Int. Symp. on Convective Heat and Mass Transfer in Sustainable Energy
April 26 – May 1, 2009, Tunisia

INFLUENCE OF COHERENT STRUCTURES ON THE WALL SHEAR STRESS IN AXIAL FLOW BETWEEN A CYLINDER AND A PLANE WALL

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ABSTRACT. Synchronised hot-film and hot-wire measurements were made in the narrower region of a rectangular channel containing a cylindrical rod. The hot-film probe was mounted flush with the channel bottom wall to measure the wall shear stress, while the hot-wire probe was placed at a fixed position, selected in order to easily detect the passage of coherent structures. Mean and rms profiles of the wall shear stress show the influence of the gap to diameter ratio on their respective distributions. The latter presented peculiarities that could only be explained by the presence of coherent structures in the flow between the rod and the wall. Evidence of this presence is seen in the velocity power spectra. The strong influence of the coherent structures on the wall shear stress spatial and temporal distributions is established through velocity-wall shear stress cross-correlations functions and through conditionally sampled measurements.

NOMENCLATURE

A	coefficient in response equation of the hot-film wall shear stress probe (V^2)
B	coefficient in response equation of the hot-film wall shear stress probe (V^2/Pa$^{1/3}$)
C_f	skin friction coefficient (dimensionless)
D	rod diameter (mm)
D_h	hydraulic diameter (mm)
E	anemometer output voltage (V)
k	threshold level used in the VITA technique
L	length of the channel (mm)
$R_{u\tau}$	two-point correlation function (dimensionless)
t	time (s)
T	time period (s)
U	streamwise velocity (m/s)
U_b	bulk velocity (m/s)
U_c	convection velocity of the coherent structures (m/s)
u	streamwise velocity fluctuation (m/s)
W	sum of the gap height and rod diameter (mm)
x,y,z	streamwise, normal and spanwise coordinates, respectively (mm)
Greek symbols	
Δt_{max}	time delay for maximum correlation (s)
ρ	density (kg/m^3)
λ	spacing of the coherent structures (mm)
τ_w	wall shear stress (Pa)
$\sigma(..)$	localized variance
$\langle ... \rangle$	phase (ensemble) averaged quantity
$\overline{(...)}, (...)'$	time averaged quantity and root mean square quantity

INTRODUCTION

In a number of practical applications, a fluid flows in a complex channel consisting of relatively large subchannels parallel to neighbouring narrower sections. Among these applications, one can mention coolant flow in nuclear reactor fuel bundles, flow in rivers with inundated floodplains and air cooling of electronic devices. Previous studies (Hooper and Rehme [1984], Meyer and Rehme [1994 and 1995], Guellouz and Tavoularis [2000a and 2000b], Gosset and Tavoularis [2006] and Harbaoui and Guellouz [2006]) have demonstrated the existence of large scale coherent structures in the narrow regions of such flow configurations. In order to isolate the effect of the gap, Guellouz and Tavoularis [2000a and 2000b] and Gosset and Tavoularis [2006] studied longitudinal flow in a rectangular channel containing a suspended rod. They showed that in the rod-wall narrow gap, the flow is dominated by large scale coherent structures, correlated some of their features with geometrical and dynamical parameters of the flow, and proposed a model for them consisting of three dimensional, counter-rotating vortices convected axially with the flow [Guellouz and Tavoularis, 2000b]. Chang and Tavoularis [2005 and 2006] using unsteady RANS numerical simulations predicted the occurrence of coherent structures and documented their significance for heat transfer in the gap region.

The aim of this study is to investigate the influence of the large scale structures on the spatial and temporal wall shear stress distributions in axial flow between a cylinder and a plane wall. The first of its kind, this experimental study uses synchronised measurements of in-flow velocity with hot-wires and wall shear stress with flush mounted hot-film probes and employs coherent structure detection methods. It is intended to complement the investigations of Guellouz and Tavoularis [2000a and 2000b], Gosset and Tavoularis [2006] and Chang and Tavoularis [2005 and 2006], which documented the flow structure for the same geometry.

EXPERIMENTAL FACILITY AND PROCEDURES

Flow Facility The flow facility (Figure 1) was set up as an open-discharge wind tunnel, whose test section consisted of a rectangular channel, with an aspect ratio of 2/3, containing a suspended aluminum pipe ("rod") with an external diameter D=101 mm. The rod was positioned so that it would form an adjustable narrow gap with the channel base, made of transparent acrylic material. The other three sides of the channel were formed by a bent aluminum sheet. All "wetted" surfaces were hydraulically smooth. The hydraulic diameter and the length of the test section were, respectively, D_h=1.59D and L=54.0D, corresponding to $L/D_h \approx 34$. The channel was supplied with air produced by a blower through a pressure box with a cross-section 9.4 times larger than the test section flow area. A metallic woven screen was stretched across the entrance of the channel in order to enhance the rate of flow development towards its fully developed state. The rod was suspended at both ends as well as at a location 20D downstream of the channel entrance. Each support was equipped with a traversing mechanism, utilizing finely threaded bolt-and-nut assemblies and dial gauges, to provide accurate positioning of the rod with respect to the channel base.

Measurement Procedures and Accuracies Hot-film and single point hot-wire measurements were made simultaneously for different gap ratios W/D (Figure 1) and stored for later processing. The sampling rate was 2500 Hz and each data record contained 750000 points. The hot-film probe (TSI, model 1268) was mounted flush with the channel bottom wall and was traversed in the transverse direction (Figure 1) over a distance of one rod diameter on each side of the channel symmetry plane with a step of 0.05D. The hot-wire and hot-film probes were positioned, respectively, at 2.8D and 1.0D upstream of the channel exit.

The measurement of wall shear stress with a flush-mounted hot-film probe is based on the analogy between heat and momentum transfer (Tavoularis [2005]) using the semi-empirical expression

$$E^2 = A + B\tau_w^{1/3} \tag{1}$$

where E is the anemometer voltage output and the adjustable coefficients A and B were determined by in situ calibration versus a Preston tube. The uncertainty on the mean and the variance of the wall shear stress were estimated to be, respectively, 3% and 6%.

The detection of coherent structures was made by a triggering hot-wire probe (TSI 1260AJ-T15 with a wire length of 1.30 mm) that was placed at a fixed position relative to the rod, namely at $y=W\text{-}D$ and $z=D/2$. This position corresponds to the region of maximum rms streamwise velocity fluctuations (Guellouz and Tavoularis [2000a]). It was selected with the aim of best detecting the passage of large scale structures.

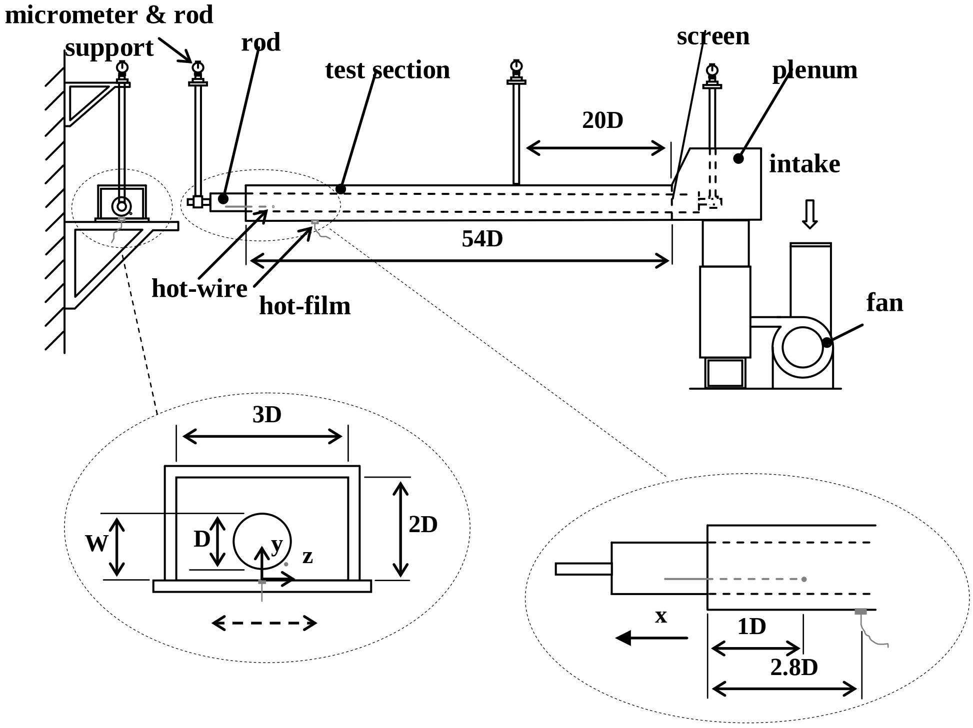

Figure 1: Experimental set up.

The Conditional Sampling Technique Several conditional sampling and phase-averaging methods have been developed in the literature, with variable degrees of complexities and sophistications. The present approach was to adopt a relatively simple method that has been successful in extracting the main features of coherent structures. The conditional sampling technique employed in this work is based on the classical Variable Interval Time Averaging (VITA) technique of Blackwelder and Kaplan [1976]. In this technique, the variable-interval time average of a random function $Q(x_i,t)$ of position x_i and time t is defined as

$$\hat{Q}(x_i,t,T)=\frac{1}{T}\int_{t-T/2}^{t+T/2} Q(x_i,s)\,ds \tag{2}$$

where T is the averaging time interval, which is chosen to be of the order of magnitude of the time scale of the phenomenon under study. For a stationary random variable, the variable interval time average approaches the conventional time average $\overline{Q}$ as $T\to\infty$. Equation (2) may also be applied to the square Q^2 of the random variable to obtain its variable-interval time average $\hat{Q}^2$. The "localized variance", defined as

$$\hat{\sigma}_Q^2(x_i,t,T)=\hat{Q}^2(x_i,t,T)-\left[\hat{Q}(x_i,t,T)\right]^2 \tag{3}$$

is a measure of the local turbulent energy.

Guellouz and Tavoularis [2000a&b] have shown that the presence of coherent structures is associated with a periodic oscillation in the velocity components. The presence of a coherent event was detected when the localized variance of the measured velocity component U exceeds a preset level, proportional to the conventional variance $\overline{u^2}$. The same coherent event was considered to be terminated when the localized variance dropped below that level. More precisely, a coherent event was considered to exist during each interval for which

$$\hat{\sigma}_U^2 > k\overline{u^2} \wedge \partial U/\partial t > 0 \tag{4}$$

where k is an adjustable “threshold level”. The condition on a positive velocity derivative was added in order to discriminate between the beginning and the end of a coherent event, and, thus, to ensure proper phase-matching among different events. In order to phase-match N detected coherent events before averaging, each event was time-shifted by the “detection time” t_j, j=1,2,…,N, corresponding to the same relative instance in the duration of a coherent event and defined as the midpoint of each time interval during which Equation (4) was satisfied. Based on preliminary tests, the optimal value for the averaging time was found to be approximately equal to ½ of the structure passage period and the optimal value for the threshold level was 0.7.

The conditional sampling (ensemble) average of property Q at a particular instant τ during the average coherent event, also known as “phase average”, was defined as

$$\left\langle Q(x_i,\tau)\right\rangle=\frac{1}{N}\sum_{j=1}^{N}Q\left(x_i,t_j+\tau\right) \tag{5}$$

This phase average corresponds to the coherent component in the double decomposition, in which, the instantaneous value Q of a random variable is decomposed into a coherent and a non-coherent component, as

$$Q(x_i,t)=\left\langle Q(x_i,t)\right\rangle+q_r(x_i,t) \tag{6}$$

Another representation employed in the literature is the triple decomposition, in which, the instantaneous value is decomposed into a time-average component (equal to the conventional Reynolds average), a coherent component and a non-coherent component, as

$$Q(x_i,t)=\overline{Q}(x_i,t)+\tilde{Q}(x_i,t)+q_r(x_i,t) \tag{7}$$

The non-coherent components in the double and the triple decompositions are identical, but the coherent components are different; the latter are related as

$$\tilde{Q}=\left\langle Q\right\rangle-\overline{Q} \tag{8}$$

RESULTS AND DISCUSSION

The present measurements were performed in the same test-section and for the same conditions as those used by Guellouz and Tavoularis [2000a&b]. The reader is therefore referred to these articles for the general documentation of the flow.

Mean and Rms Wall Shear Stress The wall shear stress measurements are presented in non-dimensional form as skin friction coefficients $C_f = \tau_w/(½\rho U_b^2)$, where τ_w is the wall shear stress, ρ is the fluid density and U_b is the channel bulk velocity. The mean and rms skin friction profiles along the channel bottom wall for different rod-wall gap sizes are presented in Figures 2a and 2b, respectively. The measurements were focussed on the gap range $1.000 < W/D < 1.100$, because, as noted by Guellouz and Tavoularis [2000a], no perceptible variation in the skin friction profiles could be observed for larger gaps. The influence of the rod presence on the C_f and C_f' profiles became increasingly significant as the gap decreased. For $W/D < 1.075$, the mean and rms skin friction coefficients had similar profiles. Both decreased towards the plane of symmetry and reached a local minimum very close to that plane, while exhibiting a local maximum on the symmetry plane. This behaviour cannot be explained by turbulent diffusion alone.

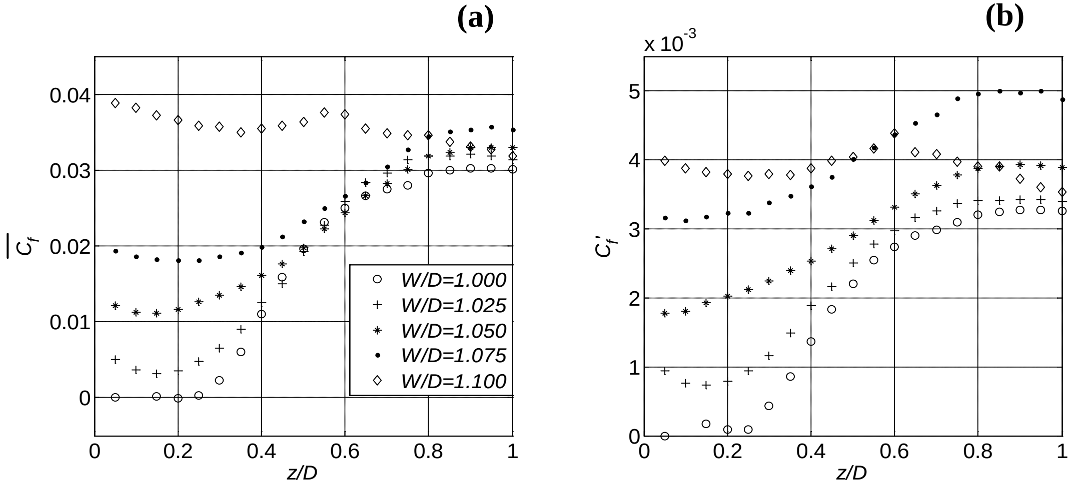

Figure 2: Profiles along the bottom wall of (a) the mean, and (b) the rms skin friction coefficients

The profiles of $C_f' / \overline{C_f}$, presented in Figure 3, exhibit an increase of this ratio under the rod ($-0.5 < z/D < 0.5$) with a maximum value of about 20%. The position of this maximum moves towards the plane of symmetry ($z/D=0$) as the gap size W decreases. Away from the rod ($z/D < -0.5$ and $z/D > 0.5$), the profiles show little, if any, variation. This behaviour cannot be explained by turbulent diffusion either, but is consistent with the passage of staggered vortices in the narrow flow region. For the gap corresponding to $W/D=1.100$, no significant variation in the $C_f' / \overline{C_f}$ profile can be observed.

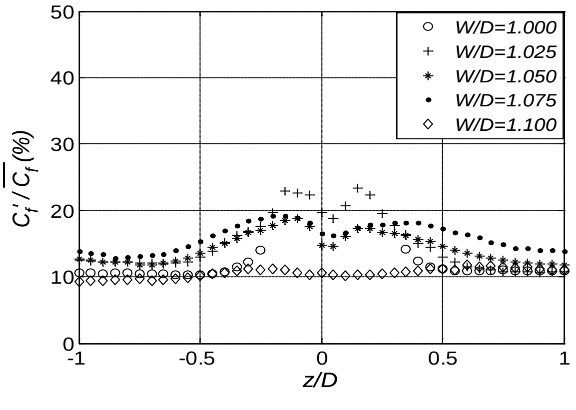

Figure 3: Profiles of $C_f' / \overline{C_f}$ (%) along the bottom wall.

Spectral Analysis Power spectra of the streamwise velocity fluctuations, measured by the hot-wire probe at its fixed position relative to the rod ($y = W - D$ and $z = D/2$), are presented in Figure 4 for several gap sizes. It is obvious that, for W/D = 1.025, 1.050 and 1.075, these spectra have a relatively wide peak around frequency values between 10 and 20 Hz. This is an indication of the presence of quasi-periodic structures. The distortion in the peaks could be explained by cycle-to-cycle variations and occasional phase shifting of these structures

[Guellouz and Tavoularis 2000a]. This implies that the selected fixed position for the triggering probe was appropriate for structure passage detection. Even so, the accurate representation of these structures should take into account their deviation from exact periodicity and their cycle-to-cycle variations. For *W/D* = 1.100 and 1.000, no eminent peaks could be observed in the velocity power spectra (Figure 4). Although this may be interpreted as evidence of lack of periodicity in the velocity signals, it may also signify that any existing periodic component is relatively weak compared to the non-coherent turbulence.

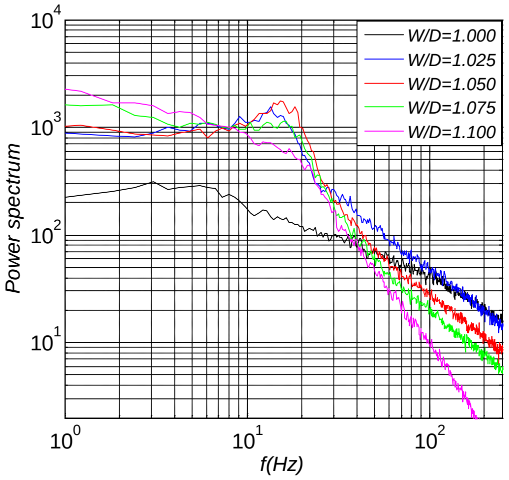

Figure 4: Velocity fluctuations power spectra for different gap sizes

Influence of Coherent Structures on the Wall Shear Stress The main goal of this study is to examine the influence of coherent structure's on the wall shear stress. Two approaches are used for this purpose. The first employs two-point space-time correlations of the streamwise velocity, *u*, (at a fixed position) and the wall shear stress, τ_w, at different locations. The second uses the Variable Interval Time Averaging (VITA) conditional sampling technique to educe the coherent structure signature on wall shear stress.

The Space-Time Cross-Correlation Function. The space-time cross-correlation function is defined as

$$R_{u\tau}(x,y,z,\Delta x,\Delta z,\Delta t)=\frac{\overline{u(x,y,z,t)\tau_w(x+\Delta x,y,z+\Delta z,t+\Delta t)}}{u'(x,y,z,t)\tau'_w(x+\Delta x,y,z+\Delta z,t+\Delta t)} \tag{9}$$

where *x*,*y* and *z* are, respectively the streamwise, normal and spanwise coordinates of the fixed velocity probe, Δz and Δx are the probe separations in the spanwise and streamwise directions, and Δt is the time lag between the correlated signals. The correlation function, examples of which are presented in Figure 5, clearly shows a high correlation between the velocity and wall shear stress, which is quite remarkable in view of the large streamwise separation of the probes (more than ten gap sizes). Clear evidence of spatial periodicity is also seen in the contours of these correlation functions. Based on these observations, one would anticipate a significant footprint of the structures on the instantaneous wall shear stress, which may explain the peculiarities in the profiles of mean and rms shear stresses.

Convective Velocity and Spacing of the Coherent Structures. The convection velocity U_c of the coherent structures and their streamwise spacing λ were estimated from the measured space-time correlations for different gap sizes. The convection velocity U_c was estimated as the ratio of the streamwise probe separation Δx to the time delay Δt_{max} for the occurrence of the maximum in the correlation function when the probes are aligned in the spanwise direction (Δz=0). Figure 6a summarizes the estimates of U_c for different gap ratios. The results closely reproduce those of Guellouz and Tavoularis [2000a], obtained from velocity measurements, as seen by their agreement with the fitted expression proposed by Guellouz and Tavoularis [2000a]:

$$\frac{U_c}{U_b}=1.04(1-e^{-10.9W/D+10.6}) \tag{10}$$

This clearly confirms that the peculiarities observed in the wall shear stress distributions are the result of the passage of the large vortical structures which dominate the flow in the narrow gap region.

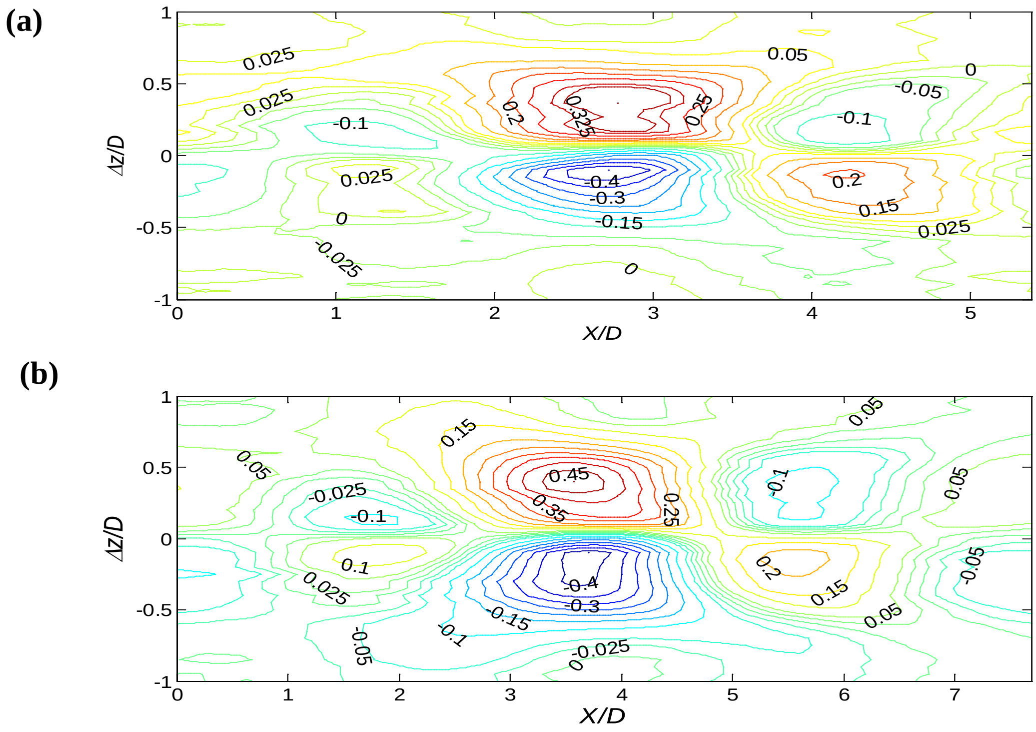

Figure 5: The space-time correlation function $R_{u\tau}$ for W/D = 1.025 (a) and 1.050 (b) (the x-axis origin is arbitrary)

The streamwise spacing between the convected structures (Figure 6b) was estimated as $\lambda=U_cT$, where T is the period of the oscillations in the autocorrelation coefficient of the streamwise velocity. The results show an increase in the spacing λ with the relative gap size, in agreement with the literature.

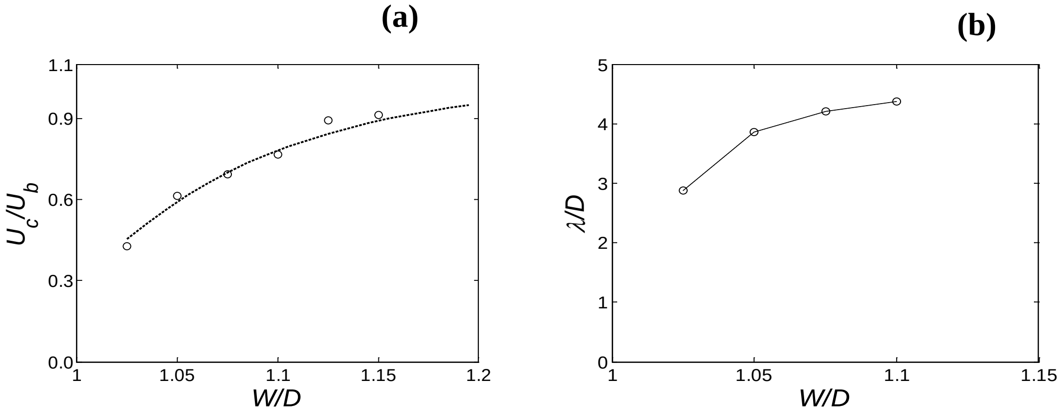

Figure 6: (a) Convection velocity of the coherent structures; (o) measurements, (---) fitted expression [Guellouz and Tavoularis 2000a], (b) Spacing of the coherent structures.

Conditionally Sampled Results. Representative ensemble-averaged skin friction maps, for *W/D* = 1.025 and 1.050, are presented in Figure 7. They were obtained by applying the VITA technique using the output of the fixed hot-wire velocity probe as the triggering signal. The flow periodicity is evident in the contours of Figure 7.

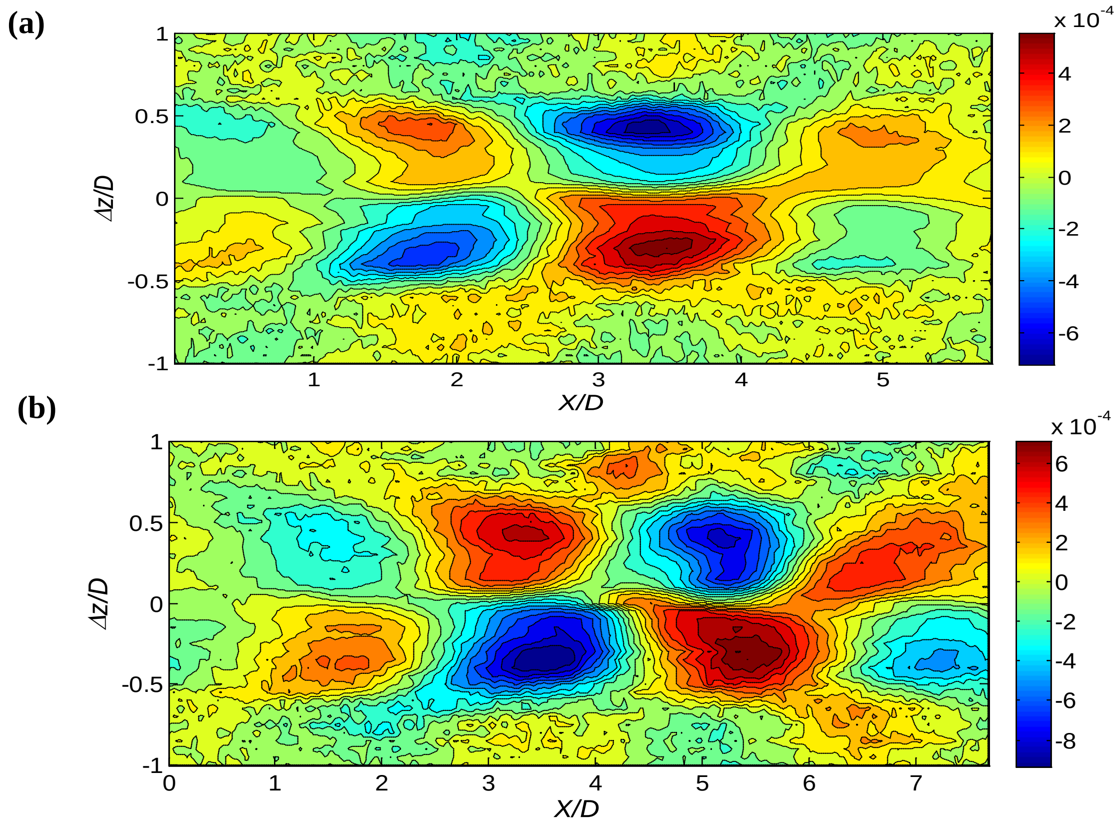

Figure 7: Coherent skin friction $\langle C_f \rangle - \overline{C_f}$ contours obtained by the VITA technique for *W/D*=1.025 (a) and 1.050 (b) (the origin of the *x*-axis is arbitrary)

Although the amplitude of the coherent wall shear stress, obtained through ensemble averaging, is attenuated due to the cycle-to-cycle variations and phase shifts, it could be observed that the peak-to-peak amplitude of the coherent wall shear stress (Figure 8) corresponds to approximately 10% (Table 1) of the local mean and reaches 77% of the local rms value. The coherent contribution to the local rms values is between 15 and 20% (Table 1). This proves that the contribution of coherent structures to the local and instantaneous wall shear stress is significant.

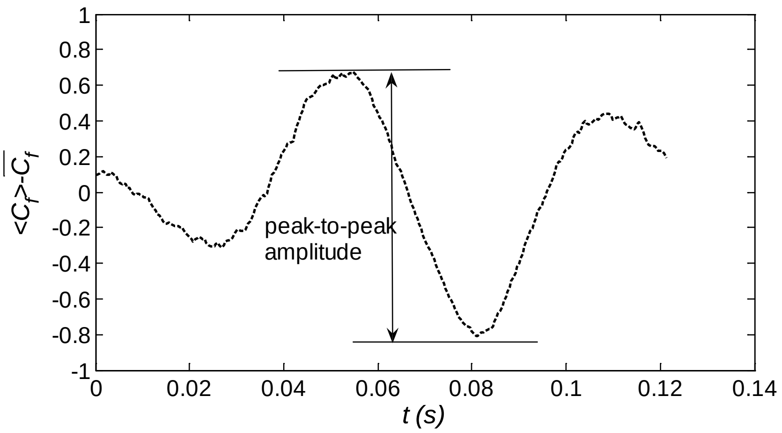

Figure 8: Representative ensemble average of the educed events showing the peak-to-peak amplitude.

Table 1
Contribution of the coherent structures to the local mean and rms values of the wall shear stress

W/D	1.025	1.050	1.075	1.100
$\frac{\{\langle C_f \rangle - \overline{C_f}\}_{peak-to-peak}}{\overline{C_f}}$ (%)	10.78	9.98	9.95	6.45
$\frac{\{\langle C_f \rangle - \overline{C_f}\}'}{C_f'}$ (%)	21,78	15.67	15.2	18.04

CONCLUSION

Synchronized measurements of wall shear stress and velocity in the narrower gap region of the axial flow in a rectangular channel containing a cylindrical rod were made for different gap sizes. Mean and rms skin friction profiles show the influence of the rod on the wall shear stress, that becomes increasingly significant as the gap decreases. Spectral analysis shows the evidence of the passage of coherent structures on the wall shear stress in the gap flow region. In order to estimate the contribution of these structures to the wall shear stress, the velocity-wall shear stress cross-correlation was computed and the VITA technique was employed to separate the coherent component of the wall shear stress, i.e. the footprint of the coherent structures. It was shown that the peak-to-peak amplitude of the coherent wall shear stress corresponds to approximately 10% of the local mean and reaches 77% of the local rms value. The coherent contribution to the local rms values is of about 15 to 20%. The implication of these results is that, in order to predict accurately the variation of the wall shear stress and, by analogy, the heat transfer coefficient in rod-bundle-type flows, it is necessary to account properly for the presence of coherent structures in the flow.

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