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Control of Vortex Shedding by a Short Asymmetrically Located Downstream Splitter Plate

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Abstract—*In this investigation the vortex shedding from a square cylinder was attempted to be controlled by placing a short asymmetrically located downstream splitter plate. The length of splitter plate is equal to the side of square cylinder denoted by 'a' with a thickness of 0.1a and the gap between cylinder and plate is denoted by G. The plate is kept within the critical gap ratio [$(G/a)_{cr} \approx 2.3$] similar to previous study by Srivastava and Sarkar [1]. However, in their work the cylinder and splitter plate shared the same axis. In the present study, the splitter plate location is varied both streamwise (G/a = 0, 0.5, 1, 2) and in flow-normal direction (y/a =0, 0.25, 0.5. 0.75). The Reynolds number is considered in the periodic vortex shedding regime (Re=100, based on free stream velocity U_∞ and a). Instantaneous and mean flow field along with aerodynamics forces and Strouhal number are depicted for extreme four cases to understand the change in vortex dynamics of cylinder with respect to an asymmetrically located downstream splitter plate.*

1. INTRODUCTION

Addition of a splitter plate along the wake centreline downstream from bluff bodies is an efficient passive means of controlling fully developed vortex shedding. The objective of this work is to observe by means of instantaneous flow visualizations and aerodynamic forces, the influence of such plate control on the early near-wake establishment stages of a square cylinder geometry at *Re* = 100.

In the last few decades, research in the field of passive steady flow control has shown that a splitter plate set along the bluff body wake centreline reduces drag and may inhibit vortex shedding [2]. For a Reynolds number of 1.45×10^4, Roshko [3] was notably one of the first to report periodic vortex formation suppression using a circular cylinder connected with a splitter plate. He also showed that, by positioning this splitter plate at different fixed distances in the fully developed cylinder-wake, the Strouhal number *St* ($St = fD/U_\infty$, where *f* is the frequency of vortex shedding, *D* is the diameter of the circular cylinder) diminishes as the distance between the cylinder and the plate increases up to a limit position .$G \approx$ 2:7*D*. In the same way, Apelt et al. [4] and Apelt and West [5] carried out experiments with two combinations, a circular cylinder connected with a splitter plate and a normal flat plate (fixed separation points) connected with a splitter plate, to show the influence of the splitter plate length (0 <*Lsp* <7) on drag and vortex shedding ($10^4 \leq Re \leq 5 \times 10^4$). They concluded that short splitter plate lengths (*Lsp* ≤ 2) can significantly change the characteristics of the downstream flow from the circular cylinder and from the normal flat plate. They also established that splitter plates longer than 2*D* decrease the drag and progressively slow the vortex shedding until *Lsp* = 3*D* for the flat plate and, until *Lsp* = 5*D* for the circular cylinder. Beyond these splitter plate lengths, no further change occurs, the drag coefficient C_D remains constant and the vortex shedding ceases. With the same purpose, Bearman [6] tested a semi-elliptical section body ($Re = 1.5 \times 10^5$). With this model, vortex shedding disappears for a connected split. Each of these steady flow studies showed that a splitter plate was an efficient passive control means in a fully developed wake. Thereby, since it has been proven that near-wake characteristics govern the far wake, it would be interesting to define the influence of such a splitter plate on the initial establishment stages of a near-wake bluff body.

Ali et al. [7] numerically simulated the flow over square cylinder attached with a varying splitter plate (length = 0.5*D* to 6*D*) at *Re* = 150. The thickness of the plate was fixed at 0.002*D*. They obtained three different flow features (here sound or tone level) depending on plate length. For the first regime ($L \leq D$), the tone levels decreased with increasing plate length. For the second regime ($2D \leq L \leq 4D$), the tone levels were always higher than the single square cylinder case and they increased with increasing plate length. For the third regime ($5D \leq L \leq 6D$), the levels of the tones decreased with the increase of the plate length but the levels are higher than the other regimes.

In another work, Ali et al. [8] simulated wake flow from a square cylinder interacted with a splitter plate at Re = 150. Sensitivity of near wake flow structure to the downstream position of plate is investigated at varying gap ratios (0< G/D <7) for a constant plate length. Two flow regimes were identified with the transition at critical gap distance ($G_{cr} \approx 2.3D$). The first regime was characterized by the completion of vortex formation in the downstream of the gap and the second regime as completion of vortex formation within the gap. The authors also observed that the splitter plate had no effect on the generation of Kármán vortex when the gap is beyond 5.6D.

Srivastava and Sarkar [1] in their simulation kept a splitter plate behind a square cylinder and vary the gap-ratio up to G/a = 2 (below G_{cr}) at Re = 100. The authors proposed to divide the inner region of critical gap in another two sub-regions due to the difference in flow physics before and after G/a = 1. Jain et al. [9] considered the same flow domain and Re, but performed their simulation for G/a = 2.5 – 4. They observed that as the gap-ratio increased, the vortex roll-up started in the intermediate region between the cylinder and splitter plate.

In the present study, simulation is carried out in Fluent for a square cylinder wake interacting with a downstream splitter plate at Reynolds number in periodic vortex shedding regime (Re = 100). The gap between cylinder and plate was varied from G/a = 0 to G/a = 2. Instantaneous flow features, aerodynamic forces and vortex shedding frequencies are reported to understand the flow physics when the gap between these two structures is less than the critical gap-ratio.

2. NUMERICAL METHODS

The performed cases in the present investigation are developed by using Gambit 2.2.30 which also helps to introduce the boundary conditions on the flow domain. Cartesian grid is used where origin of the axes lies at the downstream side of cylinder; x- and y- coordinates indicate the streamwise and flow-normal directions respectively and their corresponding velocities are denoted by u and v.

The computational domain is extended up to -8.5D in the inflow and in the flow normal direction it is extended up to ±8D from the origin and 27.5D in the outflow from the trailing edge of the flat plate for all cases.

Fig. 1 shows the schematic diagram of flow problem with imposed boundary conditions. After performing grid independent test a mesh of 268 × 208 points are allotted in streamwise and flow-normal direction for G/a = 0. The number of grid points are increased in both directions (streamwise and flow-normal) with the increase of G/a and y/a values. The grid distribution in detail is given in Refs. 1 and 9. Also similar kind of grid distribution was considered by Pal and Sarkar [10] and Raees and Sarkar [11] in their work at Re = 100.

The 2-dimensional Navier-Stokes (momentum) equations are non-dimensionalized by considering a and U_∞ as unity. The flow field is then solved by Ansys Fluent 14.5 using SIMPLE algorithm [12] in second-order upwind momentum scheme with a standard pressure solver. A total of 20 iterations at each time step are considered for the pressure correction.

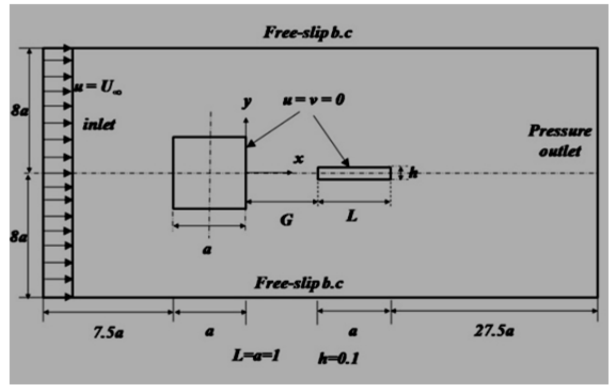
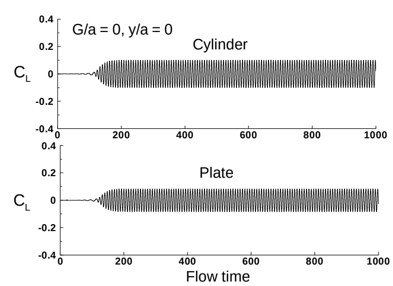


Fig. 1: Schematic diagram of flow geometry

3. RESULTS AND DISCUSSION

To understand the flow physics results from both the mean and instantaneous flow field are depicted. In this regards aerodynamic forces, Strouhal number, mean streamwise velocity at different sections and instantaneous vorticity contours are discussed for the extreme four cases (y/a = 0, 0.75 at G/a = 0, 2).



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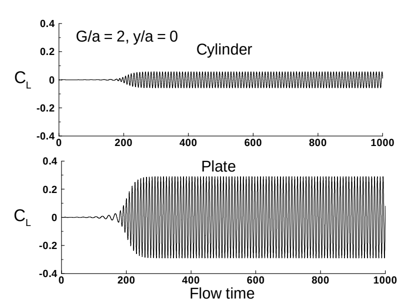

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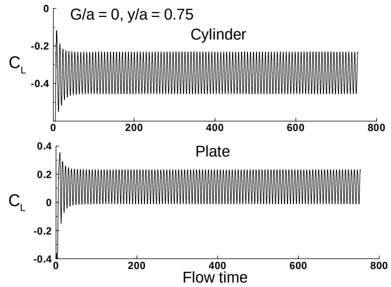

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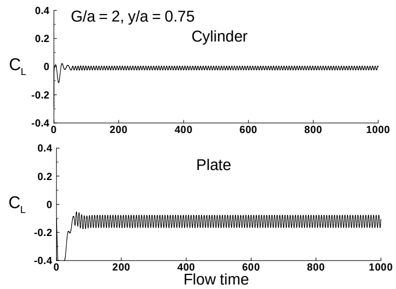

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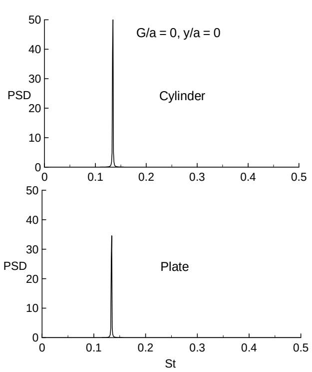
Fig. 2: Time evolution of C_L for both the cylinder and plate at (a) *G/a* = 0, *y/a* = 0; (b). *G/a* = 2, *y/a* = 0; (c) *G/a* = 0, *y/a* = 0.75 and (d) *G/a* = 2, *y/a* = 0.75.



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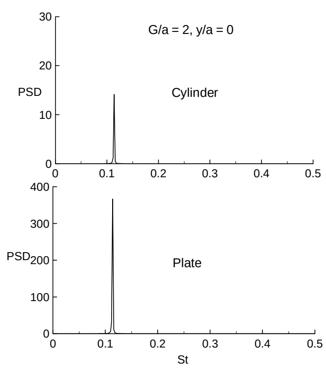

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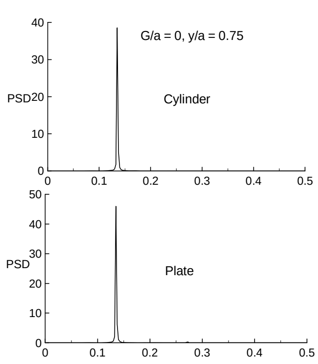
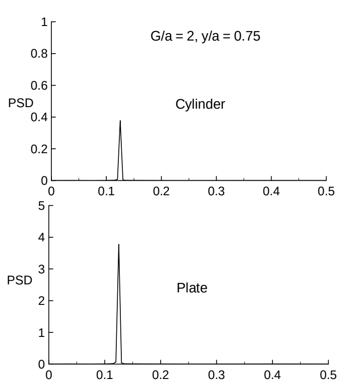




(c) **(d)**

Fig. 3: Power spectra density vs. *St* for both the cylinder and splitter plate: (a) *G/a* = 0, *y/a* = 0; (b). *G/a* = 2, *y/a* = 0; (c) *G/a* = 0, *y/a* = 0.75 and (d) *G/a* = 2, *y/a* = 0.75.

Fig. 2 illustrates the variation of coefficient of lift ($C_L = \frac{F_L}{\frac{1}{2}\rho U_\infty^2 A}$, F_L is the lift force, ρ is the density and A is the projected area of the cylinder in horizontal plane) with flow time for both the cylinder and plate. It has been observed that the flow field is developed after 150 time period. It should be noted here that the calculation of mean flow field started at least after 300 flow time.

At *G/a* = 0 & *y/a* = 0, the variation in C_L value is identical for both the cylinder and plate that illustrates that the combination behave like a single body while attached and sharing the same axis line. As the gap ratio increases for the similar vertical position, little variation in C_L value for cylinder indicates the suppression of vortex shedding in between the cylinder and plate. High range of C_L for plate is attributed to the proper vortex shedding downstream of the plate.

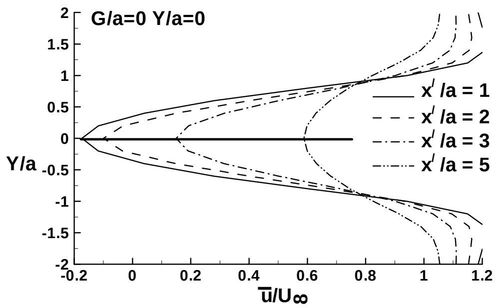
When the plate is kept offset from the cylinder axis (*y/a* = 0.75, Figs. 2c-d), the mean C_L value do not remain zero both for the cylinder and plate. Opposite sign of mean C_L for cylinder and plate can be seen which illustrate both of them affect the other's vortex shedding in a more pronounced way.

The power spectra density with Strouhal number ($St = \frac{fD}{U_\infty}$, f is the frequency of vortex shedding) are depicted in Fig. 3 for the four extreme cases as described above. A single peak was obtained for all diagrams, but the peak value is less as compared to a single cylinder placed in an unbounded condition.

Table 1: Flow parameters for square cylinder

y/a	*G/a*	$\overline{C_L}$	$\overline{C_D}$	*St*
0	**0**	**0**	**1.399**	**0.134**
	0.5	0	1.462	0.132
	1	-0.01	1.44	0.127
	2	**0**	**1.432**	**0.114**
0.25	0	0.16	1.36	0.135
	0.5	0.023	1.455	0.135
	1	0	1.448	0.125
	2	-0.023	1.430	0.115
0.5	0	0.1	1.40	0.140
	0.5	0.005	1.429	0.135
	1	0.009	1.448	0.130
	2	0	1.42	0.120
0.75	**0**	**-0.385**	**1.57**	**0.135**
	0.5	0.062	1.439	0.135
	1	-0.02	1.431	0.131
	2	**-0.01**	**1.4**	**0.124**

The mean values of lift ($\overline{C_L}$) and drag ($\overline{C_D}$) coefficients along with vortex shedding frequency (St) are tabulated in Table 1 for all 16 cases considered within the critical gap ratio. The values of four extreme cases for which the figures are enlisted are given in bold font to differentiate them with other cases. The minimum $\overline{C_D}$ value is obtained at G/a = 0 and y/a = 0.25, but interestingly the value of $\overline{C_D}$ is also quite low at G/a = 2 and y/a = 0.75 which reveals vortex suppression at this high offset.



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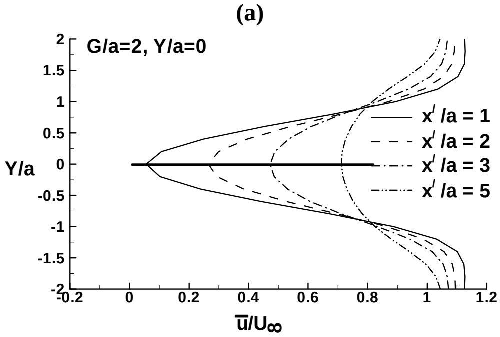

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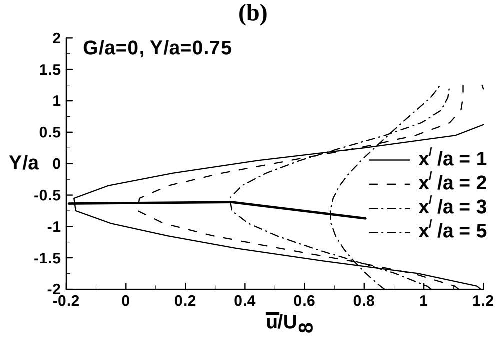

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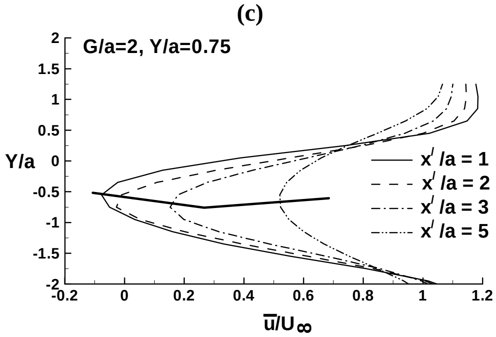

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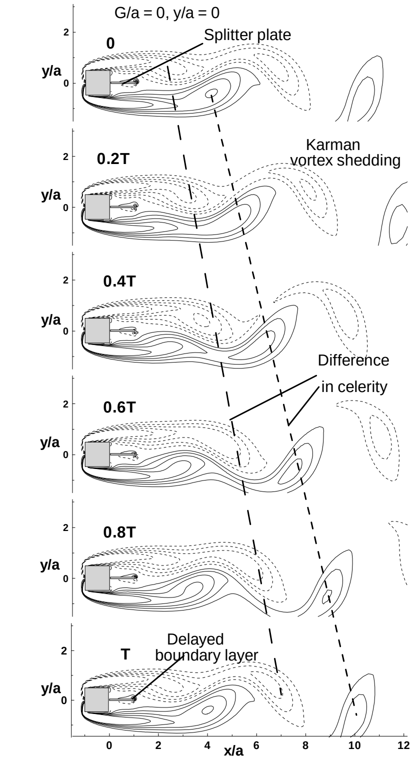
Fig. 4: Mean velocity profiles at different streamwise locations. Four extreme cases have been considered.



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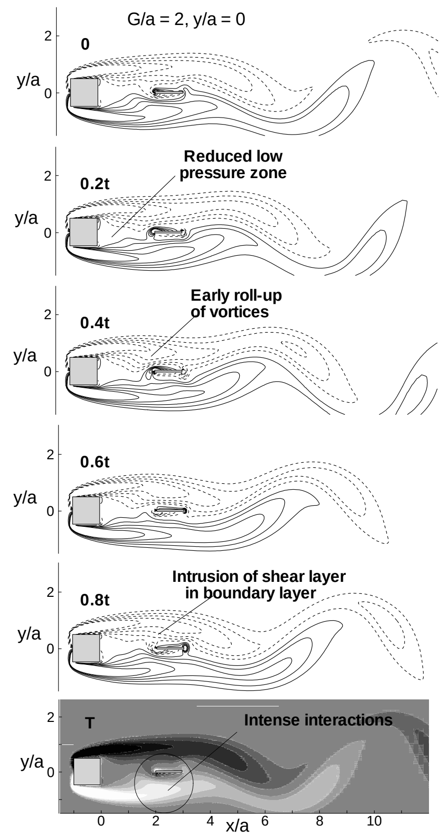

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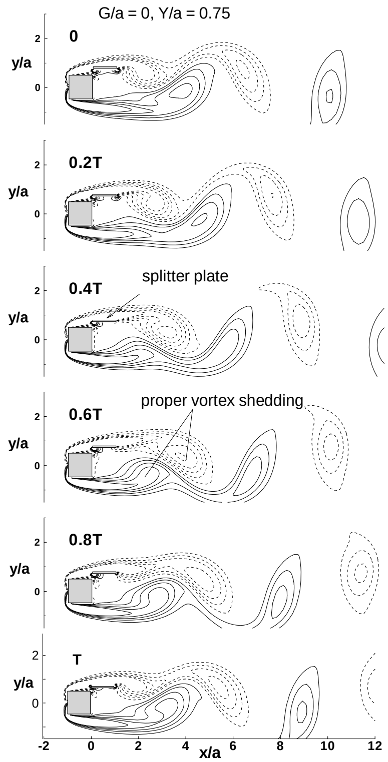

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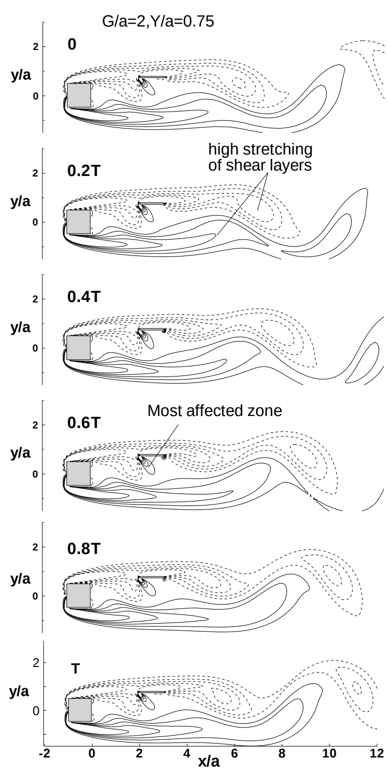

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Fig. 5: Instantaneous vorticity contours in a time period (*T*). Four extreme cases have been considered.

Mean streamwise velocity ($\bar{u}/U_\infty$) profiles at four different sections ($x^{/}/a$ = 1, 2, 3, 5, $x^{/}$ being the streamwise distance from the downstream face of the splitter plate) are drawn for the four cases mentioned above in Fig. 4a-d. It should be noted that the mean flow field is calculated by time averaging the flow variables considering five time periods after the flow field is developed. Five time periods are sufficient to describe the mean flow because *Re* belongs to laminar periodic vortex shedding regime with a low value.

From Figs. 4a, b it can be seen that when the cylinder and plate share the common axis, the peak values of $\bar{u}$ also lie in the centerline. A bold line joining all peaks has been drawn to understand this physics. But when the plate moves in an offset position with respect to the cylinder (*y*/*a* = 0.75), the peaks corresponding to different sections shift downwards (refer Fig. 4c, d). For *G*/*a* = 0, *y*/*a* = 0 (Fig. 4a) and *G*/*a* = 2, *y*/*a* = 0.75 (Fig. 4d), $\bar{u}$ becomes negative at $x^{/}/a$ = 1, 2 sections indicating a big separation bubble just behind the plate. A reduced bubble can be seen at *G*/*a* = 0, *y*/*a* = 0.75 and no bubble is formed at *G*/*a* = 2, *y*/*a* = 0. From all figures it can be concluded that the deficit of velocity remains even at $x^{/}/a$ = 5.

Instantaneous contours of spanwise vorticity (ω_z) at *G*/*a* = 0, *y*/*a* = 0 (Fig. 5a); *G*/*a* = 2, *y*/*a* = 0 (Fig. 5b); *G*/*a* = 0, *y*/*a* = 0.75 (Fig. 5c) and *G*/*a* = 2, *y*/*a* = 0.75 (Fig. 5d) are portrayed to understand the instantaneous flow features of the present problem. These figures are drawn between a time period (*T*) of vortex shedding that has been calculated from Strouhal frequency already discussed in Table 1. Six time frames of equal spacing are considered in a single time period (*t*/*T*= 0.2, 0.4, 0.6, 0.8 and 1) to pertain the value of ω_z. A detail description of the vortex shedding formation from the cylinder and their downstream convection are given for these figures.

From Figs. 5a-b authors observed that when *y*/*a* = 0, the shear layer are stretched and rolls behind the cylinder and it also suppress the formation of boundary layer on splitter plate. A big separation zone is created behind the cylinder. In Figs. 5c-d the lower and upper shear layer both rolls-up and form the vortex shedding behind the cylinder but only the upper shear layer interacts with the splitter plate due to the plate's offset position. The most affected zone is the plate's corner, but the position changes depending on the value of *G*/*a* and *y*/*a*.

All the 16 cases considered in this present work are within the critical gap ratio as per Ref. [1]. Therefore the roll-up of shear layers takes place in the downstream side of splitter plate as confirmed from figures. Also, with the increase in the gap the stretching of shear layer increases because no roll-up of vortices take place within the gap.

But as the splitter plate is placed in an offset position with respect to the cylinder (*y*/*a* = 0.75) the shear layers try to roll-up early. Particularly at *G*/*a* = 2, *y*/*a* = 0.75 it looks like the critical gap ratio (which is 2.5) moves in the upstream location and is close to 2. The reason of decrement in critical gap ratio is that the vortices try to roll-up before the splitter plate (within the gap). Also the interaction of vortices with the plate boundary layer is more intense in this case.

4. CONCLUSION

A short asymmetrical plate is placed downstream of a square cylinder within the critical gap ratio to study the effect of plate on vortex shedding. Gambit software is used to develop the flow geometry along with the generation of grid, Ansys Fluent is employed to solve the Navier-Stokes equations and for the post processing of the results Tecplot is used. Both the mean and instantaneous flow fields are portrayed along with aerodynamic forces and Strouhal frequency. The following conclusions are made from the present simulation:

1. At $G/a = 0$ & $y/a = 0$, the cylinder and plate behave like a single body while attached and for that the variation in C_L value is identical for both of them.

2. As the gap ratio increases for the similar vertical position ($G/a = 0$ & $y/a = 2$), little variation in C_L value for cylinder indicates the suppression of vortex shedding in between the cylinder and plate.

3. Mean C_L value changes from zero as the plate is kept offset from the cylinder axis ($y/a = 0.75$). Here the opposite sign in $\overline{C_L}$ value is seen for the cylinder and plate.

4. The minimum $\overline{C_D}$ value is obtained at $G/a = 0$ and $y/a = 0.25$ making it the most effective case.

5. Mean velocity profiles indicate a big separation bubble just behind the cylinder at $y/a = 0$. The size of the separation bubble reduces with high y/a value.

6. Similar conclusion can also be made from the instantaneous flow field where at $y/a = 0$, the shear layer are stretched and rolls behind the cylinder and it also suppress the formation of boundary layer on splitter plate.

7. At offset position of the plate ($y/a = 0.75$), both the lower and upper shear layer rolls-up and form the vortex shedding behind the cylinder but only the upper shear layer interacts with the splitter plate.

8. The most affected zone in the flow field is the corner of the splitter plate, however the position is not fixed and it depends on the value of G/a and y/a.

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