

Influence of Lateral Boundaries and Grid Spacing on Steady Flow past a Square Cylinder

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ABSTRACT: In this paper, the influence distance of lateral boundaries of rectangular flow domain from the cylinder wall surface and grid spacing on flow past a square cylinder at low Reynolds number is numerically investigated using ANSYS Fluent. Two dimensional steady incompressible flow past a circular cylinder is solved numerically using finite volume method with second order accuracy in space. Pressure-velocity coupling scheme employed is SIMPLE. A domain independent study was conducted by varying the size of flow domain to ensure that the location of lateral boundaries does not influence the flow parameters. Then on the flow domain chosen, grid independence study is conducted so as to optimize computational hardware resource and time while ensuring that the results predicted are accurate and is not altered with the variation in the computational grid. The flow pattern and flow characteristics past a square cylinder at low Reynolds number were studied by means of vorticity magnitude contour, flow streamlines coefficient of drag and variation of x-component of velocity.

Keywords - coefficient of drag, coefficient of pressure, incompressible flow, grid, Reynolds number, square cylinder.

I. INTRODUCTION

Vortex shedding behind bluff bodies is encountered in many engineering applications. The study of the flow around bluff body is important in terms of the effects of wind on such bodies. Bluff bodies are structures with shapes that significantly disturb the flow around them, as opposed to flow around a streamlined body. A bluff body is one in which the length in the flow direction is close to or equal to the length perpendicular to the flow direction. Examples of bluff bodies include circular cylinders, square cylinders and rectangular cylinders. Cylinders of different cross-sectional shapes (e.g., circular, elliptical, rectangular) are the basic building blocks of many engineering applications such as heat exchangers, nuclear

reactors, and offshore structures. Long span bridges and high rise buildings are susceptible to wind loads excitation due to the shape and their flexibility. The fluid flow around an isolated cylinder placed in an open atmosphere is considered as unbounded flow. Thus due to engineering significance, laminar steady viscous flow around an isolated square cylinder has been the subject of numerous research works which includes experimental and numerical studies.

Zakir Faruquee et.al [1] conducted domain independent study for flow past circular cylinder using circular domain whose far-field boundary radius was varied from 10D-60D. In all cases, the same cell distribution was used for common subdomains. The influence of the far-field boundary on the drag coefficient was studied. Behr et al. [2] studied the influence of the location of the lateral boundaries on the unsteady flow past a circular cylinder at $Re = 100$. They have suggested that the lateral boundaries should be away from the cylinder by a distance of at least 8 cylinder diameters. Inoue et.al [3] constructed a non-uniform mesh but divided the computational domain into three regions, each with a different grid ratio. Mohamed Sukri Mat Ali et.al [4] 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. Sumer et.al [5] investigated and reported that the flow field over the circular cylinder is symmetric at low values of Reynolds number. As the Reynolds number increases, flow begins to separate behind the cylinder causing vortex shedding which is an unsteady phenomenon. Kovaszny [6] and Roshko [7] determined experimentally that for Re less than 40, the flow remains laminar, two-dimensional and steady, but can become unstable under the influence of external excitation. Braza et.al [8] showed that when the Reynolds number is increased beyond 40, not every destabilization of the flow, random or not, can be damped out.

II. NUMERICAL SIMULATION PROCEDURE

2.1 Governing equations

A single square cylinder subjected to a uniform air flow (unbounded flow) is the physical model of the problem. Flow over the cylinder is governed by the partial differential equations derived from the laws of conservation of mass (continuity equation) and momentum (Navier–Stokes equations), which can be written as follows:

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

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

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

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 $\rho=1.225 \text{ kg/m}^3$ and $\mu=1.7894 \times 10^{-5} \text{ kg/m s}$.

2.1 Computational domain

A rectangular flow domain is employed in this study. To minimize the effect of the far-field boundary conditions, the lateral boundaries of the computational domain must be placed sufficiently far away from the cylinder.

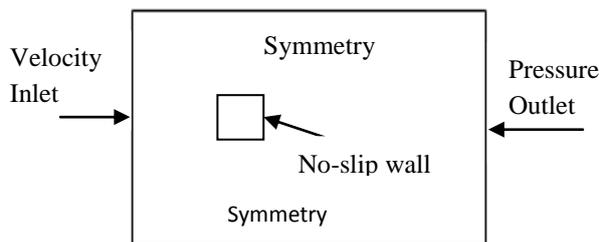


Figure 1: Schematic of computational domain and boundary conditions

A computational domain extending up to a length of 4D (i.e., 4 times cylinder diameter) in the upstream, to a length of 4D in transverse directions and 9D in the downstream direction from the leading edge, top-bottom edges and trailing edge of the cylinder respectively was initially employed. Then, to determine an appropriate location for the outer boundaries, length of boundaries was varied

upto 11D in upstream and transverse direction and 16D in downstream direction with corresponding variations in lateral boundaries. The influence of the far-field boundaries on the drag coefficient is given in Table 1 at $Re = 40$.

TABLE 1

Effect of far-field boundaries on the drag coefficient for a square cylinder at $Re = 40$

Far-field boundaries	No. of cells	C_D
4D, 4D and 9D	15600	2.068
5D, 5D and 10D	22464	1.953
6D, 6D and 11D	32654	1.881
7D, 7D and 12D	47425	1.833
8D, 8D and 13D	68376	1.799
9D, 9D and 14D	98552	1.774
10D, 10D and 15D	141662	1.755
11D, 11D and 16D	203690	1.749

As seen from this table, moving the outer boundaries from 10D, 10D and 15D, does not have any noticeable effect on the flow parameter. Therefore, computational domain having an upstream length of 10D, transverse length of 10D and downstream length of 15D was chosen to simulate the unbounded flow past square cylinder. The application of appropriate boundary conditions at the cylinder surface and at the outer boundary is crucial for accurate simulation. A uniform approach velocity was imposed on the upstream of the outer boundary of the computational domain, while symmetry condition was imposed on top and bottom free-streams and a pressure outlet condition was imposed on the downstream. No-slip condition was applied along the cylinder wall. In this study, the QUICK method of interpolation was used for solving velocity and momentum. The SIMPLE method was employed for the pressure– velocity coupling for all simulations. The second order interpolation scheme was applied for pressure. Convergence criterion employed is 10^{-6} .

III. GRID INFLUENCE

Within the scope of 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 construction of the mesh. Generally, the accuracy of a numerical

solution increases as the number of cells increases. But employing a larger number of cells requires more computer hardware resource and computing time. All simulations performed in this study employed quadrilateral cells. Grid spacing was gradually increased from the cylinder surface towards the outer boundaries in order to avoid sudden distortion and skewness, and to provide a sufficiently clustered mesh near the cylinder wall where the flow gradients are large and to capture flow regime within the boundary layer.

Grid independency was achieved in this study according to the procedure outlined by Yunus A. cengel and Michael A. Boles [10]. Several meshes, with increasing refinement, were tested to ensure that the solution was independent of the mesh. These meshes and the drag coefficient (C_D) predictions are reported in Table 2 for the case of a square cylinder at $Re = 40$. It is observed that the value of drag does not vary much for mesh finer than 87652 cells.

TABLE 2

Effects of cell density on drag coefficient for a square cylinder at $Re = 40$

No. of cells	C_D
29385	1.762
42516	1.764
61328	1.766
87652	1.768
126494	1.769

IV. RESULTS AND DISCUSSIONS

From the domain independence study, it was observed that rectangular domain with dimensions 10D in upstream direction, 10D in transverse direction and 15D in the downstream direction predicts the results accurately for flow past a square cylinder at $Re=40$. Then grid independence study was conducted on this domain with grid refinement starting from 29385 cells. It was observed that grid refinement beyond 87652 cells did not make any significant changes on flow parameters. Variation in the value of drag coefficient was taken for grid refinement study. 2D steady and incompressible flow over a square cylinder was simulated at $Re=40$ using the above mentioned computational domain and grid. Flow at $Re=40$ is laminar and steady. As flow approaches the leading point of a square cylinder, the fluid is brought to rest, causing a pressure rise and a boundary layer develops along the surface. The leading point is called the forward stagnation point. For very low Reynolds number ($Re < 5$), the flow splits into two symmetrically equal parts and passes around the cylinder to the rear stagnation point.

When Reynolds number is increased, small size eddies develop in the immediate vicinity of the rear stagnation point of the cylinder, where the velocity is extremely small and pressure gradient is unfavorable. The recirculation zone remains steady, two dimensional and symmetrical about the streamwise center line of the flow. The contours of vorticity magnitude at $Re=5$ and $Re=40$ are shown in fig.2.

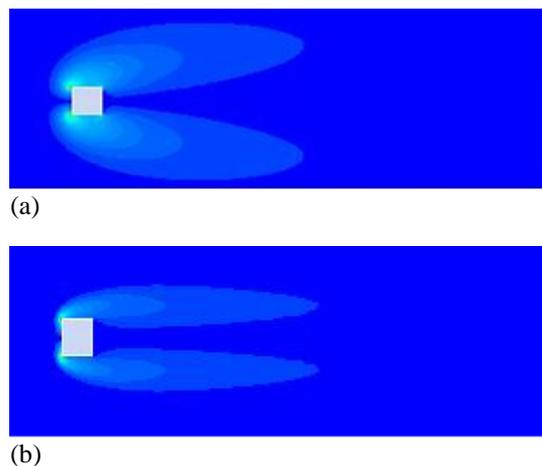


Figure 2: Contours of vorticity magnitude (a) At $Re=5$ and (b) At $Re=40$

The flow streamlines for flow past square cylinder at $Re=5$ and $Re=40$ are shown in fig.3.

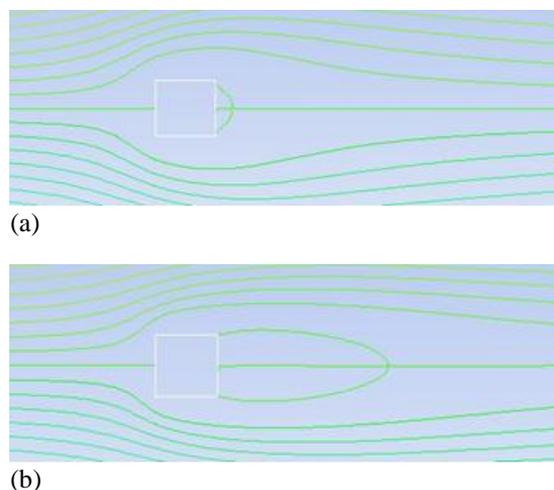


Figure 3: Flow streamlines (a) At $Re=5$ and (b) At $Re=40$

At $Re=40$, only recirculation eddies are formed immediately downstream of the cylinder, near the rear stagnation point as indicated by streamlines. Variation of x-component along the wake centerline is shown by non-dimensionalised parameter of x-component velocity. Fig.4 shows the variation of x-component velocity along wake centerline at $Re=5$ and $Re=40$.

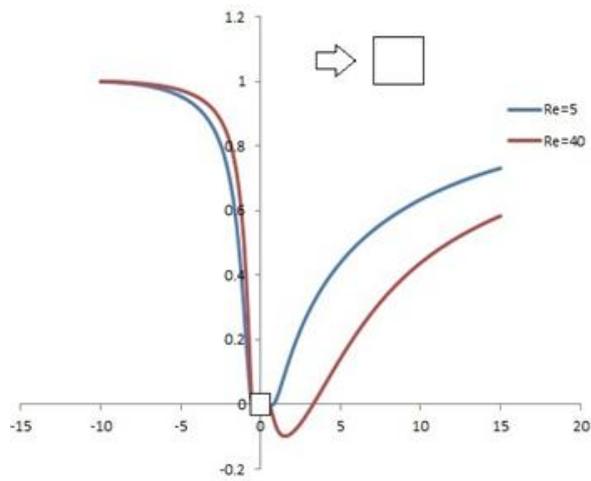


Figure 3: U/U_{ref} along the wake centerline

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