INTERNATIONAL JOURNAL OF RESEARCH IN AERONAUTICAL AND MECHANICAL ENGINEERING
ISSN (ONLINE): 2321-3051

Vol.3 Issue.1, January 2015. Pgs: 104-118

Numerical Investigation of Flow Characteristics over a Square Cylinder with a Detached Flat Plate of Varying Thickness at Critical Gap Distance in the wake at Low Reynolds Number

Nidhul K[1], Sunil A S[2], Kishore V[3]

PG student, Govt. Engineering College Thrissur, nidhul07@gmail.com[1]
Associate Professor, Govt. Engineering College Thrissur, sunilkoni@gmail.com[2]
Assistant Professor, Govt. Engineering College Kannur, kish.venugopal@gmail.com[3]

Abstract

Flow past a square cylinder with and without corner modifications is carried out numerically by using CFD fluent. The wake is generated by a uniform flow of Reynolds number (Re) 150 based on the characteristic length of the cylinder, D. 2D unsteady numerical simulation is done using FVM employing pressure based solver and PISO scheme. A computational grid independence study has been done to obtain a grid resolution which predicts the results without any discrepancies. The flow separation point for the square cylinder with and without corner modifications is obtained. The pressure distribution in the near wake region and around the square cylinder surface is also investigated for different corner geometries. The results are presented in the form of coefficient of pressure Vs Domain length/D, Coefficient of pressure along the cylinder wall and wall shear stress along the cylinder wall. The results indicate that the flow separation in case of square cylinder without sharp corners is delayed. The adverse pressure gradient along the surface of the cylinder and in the near wake region is smaller for round corners. The tangential velocity of square cylinder with sharp corners is large when compared with modified corners.

***Keywords**:* Square Cylinder, Corner modifications, Reynolds number, wake, grid independence, flow separation point, Pressure distribution, Lift coefficient, Drag coefficient.
.

1. Introduction

Vortex shedding behind bluff bodies is of concern for many engineering applications. Bluff bodies are structures with shapes that significantly disturb the flow around them, as opposed to flow around a streamlined body. Fluid flow past a cylindrical object generates vorticity when Re is increased due to the shear present in the boundary layer. This vorticity in the flow field coalesces into regions of concentrated vorticity known as vortices. Further increase of the Reynolds number (Re > 40) makes the steady vortices to become unstable and the flow bifurcates to a time-periodic state, in which opposite-signed vortices are periodically shed from the opposite sides of the near wake; this is known as the primary instability of the wake. The periodic vortex shedding generates oscillatory forces on the cylinder. The forces on the plane of the cross-section of the cylinder can be decomposed into drag– the force acting in the same direction of the free-stream – and lift – the force acting in the cross-stream direction. Due to the existence of these oscillatory forces imposed by the flow, flexible cylinders and rigid cylinders mounted on flexible structures vibrate when immersed in a uniform stream. This vibration occurs predominantly in the cross-stream direction and since the origin of the forces is associated with the vortex shedding, this type of structural response is called vortex-induced vibration (VIV). VIV is a strongly nonlinear phenomenon, since the movement of the cylinder alters the flow field, and the flow field is ultimately responsible for the forces exerted on the cylinder. Vortex shedding is responsible for structural movement of high rise buildings, scour development around bridge piers in channel beds, vibrations of industrial components, acoustic radiation from aircraft landing gear and other related problems. Therefore, it is important to understand and control these flow-induced problems so that engineering design and public comfort can be improved continuously.

As a result, this subject requires investigation, particularly when the near wake is interfered with, e.g., by a flat plate, so that a comprehensive understanding about behaviour of the flow for a wide range of conditions can be obtained. Thus the fluid flow around a cylinder, because of complicated phenomena such as vortex shedding and flow separation behind the cylinder, has been studied by many researchers and scientists. They applied some methods and devices to control this phenomenon. Methods are classified in three groups: (1) passive control, (2) active control and (3) compound control. Passive control techniques do not need any external energy during application. Additional devices in the fluid flow or changing the geometry of the bluff body such as splitter plate, base bleed and roughness are applied in this method. Active control techniques such as EHD actuators and vibrators need external energy to affect the fluid flow. When Active and passive techniques are applied simultaneously, it is called compound method.

Over the last twenty years, a vast amount of studies has been conducted to increase the understanding of different transition processes of the flow past a circular cylinder-experimentally, numerically and theoretically. By contrast, there are very few similar studies found on flow past rectangular cylindrical structures, e.g. the square cylinder, at moderate Reynolds number. Inoue et.al [1] constructed a non-uniform mesh but divided the computational domain into three regions, each with a different grid ratio. At Reynolds numbers less than about 500 there is only one single set of experiments, Okajima et al.[2] reported the influence of Reynolds number on the mean drag coefficient. Mohamed Sukri Mat Ali et.al [3] numerically investigated the sensitivity of the computed flow field to flow parameters for a flow with Reynolds number 150.They constructed computational meshes based on reasonable estimates of cell size and grid stretching ratios. S. Ozono [3] conducted experiments over a circular and rectangular cylinder with a horizontal short thin splitter plate below wake centerline and showed that vortex can be suppressed even when the splitter plate is asymmetrically behind the cylinder. Mittal [4] numerically investigated the effect of varying plate length and its position downstream on the near wake of a circular cylinder at a Reynolds number of 100. Slip boundary condition was imposed on the plate, which may not be relevant to practical applications. Rathakrishnan [5] comprehensively studied the vortex shedding suppression using the splitter-plates attached to the end of the cylinder. Doolan [6] numerically studied flow around square cylinder of side length D with a downstream flat plate of length 0.834D laid at 2.37D from the rear surface of the cylinder. A strong interaction between the shear layers from the square cylinder wall with the flat plate was observed. Mohamed Sukri Mat Ali et.al [7] observed numerically that the critical gap distance Gcr for a detached splitter plate is 2.3D. The plate had no significant effect on the generation of the von Kármán vortex when the separation is beyond 5.6D. Many studies show that it is very important to accurately obtain the value of G_{cr} as flow transits to a new flow regime after critical gap distance. (e.g., Bull et al. [8]; Carmo et al. [9]; Papaioannou et al. [10]; Zdravkovich [11]). The current study aims to investigate the influence of a detached flat plate of length L=D and its varying thickness on the flow characteristics around the square cylinder.

2. Numerical Simulation Procedure

2.1 Flow Field Formulation

The governing equations on the flow field are the continuity and momentum equations (Navier–Stokes equations), which can be written as follows:

$$\frac{\partial \rho}{\partial t} + div(\rho V) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u) + div(\rho V u) = -\frac{\partial p}{\partial x} + div(\mu\, grad u) + B_x \tag{2}$$

$$\frac{\partial}{\partial t}(\rho v) + div(\rho V v) = -\frac{\partial p}{\partial y} + div(\mu\, grad v) + B_y \tag{3}$$

Where ρ is the fluid density, μ is the fluid viscosity, V is the velocity vector of the flow field, p is the pressure, and u and v are the velocity components in the x- and y-directions, respectively. B_x and B_y are also the body forces per unit volume, which are negligible in the present study. The fluid is assumed to be incompressible, and its properties has been taken as $\rho=1.225$ kg/m^3 and $\mu=1.7894\times10^{-5}$ kg/m s.

2.2 Limits of the problem

A rectangular domain was used with a length of 38D and a width of 20D, where D=0.04 m is side length of the cylinder. The cylinder center has the coordinates x=10.5D and y=10.5D as shown in fig.1 (from Ref .5). The position of the splitter-plate is specified by G in the horizontal direction, from the trailing edge of the cylinder. The splitter plate length and thickness are D and 0.02D, respectively. Splitter plate thickness (H) is varied in the range $0.02D \leq H \leq 0.08D$.

The fluid flows uniformly (with velocity U_∞) from left to right into the downstream of the domain. Boundary conditions should be enforced at the outlet and the lateral boundaries of the computational domain, as well as on the surfaces of the embedded bodies. At domain inlet and outlet, velocity inlet and pressure outlet respectively have been employed. A symmetry boundary condition at the lateral boundaries of the domain and wall with no-slip condition has been used at the cylinder wall. On the splitter plate, no-slip condition has been applied.

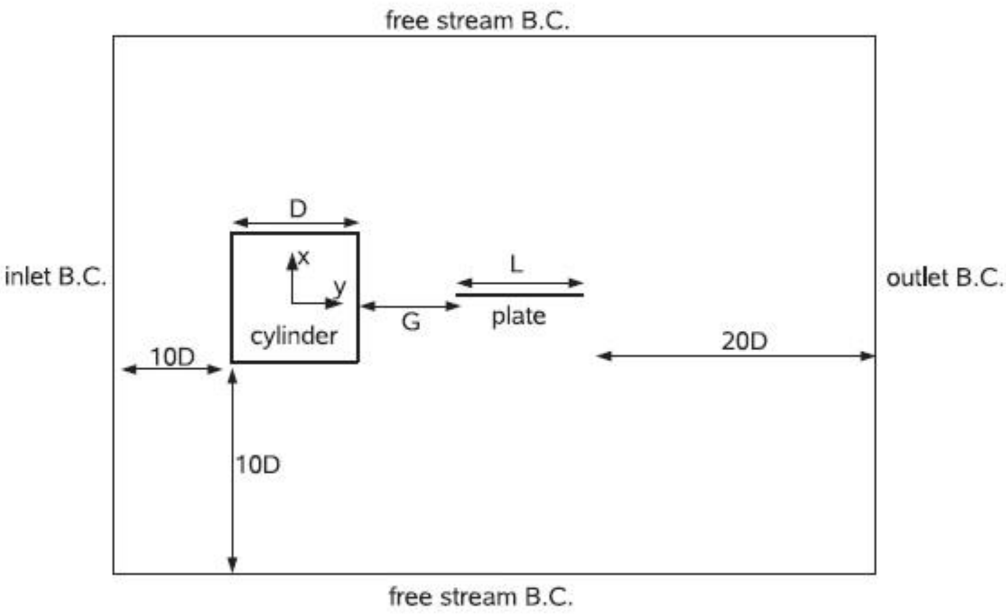


Figure 1: Flow domain for a square cylinder with a splitter plate

2.3 Discretization method

Transforming continuous fluid flow problem into discrete numerical data which are then solved by the computers is known as Discretization. The governing equations have been discretized using the finite-volume method on a fixed Cartesian-staggered grid with non-uniform grid spacing. The grids in the region of the embedded boundaries are sufficiently fine in order to achieve the reasonable accuracy. The spatial discretization has been performed by using multi-block analysis with structured mesh for square cylinder case and for square cylinder with detached flat plate, unstructured mesh near the plate. The temporal discretization has been done in conformity with the second order implicit scheme. Temporal discretization involves the integration of every term in the differential equations over a time step Δt. The simulations were carried out as an unsteady state with a time step (Δt) size of 0.07 sec with 2000 time steps.

2.4 Grid influence study

For predicting the flow field around a square cylinder using numerical analysis, many similar investigations have been made, but the results always show small discrepancies even though the overall global trends are similar. One of the reasons for these discrepancies is the difference in the mesh or grid used for numerical simulation. The mean axial velocity along the center-line of the wake region is shown in fig.2. Six different 2D grids are used ranging from coarse grid to fine grid. The results of the simulations show a certain dependency on the grid resolution for the different grids used. It is observed that in the upstream all the runs predict identical results, whereas a faster recovery of mean axial velocity is predicted when the grid resolution is increased. The mean velocity of recirculation is approximately the same in all runs.

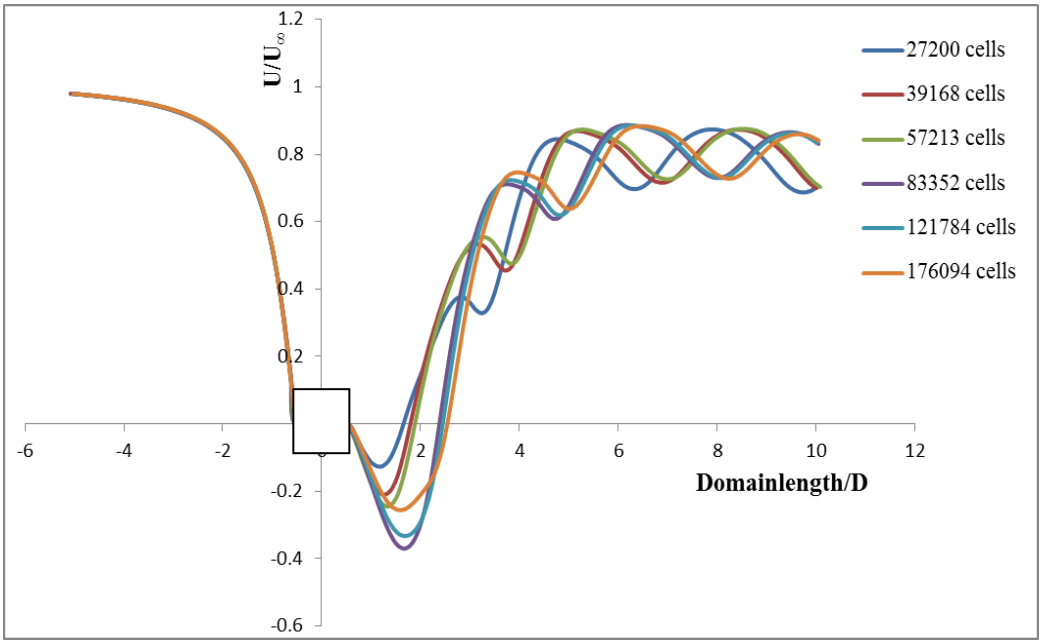


Figure 2: Mean axial velocity distribution along the center-line of the wake

2.5 Verification of the solver

Accuracy of the solver is validated in this section by simulation of flow around a square cylinder. Various parameters such as drag coefficient Cd= F_d /0.5ρu^2_∞D, pressure coefficient Cp= P-P_{atm}/0.5ρu^2_∞ and Strouhal number St=fD/U∞ has been used. Grid independency of the solver has been performed and showed that the results are not sensitive to the grid size. Hereinafter, all the results presented have been obtained with fine grid consisting of 83352 cells. Assuming that this grid provides a sufficient grid-independency for the Reynolds number considered in this paper.

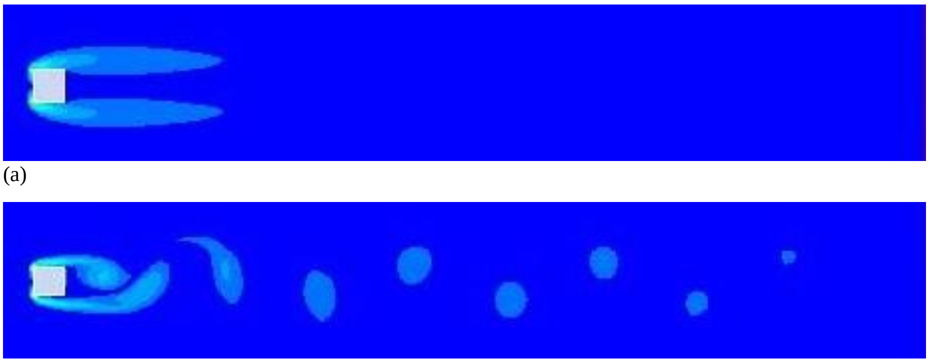
The results of the flow around square cylinder were verified using the dimensionless parameters defined above. The value of St obtained by running the simulation at Re=150 was in good agreement with experimental studies of Okajima, 1982and Sohankar et al., 1999. The experimental value of Strouhal number obtained by above mentioned authors was in the range 0.148-0.155 and the present study obtained the value 0.15.Similarly, the value of C_d obtained experimentally by above mentioned authors was 1.40 and the present study obtained the value as 1.58.

3. Results and Discussion

In the first section, the results are demonstrated and analyzed for Reynolds numbers of 40 (non-vortex shedding case) and 150 (vortex shedding case) for square cylinder of side length, D. Second section investigates the effect of downstream flat plate of constant thickness by varying the gap distance (G) along the wake centerline in the range 0.5 D ≤ G ≤ 4 D for a constant plate length of L= D. Third section of the paper investigates the effect of varying thickness of the plate placed at critical gap distance from the trailing edge.

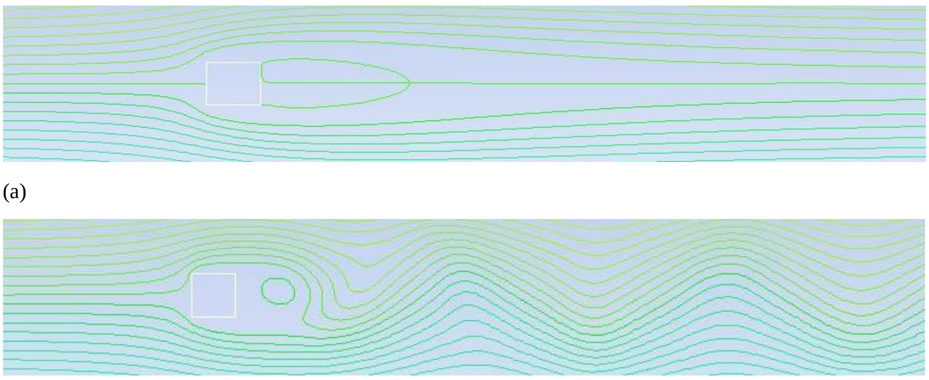
3.1 Non-vortex shedding case (Re=40)

Simulation was performed for square cylinder with Re = 40. The principal goal here was to characterize the flow structure around the square cylinder, to obtain the flow variables, pressure variation along the surface of the cylinder and in the near wake region and to obtain drag coefficient. Since a contour plot can quickly reveal regions of high (or low) values of property being studied, fig.3 (a) shows the vorticity magnitude contours for Re=40 which indicate that there is no vortex street. At Re=40, only recirculation eddies are formed immediately downstream of the cylinder as indicated by streamlines shown in fig.4.The U/U_∞ plotted in fig.5 is in agreement with the literature. The fluid comes to a complete stop at the mid-point of incident face of the square cylinder i.e. at the stagnation point. The flow accelerates around the upstream corner ,so much that boundary layer cannot negotiate the sharp corner and separates and reverse flow occurs in the immediate downstream of the cylinder. While moving further downstream of the wake region, flow slowly regains its velocity.



(a)
(b)

Figure 3: Vorticity magnitude contour for (a) Re=40 and (b) Re=150



(a)
(b)

Figure 4: Stream function contour for (a) Re=40 and (b) Re=150

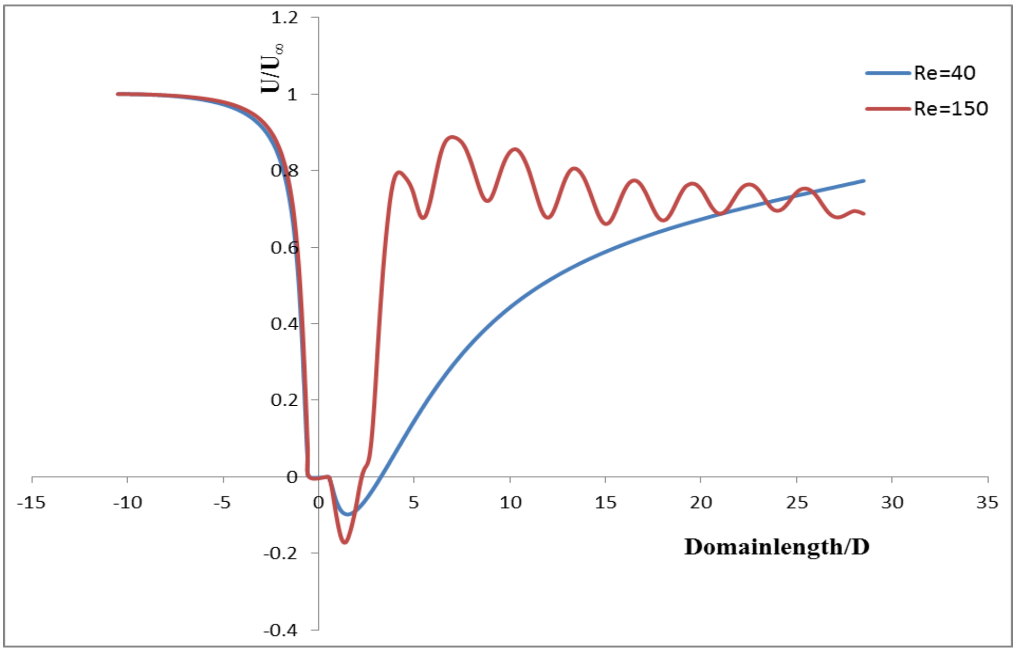


Figure 5: U/U_∞ along the wake center-line for (a) Re=40 and (b) Re=150

Apart from velocity profile, pressure distribution is an important parameter in the study of flow around a cylinder. Pressure changes accordingly with the vortices motion in the vicinity of the body. At stagnation point, located at midpoint of face 0-1as shown in fig.5, flow comes to rest and pressure thus reaches maximum value (By Bernoulli's theorem).It is also noticed that the pressure shows symmetrical distribution; which suggest that problem has been simulated to satisfactory computational time to achieve a convergent solution.

Near the top surface of the cylinder, flow momentum is quite low due to viscous effects and is thus sensitive to changes of pressure gradient. The flow has to move against pressure force in addition to the viscous force. This leads to reduced velocity and wall shear stress. Flow separation occurs when shear stress cannot overcome adverse pressure gradient. At Re=40, flow separation occurs just after top right corner of the square cylinder where wall shear stress is zero as shown in the fig.6. Coefficient of drag (C_d) and coefficient of lift (C_l) for the square cylinder at Re=40 is obtained as 1.76 and 0.0002953.

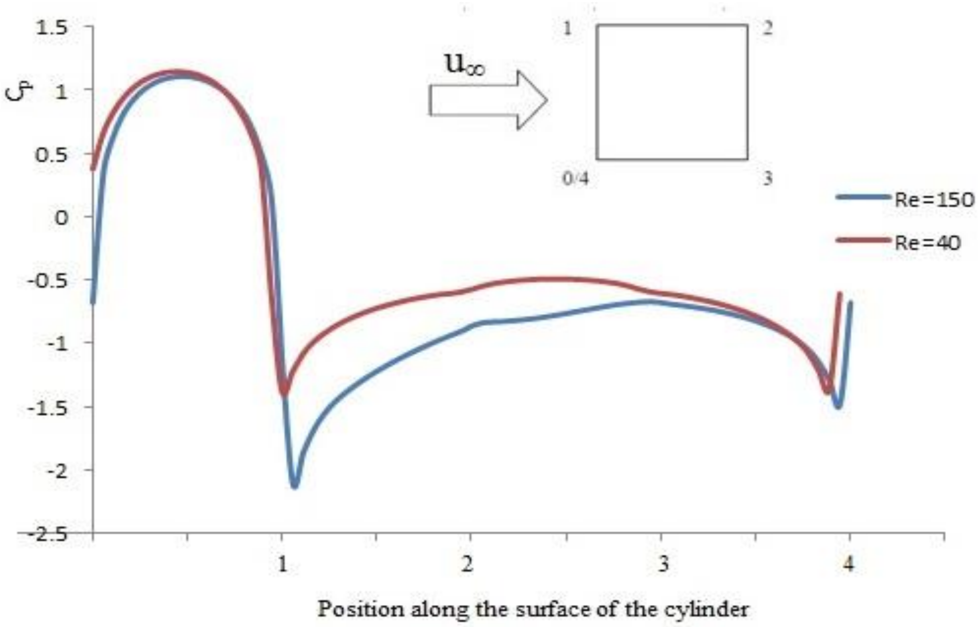


Figure 6: Pressure variation along the surface of the square cylinder for (a) Re=40 and (b) Re=150

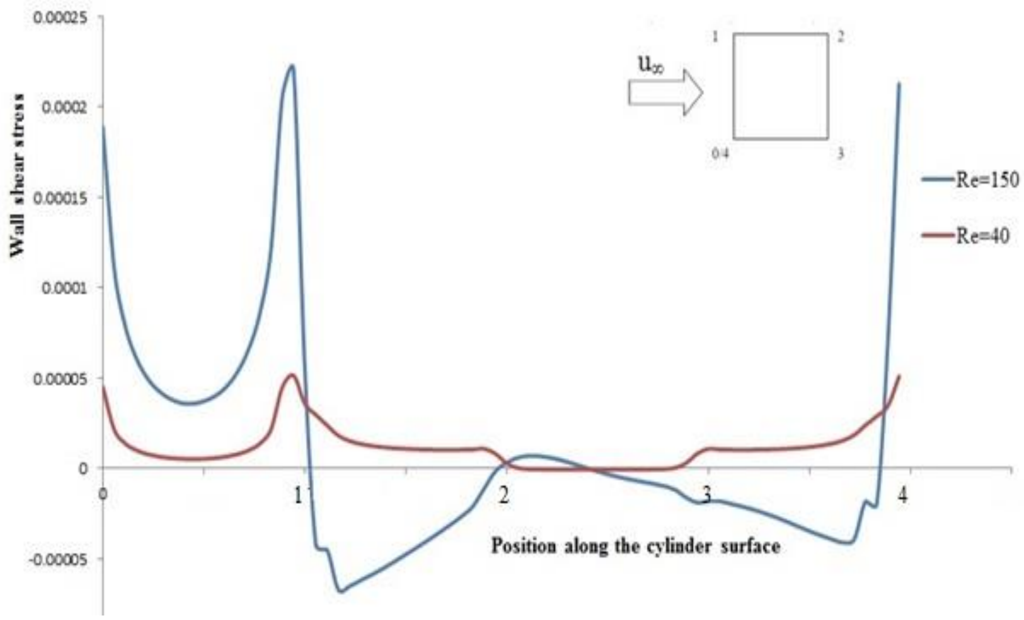


Figure 7: Wall shear stress along the surface of the square cylinder for (a) Re=40 and (b) Re=150

3.2 Vortex shedding case (Re=150)

When Re is increased beyond 40, wake behind the cylinder becomes unstable. Wake develops a slow oscillation in which the velocity is periodic in time and downstream distance, with amplitude of oscillation increasing downstream. Oscillating wake rolls up into two staggered rows of vortices with opposite sense of rotation. Because of similarity of the wake with the footprints in a street, staggered row of vortices behind the square cylinder is called as Von-Karmann Vortex Street. Eddies periodically break off alternately from 2 sides of the cylinder as shown in fig.3. While an eddy on one side is shed, that on the other side forms resulting in an unsteady flow near the cylinder. As vortices of opposite circulations are shed off alternately from 2 sides of the cylinder, results in an oscillating "lift" or lateral force which can be obtained by plotting variation of C_l Vs flow simulation time. Fig.4 shows the streamline pattern for Re=150 indicating a rotating lump of fluid shed from the top portion of the cylinder. From fig.5 it is clear that velocity in the wake region of cylinder at Re=150 is lower than that of Re=40.It also indicates that vortices are shed over a much larger length of the wake.

The pressure variation near the top left corner and top surface of the cylinder is much larger creating a greater adverse pressure gradient (than that of Re=40) opposing the flow as shown in fig.6.Hence the flow around the square cylinder at Re=150 separates off much earlier i.e. at the top left corner of the cylinder as wall shear stress approaches zero after point 1 along cylinder surface as shown in fig.7.The values of C_d, C_l and Strouhal number obtained by simulation are compared with experimental and simulation work of other authors.

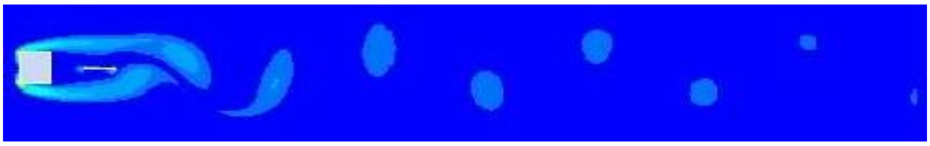
Table 1: Comparison of the Present study with other previous studies and experiments

Study	St	C_D	C_L
Experiments(Okajima, 1982; Sohankar et al., 1999)	0.148-0.155	1.40	-
Sohankar et al. (1998)	0.165	1.44	0.230
Doolan (2009)	0.156	1.44	0.296
Inoue et al. (2006)	0.151	1.40	0.40
Ali et al. (2009)	0.160	1.47	0.285
Present study	0.150	1.58	0.196

3.3 Effect of detached flat plate on vortex shedding

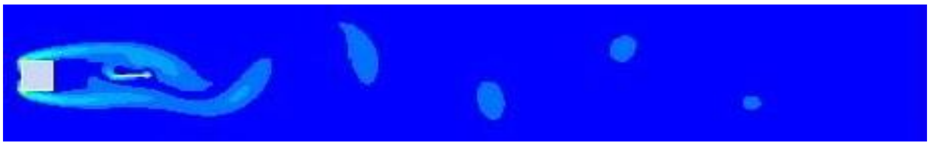
Simulation was performed for a square cylinder at Re=150 with a detached flat plate of constant thickness along wake center-line at varying gap distance 0.5D ≤ G ≤ 4D.The vorticity magnitude contours for each gap distance was obtained as shown in fig.8.

(a)



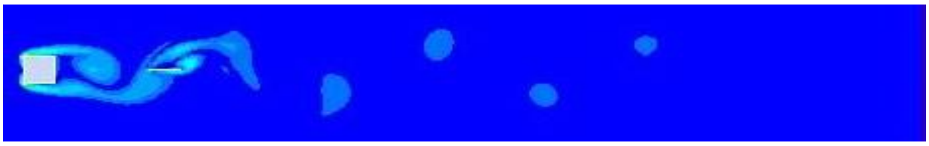
(b)

(c)



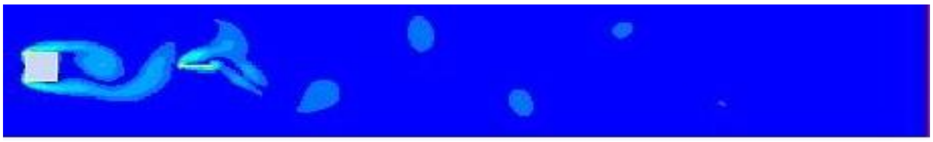
(d)

(e)



(f)

(g)



(h)

Figure 8: Vorticity magnitude contours of square cylinder with detached plate at varying gap distances (a) G=0.5D (b) G=1D (c) G=1.5D (d) G=2D (e) G=2.5D (f) G=3D (g) G=3.5D (h) G=4D

The space between cylinder and the plate provides an opportunity growing vortex to entrain fluid from other side of the cylinder through the gap and thus there is a change in vortex shedding pattern from that of square cylinder without a plate in the wake region. For close-proximity gap distances, G ≤ 1.5D, there is no direct fluid entrainment into vortex core, as it is prevented by the plate. Beyond gap distance of 2.5D, fluid entrainment process via the gap generates additional vortices in the vicinity and a secondary vortex accumulates at the plate leading edge. The variation of Strouhal number with gap distance is shown in fig.9.

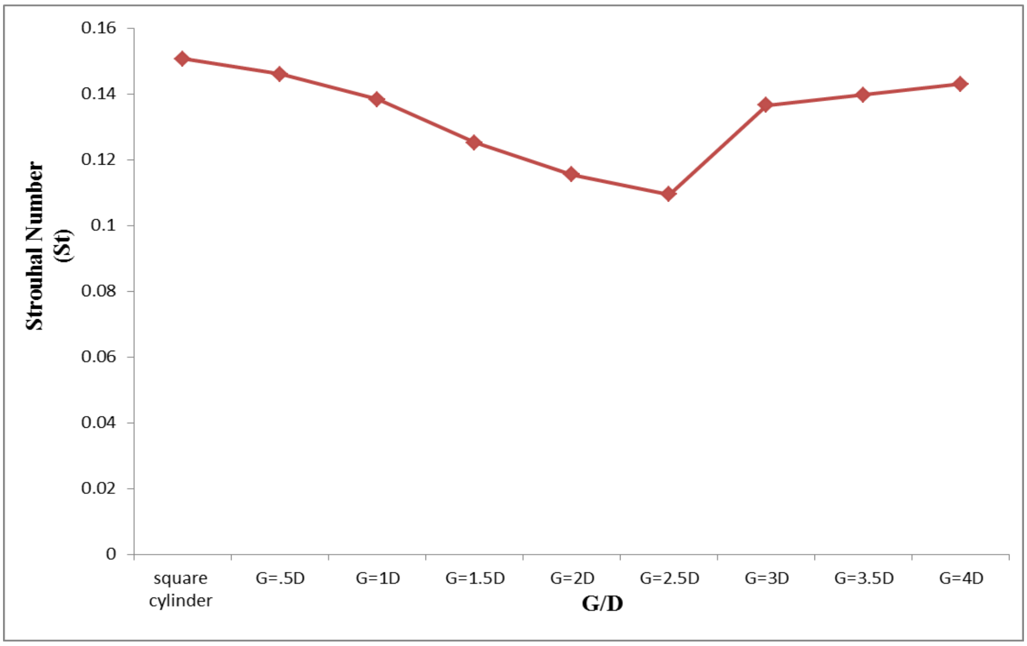


Figure 9: Strouhal number variation for varying gap distances

For 0.5 ≤ G ≤ 2.5D Strouhal number decreases with gap distance. As plate moves closer to core of the growing vortex i.e. as G increases interaction between shear layers is reduced and shear layers interact with the plate. These effects delay vortex formation process that consequently reduces Strouhal number upto G=2.5D.Beyond G=2.5D there is sharp increase in St. This is due to blockage effect created by the plate which reduces convective speed of the shear layers. However the effect slowly weakens as gap distance further increases. The sharp increase in Strouhal number at G=3D is also due to secondary vortex accumulating at the leading edge of the plate. The variation of coefficient of drag with gap distance is shown in fig. 10 and fig.11 respectively.

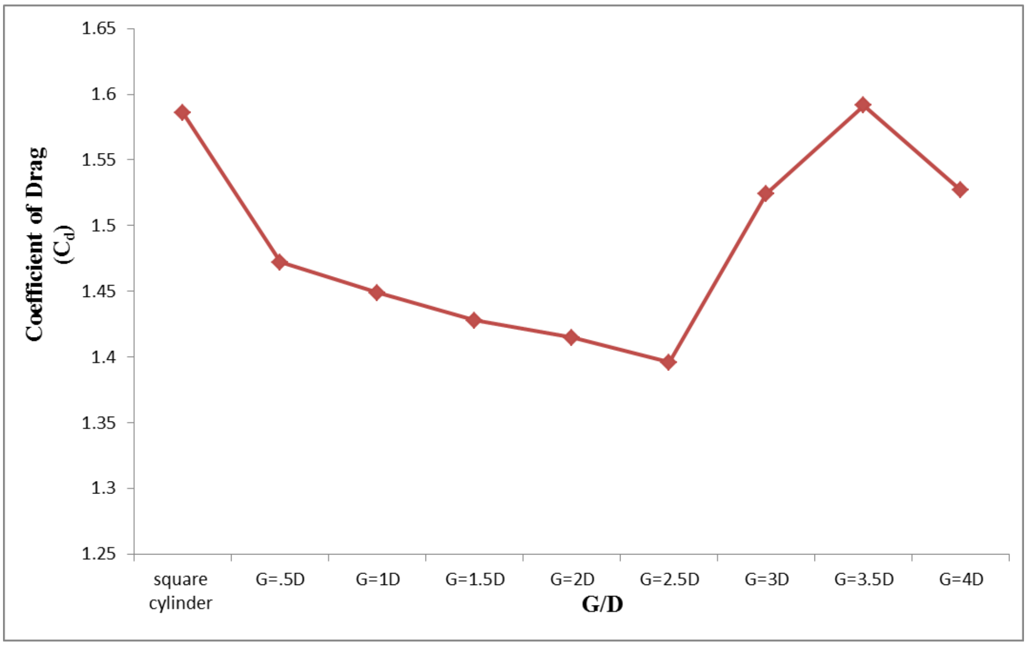


Figure 10: Coefficient of drag variation for varying gap distances

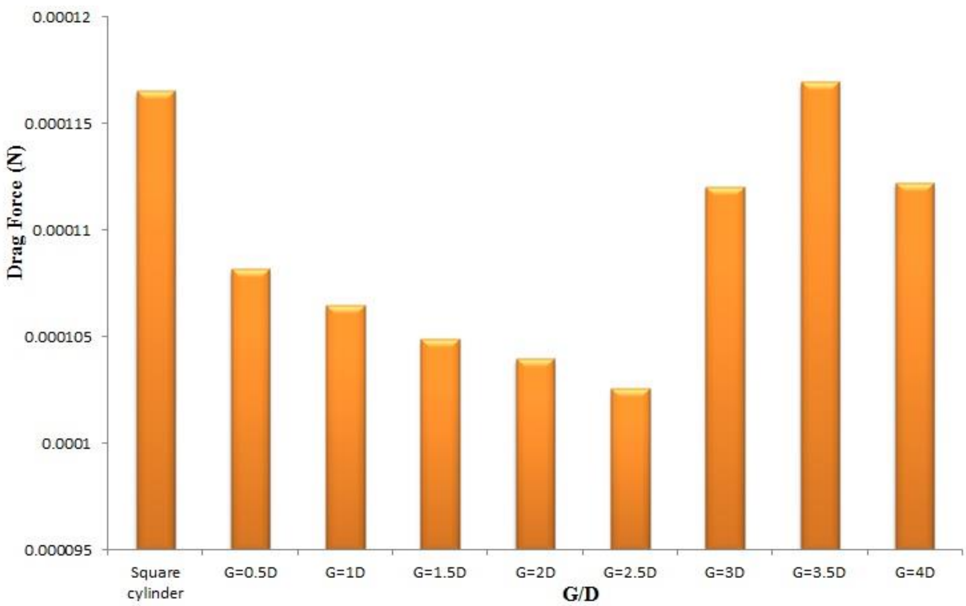
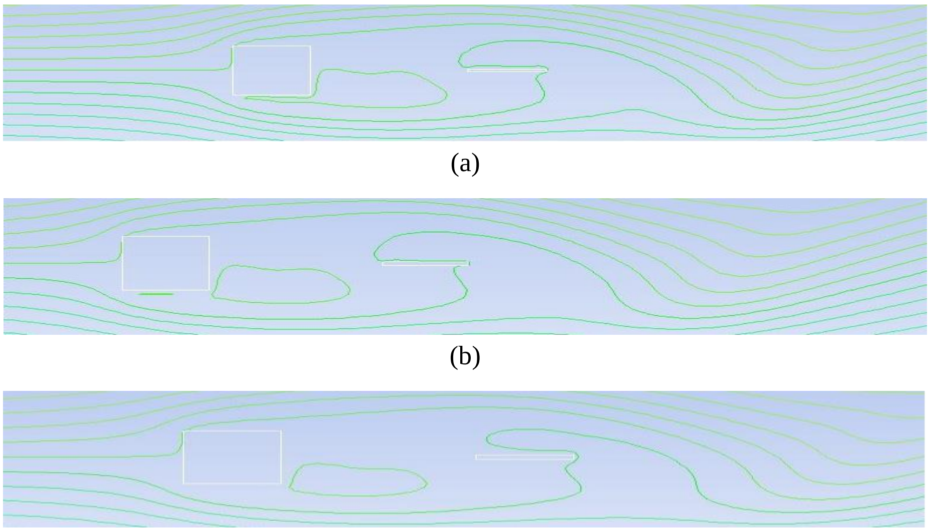


Figure 11: Drag Force variation for varying gap distances

3.4 Effect of thickness of detached flat plate on vortex shedding

The last part of this paper investigates the effect of varying the splitter plate thickness in the range 0.02D ≤ H ≤ 0.08D placed at critical gap distance. The variation of Cp in the near wake region for different plate thickness is shown in fig.13.It is evident that there is no significant variation of pressure in the near wake region when the plate thickness is varied. There is only 1.5% increase of drag coefficient when the plate thickness is increased to H=0.04D.Beyond H=0.04D there is no change in the value of drag coefficient. Similarly there is 4.16 % increase in the value of Strouhal number when plate thickness is increased to H=0.04D. Beyond H=0.04D there is no change in the value of St.



(a)

(b)

(c)

Figure 12: Stream function contour for (a) H=0.04D (b) H=0.06D and (c) H=0.08D

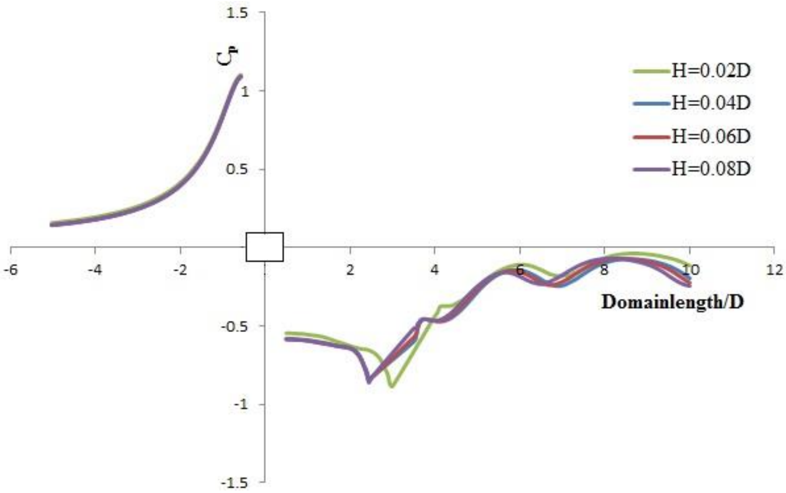


Figure 13: Variation of C_p in the near wake region for varying thickness of the plate

4. CONCLUSION

The major conclusions are drawn as follows:

(1) At Re=40, only recirculation eddies are formed immediately downstream of the Square cylinder and there is no periodic vortex shedding. For Re>40, flow around square cylinder becomes unstable and results in an oscillating flow with amplitude of oscillation increase downstream. This exerts a force on the cylinder in the lateral direction.

(2) The flow separates at top right corner of square cylinder i.e. flow wraps the cylinder at the top and bottom face at Re=40.But at Re=150, the flow separates much earlier i.e. at top left corner since the wall shear approaches zero after point 1 on the cylinder. Since it is due to this flow separation, rotating lump of fluid masses are formed, flow separation on a square cylinder can be delayed by making the corners smooth.

(3) Detached flat plate suppresses the vortex shedding and reduces the flow induced forces by interrupting the regular vortex shedding. The flow induced force and Strouhal number for the flow around square are cylinder greatly dependent on the position of the flat plate. As gap distance increases, the drag force and Strouhal number decreases and reaches a minimum value at G=2.5D. This gap distance is called the Critical gap distance (G_{cr}) since beyond this gap distance, both Strouhal number & F_d increases. The steep increase in St beyond G_{cr} is due to accumulation of a secondary vortex on the leading edge of the flat plate.

(4) A reduction of 12 % and 27.34 % respectively for drag force and St was obtained by embedding flat plate at G_{cr}=2.5D downstream of the cylinder.

(5)There is no significant variation in flow pattern and flow induced forces when the plate thickness was varied at critical gap distance.

References

[1] Inoue, Iwakam, and Hatakeyama (2006). "*Aeolian tones radiated from flow past two square cylinders in a side-by-side arrangement*" Physics of Fluids, *18(4), 046104.*

[2] Okajima, A., 1982, *Strouhal numbers of rectangular cylinders*. Journal of Fluid Mechanics *123, 379–398.*

[3] Ozono, S., 1999. *Flow control of vortex shedding by a short splitter plate asymmetrically arranged downstream of a cylinder*. Physics of Fluids *11, 2928–2934.*

[4] Mittal, S., 2003. *Effect of a ''slip'' splitter plate on vortex shedding from a cylinder*. Physics of Fluids *15, 817–820*.

[5] Rathakrishnan, E., 1999, "*Effect of Splitter-Plate on Bluff body Drag*" AIAA Journal., *37(9), pp. 1125–1126.*

[6] Doolan, C.J., 2009. *Flat-plate interaction with the near wake of a square cylinder*. AIAA Journal *47, 475–478*.

[7] Mohamed Sukri Mat Ali , Con J. Doolan & Vincent Wheately,2012, "*Low Reynolds number flow over a square cylinder with a detached flat plate*", International Journal of Heat and Fluid Flow, International Journal of Heat and Fluid Flow *36 (2012) 133–141*.

[8] Bull, M.K., Blazewicz, A.M., Pickles, J.M., Bies, D.A., 1996. *Interaction between a vortex wake and an immersed rectangular plate*. Experimental Thermal and Fluid Science *12, 209–220*.

[9] Carmo, B.S., Meneghini, J.R., Sherwin, S.J., 2010. *Secondary instabilities in the flow around two circular cylinders in tandem*. Journal of Fluid Mechanics *644, 395–431*.

[10] Papaioannou, G.V., Yue, D.K.P., Triantafyllou, M.S., Karniadakis, G.E., 2006. *Three dimensionality effects in flow around two tandem cylinders*. Journal of Fluid Mechanics *558, 387–413.*

[11] Farhadi, M., Sedighi, K., Fattahi, E., 2010. *Effect of a splitter plate on flow over a semi-circular cylinder*. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering *224, 321–330.*

[12] Zdravkovich, M.M., 1987. *The effects of interference between circular cylinders in cross flow*. Journal of Fluids and Structures *1, 239–261*.

[13] Behzad Ghadiri Dehkordi and Hamed Houri Jafari 2010, *On the Suppression of Vortex Shedding From Circular Cylinders Using Detached Short Splitter-Plates*. Journal of fluids Engineering, *April (2010) Vol. 132 / 044501-1*.

[14] Sohankar, A., Norberg, C., Davidson, L., 1999. *Simulation of three-dimensional flow around a square cylinder at moderate Reynolds numbers*. Physics of Fluids *11, 288–306*.