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Review Article

Flow Modification around a Circular Cylinder Applying Splitter Plates

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ABSTRACT

A number of different studies were reviewed to investigate the functionality of splitter plates for the purpose of drag reduction and vortex elimination behind a circular cylinder. The studies were carried out numerically or experimentally in different combinations of Reynolds range, 2D or 3D dimensions, with intention of drag reduction, vortex suppression or both. Results were compared to discover the generalities of a splitter plate's applications and its performance in drag reduction and vortex control. The reduction of 12% up to 38.6% in drag coefficient suggests that all reviewed studies verified the effectiveness of upstream plate in drag reduction. Varied upstream plate's gap ratios (gap between the plate and cylinder) were tested and the optimum position was obtained. For the finite cylinder case, however, the studies discovered that the effectiveness of upstream plate decreased severely and thus, are barely considered as a drag reductive tool for shorter cylinders. Although downstream plate influences drag force, its prominent application is found to be vortex shedding elimination (up to 14.7%). The length ratio and gap ratio of downstream plate were varied in these studies and it was found that the length ratio was a more important factor compared with the gap ratio in the case of vortex suppression.

Keywords: Circular cylinder, Drag reduction, Flow control, Vortex shedding, Vortex suppression, pressure coefficient, Strouhal number, Aspect ratio

INTRODUCTION

BLUFF bodies which are immersed in a flow field endure high drag forces due to their non-streamlined shapes. These drag forces cause many undesirable consequences such as energy loss. As flow passes a bluff body, depending on the Reynolds number and

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corresponding flow regime, various regions, such as separated flow, wake and periodic vortex shedding regions form behind the body. Each of these formations can be considered as either a desirable phenomenon (turbulence vortex shedding in heat transfer applications) or an unwanted occurrence. The aim of preventing those undesirable excitations has made the topic of flow control more significant among scientists in the past three decades. The purpose of reducing drag forces, delaying separation and suppressing vortex shedding in order to overcome erosion problem and reducing undesirable vibrations have motivated researchers to conduct various methods to achieve these goals in the field of flow control.

Flow over circular cylinders recently has become a matter of consideration due to its applications in industries. Bridge pillars and industrial stacks are examples which demand flow enhancement in order to increase their lifespan. There have been several methods to control the flow over these bodies; however, they are all categorised as active and passive flow control. As the presence of external energy is demanded in an active flow control, this type of flow control requires a more complex structure compared with passive control. Electric motors, pumps and speakers are some devices used in an active flow control to generate blow, suction and sound wave exertion. Endeavours of researchers in flow modification applying acoustic perturbation (Okamoto et al., 1981), cylinder oscillation (Suryanarayana et al, 1993;) Nakano & Rockwell, 1991), heating cylinder (Wang et al., 2000), applying electromagnetic forces (Kim & Lee, 2001), and blowing and suction (Bearman, 1965) are some of the examples within the scope of active flow control. Alternatively, applying changes to the body shape, attaching extra elements, changing the surface roughness, creating grooves or bumps on the surface are cheaper and easier ways to control and enhance the flow which are all considered as passive control method. Some typical examples of studies on passive control are controlling the separation of shear layers, effect of surface roughness (Buresti, 1981), applying different arrangements between two cylinders (Zdravkovich, 1977), controlling induced vibration among tandem cylinders (Assi et al., 2010), using small control cylinders (Kuo et al., 2007), (Bouak & Lemay, 1998), and utilising splitter plates downstream and upstream of a cylinder (Cimbala & Leon, 1996; Kwon & Choi, 1996; Anderson & Szewczyk, 1997; Hwang & Yang, 2007; Shukla et al., 2009).

Ensuring various effective influences on flow control over cylinders and application of splitter plates have recently become a focus among researchers. They have been used in the form of attached (Cimbala & Leon, 1996; Shukla et al., 2009) and detached (Hwang & Yang, 2007; Igbalajobi et al., 2013) upstream and downstream of the circular cylinder for the purpose of drag reduction, separation delay, vortex suppression and fluctuating lift assuagement. Apelt and West (1973) studied the effect of adding splitter plate by investigating pressure distribution (Apelt et al., 1973). Their research demonstrated the high level of dependency of drag force, base pressure and wake area to the presence of splitter plate. Zdravkovich researched on various aerodynamically control methods and mentioned splitter plate as a device to stabilise the wake (Zdravkovich, 1981). Kwon & Choi studied vortex shedding behind a circular cylinder numerically and discovered how the attached splitter plate affects it. In their research, it was shown that the Strouhal number is dependent on the length of plate. The presence of splitter plate is effective as long as it is completely positioned on the cylinder stream line, so it must be aligned with the mean flow direction (Kwon & Choi, 1996). This fact convinced some researchers to apply hinged plates to the cylinder as demonstrated by Cimbala & Leon (year of publication) who conducted their experiments using attached hinged plates, so plates were able to rotate in some pre-defined angles (Cimbala & Leon, 1996). Anderson & Szewczyk (year of publication) carried out an experiment for a variety of splitter plate lengths and found out that there was a reverse relation between base pressure and formation length. In their experiments, different plates with different length ratio (L/D =0-1.5) were tested (Anderson & Szewczyk, 1997). Ozono's study illustrated that in certain range of spacing between the cylinder and plate, the Strouhal number exceeds the natural vortex shedding frequency of the cylinder (Ozono, 1999). Shukla et al. (year of publication) also used hinged splitter plate behind the cylinder; likewise, the effect of plate on the vortex shedding suppression was observed (Shukla et al., 2009). Alam et al. (year of publication) applied tripping rods to reduce fluctuation fluid forces in two side-by-side and tandem cylinders (Alam, Sakamoto, & Moriya, 2003). Akilli et al. showed in their experiments that the plate thickness has no effect on the flow characteristic. They experimentally tested the effect of detached plate on the vortex shedding suppression in the shallow water using PIV techniques (Akilli, Sahin, & Filiz Tumen, 2005). In order to achieve more drag reduction using splitter plates, Hwang & Yang (year of publication) placed dual detached splitter plates, one upstream and the other downstream, on (or behind?) the cylinder. In their experiment, the position of the splitter plates were a matter of consideration (Hwang & Yang, 2007). Recently, many studies have been conducted considering the cylinder as a finite object with regards to its aspect ratio- the ratio of its height to its diameter (Uematsu & Yamada, 1995; Sumner, Heseltine, & Dansereau, 2004; Cimbala & Çengel, 2008; Igbalajobi et al., 2013; H. F. Wang, Zhou, & Mi, 2012). The current review attempts to compile the results of those studies on the application of upstream, downstream and dual plate, and make a comparison between the results of finite and infinite (2D and 3D) analysis. Table 1 summarises the specifications of these studies which will be compared and discussed in this review article.

Table 1
List of selected studies and their test details

Study	Test Method	Re Range	Dim.	Plates used
Apelt & West 1973	Experimental	$1X10^4 – 5X10^4$	2D	Downstream
Apelt et al. 1975	Experimental	$1X10^4 – 5X10^4$	2D	Downstream
Hwang et al. 2003	Numerical	30 – 100 – 160	2D	Upstream + Downstream
Hwang & Yang 2007	Numerical	30 – 100 – 160	2D	Upstream + Downstream
Igbalajobi et al. 2013	Experimental	$7.4 X 10^4$	3D	Downstream

DRAG REDUCTION

Pressure distribution around a circular cylinder is the reason for drag formation on the cylinder. The non-streamlined shape of the cylinder causes significant differences between the stagnation pressure (P_s) and the base pressure (P_b). The higher pressure on the stagnation point results in generating a drag force on the opposite direction of the body movement (in case the body is moving) or on the direction of the fluid flow (in case the fluid is moving over the body). Pressure drag is the most dominant type of drag on the cylindrical shaped bodies in the laminar flow, thus modifying the flow in a way that diminishes the pressure difference between those two points resulting in drag reduction. Figure 1 demonstrates the distribution of pressure coefficient along the circumferential direction of an isolated circular cylinder (Apelt & West, 1975; Hwang et al., 2003). Pressure coefficient for cylinder stagnation point is shown at θ=0o while the cylinder stagnation point is shown at θ=180^{o}.

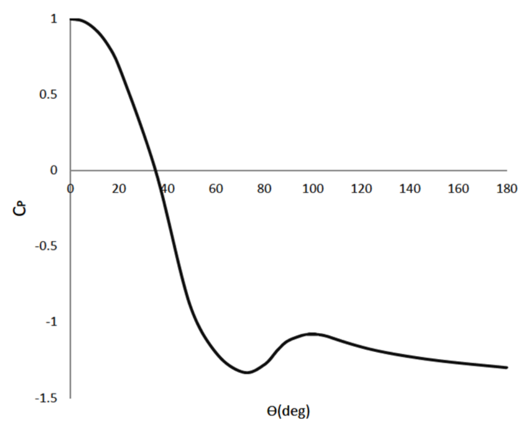

Figure 1. Distribution of pressure coefficient along the circumferential direction of the circular cylinder (Apelt & West, 1975).

In a referred study, a wake splitter plate was placed along the centreline of the cylinder to augment the pressure coefficient on the cylinder base (C_{pb}). Based on the cylinder diameter (D), length ratio of splitter plates was defined as (L/D) varying from 2 to 7. It was found that the pressure drag coefficient was independent of Reynolds number as C_p values were identical for all the velocities corresponding to $10^4<Re<5x10^4$. Figure 2 illustrates how drag coefficient (C_D) varies as C_{pb} changes in different plate's L/D. C_D follows a descending order until it reaches L/D=1.5, then the trend changes direction in L/D=2 where a relative maximum is observed in C_D diagram. For length ratio longer than 5, no significant changes in C_D have been noted. The length ratio of wake splitter plates is a dominant factor in vortex shedding elimination which will be discussed later. Therefore, a more serious consideration has been given to L/D>2. A study on the effect of splitter plates L/D≤2 was conducted by Apelt et al. (year of publication) and it was ascertained that the presence of splitter plate increases the base pressure and subsequently reduces pressure drag. It was also observed that even shorter splitter plates made remarkable changes in C_{pb} and C_D (Apelt et al., 1973). Increasing L/D however, proved to have improved modification in vortex suppression resulting in the author continuing investigation on splitter plates as long as L/D≥2. The maximum drag reduction obtained was 33% based on Apelt's study (year of publication) which was acquired by implementing splitter plates longer than 5D. Applying splitter plates with L/D≥5 has no significant changes in drag reduction (Apelt & West, 1975). Based on visualisation studies downstream of the cylinder, for very large splitter plates, the flow reattaches on the plate at the L/D=5 regardless of the length of the plates.

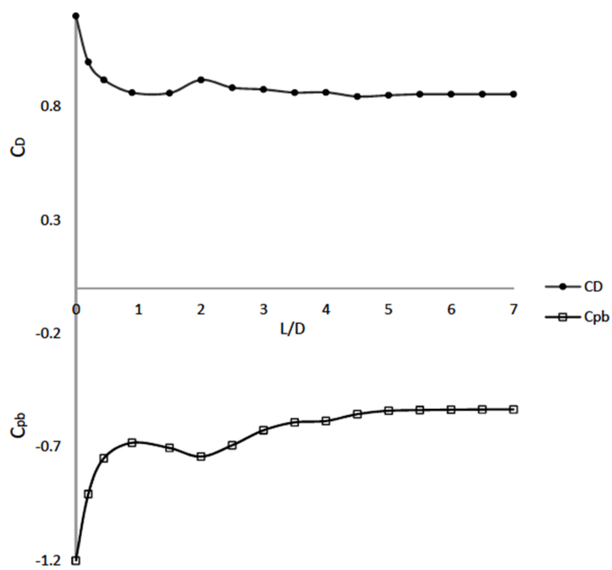

Figure 2. Variation of C_{pb} and C_D with downstream plate's length ratio. L/D≤2 (Apelt et al., 1973), 2≤L/D≤7 (Apelt & West, 1975).

Hwang (year of publication) had studied the use of splitter plates as C_P modifier) in order to reduce drag on the circular cylinder. The study was conducted numerically at laminar flow with Re=30,100 and 160 and the upstream plate was settled in front of the cylinder centreline without relative angle (Hwang & Yang, 2007). The mechanism of drag reduction differs from what was used in Apelt's (year of publication) study as pressure coefficient at cylinder stagnation point (C_{Ps}) was the varying parameter. By decreasing C_{ps} the difference between C_{ps} and C_{pb} is reduced which in turn diminished the drag force. The two controlling parameters were the plate's length ratio to the cylinder diameter (L_l/D) and the gap between the plate's trailing edge and cylinder stagnation point measured relatively to the cylinder diameter (G_l/D).

As seen in Figure 3, there is a minimum value for C_D and the upstream plate's position varies along the cylinder centreline. Hwang's justification vindicates this phenomenon using pressure distribution in fluid along the cylinder centreline shown in Figure 4. The dashed-dotted line represents the distribution of C_P without a splitter plate while the solid line denotes the case with upstream plate. The solid line is not continuous and is intercepted in a position of x which corresponds to place in which the plate is implemented. That's where the line becomes dashed-double dot and represents the C_p on the plate's surface. The mechanism of drag reduction using upstream splitter plate differs from what a downstream splitter plate does. They even act independently in the case of applying dual splitter plates (one upstream and one downstream). Upstream plates cause a sudden reduction in the flow's momentum energy while the flow reaches the plate's leading edge. At that point, pressure escalates drastically due to the conservation of energy. By moving along the plate, the flow's energy is converted to momentum energy gradually, thus a sudden fall is observed for the pressure until the flow attains the trailing edge of the plate. The flow continues its path recovering the kinetic energy till it gets to the cylinder stagnation point. Once more, energy conversion happens and momentum turns into pressure due to the blockage of the cylinder. Compared with an isolated cylinder, this pressure at stagnation has a lower value, and this fact is legitimatised by considering energy loss via friction and blockage during the flow passage over the plate.

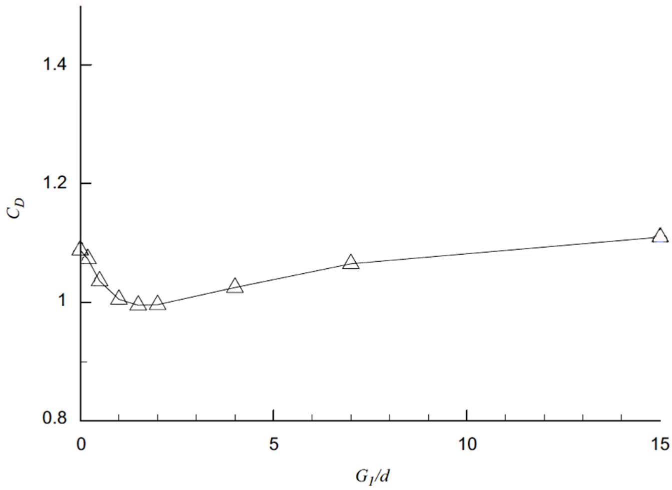

Figure 3. Drag coefficient in different upstream plate's gap ratios. Re=160 (Hwang & Yang, 2007).

The minimum drag coefficient is obtained by locating the plate in a proper position which causes the flow to have its minimum possible pressure magnitude at the vicinity of the cylinder. The variation of C_p along cylinder centreline is demonstrated for three different gap ratios of 0.5, 1.5 and 4 in Fig. 4 a, b, and c respectively. It is noticed that by moving the plate further to the cylinder, a lower pressure flow comes out of the trailing edge of the plate, which is promising to obtaining lower C_D on the plate. Additionally, the wider the distance of the plate from the cylinder, the more time it takes for the flow to recover its energy and consequently the higher value it has in the vicinity of the cylinder. Therefore, there is an optimum position where the value of C_P is minimum at the stagnation point of the cylinder which is at G_1=1.5D.

To enhance the flow characteristics around the cylinder, Hwang (year of publication) also applied an additional downstream splitter plate while the upstream plate was fixed in its proper position. Although employing a splitter plate behind the cylinder follows the primary objective of vortex shedding elimination, it has a positive effect on the reduction of drag force over the cylinder. The length ratio was defined as G_2/D and L_2/D corresponds to the distance between cylinder stagnation point and the downstream plate's leading edge. Figure 5 represents the variation of C_D for two cases - G_2/D varies when only downstream plate is implemented (Δ) and when dual plates are applied (□). The value for drag coefficient reaches its minimum at G_2/D=2.5 regardless of the presence of upstream plate. The figure also indicates the same pattern of C_D response to the variation of G_2/D in both cases. This similarity indicates that the mechanism of drag reduction for downstream splitter plate is completely independent of the upstream plate's performance.

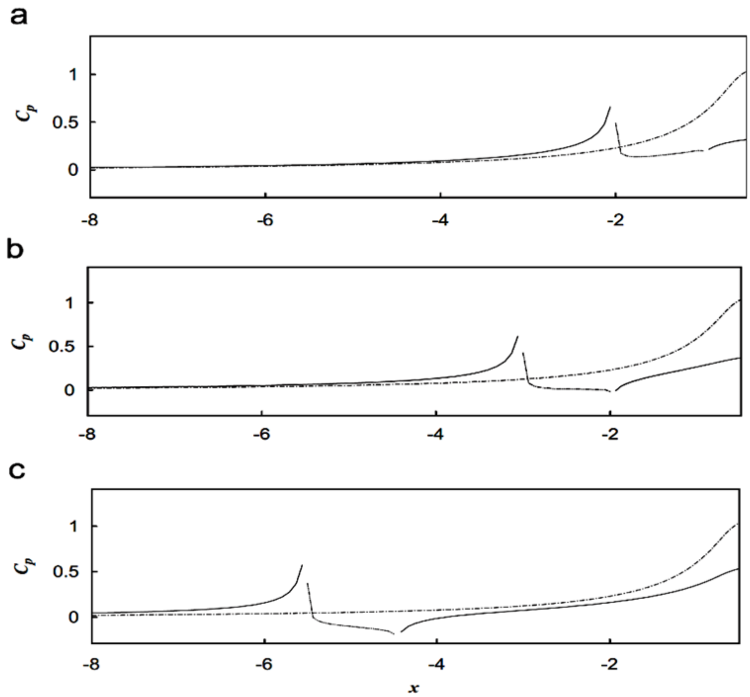

Figure 4. Variation of C_p along the upstream centreline for three different upstream gap ratios. (a) $G_1/D = 0.5$, (b) $G_1/D = 1.5$, (c) $G_1/D = 4$ (Hwang & Yang, 2007).

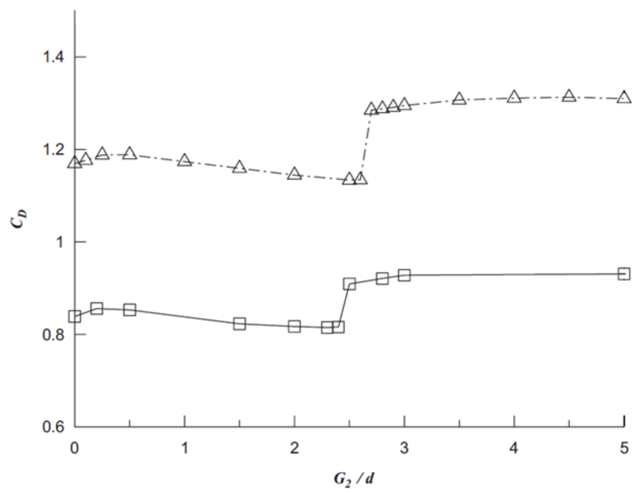

Figure 5. C_D distribution for different downstream gap ratios, $G_1/D = 1.5$. (Δ) Downstream plate (Hwang et al. 2003), (□) Dual plate (Hwang & Yang, 2007)

The effect of downstream plate in its optimum position ($G_2/D = 2.4$) was reported at 14.7% in Hwang et al.'s study (2003). The reason for this effect is that when a downstream plate is settled, C_{pb} increases and lessens the difference between C_{pb} and C_{ps} as shown in Figure 6.

The time-averaged distribution of pressure along the circumferential direction of the cylinder coefficient for other cases is plotted in Figure 6. The reason for C_{pb} augmentation due to the implementation of upstream plate solely (even a very small effect) is that it affects vortex shedding indirectly by generating free shear layers. The maximum drag reduction happened when both plates were applied and caused C_{ps} to decrease (upstream) and C_{pb} to increase (upstream and downstream), and since its maximum obtained value was 38.6%, it was found out that the upstream plate plays a more important role for this purpose (compared with a value of 14.7% which was caused by using the downstream plate only). Apelt and West (1975) had reported a 33% of drag reduction by only applying a plate behind the cylinder/ They discovered that unlike for the upstream plate, the determinant factor for downstream plate is the length ratio of the plate. As discussed later, longer plates are more applicable for vortex shedding suppression, thus, implementing short plates behind the cylinder would not be a rational choice for any purpose of drag reduction or vortex shedding elimination.

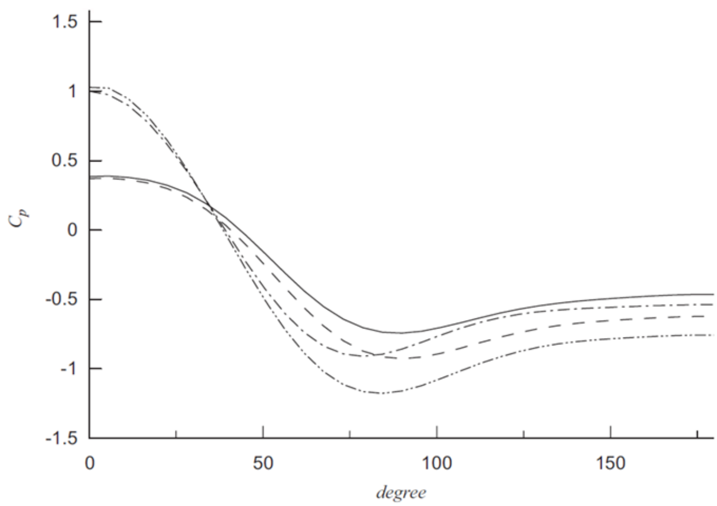

Fig. 6. Distribution of C_p along the circumferential direction of cylinder. (Dashed) upstream only, (Dashed-dotted) downstream only, (Solid line) dual plate, (Dashed-double dotted) no plate (Hwang & Yang, 2007)

Igbalajobi et al. (2013) looked at a broader application of downstream splitter plate as he experimentally applied the same plates as Apelt and West (correct?) to investigate their effectiveness in cylinders with aspect ratio (the ratio of cylinder height to its diameter). The experiment was conducted in a low-speed wind tunnel at a Reynolds number of $7.4x10^4$[17]. Figure 7 contains data for different aspect ratios of AR=9, 7, 5, and 3 in plate's length ratio varying from 1 to 7. Unlike certain studies (Apelt et al., 1973; Apelt & West, 1975) the plate is not attached to the cylinder; (note that the data presented for mean drag coefficients concern total cylinder drag (pressure and skin friction drag) and the drag generated by the plate is not considered in the calculations). Based on Figure 7, for the shorter cylinders, the effect of downstream splitter plate in drag reduction is less compared with the infinite cylinder (data for infinite cylinder are from Apelt & West, 1975). The bulkier the cylinders gets, the less effective the plate becomes; in the case AR≤7 this effect is negligible (maximum 3%). The difference between two trend lines of infinite and AR=3 proves this statement. Even for the case AR=9 for which the maximum effect reaches up to 12%, the pattern for C_D behaviour to the L/D changes is different from what was observed for the infinite cylinder in Apelt's study. The reason relates s to the effect of tip vortex structure. For shorter cylinders, this structure absorbs a greater portion of the wake and becomes the leading aspect which determines wake behaviour. Thus, the drag is no longer influenced by the plate behind the cylinder.

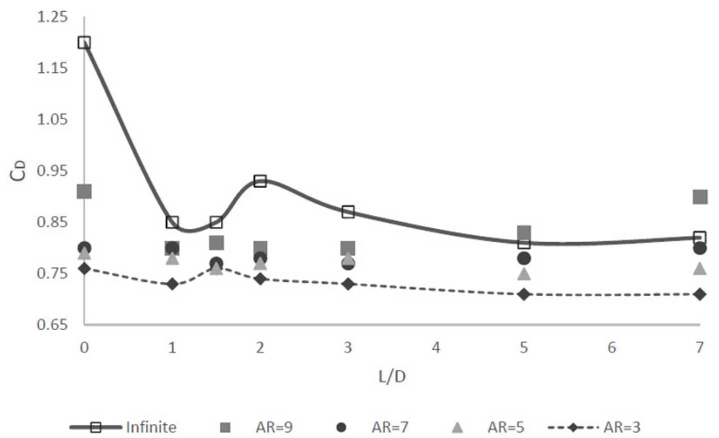

Figure 7. Mean C_D in different downstream plate's length ratio. Infinite cylinder (Apelt & West, 1975), Finite cylinder (Igbalajobi et al., 2013).

VORTEX SHEDDING SUPPRESSION

Power spectra graph for vortex frequencies behind a circular cylinder experience a peak at a frequency corresponding a specific Strouhal number (Igbalajobi et al., 2013). This peak reduces in its amplitude as the downstream plate is placed behind the cylinder till the peak decays and the power spectrum follows a steady trend. Figure8 shows a power spectrum for a cylinder with AR=9. For splitter plates above 3D, no peak is observed which shows the shedding suppression by the mean of plates longer than 3D. The frequency where the peak occurs corresponds to the Strouhal number where vortices are shed behind the cylinder. This occurrence which is based on instabilities of shear layer (Nakamura, 1996) can be neutralised by implementation of splitter plates downstream of the cylinder. Splitter plates if placed in a proper gap relative to cylinder diameter are able to extend upwards the shear layer to its trailing edge and barricade the free-stream flow to be carried along into the base region (Akilli et al., 2005). This is categorised as a direct wake modification based on the classification of flow control into 2 major types of boundary-layer controls and direct-wake modifications (Choi et al., 2008). Altering a downstream splitter plate's length ratio (L_2/D) (Apelt & West, 1975; Igbalajobi et al., 2013), gap ratio (G_2/D) (Akilli et al., 2005; Hwang & Yang, 2007) or picking a suitable combination between them results in vortex shedding suppression behind the cylinder. Table 2 lists four different studies with information about the state in which vortex shedding suppression has occurred.

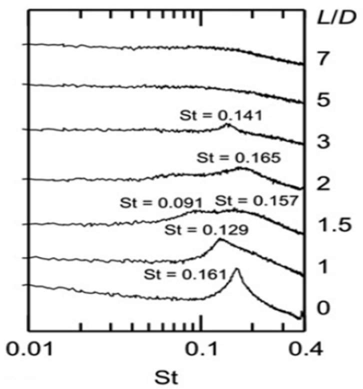

Figure 8. Power spectrum of vortex frequency for different L_2/D behind a finite circular cylinder with AR=9 (Igbalajobi et al., 2013).

Table 2
States in which suppression of shedding happens in four different studies

Study	Re	L_2/D	G_2/D	St	Dimension
Hwang et al. (2007)	100	Cte = 1	2.4	0.122	Infinite
Apelt et al. (1975)	1-5 X10^4	≥3	Cte = 0	0.165	Infinite
Akilli et al. (2005)	5 x 10^3	Cte = 1	1.75	0.163	Infinite
Igbalajobi et al. (2013)	7.4 x 10^4	≥3	Cte = negligible	0.141	AR=9

In a similar situation, Strouhal number for infinite cylinder is higher than the finite one. Looking deeper in a finite case , shorter cylinders possess lower value of Strouhal number as base pressure is higher and vortex formation length becomes longer (Igbalajobi et al., 2013). In the study by Igbalajobi et al. the length ratio was the altering parameter of the splitter plate with a constant gap ratio relative to the cylinder diameter ($G_2/D=1$). Splitter plates with length ratio of 1-7 were examined to determine the minimum length to eliminate shedding for each cylinder aspect ratio. It was discovered that as the cylinder gets bulkier, a shorter plate is needed to attenuate the shedding. The behaviour of cylinders with AR=7, 9 was found to be similar to the infinite as the vortices were not shed with a same pattern along the height of the cylinder. In fact, there is no shedding at the tip and near the ground plane. Unlike for the long cylinder, a uniform shape of vortices covers along the whole downstream from the ground plane to the tip. This is justified by the prominence of tip structure in bulkier cylinders compared with longer cylinders. This phenomenon makes shedding control easier in short cylinders even by using shorter plates (Igbalajobi et al., 2013).

Both Hwang (2007) and Akilli (2005) considered constant length for the downstream plate and the varying parameter is determined to be the gap ratio. The differences between their studies were the range of Reynolds number and the presence of upstream plate, which was implemented in Hwang's study but not in Alilli's. The critical G_2/D was 2.4 in Hwang's case as the vortex shedding was effectively suppressed. By moving the plate to the position of 2.5D this effect is no longer stable and vortices start to shed behind the trailing edge of the plate as it is seen in Fig. 9. The significant rise in Strouhal number (St = 0.122 at $G_2/D = 2.4$ to 0.146 at $G_2/D = 2.5$) also confirms this fact. The effectiveness of the upstream plate in the reduction of Strouhal number was reported at10% (Hwang & Yang, 2007), and that's why the critical state in Akilli's study (with no upstream plate) experienced a higher Strouhal number compared with Hwang's study despite the same configuration of the cylinder and plate. Figure 10 shows how the splitter plate loses its functionality as it exceeds the critical gap which was obtained in Akilli's study and was reported to be $G_2/D = 1.75$. The Strouhal number however, continues to diminish as the gap gets bigger until it reaches the value of 2.7D (Akilli et al., 2005) unlike Hwang's study in which the shedding suppression and Strouhal number reduction stop after achieving a same gap ratio.

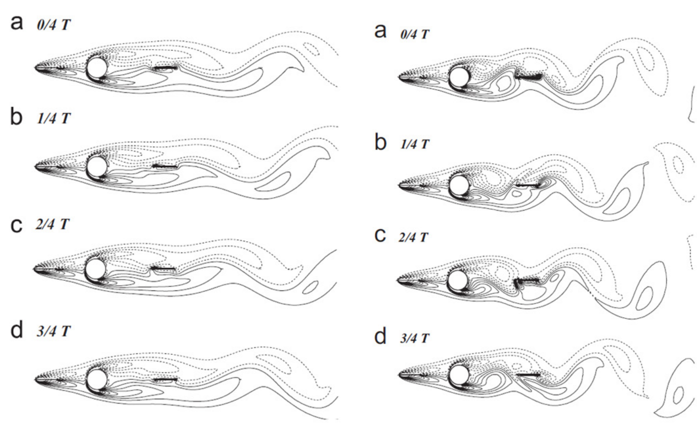

Figure 9. Vorticity contour in 4 intervals of a period. Left: $G_2/D=2.4$ (critical), Right: $G_2/D=2.5$ (supercritical) (Hwang & Yang, 2007)

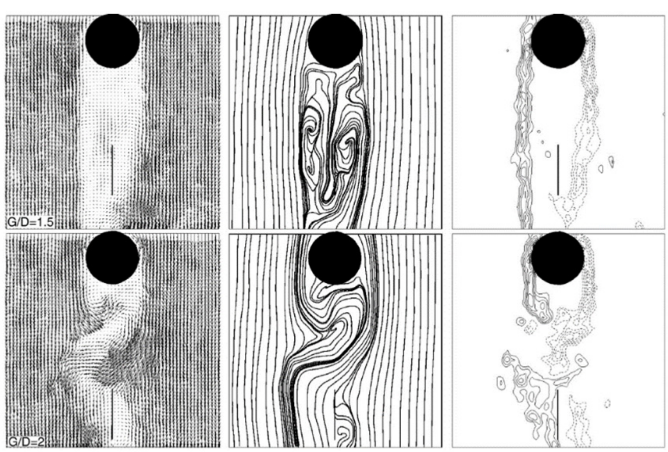

Figure 10. Velocity vector field, streamlines and vorticity contour for two gap ratios. G_2/D subcritical, G_2/D supercritical. Shedding appears when G_2/D exceed the critical value of 1.75 (Akilli et al., 2005).

It is deduced in Akilli's study that the peak is observed in the power spectra and vortices are even shed in low frequencies. Low Reynolds number in this study may be the reason for this phenomenon. The unclear state and lack of a precise setting for splitter plates make this topic open for further investigations. Besides, applying plates with a height similar to the cylinder may not be practical especially in large structures. This consideration necessitates a new scope for future experiments concerning 3D analysis to investigate whether or not shorter plates (in height) have the same functionality in drag reduction and vortex shedding suppression.

SUMMARY

A review of the effectiveness of splitter plate in drag reduction and vortex suppression of a circular cylinder was conducted. All the reviewed studies verified that the presence of upstream plates has a significant influence on drag reduction since they lessen the pressure at the stagnation point and partly augment the base pressure behind the cylinder. The important parameter of the upstream plate is discovered to be its position to the cylinder, relative to the cylinder diameter. This plate has no impact on the vortex shedding behind the cylinder. Downstream plate has less effect on the drag compared with the upstream one and this fact was confirmed in all studies. The main use of a downstream plate is vortex shedding suppression which can be optimised through altering the combination of its relative position and length to the cylinder. Regarding the 3-dimensional analysis, bulkier cylinders sustain less drag force and experience lower frequency of vortices. However, the effect of plates in drag reduction were observed less when compared with the infinite case. Yet, it was easier to achieve the elimination of shedding behind the finite cases and which required shorter plates. In case of failure of suppression, downstream plates cause a significant reduction in the frequency of remaining vortices.

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