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Drag Reduction of a Circular Cylinder by an Upstream Splitter Plate

Shubham Jain[1], Shubham Sharma[2] and Sudipto Sarkar[3]

[1,2]Undergraduate Student, School of Mechanical Engineering, Galgotias University, India
[3]School of Mechanical Engineering, Galgotias University, India
E-mail: [3]sudipto.sarkar@galgotiasuniversity.edu.in

Abstract—*The fluid forces and vortex shedding of a circular cylinder can be controlled by placing an upstream splitter plate of very small thickness. Considering this phenomenon, in the present study the flow field for six different cases was simulated by varying the gap ratio (G/D = 2.5, 3 and 3.5, where G is the gap between a vertically placed upstream splitter plate with the circular cylinder, and D is the diameter of the cylinder) and Reynolds number (Re = 100, 160) based on free-stream velocity* U_∞ *and D. The plate length is considered as 0.5D with 0.05D thickness. Ansys Fluent is used for this two-dimensional simulation and the flow field is described with the help of instantaneous flow visualization, vortex shedding frequencies and aerodynamic forces. Also, the present research is in agreement with the work of Malekzadeh & Sohankar [1] who gave the optimum position of the upstream splitter plate at Re=160.*

1. INTRODUCTION

A lot number of numerical and experimental studies have been carried out to understand the fluid flow around a circular cylinder which is characterized by zero lift and high drag.

Many researchers have employed different control mechanism to prevent vortex shedding and to reduce drag force which is the reason behind power loss. These methods can be categorized as active and passive control of vortex shedding. Using an upstream or a downstream splitter plate is one of the popular passive control method mainly employed for its simple geometry and high effectiveness to control the flow field.

The first of its kind was performed by Roshko [2] who placed a splitter plate downstream of a circular cylinder at *Re* = 14500. He observed that the vortex shedding disappeared completely and the pressure drag reduced significantly. Gerrard [3], Apetl et al. [4], Apetl and West [5] have performed experimental studies on the effect of a downstream splitter plate in drag reduction, vortex shedding and suppression change in Strouhal number. These studies are mostly associated with the critical gap ratio in which the vortex formation stop occurring between the gap of the cylinder and plate.

Substantial number of numerical studies of flow past a cylinder (both circular and square cross-sections) with a downstream splitter plate can be seen in literature [6-11]. Most of these studies considered the range of Reynolds number in laminar vortex shedding regime (*Re* = 49 - 194). This range helps to simulate unsteady laminar flow field at a reduced computational cost.

Malekzadeh and Sohankar [1] investigated the fluid forces of a square cylinder in a laminar flow regime using a control plate between gap ratios 1.1 $\leq G/D \leq 7$. (*D* is the side of square cylinder). The plate height is kept in between 0.3*D* - 0.9*D* and *Re* was considered as 160. They concluded that the optimum position and width for the central plate are at a distance of 3*D* away from the cylinder and width of 0.5*D* respectively. The maximum reduction of drag force occurs at that optimum value.

In the present work, the effect of upstream splitter plate on the vortices from a circular cylinder was investigated. 2-D Navier Stokes (momentum) equations have been solved with the help of Ansys Fluent for gap ratios 2.5 $\leq G/a \leq$ 3.5 at *Re* = 100 and 160 which comes under unsteady laminar flow. The changes in aerodynamic forces, instantaneous flow visualization and vortex shedding frequencies are reported to understand the effect of *Re* along with upstream splitter plate location.

2. NUMERICAL METHODS

Computational fluid dynamics (CFD) tool is used to simulate the effect of an upstream splitter plate on vortices formed by a circular cylinder. In this respect 2-D Navier-Stokes equations are solved by commercial software Ansys Fluent 14.5. To generate the flow domain, generating the grids and implementing the boundary conditions, Gambit 2.2.30 is used.

The flow domain along with the boundary conditions is depicted in Fig. 1. The origin of the axes is considered at the centre of the circular cylinder and *x*, *y* axes represent the streamwise and flow normal directions respectively. Velocity components in *x*, *y* directions are represented by *u* and *v*. The diameter of the circular cylinder is considered as *D*, length of splitter plate $h = 0.5D$ and width $w = 0.05D$. The domain of this problem is extended up to -8*D* to +8*D* in the flow normal direction from the origin. The inlet is at a distance of 7.5*D* from the upstream face of the vertical splitter plate, whereas the outlet is considered after 28*D* from the origin in the streamwise direction. Both the circular cylinder and the splitter plate are symmetrically placed with respect to the *x*-axis.

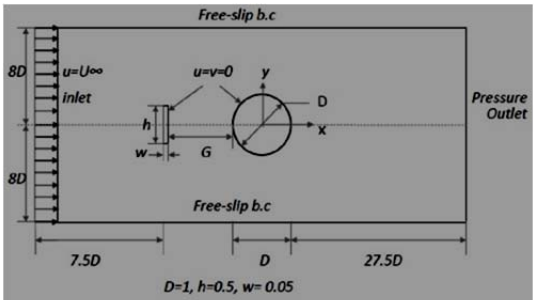

Fig. 1: Schematic diagram of flow geometry along with the boundary conditions

At the inlet a uniform velocity U_∞ is considered, whereas at the outlet convective boundary condition is used. In the upper and lower domain of the problem free-slip boundary conditions and at cylinder and plate surfaces no-slip boundary conditions are imposed. To generalize this problem, both U_∞ and *D* are considered as unity and other variables are non-dimensionalized by using velocity and length scale. The Reynolds number is defined as $Re = \frac{U_\infty D}{\nu}$, where ν is the kinematic viscosity of the fluid. For the present problem, *Re* is considered as 100 and 160 which belong to the laminar vortex shedding regime.

A grid of 409 × 258 points in the streamwise and flow-normal directions are employed for $G/D = 2.5$. The grid points are implemented in a fashion such that surrounding the cylinder and plate uniform grid points are used. Also, in between of the cylinder and plate grids are stretched suitably to accommodate smooth grid distributions. In detail, 120 × 80 grid points are used in between -*D* to +*D* in streamwise direction and -*D* to +*D* in flow-normal directions respectively surrounding the cylinder. The box (1.05*D* × 2*D*) surrounding the vertical splitter plate is having 63 × 80 uniformly distributed grid points. For other two cases ($G/D = 3$ and 3.5) no change occur in transverse direction for total grid points, whereas total grid in stream wise direction are 419 and 429 respectively. The non-dimensionalized spacing varies as Δx= 0.1108 - 0.2461, Δy= 0.025 - 0.1017 in the near wake region ($x/D = 3$ to 15 and $y/D = 0$ to ±3) for all *G*/*D* cases. These values are in the same range of grid distributions used for a circular cylinder in laminar periodic vortex shedding regime by Sarkar and Sarkar [12] and square cylinder in the same regime by Pal and Sarkar [13], Raees and Sarkar [14].

3. RESULTS AND DISCUSSION

To understand the vortex dynamics of a circular cylinder in the presence of a downstream splitter plate during a shedding cycle, the snapshots of iso-contours of spanwise vorticity (ω_z) are presented in Figs. 2 - 5 for two different gap-ratios (G/D = 2.5 and 3.5) at two different *Re* (*Re* = 100, 160). The time period (*T*) of vortex shedding has been calculated with the help of the Strouhal number (*St*). For each case (except G/D = 2.5), six time-frames are drawn within a time period (t/T = 0, 0.2, 0.4, 0.6, 0.8 and 1). Also zoom views of the flow domain near the plate and cylinder are given for a clear view. A brief description of the vortex formation from the cylinder, their downstream convection and interaction with the splitter plate are described.

Fig. 2 illustrates ω_z contours at $Re = 100$ and $G/D = 2.5$. No roll-up of vortices are found for this case. Also *Re* here belongs to laminar periodic vortex shedding regime. It can be concluded that due to the presence of an upstream splitter plate the cylinder is unable to produce vortices.

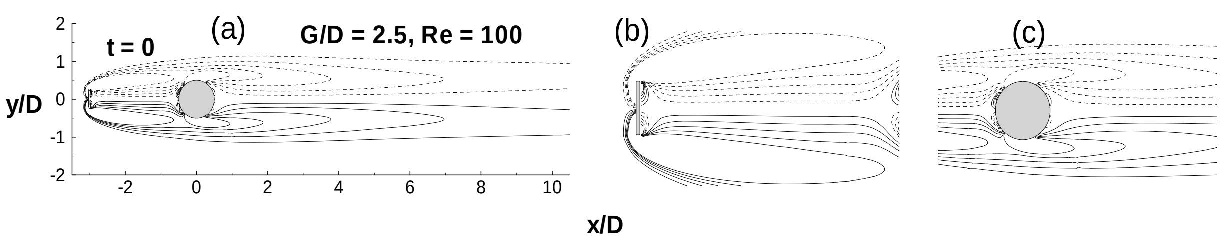

Fig. 2: (a) Instantaneous vorticity at *G*/*D* = 2.5 and *Re* = 100, (b), (c) Zoom view close to plate and cylinder respectively.

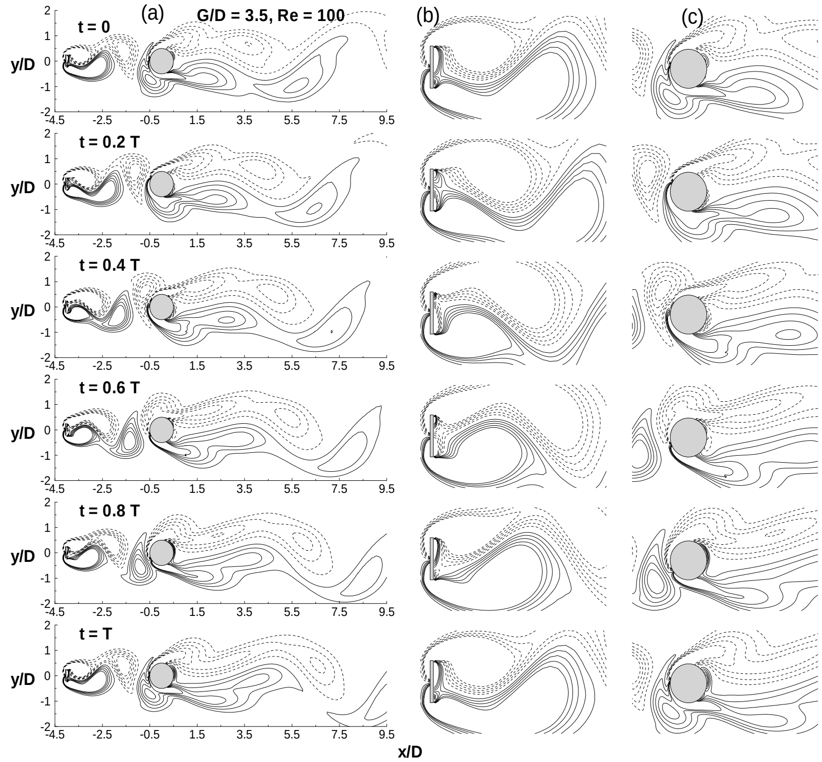

Fig. 3: Instantaneous vorticity contours in a time period (*T*) at *G*/*D* = 3.5 and *Re* = 100. For detail refer Fig. 2.

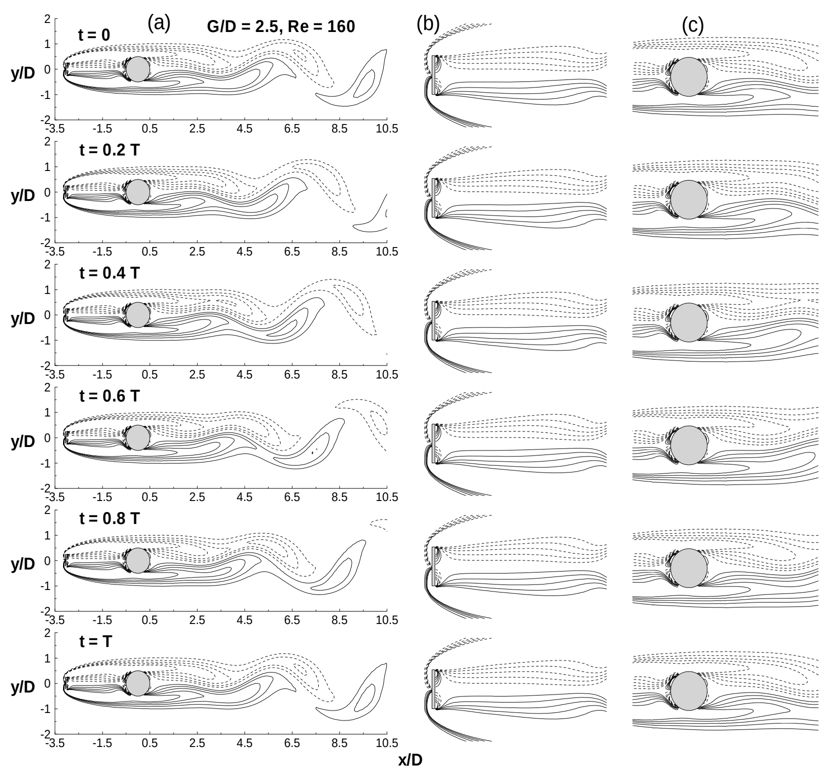

Fig. 4: Instantaneous vorticity contours in a time period (*T*) at *G*/*D* = 2.5 and *Re* = 160. For detail refer Fig. 2.

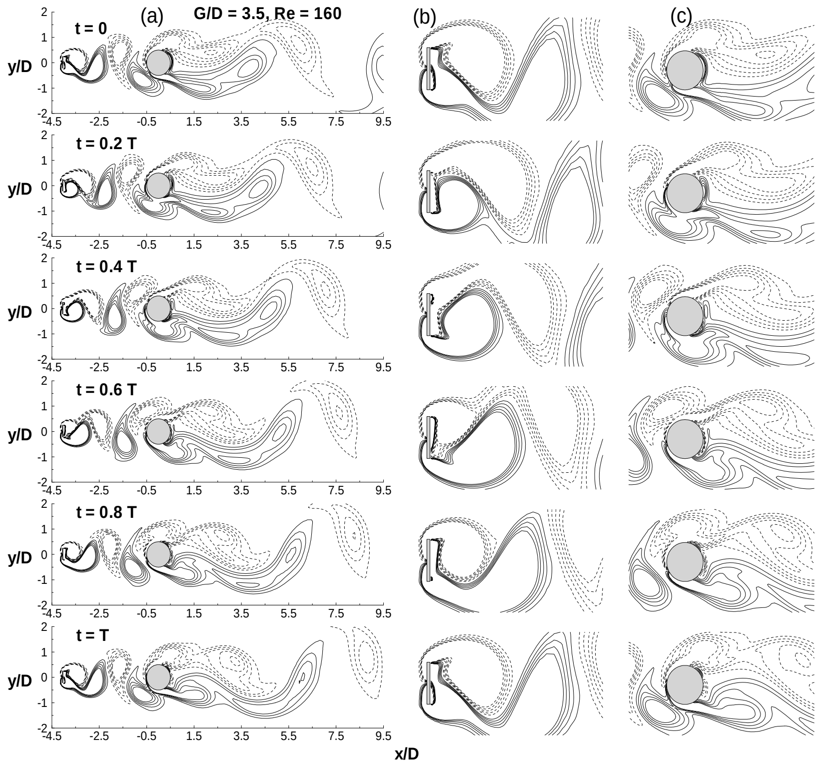

Fig. 5: Instantaneous vorticity contours in a time period (*T*) at *G*/*D* = 3.5 and *Re* = 160. For detail refer Fig. 2.

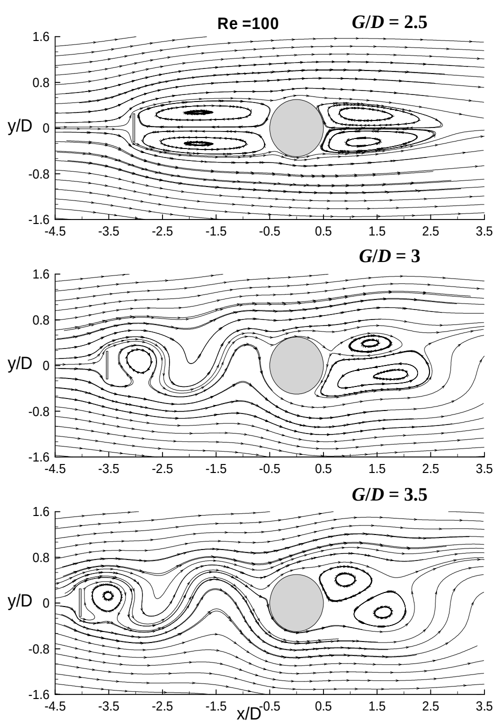

Fig. 6: Instantaneous streamlines at *G*/*D* = 2.5, 3 and 3.5; *Re* = 100.

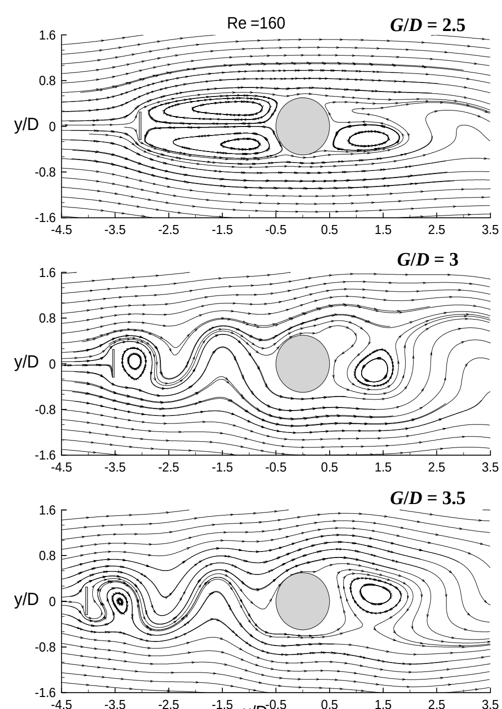

Fig. 7: Instantaneous streamlines at *G*/*D* = 2.5, 3 and 3.5; *Re* = 100.

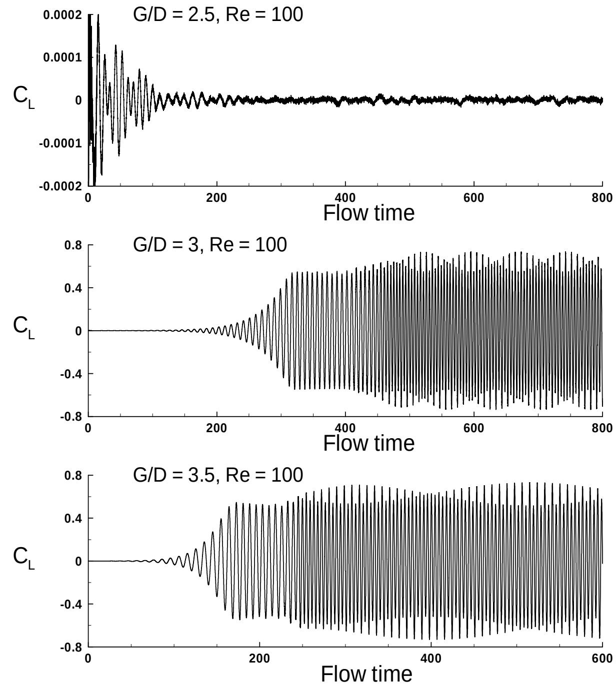

Fig. 8: Variations of C_L with flow time at *G*/*D* = 2.5, 3 and 3.5; *Re* = 100.

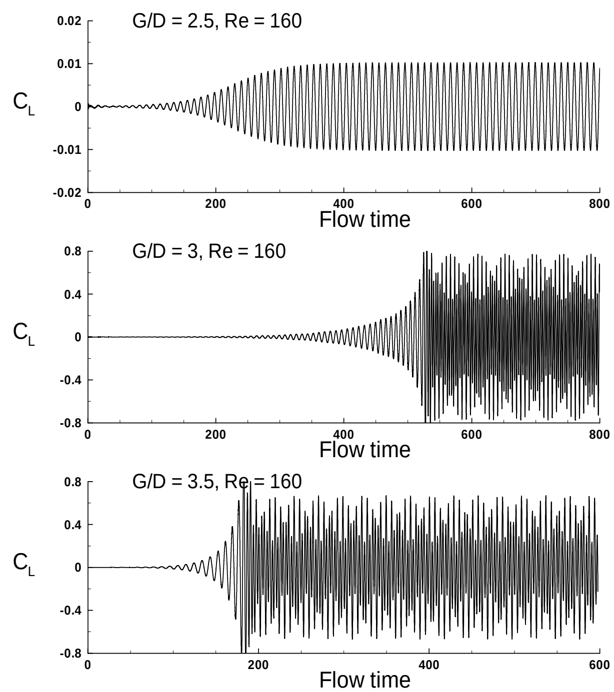

Fig. 9: Variations of C_L with flow time at *G*/*D* = 2.5, 3 and 3.5; *Re* = 160.

For high gap ratios, *G*/*D* = 3 and 3.5, periodic vortex shedding starts from the vertical plate itself and which impinges on circular cylinder. Due to lack of space, only *G*/*D* = 3.5 case has been portrayed here (Fig. 3) and it can be seen from the Fig. that the vortex shedding occurs from the cylinder in a different fashion as compared to an unbounded cylinder. This difference is due to the synchronization of vortices from the plate and from the circular cylinder.

At *Re* = 160, the flow visualization for *G*/*D* = 2.5 case (Fig. 4) is different as compared to previous case. Although there is a high stretching of upper and lower shear layers, but vortex shedding starts from the cylinder. At Re = 160, *G*/*D* = 3.5 (Fig. 5), vortex shedding from the cylinder is almost similar to Fig. 3 and the effect of roll-up vortices on circular cylinder shear layers is clearly visible.

The instantaneous streamlines are plotted for all *G*/*D* values and for both the Reynolds numbers and depicted in Figs. 6 and 7. These plots show stable vortices in between splitter plate and cylinder and also behind the cylinder in case of *G*/*D* = 2.5 and *Re* = 100. For the same gap ratio at *Re* = 160, stable vortices are seen in between the plate and cylinder, but downstream of the cylinder vortices become unstable which proves the roll-up and breakdown of the vortices behind the cylinder. For other four cases when the gap-ratio is the higher side, vortices are unstable even behind the vertical plate. These unstable vortices change the vortex dynamics of the circular cylinder by merging with the cylinder's vortices.

Figures 8 and 9 illustrate the time evaluation of the 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 respect to the flow time for all six cases. As stated earlier, at *Re* = 100 with low-gap ratio (*G*/*D* = 2.5), no vortex shedding is observed behind the cylinder. This is also evident from the C_L diagram where the variation in C_L value is neglected after the flow field is developed. At *Re* = 160, *G*/*D* = 2.5 case proper variation of C_L is obtained with a single frequency pertaining the presence of roll-up of vortices downstream of the cylinder.

For other four cases presence of two different modes of frequency are observed from the Figures 8 and 9. These two modes can be attributed to the mixing of roll-up vortices from the plate and the cylinder.

Few flow parameters like C_L range (average difference between maximum and minimum C_L values), r.m.s. of lift coefficient ($C_L^/$), mean drag coefficient ($\overline{C_D} = \frac{1}{T}\int_0^T C_D$, where, $C_D = \frac{F_D}{\frac{1}{2}\rho U_\infty^2 A}$, F_D being the drag force) and Strouhal number ($St = \frac{fD}{U_\infty}$, f is the frequency of vortex shedding) are tabulated in Table 1 for quantitative comparison among all cases.

Table 1: Flow parameters related with present study

Re	*G*/*D*	C_L Range	$C_L^/$	$\overline{C_D}$	*St*
100	2.5	0	0	0.299	0.012
	3	1.467	0.519	0.599	0.07
	3.5	1.462	0.517	0.661	0.07

160	2.5	0.021	0.007	0.132	0.036
	3	1.542	0.547	0.476	0.09, 0.047
	3.5	1.337	0.472	0.485	0.1, 0.04

It has been observed that the maximum range of C_L with C_L r.m.s. value is obtained at Re = 160 and G/D = 3. These two values are zero at Re = 100 and G/D = 2.5 due to no vortex shedding at that particular case. The value of mean drag coefficient ($\overline{C_D}$) is minimum at Re = 160 and G/D = 2.5 and hence is the most optimum case for drag reduction. The lowest drag for Re = 100 is also obtained at the same gap, which means G/D = 2.5 can be considered as the critical gap in terms of achieving minimum drag. The non-dimensional vortex shedding frequency St value is very close to zero for Re = 100 and G/D = 2.5 case and can be attributed to the negligible vortex shedding. Two values of St at Re = 160 and for high gap ratios (G/D = 3, 3.5) illustrate the presence of two different vortex shedding behind the cylinder that is due to merging of vortices from the plate and from the cylinder.

4. CONCLUSION

A vertical splitter plate is placed upstream of a circular cylinder to determine its effect on vortex formation from the cylinder and reduction of its drag coefficient. Total six cases have been evaluated considering two different Reynolds numbers (*Re* = 100, 160) in the laminar periodic vortex shedding regime and three different gap ratios (*G*/*D* = 2.5, 3 and 3.5). Detail physics is discussed with the help of instantaneous flow visualization, aerodynamic forces and vortex shedding frequencies.

From the instantaneous flow visualization it can be concluded that at *Re* = 100 and low gap-ratio (*G*/*D* = 2.5) suppression of vortex shedding occurs. For all other cases proper vortex shedding is noticed and particularly at high gap ratios (*G*/*D* = 3, 3.5) for *Re* = 160 two frequencies in vortex formation is reported that can be attributed to the impingement of vortices from vertical splitter plate to the cylinder vortices. The *St* values enlisted in the Table also explain the same physics.

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