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WHAT HAPPENS IF A LEBU DEVICE IS INSERTED IN THE INNER WALL REGION?

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ABSTRACT

The effect on the turbulence characteristics of locating a LEBU device in the inner wall region of a fully developed pipe flow has been studied by conducting experiments in a circular pipe at a friction velocity of 0.61 m/s corresponding to a Reynolds number of 268000 (based on pipe diameter and average velocity). Two LEBU devices both of non-dimensional length, l^+=400, and thickness, t^+= 25 and 40 respectively were tested. The devices were located at y^+=125 where dominant shear stress production occurs. Here, inner wall scaling was used for non-dimensionalization. Mean velocity and turbulence intensity distributions downstream of the LEBU devices have been measured by a single hot-wire and their departure from fully developed turbulent flow will be highlighted. Pressure drop over 2.2m length of pipe and frequency spectra of the longitudinal turbulent velocity fluctuation with and without the installation of a LEBU device are also presented.

NOTATION

k	wavenumber
l	LEBU length
Re	Reynolds number
t	LEBU thickness
u	longitudinal turbulent velocity
U	mean longitudinal velocity
U_τ	friction velocity
x	longitudinal coordinate
y	distance from wall
δ	boundary layer thickness
λ	wavelength
ν	viscosity
τ	shear stress
ϕ	spectral density function
ω	circular frequency (rad/sec)
Superscript	
+	quantity nondimensionalized using U_τ and ν.
'	rms value

INTRODUCTION

Since the identification of coherent structures in a variety of fluid flows, considerable efforts have been devoted to controlling these structures using either active or passive means for practical applications. Riblets and Large Eddy Break Up (LEBU) devices have been studied for drag reduction purposes (Savill et al, 1988). While Corke et al (1979) has shown that a pair of carefully designed two-dimensional flat plates placed in a tandem configuration within the boundary layer can yield a net drag reduction of up to 20%, there has been considerable debate as to whether a LEBU device produces net drag reduction (Prabhu et al, 1987; Sahlin et al, 1988). There is, however, a general consensus that a LEBU device does reduce the skin friction drag in the flow being manipulated, although the drag introduced by such a device may more than offset such reduction. Numerous LEBU studies have been conducted to determine the optimum dimensions and locations of a single LEBU device and other configurations such as two devices arranged in tandem. It has been found in external flows that the optimum location of a single LEBU device is at about 0.8δ from the wall (where δ is the boundary layer thickness).

The mechanism by which skin friction drag is reduced through introduction of plate manipulators into external boundary layer flows is not fully understood, although several mechanisms have been proposed. Some of the mechanisms suggested include suppression of large-scale motion (hence the name LEBUs) (Guezennec & Nagib, 1990) through inhibition of the vertical velocity component of the large eddies by the manipulators and an interaction between the vortices introduced via the wake and the near-wall structure (Savill & Mumford, 1988). For these reasons, Guezennec & Nagib (1990) suggested a more appropriate terminology for these plate manipulators should be Boundary-Layer Alteration Devices (BLADES).

The LEBU devices in the outer regions of boundary layers alter the structure of the boundary layer by breaking up the large scale structures which exist in the developing boundary layer (Corke et al, 1979). This stabilises the interface between the inner and outer fluids of the boundary layer. In an internal flow, such as fully developed pipe flow where similarity is reached, there is no inner/outer fluid interface so any devices used must manipulate a different region in the flow. Experiments have been conducted in developing pipe flows (Pollard et al, 1989, 1990). However, little data exist for devices placed in either a fully developed flow or in the inner regions of a boundary layer. Although Bullock et al (1990) studied the flow behind attached ring-type turbulence promoters in a fully developed pipe flow, these devices were used to promote turbulence and skin friction drag was increased rather than being reduced.

In this study, it will be argued that an appropriate location for a LEBU device in a fully-developed turbulent pipe flow is in the inner wall region. Furthermore, the effect of locating a LEBU device in the wall region of a fully-developed pipe flow has been studied through measurement of pressure drop, mean velocity and turbulence intensity distributions.

LOCATION AND DIMENSION OF LEBU DEVICE

In studying the effect of a LEBU device in a fully-developed turbulent pipe flow, it may be considered more appropriate to manipulate the most energetic waves that exist in the near wall region. The peak energy in the spectrum in the near wall region has been found by Bullock et al (1978) to be at $\omega^+=0.05$ (200 Hz). Here, inner wall scaling variables have been used for nondimensionalization. From Morrison et al (1971), the wave size of the maximum energy waves at the wall is $k^+=0.048$ ($\lambda^+=131$) for waves travelling at 12^0 to the flow. The phase jump associated with the critical layer height of the waves occurs at $k^+y^+=6$ (Bullock et al, 1987). Thus, a device located at this height should cause the maximum reduction in both the v turbulence component and the uv Reynolds stress and hence the gradient of mean velocity at the wall. The resulting y^+ for the device is 125. At this y^+, the dominant waves travel at 20^0 hence the longitudinal length scale corresponding to a wavelength $\lambda^+=131$ is $l^+=383$. The actual length of the device used in the present work was $l^+=400$ (10mm). The device should be as thin as possible to reduce the form drag from the device but stiffness requirements dictate the minimum thickness possible. Two thicknesses of devices were used, 0.625 mm and 1 mm which corresponded to non-dimensional thicknesses, t^+, of 25 and 40 respectively. The devices should also be streamlined to reduce the form drag but the devices used were rectangular in cross-section for ease of manufacture.

APPARATUS AND EXPERIMENTAL CONDITIONS

Experiments were conducted in a smooth steel pipe of internal diameter 254 mm and length 14.675m. The pipe has a surface roughness of 63CLA and is circular within 0.1 mm and straight within 1 mm/m of axial length. The testing section was located downstream at stations between 53.3 and 58.3 pipe diameters. Air, supplied by a centrifugal fan powered by a shunt wound DC motor, was first passed through a heat exchanger to keep its temperature constant. Swirl and large scale turbulence generated by the fan and associated diffuser were eliminated by a settling chamber. A wire gauze was placed at the entrance of the pipe to promote flow development.

The data acquisition system consists of an AT personal computer which scheduled the operations of the various components, checked the experimental conditions by monitoring the fan speed, the fluid temperature and position of the hot-wire probe which consisted of a 5μm silver plated tungsten wire with a working length of 0.7 to 0.8 mm and operated at a constant overheat ratio of 1.3. The signal from the hot-wire probe was first linearized on an EAI680 analogue computer, then high pass filtered to yield the fluctuating component and processed by a Bruel and Kjaer (B&K) 2034 dual channel FFT analyzer to generate frequency spectra of the longitudinal component of turbulence, u. The frequency range of the spectra was 1600 Hz giving spectral lines spaced at 2 Hz. A Hanning window with zero overlap and record length of 180 seconds (360 spectra) were used. The spectra were then smoothed using a raised cosine function of 7.5% bandwidth. The velocity and spectral measurement experiments were conducted at a constant flow rate which corresponded to a friction velocity of U_τ =0.61 m/s in an unmanipulated flow (Re=268000 based on pipe diameter and centreline velocity).

The distance of the hot-wire sensor from the wall was measured by a Rank Taylor alignment telescope. Because of the flexibility of the thin rings, the precise distance from the wall to the lower edge of the device could not be assured so the devices were inserted in the tunnel and then the distance from the wall was indicated by bringing the hot-wire sensor away from the wall until no parallax was observed between the hot-wire and the lower edge of the device through the alignment telescope. Three spacers (of the same rectangular cross-section as the device) were used around the device to assist in the location of the device. These spacers were at least 80^0 from the measurement location. The final locations of the devices in the experiments were $y^+=110$ to 135 and $y^+=125$ to 165 for the thin and thick devices respectively. The origin for the longitudinal coordinate x^+ is the trailing edge of the device.

Pressure measurements were obtained by measuring the pressure drop over a length of 2.17m between a static pressure tapping and the end of the pipe with a Combist manometer which could be read to an accuracy of 0.01 mm. of manometer fluid (0.08 Pa). The friction velocity was varied from 0.17 to 1.24 m/s for these experiments.

RESULTS

The results for both the thin and thick devices show similar trends and only the results for the thin device will be presented here.

Pressure Measurements

The change in the pressure drop by the addition of the LEBU device is shown in Figure 1 for a range of friction velocities. The data shows that there is an increase in the pressure drop associated with the devices and the thicker device has the larger pressure drop. The percentage increase in pressure drop is seen to decrease with increasing U_τ. It should be noted that the devices were a fixed distance from the wall hence the non-dimensional height of the device varies with U_τ. These heights (from

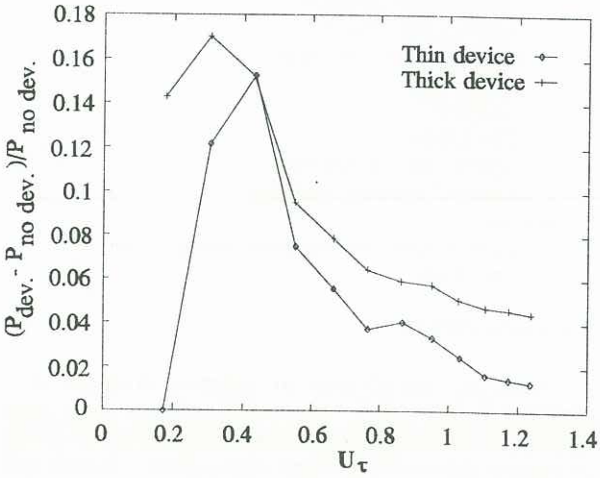

Figure 1. Variation of change in pressure drop with friction velocity.

the wall to the lower edge of the device) varied from $y^+=30$ (lowest U_τ) to 225 (highest U_τ) and is $y^+=125$ at $U_\tau=0.61$ m/s. The velocity and spectral information presented below were obtained at $U_\tau=0.61$ m/s where the theoretical pressure drop for fully developed turbulent pipe flow is 15.0 Pa. Because the pressure drop has increased, there is no net drag reduction by the installation of these particular devices. Streamlining of the devices and their associated mountings should reduce the form drag on the device itself and it may be possible to achieve a net drag reduction by optimizing the shape and location of the device.

Velocity Field

Mean velocity. The change in the mean longitudinal velocity field, $(U-U_0)/U_\tau$, caused by the introduction of the thin device is shown in Figure 2. The device is shown as a shaded rectangle on this figure. There is clearly a wake evident immediately downstream of the device and it is seen that the flow is still affected at $X^+=6000$ (48 device heights downstream from the device). The velocity below the device ($x^+<0$) is increased due to the blockage effect of the device and the skin friction (deduced from the gradient of the longitudinal velocity) in this region is also increased. The velocity at the wall is reduced for $x^+>50$ which indicates that the skin friction drag behind the device is reduced for this distance also. Data, not shown here, indicate the mean longitudinal velocity distribution has approached that of the unmanipulated flow at around $x^+=8000$.

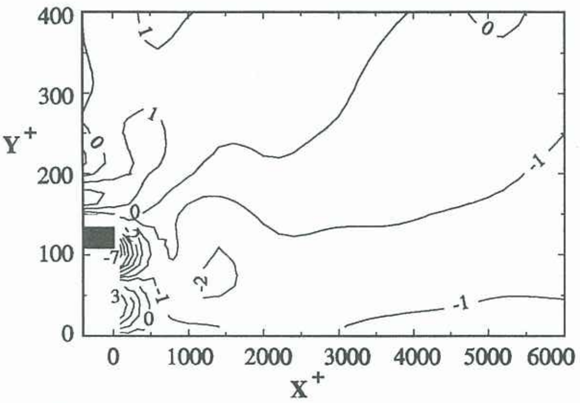

Figure 2. Mean longitudinal velocity field, $(U_{device}-U_{no\ device})/U_\tau$.

Turbulent velocity. The change in the turbulent velocity field is shown in Figure 3 for the thin device. The turbulence is significantly altered downstream of the device with a significant reduction occurring in the region $X^+=1000$ to 2000, $Y^+=50$ to 100. The turbulence reduction is seen to propagate towards the wall with little increase in the turbulence above the device. Increases in the turbulence levels are seen in the immediate wake region of the device and close to the wall below the device. These regions have high velocity gradients where turbulence is being generated. The turbulence suppression covers a large area of the flow downstream of the device and is significant because it shows that a large region of the flow can be manipulated by the introduction of a relatively small device into the flow.

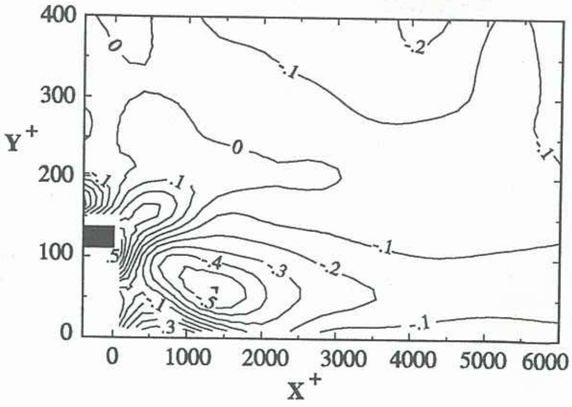

Figure 3. Contours of longitudinal turbulence intensity, $(u'_{device}-u'_{no\ device})/U_\tau$.

Spectra

The frequency spectra downstream of the device at $x^+ = 50$ and 1000 for a range of y^+ are shown in Figure 4. It is clear from this figure that a significant alteration to the distribution of turbulent energy occurs due to the device. There is a reduction in energy in wave sizes that correspond to the maximum energy waves in an unmanipulated flow in the regions $x^+=50$, $70<y^+<120$ and

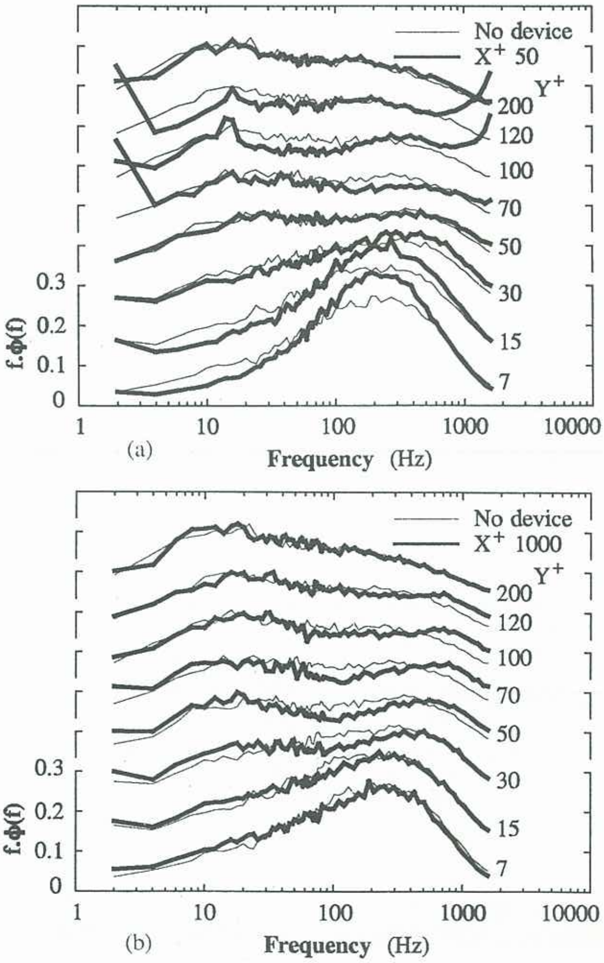

Figure 4. Longitudinal turbulence intensity spectra (a) $x^+=50$, (b) $x^+=1000$.

$x^+=1000$, $30<y^+<100$. This is expected as the device was designed to affect the maximum energy region of the spectra and indicates that the device is working as predicted. The energy is shifted to the higher frequencies in the flow as the device causes the breakdown of structures into smaller scale turbulence as well as suppressing the magnitude of the turbulence (Figure 3). There is a large peak in the high frequency end of the $x^+=50$ spectrum which may be due to vortex shedding in the wake of the device. At $x^+=50$, $y^+<30$, it is seen that the peak of the spectrum has increased significantly and there is a reduction in energy in the low frequency region. This is due to blockage effect of the device as large, low frequency structures are limited in size by the LEBU device.

CONCLUSIONS

The introduction of LEBU devices into the inner wall region of a boundary has been found to have a significant effect on the turbulence structure of the flow downstream of the device. The devices were designed to break up the dominant wave sizes in the near wall region and have been found to achieve this aim by shifting the energy to higher frequencies in the flow. Although mean velocity and turbulence intensity distributions indicate that there is a reduction in skin friction drag downstream of the device up to 48 device heights, pressure drop measurements show that there is no net drag reduction. It remains to be seen whether streamlining of the devices and mountings, alterations of the device dimensions and repositioning of the device will result in net drag reduction in internal flows.

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