recently come under question (see George & Castillo 1997 and Barenblatt 1993) and therefore, so also have methods of measuring skin friction such as the Clauser chart. To help resolve this issue, what is required is an accurate independent method of measuring skin friction which does not depend on the law of the wall and preferably one which does not require calibration. A skin friction meter using optical interferometry and the floating element gauge are probably the only two presently used methods which satisfy both these criteria.

Tanner & Blows (1976) were the first workers to use optical interferometry to infer wall shear stress by monitoring the movement of interference fringes of a thin oil film on a smooth surface. Since then numerous workers (see Fernholz *et al.* 1996 for a review) have explored various techniques using either single or dual laser beams. Seto & Hornung (1991, 1993) developed a robust oil film skin friction meter which could be used in flight conditions as all instrumentation is within the model. An attractive feature of their design is that it uses a collimated laser beam over a finite area and thus provides information on the oil film behaviour over a given area rather that at one or two distinct points. Such information is necessary in order to achieve greater accuracy.

Seto & Hornung showed comparisons of wall shear stress measurements taken side by side of their oil film interferometer and a floating element gauge. The advantage of the oil film method was clearly shown in flows with pressure gradient as floating element gauge reading are affected in such conditions. From thin-film lubrication theory, Tanner & Blows (1976) showed that pressure gradients have a negligible effect on the oil-film interferometry measurements.

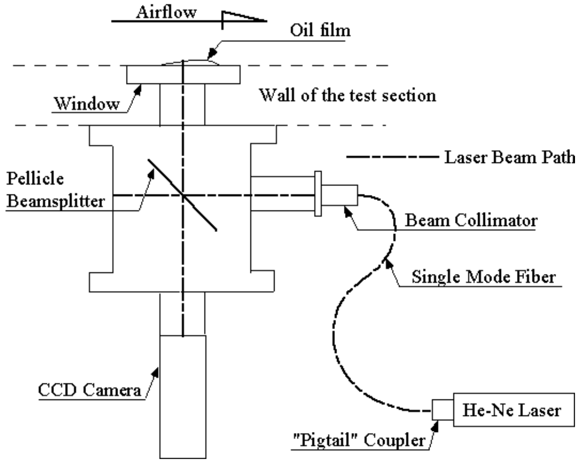

Figure 1: Laser Interferometer.

Based on the design of Seto & Hornung a new oil film interferometer was built and details are shown in figure 1. An oil film deposited on the flat test plate is deformed by the effect of the wall shear stress when exposed to the air flow. Once the oil film becomes thin it forms a wedge with a uniform slope which decreases with time. Based on thin-film lubrication theory, the slope dy/dx is given by

$$\frac{dy}{dx} = \frac{\mu_{oil}}{\tau_0 t} \tag{2}$$

where μ_{oil} is the oil viscosity, τ_0 is wall shear stress and t is time. The oil film slope is monitored by the apparatus shown schematically in figure 1. The light source is a 20 mW He-Ne laser which is collimated in a beam of approximately 3 mm diameter. The beam is passed through the oil film and the CCD camera monitors the interference pattern formed by the reflections from the oil-window interface and the tilted oil-air interface. Figure 2 shows a typical recorded interference pattern. The relation between the fringe spacing and the film slope is expressed as follows:

$$\frac{dy}{dx} = \frac{\lambda}{2nd} \tag{3}$$

where λ is the wavelength of the laser beam, n is the refractive index of the oil and d is the fringe spacing. From (2) and (3), τ_0 can be expressed as

$$\tau_0 = \frac{2n\mu_{oil}}{\lambda}\frac{d}{t}. \tag{4}$$

By plotting the fringe spacing d versus time t, the slope of the graph is directly proportional to τ_0 and the constant of proportionality consists of all known constants.

Figure 2: Sample fringe pattern.

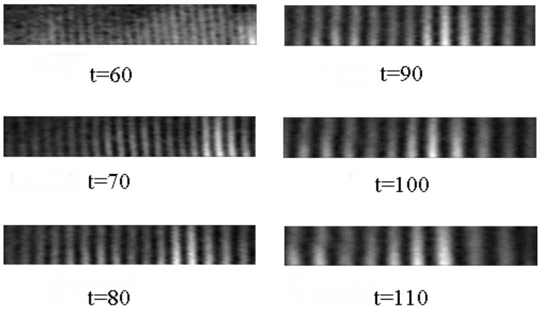
t=60
t=90
t=70
t=100
t=80
t=110

Figure 3: Example of time-varying fringes.

EXPERIMENTAL METHOD

The experiments were conducted in a low-speed closed circuit wind tunnel. The operating speed range for the tunnel was from 5 to 25 m/s. In order to create a fully turbulent boundary layer, a tripping wire of diameter 1.2 mm was attached to the leading edge of the test section. An adjustable wall made out of an acrylic flexible sheet was hung from the ceiling in order to create the streamwise pressure gradients. Wall pressure taps were mounted along the centreline of the boundary layer wall for the pressure gradient measurements and the skin friction meter was mounted at $x = 1150$ mm downstream of the tripping wire.

A Pitot-static tube with a total head tube diameter of 1.0 mm, calibrated against an N.P.L. standard, was used to measure the mean velocity profiles. Pressure differences were measured with a MKS Baratron 698A manometer with a type 270D signal conditioner. The Preston tube method was used when the total head tube was resting on the window of the laser interferometry device, which was set flush with the boundary layer wall.

For the oil film measurements, Dow Corning 200 silicon oil was used (100 cs). Silicon oil is favoured because of its low vapour pressure, chemical inertness and its low temperature coefficient of viscosity. The interference images are captured by a CCD camera and recorded on video tape as a continuously moving image and the image was sampled at certain time intervals on the computer. By scanning through the flow direction, this fringe pattern is recognised as a periodic curve of intensity distribution. Figure 3 shows an example of time-varying fringe spacing. Applying an FFT to this, the fringe spacing is obtained as a peak frequency. As we have equation (4), τ_0 is obtained by plotting the fringe spacing versus time t which gives d/t.

RESULTS AND DISCUSSION

Measurements of skin friction were made with the oil film interferometer and Preston tube in 48 different flows, ranging from flow with strong favourable pressure gradient to strong adverse pressure gradient. In 17 of these cases, mean flow profiles were also measured and thus Clauser chart estimates of skin friction were obtained. Some results are summarised in figures 4 and 5.

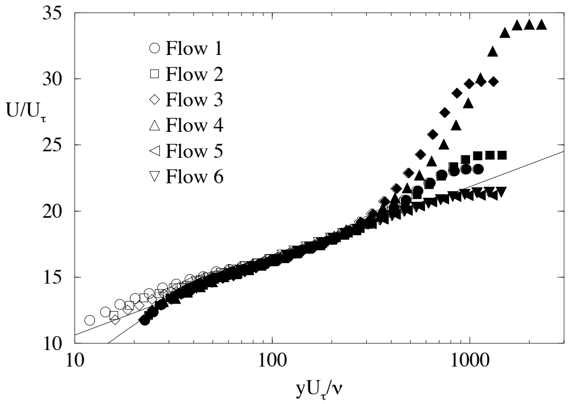

Figure 4: Mean velocity profiles. Filled symbols correspond to corrected y values. Solid line represents equation (1) with Reichardt (1951) buffer zone.

Flow	U_1 (m/s)	Δ	Π	R_θ
1	8.60	0.0	0.32	1980
2	12.21	0.0	0.50	2710
3	11.62	0.00753	1.58	4193
4	24.29	0.00816	2.21	8125
5	14.71	-0.00534	≈ 0.0	1334
6	19.64	-0.00463	≈ 0.0	1519

Table 1: Pressure gradient parameters. $R_\theta = \theta U_1/\nu$ where θ is the momentum thickness.

In figure 4, representative mean flow profiles are shown for 6 flow cases and the relevant parameters are given in table 1. The data have been normalised using the Clauser chart estimates of U_τ and good agreement is seen with (1) in the turbulent wall region. Here the constants $\kappa = 0.41$ and $A = 5.0$ have been used. In table 1, the pressure gradient has been characterised

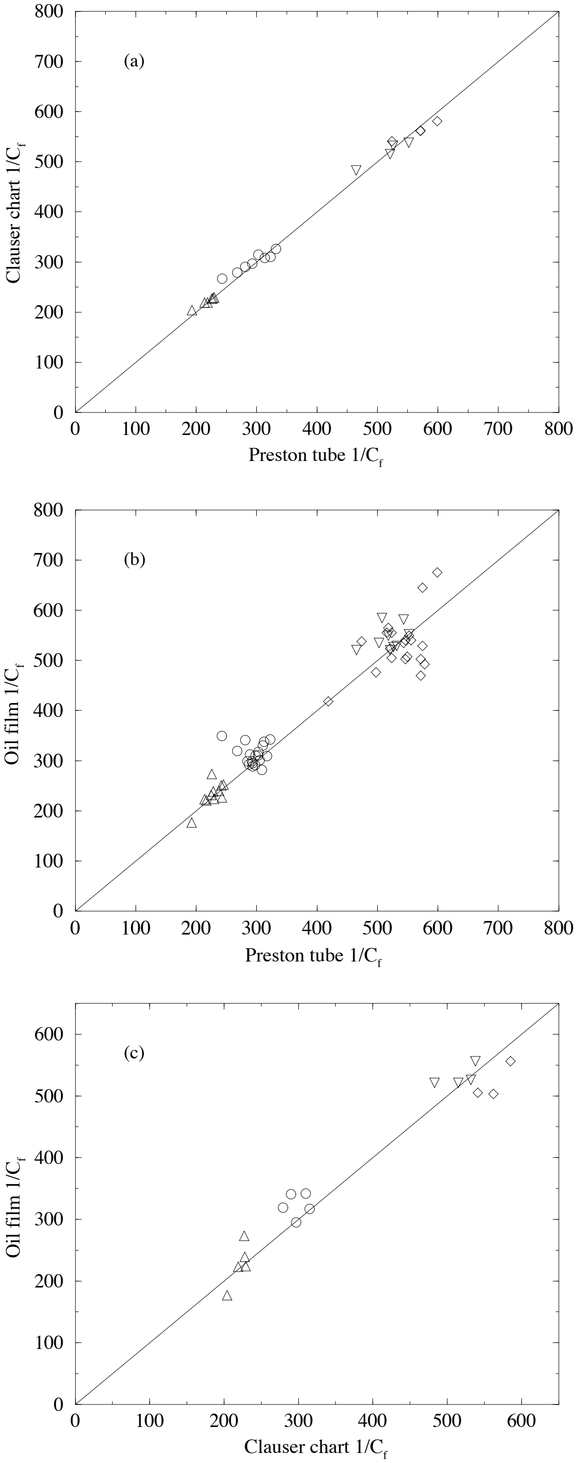

Figure 5: Comparison of skin friction coefficient data. (a) Preston tube and Clauser chart, (b) Preston tube and oil film, (c) Clauser chart and oil film. ○ = Zero pressure gradient, △ = strong favourable pressure gradient, ▽ = weak adverse pressure gradient, ◇ = strong adverse pressure gradient.

by two parameters. The first is the pressure gradient parameter

$$\Delta = \frac{\nu}{\rho U_\tau{}^3} \frac{dp}{dx} \qquad (5)$$

where p is static pressure. The second is Π, Coles(1956) wake factor.

One of the problems experienced with the Pitot-static tube measurements was in the near-wall region. As seen in figure 4, the raw data show a "kick-up" in the area of the buffer zone. The filled symbols show the results with a correction applied to the wall-normal distance y so that the data agree with the Reichardt (1951) formulation. It was noted that the amount of y correction was not constant and seemed to be a function of free stream velocity. This is consistent with the need for a high turbulence intensity correction in which case Pitot tubes are known to overestimate velocity. Tests done in another boundary layer flow (M.B. Jones, private communication) show that the "kick-up" in velocity profile in the buffer zone region is not present in hot-wire measurements where no turbulence intensity corrections are required.

Despite the existence of the above problem, the results in figure 4 show that the near-wall effects are of little consequence to the study here as the y correction quickly becomes insignificant for flow above $yU_\tau/\nu > 100$.

Comparison between the three methods of measuring the skin friction coefficient $C_f = 2\tau_0/(\rho U_1^2)$ is shown in figure 5. Although some scatter is present, overall there seems to be good agreement between the three methods. With the oil film measurement, once a clear signal is obtained, the main error is in the estimation of the viscosity of the oil. We estimate the uncertainty to be ±1.5%. With the Preston tube, no pressure gradient correction has been applied. This may account for some of the scatter as Patel (1965) has shown that the Preston tube in both favourable and adverse pressure gradients may give overestimates of 6% for the range of Δ considered here. The largest scatter is noted in the Preston tube and oil film method comparisons.

INSTRUMENTATION DIFFICULTIES

Accurate oil film interferometer readings rely on a clear interference signal. We have found the method to be quite sensitive to any debris or air bubbles which can easily appear in the oil film. For this reason, great care has to be taken in the application of the oil film to the surface. For simplicity, oil droplets were manually introduced with a syringe before turning on the air flow. Further problems were occasionally encountered from contamination due to dust in the air flow which may not be immediately obvious.

Another difficulty was encountered when we originally used a small surface window of 10 mm diameter. A small step between the glass window and the surrounding floor caused an oil surface tension effect which gave serious errors. These problems were overcome by going to a 50 mm diameter flush mounted window.

CONCLUSIONS

An oil film interferometer has been built and used to measure skin friction in a range of turbulent boundary layer flows. The instrument has been found to be very sensitive and obtaining successful readings requires some caution. Comparisons were made with the more conventional techniques of the Preston tube and Clauser chart. Over a considerable range of streamwise pressure gradient, although some scatter is present, it is noted that the three methods generally agree.

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