RELATING PRESSURE FIELD AND VORTEX SHEDDING SUPPRESSION FOR A SQUARE CYLINDER IN THE VICINITY OF A SOLID WALL

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ABSTRACT

Surface pressure and wake velocity field fluctuations are investigated for a square cylinder mounted in the vicinity of a solid wall as functions of the boundary layer thickness and cylinder-to-wall gap heights for Reynolds number between 20000 and 40000. The study focuses on the suppression of vortex shedding occurring around critical gap heights. Mean data are combined to identify three distinct flow regimes. Time and frequency analyses show that at large gap heights periodic vortex shedding is perturbed by underlying large-scale structures leading to phase jitter and long-term loss of correlation. For small gaps, there is no evidence of periodic motion. For intermediate gap heights, there is a gradual loss of correlation between the pressure field on the top and lower cylinder surfaces, which leads to periods of sinusoidal fluctuations interspersed with incoherent motion in the wake. It is found that the Reynolds number influence is negligible and that an increase in the boundary layer thickness results in a reduction of the critical gap height. Stability considerations suggest that a stable vortex street can only exist for a certain range of the top shear layer to bottom shear layer circulation ratio.

INTRODUCTION

When a bluff body is placed in the proximity of a solid wall, the structure and dynamic behavior of the flow changes significantly as a function of the obstacle-to-wall gap height, S. Okajima (1982) showed that the flow around a square cylinder immersed in a uniform stream is independent of Reynolds number, based on side dimension D, in the range 10000 to 100000. The wake flow is highly turbulent and characterized by the nearly regular passage of large-scale coherent structures ("von Karman" vortices). The formation and shedding of these vortices is related to the flow separation at the leading edges giving rise to intense shear layers over each of the lateral faces. As discussed by Lyn *et al.* (1995), the phase difference between the oscillation of these shear layers fluctuates about 180°.

If the cylinder is mounted close to the wall below a critical gap height, the vortex shedding mechanism can be completely suppressed. Even for a specific geometry, however, a general consensus does not exist for the critical S. For circular cylinders, Grass *et al.* (1984) report critical values of $S/D \approx 0.3$ where Tanigushi and Miyakoshi (1990) report critical gaps of $S/D \approx 0.3$ for boundary layer thickness, $\delta/D < 0.4$, and $S/D \approx 0.8$ for $\delta/D \approx 1$. For a square cylinder, Bosch *et al.* (1996) and Wu and Martinuzzi (1997) report critical values of $S/D \approx 0.35$ for $\delta/D \approx 0.8$ and $S/D \approx 0.3$-0.35 for $\delta/D \approx 1.5$. In both studies, it is reported that there exists an S/D range in which vortex shedding can be intermittently observed. However, there are no detailed investigations into the dynamic flow characteristics in the intermittent regime.

Bosch *et al.* (1996) suggest, although without proposing a mechanism, that the suppression of vortex shedding is related to the production of counter-rotating vorticity in the wall boundary layer. However, both the data of Bosch *et al.* (1996) and Wu and Martinuzzi (1997) show that the magnitude of the maximum vorticity in the lower (near wall) shear layer exceeds that in the upper shear layer, which observation is difficult to reconcile with a vorticity annihilation argument.

Tests are conducted for a Reynolds number range of 20000 to 40000. The boundary layer thickness is varied from 0.07D to 1.8D and the spacing from 0.1D to 1.6D. Surface pressure and hot-wire anemometry measurements are used to identify and describe the three flow regimes. This experimental study addresses three issues pertinent to the suppression of vortex shedding from a square cylinder in the vicinity of a solid wall. First, the influence of the boundary layer thickness on the critical gap height is investigated. Second, time and frequency domain analysis is used to characterize the dynamic behavior of the flow in full shedding and intermittent regimes. The mechanism leading to vortex suppression is related to pressure distribution along the lower cylinder face. Finally, stability considerations provide conditions for suppression.

EXPERIMENTAL SETUP

The experimental geometry is defined in Fig. 1. Experiments were performed in a 0.45m X 0.45m suction-type wind tunnel. A smooth, flat plate, 0.92m long and 5mm thick, was placed about 0.15m from a tunnel wall. The plate had a sharpened leading edge and a trailing edge flap to control the plate boundary layer and leading edge separation. A square cylinder of side dimension D=30mm was placed 14.5D downstream of the plate leading edge. The cylinder aspect ratio was 15 and the blockage ratio was 6.6%.

Experiments were conducted for Reynolds number (Re, based on D; the free stream velocity, U_∞; the density, ρ; and viscosity, μ) between 20000 and 40000. The on-coming free stream turbulence intensity was 1%. The boundary layer thickness was controlled by adjusting the plate end flap. Thicker turbulent boundary layers were obtained by tripping the on-coming flow at the leading edge.

One hundred and eleven pressure taps were located along the centerline: 79 on the plate and 32 around the cylinder circumference. The pressure tap tubing was constricted in order to provide full frequency response to 200Hz.

Two hot-wire probes were located 2.2D downstream of the cylinder. These were mounted at a fixed distance relative to the cylinder in the shear layers symmetrically about the cylinder centerline. Free stream conditions were continuously measured from a pitot-static tube located 5D upstream of the cylinder and 4D away from the tunnel wall. The pressure taps, pitot-static tube and hot-wires were sampled simultaneously at 400Hz for periods of 60s to 120s.

Oil film and laser light sheet visualizations provided qualitative information about the near-wall flow behavior.

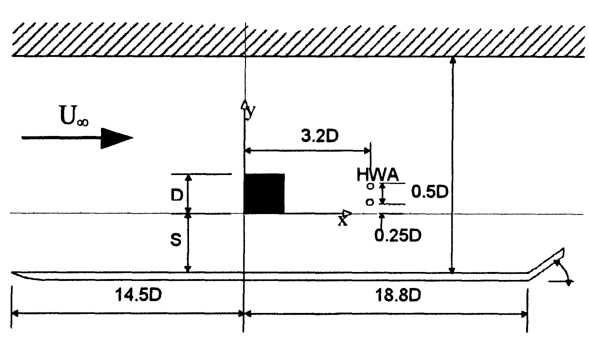

Figure 1. Experimental geometry and nomenclature.

RESULTS

This study focuses on the suppression of vortex shedding occurring at critical gap heights. Based on the velocity results of Wu and Martinuzzi (1997), tests were conducted in the gap height range $0.07 \leq S/D \leq 1.8$ for $0.46 \leq \delta \leq 1.6$ and $20000 \leq Re \leq 40000$. Measurements of the mean surface pressure distributions, vortex shedding frequency and wall flow separation and reattachment patterns are used to identify three different flow regimes as a function of gap height. Examination of the data time series and correlation functions allow the definition of some of the dynamic characteristics for each regime. Power spectra and joint time-frequency analysis provide further details of the changes in the periodic flow behavior.

Identification of Flow Regimes

Mean Pressure on Cylinder. The influence of the gap height, S/D, on the mean pressure distribution on the cylinder surface can be conveniently summarized in terms of the average per unit length lift and drag coefficients:

$$C_L = Lift/(1/2 \rho U_\infty^2 D) \;;\; C_D = Drag/(1/2 \rho U_\infty^2 D) \qquad (1)$$

as shown in Fig. 2. These results indicate that the influence of the Reynolds number is negligible in the range $20000 \leq Re \leq 40000$. The existence of three flow regimes based on S/D is clearly suggested. The lift coefficient decreases rapidly as the gap height is increased for S/D<0.4. C_L increases for S/D>0.4, but there is a noticeable change in slope between S/D=0.53 and S/D=0.6. The drag coefficient increases monotonically with increasing gap height, but again there is a sharp change of slope between S/D=0.53 and S/D=0.6.

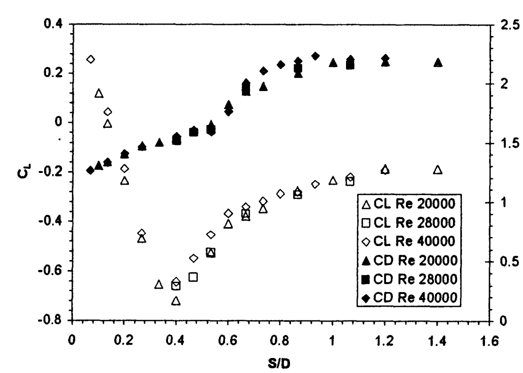

Figure 2. Lift and drag coefficients.

For S/D>0.6, both C_L and C_D gradually increase approaching asymptotically the values reported by Lee (1974) for a square cylinder in a uniform on-coming flow

(C_L=0, C_D=2.1). Non-zero values of C_L imply that a net circulation about the cylinder exists and, by extension, the strength of the upper and lower shear layers in the cylinder wakes will be different. As will be shown later, this observation has important implications for the stability characteristics of the shed vortices.

Mean Pressure Field and Flow Patterns on Surface of Plate. The location of the mean flow separation lines, obtained with the oil-film technique, and the mean pressure distribution along the plate for several S/D are shown in Figs. 3 and 4, respectively. There is a distinct flow separation line directly upstream of the cylinder for S/D<1. The location of this separation line varies weakly with S/D. For these cases, the pressure on the plate increases rapidly before sharply dropping off at the separation location. The sudden drop of pressure is due to the rapidly flowing stream of fluid entering the gap region, which was deflected at the cylinder windward face. The separation point predicted using the measured pressure gradient and a calculated velocity profile (Schlichting, 1979, pp. 206-214) agrees well with that observed. The same method indicates that for S/D≥1, the flow would not separate upstream of the cylinder in the mean, which agrees with the present observation.

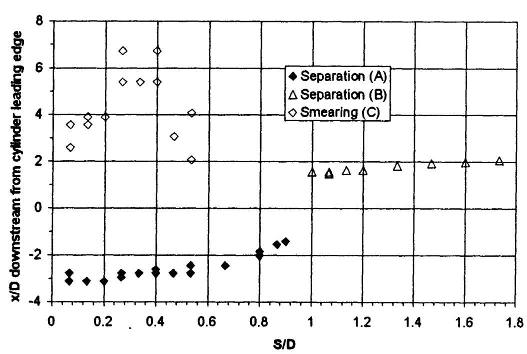

Figure 3. Oil film separation location.

For S/D≤0.4, a separation line can be observed downstream of the cylinder that coincides with a sudden change in the C_P slope (see Fig. 4) and an increase in the RMS values for C_P. The location of this separation line depends strongly on S/D. For 0.44<S/D≤0.53 this wake separation line is difficult to recognize from the surface flow patterns or the plate C_P distribution. Laser light sheet and dye flow visualizations suggest that this flow separation is intermittent. For 1≤S/D≤1.8 a single separation line is observed directly downstream of the cylinder. Its location coincides with the increase in plate pressure (see Fig. 4) and an increase in C_{Prms}. Wu and Martinuzzi (1997) observe this pattern for S/D=1 but not for S/D≥2.

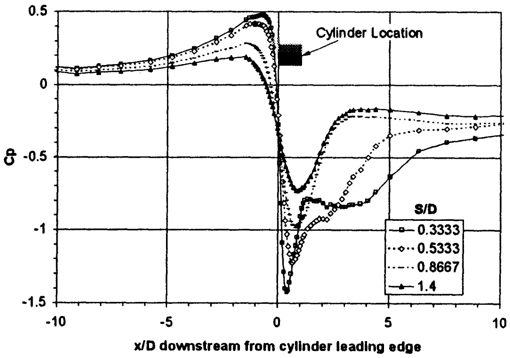

Figure 4. Plate pressure distribution.

Classification of Flow Regimes

From the previous discussion, it is seen that the Re influence is negligible. The flow characteristics for S/D≤0.4 differ significantly for S/D≥1. For 0.4<S/D<1, a flow description requires further analysis. In this section, the results of frequency and time domain analysis are considered.

Frequency Analysis. Power spectral density functions (PSDF) were obtained from the time traces of the surface pressure on the cylinder and velocity in the wake. The PSDF peak was associated with the vortex shedding frequency, f. Expressed in terms of the Strouhal number, $St=fD/U_\infty$, the results are shown in Fig. 5 as a function of

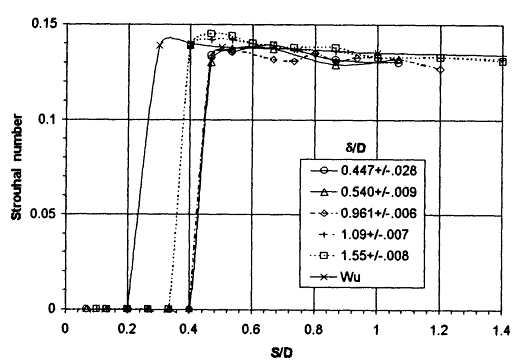

Figure 5. Strouhal number as a function of gap height.

S/D for several boundary layer thicknesses, δ. Preliminary results show that St is independent of Re so that all results presented are for Re=20000. For large gap heights, St=0.134±0.03 which agrees well with earlier studies. As S/D is decreased, St increases slightly as was also observed by Bosch *et al.* (1996) and Wu and Martinuzzi (1997). The peak power of the PSDF does not change for S/D>0.8 and

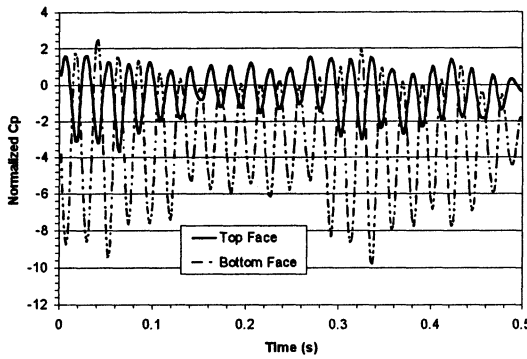

Figure 6a. Normalized C_P time trace for S/D=0.6.

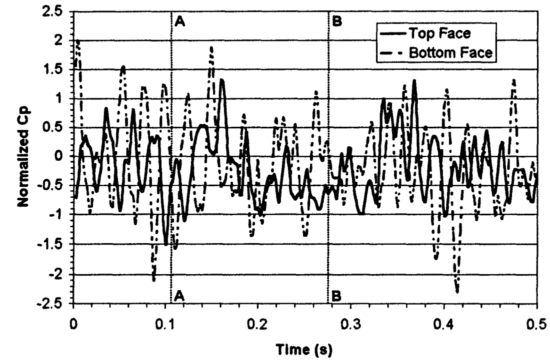

Figure 7a. Normalized C_P time trace for S/D=0.53.

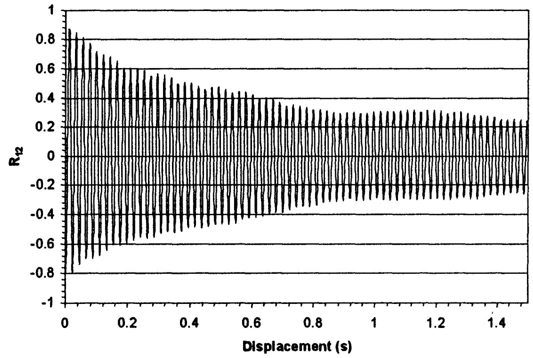

Figure 6b. Cross-correlation of pressure along top and bottom cylinder faces for S/D=0.6.

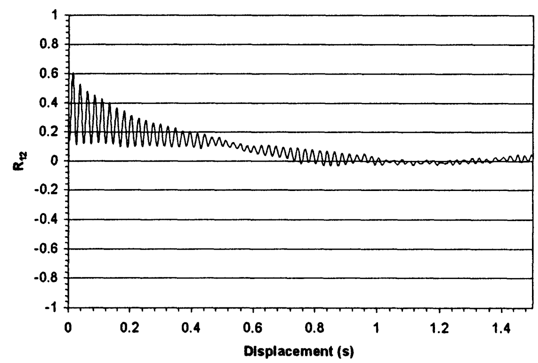

Figure 7b. Cross-correlation of pressure along top and bottom cylinder faces for S/D=0.53.

drops slightly between $0.6<S/D<0.8$. In the range $0.4<S/D<0.6$, the power drops significantly, indicating a change in the signal nature.

The exact critical gap height, below which no evidence of vortex shedding could be detected, depends on δ/D. For $\delta/D<1$, vortex shedding could not be detected for $S/D<0.44$ while for $1<\delta/D<1.5$, the critical gap height occurs between $S/D=0.33$ and $S/D=0.4$. For larger values, critical gap height occurs between 0.33 and 0.4. Wu and Martinuzzi (1997) with $\delta/D\approx1.5$ report a critical gap height of $S/D\approx0.30$, while Bosch *et al.* (1996) report $S/D\approx0.35$ with $\delta/D\approx0.8$. This influence of δ/D can thus help explain some of the discrepancies noted in the literature.

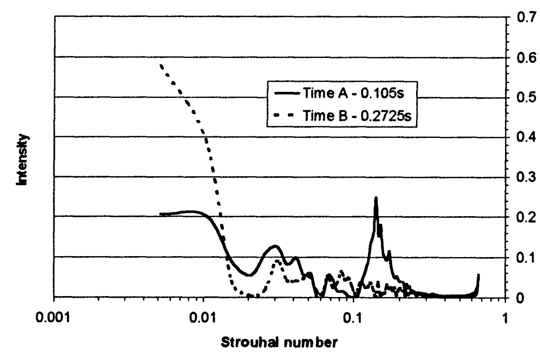

Figure 7c. Instantaneous FFT of point A and point B specified in Figure 7a.

Time Domain Analysis. Details of the time traces were investigated for each regime. For S/D less than the critical gap height, evidence of sustained periodicity could not be found. The pressures over the top and bottom faces of the cylinders are not correlated. For $S/D\geq0.6$ the velocity or pressure time traces show sustained periodicity in terms of continuous vortex shedding activity. For $S/D<0.6$ but greater than the critical gap height, the time traces show sequences of strongly modulated periodicity interspersed with sequences of random fluctuation. Illustrative examples are provided for a full vortex shedding case, S/D=0.6, in Fig. 6 and for an intermittent case, S/D=0.53, in Fig. 7. Time traces of the surface pressure measured at a point on the upper and lower cylinder surfaces, normalized according to

$$C_{Pn}(t)=(C_P(t)-C_{Pave})/C_{PRMS} \qquad (2)$$

are shown in Fig. 6a for S/D=0.6. Both sides show well-defined periodic behavior and a nearly constant phase difference around 180°. The cross-correlation function for these two signals, Fig. 6b, shows the strong coupling. The long term weakening of correlation is due to a long wave modulation that causes the observed phase jitter.

Pressure traces on the two cylinder faces and their cross-correlations for S/D=0.53 are shown in Fig. 7a,b. While strongly modulated, these time traces maintain periodic character over long intervals. During these intervals, the phase difference between the two pressure signals remains close to 180°. There exists, however, clear sequences where the correlation is lost (i.e. between 0.16s and 0.34s). As shown in Fig. 7b, this behavior results in an alternation of strongly and poorly correlated sequences.

Instantaneous Fast Fourier Transforms, Fig. 7c, at 0.105s (when the two signals are roughly 180° out of phase) shows a dominant fluctuation frequency in the pressure signals, which corresponds to the shedding frequency measured with the hot wires in the wake, from which the Strouhal number was evaluated. During periods of weak correlation, for example at 0.2725s, vortex shedding activity is interrupted. In this context it is thus appropriate to describe the flow regime between the critical gap height and S/D=0.6 as intermittent in terms of random periods of suppressed vortex shedding activity.

Gap Pressure Distribution. Okajima (1982) suggested that intermittency in vortex shedding on rectangular cylinders was caused by intermittent reattachment of the shear layer on the upper or lower cylinder surfaces. Based on present and earlier data, the flow over the top cylinder face does not reattach. The mean pressure distributions along the cylinder lower face and the plate directly underneath are shown in Fig. 8. The pressure trough is due to the leading edge recirculation bubble. Continuity requires that the stream-wise momentum flux be greatest where the recirculation bubble extends furthest from the walls. It directly follows that this point must also coincide with the local pressure minimum. This is confirmed through the oil film as the location of the pressure trough coincides with an area where the oil film has been completely removed. Note that this bubble center moves downstream as S/D increases from 0.1 to 0.4.

Past this point, the flow must expand resulting in a pressure increase as per the previous argument. This expansion is limited by the reattachment of the shear layer, downstream of which the pressure gradient is nearly zero (except for viscous losses). It follows from Fig. 8 then, that the flow reattaches in the mean, upstream of the trailing edge on the cylinder bottom face for S/D≤0.4. For 0.4<S/D<0.6, the mean reattachment occurs very close to the trailing edge, leading to a similar situation as described by Okajima (1982). For S/D≥0.6, reattachment in the mean clearly does not occur. As shown by Mason and Morton (1987), the adverse pressure gradient generates clockwise vorticity (of same sign as that generated in the upper shear layer) which would be of opposite sign to that generated at the leading edge and thus contribute to the difference between the circulation of the top and lower shear layers.

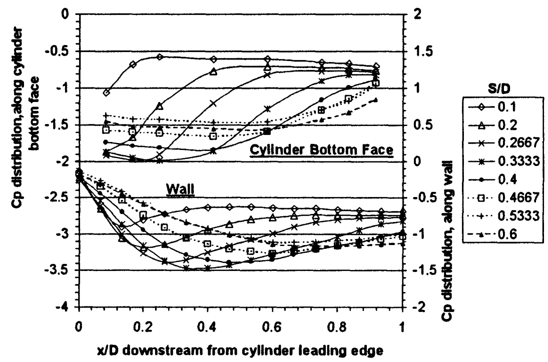

Figure 8. Gap pressure distribution.

Stability Analysis

Based on these and earlier studies, regular periodic vortex shedding cannot be sustained below a critical cylinder-to-wall gap height. The present results also indicate that an increase of the on-coming boundary layer thickness can slightly decrease the critical gap height. Thus, noting that the rotational flow from the boundary layer appears to be a second-order effect, the stability analysis of Kochin *et al.* (1964) is revisited to establish the conditions leading to vortex suppression. Only the major points of the analysis will be presented. Following the earlier study, it is assumed that the shedding mechanism can be described in terms of two infinite and parallel vortex streets, separated by a distance h, each of which consists of an equidistant train of vortices travelling at a constant convective speed and a separation b.

The intensities (circulations) of the upper and lower streets are assumed constant and are designated Γ_1 and Γ_2, respectively. It is further required that Γ_1 and Γ_2 have opposite signs. As shown by several earlier studies, only a staggered arrangement will lead to a stable solution.

The mean center of each vortex in the upper row is separated by ±b/2+ih from that of the closest vortex in the lower row, where i is the imaginary root. For the purpose of a stability analysis, it is convenient to study a cell of four vortices, yielding the complex potential for this flow:

$$\Omega(z)=\Gamma_1/(2\pi i)\ln(\sin[\pi/b(z-z_1)])+\Gamma_1/(2\pi i)\ln(\sin[\pi/b(z-z_3)])+ \Gamma_2/(2\pi i)\ln(\sin[\pi/b(z-z_2)])+\Gamma_2/(2\pi i)\ln(\sin[\pi/b(z-z_4)]) \qquad (3)$$

where it is arbitrarily chosen, but without loss of generality, that the two streets are located symmetrically about one coordinate axis. Since the vortices are regularly spaced, z_1, z_2, z_3 and z_4 express the locations of any four adjacent vortices. The traditional approach is to assume $\Gamma_1=-\Gamma_2$ and to impose an infinitesimal perturbation, δz, for each vortex. It is further assumed that $\delta z_1=-\delta z_3$ (in upper street) and $\delta z_2=-\delta z_4$ (in lower street). The stability properties are then investigated using classical methods.

In order to study the stability properties in the present case, a similar approach was taken, but it was assumed that $\Gamma_1\neq\Gamma_2$. By letting $\Gamma_1=\Gamma$ and $\Gamma_2=-\gamma\Gamma$.

The resulting dynamic system is

$$d/dt(\delta z_1)=\pi\Gamma/(8b^2)[i(2-\gamma E)\delta z_1-\gamma D\delta z_2] \quad (4)$$

$$d/dt(\delta z_2)=\pi\Gamma/(8b^2)[D\delta z_1-i(2\gamma-E)\delta z_2] \quad (5)$$

where $E=4/\cosh^2(\pi h/b)$; $D=-4\sinh(\pi h/b)/\cosh^2(\pi h/b)$ (6)

and $\delta z_1=Me^{\omega t}+iPe^{\omega t}$; $\delta z_2=Ne^{\omega t}+iQe^{\omega t}$ (7)

It is found that, at least to the first order, the stability condition must be

$$\cosh(\pi h/b)=(2\gamma)^{1/2} \text{ for } \gamma<1 \text{ , } \cosh(\pi h/b)=(2/\gamma)^{1/2} \text{ for } \gamma>1 \quad (8)$$

By substituting $\gamma=1$ ($\Gamma_1=-\Gamma_2$) the classical stable solution, $h/b=0.28$, is regained. This equation yields that no physical solution can exist if $\gamma<1/2$ or $\gamma>2$.

Data from velocimetry studies support this observation. For reasons of symmetry, for the freely suspended cylinder, the ratio of circulation is observed in the shear layers above and below the cylinder must be 1. The velocity data of Wu and Martinuzzi (1997) were integrated in the wake, between 3D and 5D downstream of the leading edge, to determine the circulation ratios in the shear layers. It was found that γ remained close to one for $S/D\geq1$ and was approximately 0.6 for $S/D=0.5$ (shedding still present, but strong phase jitter observed) and dropped to ≈0.3 for $S/D=0.25$ (no shedding case). The vorticity generated along the wall boundary layer upstream of the cylinder can also affect Γ_2.

The vorticity flux convected from the boundary layer to the front of the cylinder can be calculated, following Mason and Morton (1987) as

$$\int_0^{SP}(u\partial u/\partial y)dy=1/2u_B^2 \quad (9)$$

where $1/2u_B^2$ represents the stagnation pressure (at SP). This vorticity is of opposite sign to that generated along the cylinder walls below the stagnation point. Observing that $u_B<U_\infty$ (i.e. $C_P<1$ at the stagnation point) when the cylinder is mounted deeper into the boundary layer, the cancellation effect due to the wall vorticity is reduced. This behavior is observed as an increase, relative to thinner boundary layers, of the lower shear layer intensity, Γ_2. Hence, γ would be higher for the same S/D. This observation is supported by a reduction of the critical gap height for larger δ/D as observed in these and earlier experiments for a square cylinder. It should be noted that the wall vorticity advected from upstream is small compared to that generated along the cylinder surface. Thus the effect is slight and helps explain some of the discrepancies reported in the literature.

CONCLUSIONS

The thickness of the boundary layer is found to reduce the critical gap height. The intermittent vortex shedding regime $0.4<S/D<0.6$ (for $\delta/D\approx0.5$) is found to be related to intermittent reattachment of the bottom shear layer on the lower cylinder face. Stability analysis performed on a potential vortex street revealed that the flow will be unstable if the circulation ratio between upper and lower vortices falls below ½ or exceeds 2.

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