Low Reynolds Number Flow Past Square Cylinder in the Vicinity of a Plane Wall

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Abstract: *The characteristics of flow over a square cylinder in the vicinity of a plane stationary wall have been numerically investigated. 2D time-dependent incompressible flow at low-Reynolds numbers of 100 and 200 has been calculated using the finite volume method. CFRUNS scheme is used for pressure-velocity coupling in numerical calculation. The authors have tried to make an attempt to analyze the features of the complex flow field through flow streamlines and the vorticity contours. The impact of the gap between the cylinder and the plane wall upon flow pattern behavior is also studied. An intense interaction between vorticity in the boundary layer generated over the plane wall and the vorticity associated with the shear layer emanating from the separation points on the cylinder surface has been observed producing a very complex flow field in the cylinder wake and the gap between the cylinder and the wall.*

Key Words: *Plane wall, Gap ratio, Reynolds number, Force coefficients, Numerical simulation*

NOMENCLATURES

$C_D=\frac{Drag}{\frac{1}{2}\rho U_\infty^2 L}$	Drag coefficient	L	Characteristic length of the cylinder
$C_L=\frac{Lift}{\frac{1}{2}\rho U_\infty^2 L}$	Lift coefficient	$St=\frac{fL}{U_\infty}$	Strouhal number
G	Gap between the cylinder and the plane wall	$t = t_{dimensional} \times U_\infty/L$	Non-dimensional time
g^*	Gap ratio (G/H)	Δt	Time step
H	Length of a side of a square cylinder	U_∞	Magnitude of free stream velocity
$Re=\frac{\rho U_\infty L}{\mu}$	Reynolds number	u, v	Velocity components in x- and -y directions respectively
p_∞	Free stream static pressure	x, y	Cartesian coordinate system

1. INTRODUCTION

A 2D cylindrical body kept in the vicinity of the plane wall is investigated at a low Reynolds number. This type of research has been a very important subject because of its physical and engineering importance. This technology has been discussed by [1] who explained that it is of a lot of importance for bridges, and pipelines under the effect of wind and submarines. The wall introduces a new set of complications to vertical flow behind the body. The shear layer generated over the wall within the boundary layer and the separated shear layer which convects downstream of the body is found to intensely interact generating a flow pattern that is much more complex near the body and in the wake. This interaction significantly alters the aerodynamic forces on the body and the vortex shedding frequency.

Beyond the critical Reynolds number for flow over a square cylinder, alternate shedding of vortices from the cylinder surface happens because of instability in flow near the wake that results in periodic oscillation of aerodynamic forces and the variation of surface pressure on the cylinder surface. This results in the cylinder being subjected to fluctuating lift and drag with addition to mean force components that might cause resonance, noise, and structural vibrations, and in a few cases could cause structural failure or could also increase the undesirable flow mixing in wake [2]. Several surveys have been performed by [2-3] on vortex-induced oscillations on bluff bodies. The development of the wake behind a cylinder of a rectangle or square shape has also been investigated experimentally by [4-9].

Four cylinders of circular shape kept in a square inline configuration are investigated. Three-dimensional laminar flow is studied and the effect of aspect ratio and the spacing ratio was investigated. The forces and pressure coefficients on cylinders have also been taken into consideration for the analysis. The authors have concluded that the aspect ratio, no-slip end wall condition and the spacing ratio have combined effects on the properties of the flow and also on the force and pressure coefficients [10]. The 2D square cylinder has been numerically investigated for studying flow and the heat transfer kept near moving wall and varying cylinder- to-wall distance ratios [11]. The analysis has been done at $Re = 100$ and the gap-ratio varying between 0.1 and 4.0. The results have shown that the average coefficient of drag and lift of cylinder increases with decreasing gap-ratio and at larger gap-ratios, the force coefficients approach the corresponding values of the isolated cylinder. The average coefficient of pressure along the bottom surface shows significant change with decreasing gap-ratios that resulted in increasing the average force coefficient values. The Strouhal number is found to increase linearly with decreasing the G/D ratio from 4 - 1 whereas it decreases gradually with a further decrease in the gap ratio to 0.4. Flow-induced vibration of two cylinders of circular shape has been studied experimentally and numerically to analyze the flow structures, fluctuating lift, time-mean lift and the flow-induced response between the cylinders [12]. The gap ratio is varied over a range of 0.1 - 5 and the angle of attack is varied from 0° to 180°. The whole regime has been divided into seven different interaction regimes with every interaction regime having varying traits connected with varying flow induced responses. In the cylinder-boundary layer interaction regime, lift force increases generating a galloping vibration and the flow-induced responses and the forces are found analogous to that of an unconfined cylinder. The results also show that although an unconfined circular cylinder does not experience galloping, two cylinders of circular shape incur violent galloping vibrations.

2D simulations were performed to investigate the flow past a cylinder of circular shape translating in parallel to, and from varying distances from, the wall using the spectral-element simulation for studying the fundamentals of boundary vorticity development and transport for 2D flow of incompressible fluids [13]. After the vorticity develops at the boundaries through relative acceleration, it could be cross-annihilated with opposite-sign vorticity. The wake characteristics and transitions are shown to vary dramatically as a result of wall proximity and cylinder rotation.

The prograde rolling decreases the critical *Re*, whereas the retrograde rolling increases the critical *Re*. Numerical calculation of shear flow over a square cylinder in the vicinity of the wall near eddy promoting cylinders of rectangular shape is performed to investigate the aerodynamics of varying gap between cylinders and the aspect ratio [14]. The simulation is performed for Reynolds numbers 100 and 200. The result shows that the transition from the steady to unsteady flow and vice versa over promoter sheds the vortices, with multiple peaks reported in the spectrum because of varied shedding downstream of the cylinder, is based significantly on the shape of the cylinder (square/rectangular) at fixed Reynolds number. At Reynolds number 100, the signals of lift force for the downstream cylinder were described with one extremum in the spectrum and at Reynolds number 200, as both the cylinders frequency of square (downstream) from rectangle (promoter) cylinder.

A numerical investigation has been performed for studying the effect of the gap spacing between the bottom wall and cylinder in a channel [15]. A performance analysis also had been performed for finding the optimum position of the cylinder for maximizing the heat transfer enhancement and a reasonable pressure drop. The observations show an increase in heat transfer in the developing flow region compared with a plane passage. The heat transfer enhancement is maximized from the channel walls when the position of the obstacle is in the middle of the duct. The analysis showed that the discussed method of maximizing heat transfer is highly beneficial for fluids with lower Prandtl numbers. Flow past two identical cylinders of square shape in tandem configuration kept near the plane wall at Reynolds number 6,300 have been investigated experimentally varying the inter cylinder spacing and cylinder to-wall gap ratio [16]. Digital particle image velocimetry is used for capturing the flow regions through a piezoelectric load cell.

The experiments have been performed for six different wall-cylinder gap ratios as well as seven different inter-cylinder spacing-ratios and the results are observed to be highly dependent on these varying configurations. The results show that the wall proximity leads mostly to positive average lift on the downstream cylinder with elongated vortex and broaden shedding peaks in the lift spectrum. The vortex shedding strength weakens as the cylinder to wall gap-ratio decreases in the intermediate cylinder to-wall gapratio range.

Flow over two twin cylinders having a circular shape in tandem configuration has been numerically investigated at Reynolds number 200 for G/D and L/D where G represents the gap between the cylinder lower surface and the plane wall, D represents cylinder diameter and L is the center to center distance between the two cylinders [17]. The results show that at very small G/D, vortex shedding is suppressed completely.

Strouhal number (*St*) for the downstream cylinder is negligible. For a similar alliance of G/D and L/D, the average drag coefficient of the upstream cylinder is higher when compared to the downstream cylinder. The results also indicate the variation in vortex-shedding modes which leads up to a significant increase in the RMS values of aerodynamic force coefficients. Numerical simulation has also been done on vortex-induced vibration on a cylinder of circular shape which is vibrating freely and has 2-DOF kept in proximity of the plane wall which is stationary [18].

A fixed stationary wall has been used for including the effect of the shear layer from the lower wall while taking into account the vortex-induced vibration characteristics. At various gap ratios, parameters like, lift and drag forces, vortex shedding frequency and vibration streamwise and the transverse vibration amplitudes have been characterized. 2D flow around a cylinder of circular shape in the vicinity of the moving wall has been investigated for *Re* between 20 and 200 [19]. A moving wall with boundary condition of no-slip has been considered instead of stationary wall to avoid the complexity of boundary layer and for focusing on shear free wall proximity effect to investigate flow fields and force dynamics. Two inline cylinders of circular shape kept in proximity to a stationary wall have been investigated numerically by employing immersed boundary method and the vortex-induced vibrations (VIV) have been studied at Reynolds number 100 [20]. Two cylinders, having similar DOF, could oscillate only in the transverse direction or both streamwise (2-DOF) and transverse directions. The presence of the stationary wall is found to have a significant impact on the wake patterns, vibration amplitudes, fluid forces, etc. Flow over a cylindrical body under influence of 1D gusty flow has also been investigated through the CFRNUS scheme [20].

However, the location of the cylinder in close proximity of the wall significantly influences the behavior of vortex shedding along with shear stress and surface pressure distribution leading to variation of aerodynamic forces acting on the body. Due to the complexities inflows, there lies an immense scope for further research.

Not a lot of investigations had been done concerning flow over multi-cylinder setup of square shape placed in close proximity to the plane wall at low Re. In laminar flow region. This problem is much more complex due to the enhanced complexity in the flow arising from multiple cylinders. The current research aims to investigate and develop keen apprehension of discussed flow physics.

2. GOVERNING EQUATIONS AND NUMERICAL CONSIDERATIONS

The present research work involves 2D flow over a square cylinder kept in close proximity to a stationary plane wall. 2D incompressible Navier-Stokes equation for viscous fluid flow is considered as the governing equation for the present flow problem. These equations with non-dimensional primitive variables can be expressed as:
Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Momentum equations:
X-momentum:

$$\frac{\partial u}{\partial t}+\frac{\partial (u^2)}{\partial x}+\frac{\partial (uv)}{\partial y}=-\frac{\partial p}{\partial x}+\frac{1}{Re}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

Y-momentum:

$$\frac{\partial v}{\partial t}+\frac{\partial (uv)}{\partial x}+\frac{\partial (v^2)}{\partial y}=-\frac{\partial p}{\partial y}+\frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

where, u and v stand for the velocity components in x- and the y-directions, respectively, Re stands for Reynolds number, p stands for the ratio of pressure and density and t is known as non-dimensional time. Continuative or Neumann boundary conditions have been used at outlet boundary.

Dirichlet condition is applied at the top, bottom and inlet boundaries. On the body surface and on the plane bottom wall, no-slip condition is considered. CFRUNS [21, 27] has been considered for solving time-dependent 2D incompressible Navier-Stokes equation. In this solver, the incompressible flow is numerically solved using the FVM formulation. The cell-center velocity-fluxes are being reformed for ensuring an effective velocity-pressure coupling.

The reconstruction of the flux on the cell-face center of the discrete element is set in the middle of two bracketing cells sharing the particular face where momentum equations are solved to calculate velocity explicitly. Poisson's equation is then used to solve cell-center pressure from reformed velocities and then cell-center velocities are updated in an explicit manner.

This scheme is used for calculating the wall proximity and unconfined flow past multiple cylinder cases in the current investigation. A set of simulation results for unconfined-flow over a square cylinder at *Re* = 100 and 200 have been authenticated with few experimental and numerical results available in the open literature.

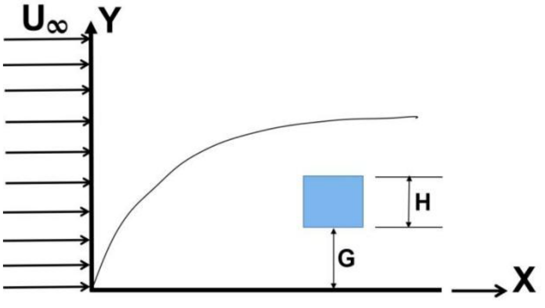


Fig. 1 - Schematic of flow over a square cylinder in vicinity of a plane wall

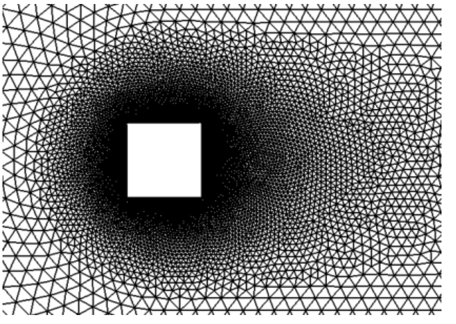


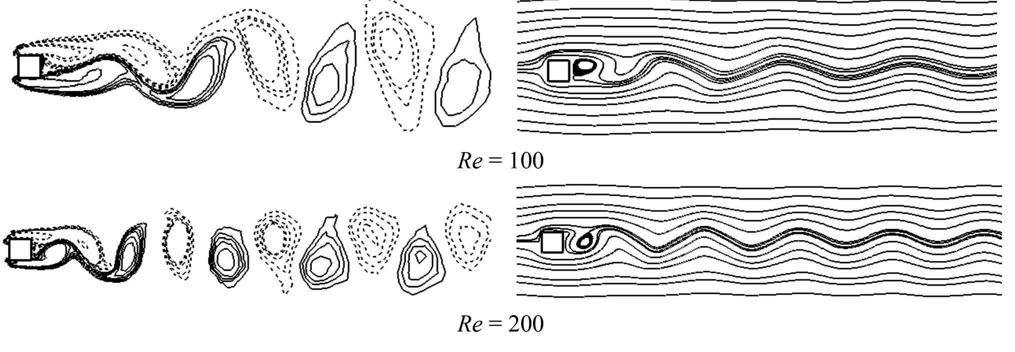
Fig. 2 - Unstructured grid around a square cylinder

Fig. 1 illustrates unconfined-flow over a square cylinder placed in close proximity to a stationary plane wall and the zoomed-in 2D-unstructured grid near the cylinder surface is shown in Fig. 2. CFRUNS method is used for simulating the flow past a square cylinder with *Re* = 100 and the mesh convergence test based on the variation of Strouhal number and drag-coefficient has been highlighted in Table 1.

The grid comprising 160 numbers of nodes on the cylinder surface is selected for every computational case in the present research work.

Table 1 - Mesh convergence test with *Re* = 100

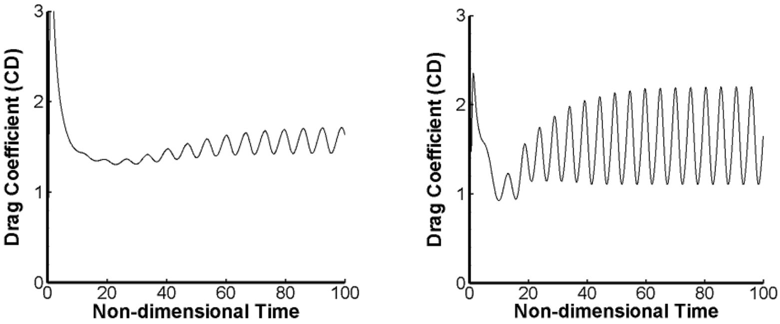
Nodes	Strouhal Number	Average Drag Coefficient
80 (Grid 1: 15,378 cells)	0.1101	1.422
120 (Grid 2: 24,128 cells)	0.1252	1.531
160 (Grid 3: 29,516 cells)	0.1294	1.551
200 (Grid 4: 36,494 cells)	0.1302	1.551



Re = 100

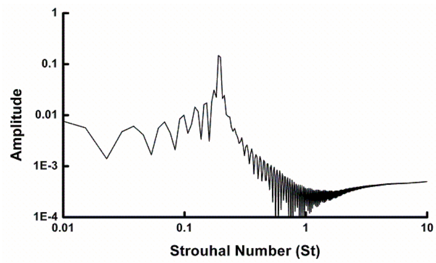
Re = 200

Fig. 3 - Vorticity and streamline contours for flow over an unconfined square cylinder



Re = 100 *Re* = 200

Fig. 4 - Temporal variation of CD for flow over an unconfined square cylinder.



Re = 100 *Re* = 200

Fig. 5 - Shedding frequency continuum for flow over an unconfined square cylinder

Table 2 - Characteristics of flow over an unconfined square cylinder with *Re* = 100 and 200

Flow Characteristics	Strouhal Number (*St*)		Coefficient of Drag (C_D)	
	Re = 100	*Re* = 200	*Re* = 100	*Re* = 200
Davis And Moore (1982) (numerical) [4]	-	-	1.64	1.72
Okajima (1982) (experimental) [6]	0.133	0.144	-	-
Treidler(1991) (numerical) [24]	0.149	0.1539	1.679	1.739
Arnal (1991) (numerical) [25]	0.152	0.157	1.41	1.52
Suzuki (1993) (numerical) [22]	0.131	0.141	-	-
Sohankar. (1998) (numerical) [26]	0.142	0.148	1.759	1.781
Roy and Bandyopadhyay (2006a) (numerical) [9]	0.1243	0.14	1.533	1.58
Present result	0.1305	0.143	1.558	1.611

Fig. 3 highlights the instantaneous streamline and vorticity contours for flow over an unconfined square cylinder at non-dimensional time $t = 100$.

Shedding of vortices has been observed from the frontal corner points of the cylinder at *Re* = 100 and 200. The temporal development of drag-coefficients is presented in Fig. 4 at both Reynolds numbers.

FFT analysis was performed on force-time history for investigating flow-periodicity and the dominating shedding frequency has been shown in Fig. 5. Strouhal number and the time-averaged drag coefficient values from the present research work are enlisted in Table 2, and are compared with other published experimental and numerical results.

The up-to-par concurrence of the flow-characteristics in the present research work catered enough authority to employ the ‘CFRUNS’ method to simulate flow over a square cylinder near a wall with assorted gap ratios.

2. RESULTS AND DISCUSSIONS

The impact of confined flow over a square cylinder being placed near a plane wall has been analyzed at *Re* = 100 and 200 for $g^* = 0.5$ and 1.0. The 2D unstructured grid around the square cylinder in close proximity to a stationary plane wall is shown in Fig. 6.

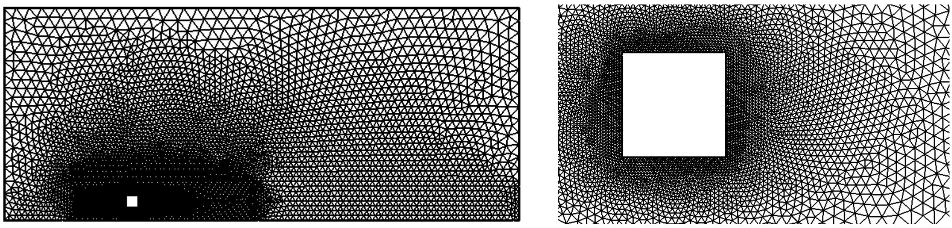
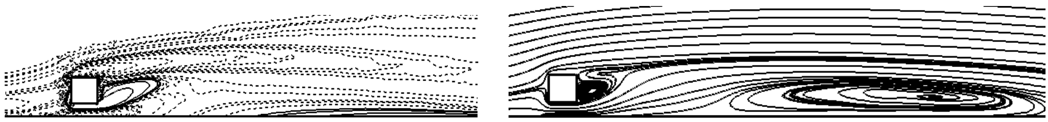
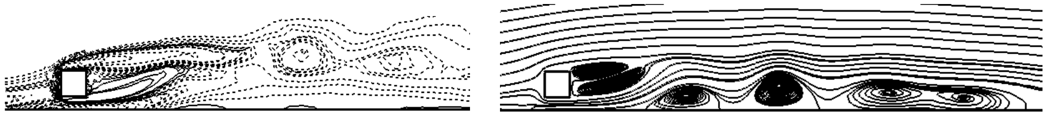


Fig. 6 - 2D unstructured grid about the square cylinder in close proximity to a plane wall.



Re = 100



Re = 200

Fig. 7 - Vorticity and the streamline contours for flow over a square cylinder with $g^* = 0.5$.

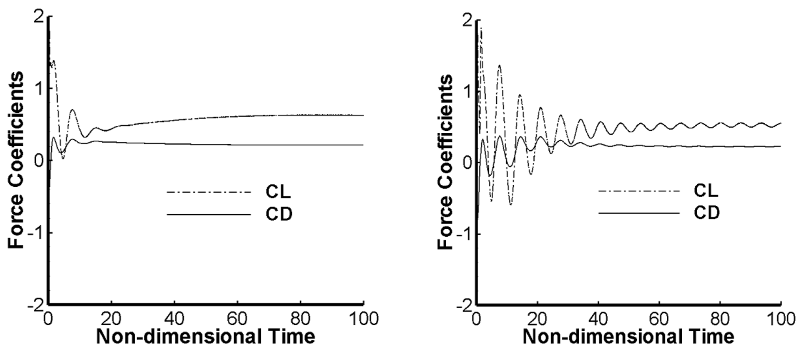
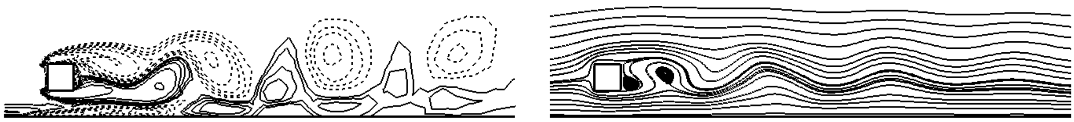
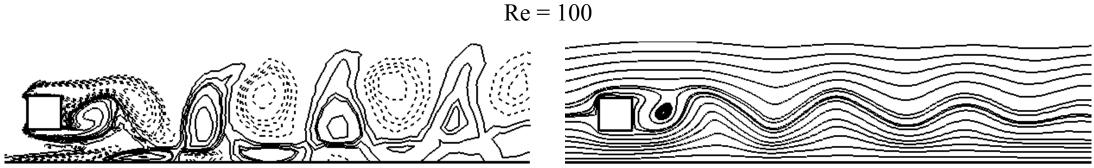


Fig. 8 - Temporal variation of force coefficients with $g^* = 0.5$.

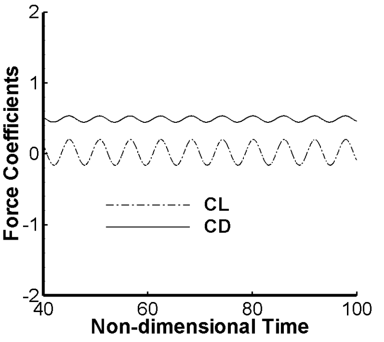


Re = 100

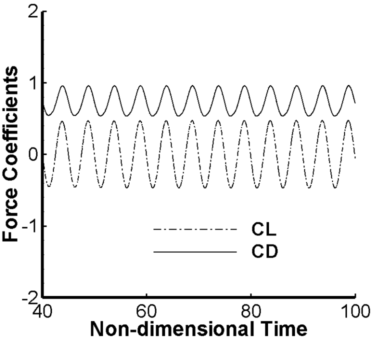


Re = 200

Fig. 9 - Vorticity and streamline contours for flow over a square cylinder with $g^* = 1.0$.



Re = 100



Re = 200

Fig. 10 - Temporal variation of force coefficients with $g^* = 1.0$.

Fig. 7 and 9 shows the streamlines and vorticity contours for flow over a square cylinder near a stationary plane wall with $g^* = 0.5$ and 1.0 for Reynolds number 100 and 200 respectively at non-dimensional time t = 100s. The plots also show that the vortex with lower intensity detaches from the bottom of the cylinder and is wrapped around the vortex with higher intensity detached from the top surface in flow downstream. This is due to the asymmetry in flow and the shear stress evoked because of the plane wall at the bottom boundary unlike the flow over a symmetrically placed unconfined-cylinder in the physical domain. Nonetheless, this 'vortex-wrapping" process has not been reported by other researchers [22] with a considerably larger blockage ratio of the order of 0.3 as opposed to the present value of 0.033. Unsteady separation from the plane wall was initiated locally near the zone where vortices are shed for a lower gap ratio. The coupling of local shear layer separation from the wall and the vortex-shedding from the cylinder was clearly noticed from the vorticity and streamline contours as presented in Fig. 7 and Fig. 9.

Table 3 - Characteristics of flow over a square cylinder near a plane wall.

Parameters		Coefficient of Lift	Coefficient of Drag	Strouhal Number
$g^* = 0.5$	$Re = 100$	0.6488	0.2266	---
	$Re = 200$	0.5348	0.2469	0.158
$g^* = 1.0$	$Re = 100$	0.0 ± 0.198	0.494	0.066
	$Re = 200$	0.0 ± 0.495	0.7738	0.266

Table 4 - Strouhal number for flow over a square cylinder near a plane wall ($g^* = 1.0$).

Li and Humphrey (1995) [23]		Present Results	
Re	*St*	*Re*	*St*
200	0.240	100	0.0668
1000	0.178	200	0.2488

Fig. 8 and 10 show the coefficient of drag and lift vs. non-dimensional time for flow over a square cylinder with Re = 100 and 200 at $g^* = 0.5$ and 1.0 respectively. The results show that the coefficients of drag and lift are highly impacted by g^*. At lower values of g^*, pressure below the cylinder drops because of accelerated gap flow. With increasing the gap ratio, the pressure distribution becomes symmetric about the horizontal axis. The zero-mean lift-coefficient at $g^* = 1.0$ shows the limited effect of the plane wall. The base pressure decreases and gets more negative as the gap ratio increases leading to an increase in drag. The C_L and

C_D show a clear periodicity implying periodic vortex shedding from the cylinder except for the case of $Re = 100$ at $g^* = 0.5$. In this case, no distinct peak has been obtained in the frequency spectrum when FFT analysis is performed for the periodic lift coefficient. Table 3 shows the mean value of force coefficients and Strouhal number for various configurations. Table 4 shows the Strouhal number values obtained from the present work with the findings of Li and Humphrey [23], and a very good match was noticed for flow at $Re = 200$ and $g^* = 1.0$ with a mere deviation of 6%. It has also been observed that the Strouhal number lowers when Re is increased over 200 for the plane wall configuration. They have taken into consideration 3D simulation in the flow for larger Re beyond 400. However, the 2D flow has been considered for the present case and the shedding-frequency is found to decrease as the Re decreases than 200. This result is found to be in good concurrence with the results available in the open literature.

3. CONCLUSIONS

The CFRNUS scheme is used for investigating and studying flow over a cylindrical buff body of square shape in the vicinity of the plane stationary wall at low Reynolds number varying the gap ratios. Two gap-ratios of 0.5 and 1.0 between the cylinder and the stationary plane wall have been considered. Streamlines and vorticity contours have been analyzed to study the effect of the vorticity field. The alternate shedding of the vortices having varying strengths curl up from the top and bottom surfaces of the cylindrical body to trigger the vortex wrapping phenomenon. The vortex pair generated from the surface of the cylinder moves slightly towards the upward direction at an angle in direction of flow and the vortices pattern is dependent upon the Reynolds number. These vortices disrupt the shear layer on the stationary plane wall which leads to temporal flow separation from the wall downstream of the cylinder.

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