Flow past an Elliptic Cylinder

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Abstract

The aim of this project is to study the variation in coefficient of discharge with time for the flow past an elliptic cylinder in laminar and turbulent regimes between a time interval of 30s<t<60s, as well as to generate the vorticity plots at the end of simulation time for the respective regimes. For simplicity in this study we have simulated a 2D incompressible flow using the pimpleFoam transient solver in OpenFOAM and adopted the k-ε RAS (Reynolds-Averaged Simulation) model to simulate the turbulent flow regime.

1. Introduction

The flow of fluids past immersed bodies is essentially studied for applications for fluidization phenomena in packed bed reactors. An important aspect of such a flow is the presence of drag force, which acts in the direction of flow exerted by fluid on the solid body. The quantitative measure of drag is coefficient of discharge defined by

$$Cd \equiv \frac{F_d/A_p}{\rho u^2/2}$$

Where u is the velocity of approaching stream, A_p is the projected area and F_d is the drag force.

Vorticity has been defined as the curl of velocity vector i.e. $\omega = \boldsymbol{\nabla} * V$ and has been defined for 2D flows only.

The parameter of the k-ε turbulent model have been calculated using the following:

$$I = 0.16 * Re^{-\frac{1}{8}} \qquad k = \frac{3 * \left(I * U_{avg}\right)^2}{2} \qquad \epsilon = \frac{0.164 * k^{1.5}}{0.07d}$$

I= Turbulent Intensity *k=turbulent kinetic energy* *ε=turbulent dissipation*

The above correlations have been established for fully developed turbulent flows.

2. Problem Statement

Consider an elliptic cylinder of aspect ratio 2 with the major axis of length 1 m placed in a 50 m×10 m domain as shown in figure. The centre of the cylinder is located 3 m from the left boundary (inlet) and 5.005 m from the bottom boundary.

$\mu = 1.5 \times 10^{-5}\ Pa \bullet s$ $\rho = 1\ kg/m^3$ $Re = 1\times10^5$

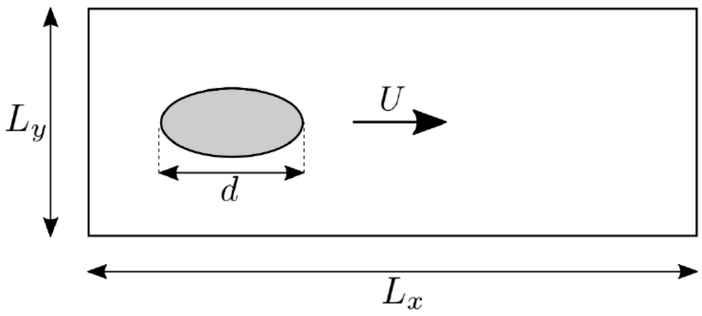


Figure 1: Schematic drawing (not to scale) of the computational domain. ($d = 1$ m, $L_x = 50$ m and $L_y = 10$ m)

Plot the vorticity field at the end of the simulation (t = 60 s). Also, calculate the time-averaged drag coefficient for 30 s < t < 60 s for the turbulent and laminar flow.

3. Governing Equations

The following equations govern the flow are Continuity equation which is based on conservation of mass and the Momentum equation which is based on conservation of energy.

- Continuity equation

$$\boldsymbol{\nabla . V = 0}$$

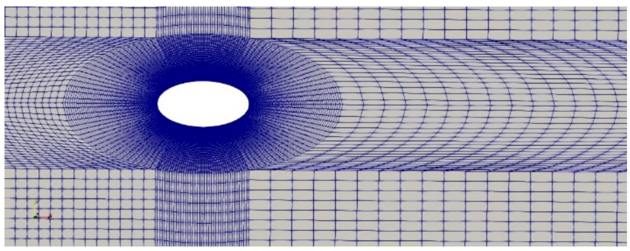
- Momentum equation (Navier Stokes Equation for Incompressible flows)

$$\boldsymbol{\frac{dV}{dt} + V * \nabla . V = -\nabla . P + \frac{\mu}{\rho} . \nabla^2 . V}$$

4. Simulation Procedure

4.1 Geometry and Mesh

The geometry and mesh were created using blockMesh built-in utility in Openfoam package. Refinement near the elliptical void was accomplished by creating blocks around and adding more number of cells as well as changing the grading of cells as per their location.



The mesh has 20 blocks, and face matching has been adopted to cater the needs of joining blocks. Due to face matching and refinement of some blocks has been set with more number of cells in a particular direction depending on the location of those blocks. Also a SimpleGrading of (5 1 1) and (1 5 1) has been adopted as per need of the face-matching and mesh.

4.2 Initial and Boundary Conditions

The boundary conditions set up are

- Inlet, Outlet to freestream velocity condition and the freestream value of 1.5m/s which was opted based on calculation from Reynolds's number. The pressure boundary condition is also freestream with a freestream value of 1 on both faces.
- The top and bottom face were symmetryPlane.
- The ellipse is considered to be smooth and hence a noSlip velocity boundary condition is imposed on it. The pressure boundary condition on the ellipse face is set to zeroGradient considering the pressure on the face to be constant.
- Since, the flow is 2D the frontandback face is set to empty.

The turbulent boundary conditions were

- ε was calculated according to the formula and imposed on internalField. The inlet, outlet were fixedValue type and value was set to the corresponding internalField. The topandbottom face were symmetryPlane and zeroGradient imposed on ellipse wall.
- k was calculated according to the formula and imposed on internalField. The inlet, outlet were fixedValue type and value was set to the corresponding internalField. The topandbottom face were symmetryPlane. The value of turbulent kinetic energy on the elliptic wall was evaluated using the kqRWallFunction with a value calculated using the formula given in intro.
- For the nut inlet, outlet were calculated type and value was set to uniform 0. The topandbottom face were symmetryPlane. The value of nut on the elliptic wall was evaluated using the kqRWallFunction with a value uniform 0.

4.3 Solver

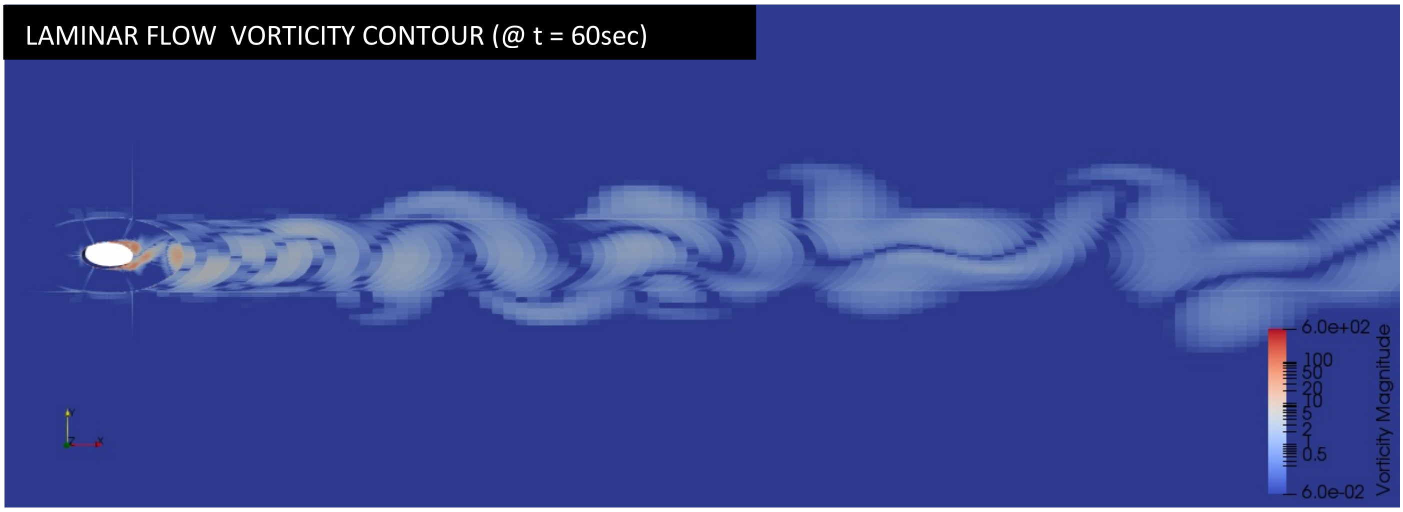
PimpleFoam solver was adopted for this study, which is a solver for transient incompressible flow. It uses a merged PISO-SIMPLE algorithm. The pimple solver was configured to correct pressure field twice using nCorrector as 2 and the Non-OrthogonalCorrector was set to 3 to evaluate the field thrice from the calculated one because the mesh had some non-Orthogonal faces which required correctness. All the equations were relaxed by a factor of 0.9 in turbulent flow whereas in laminar flow no relaxation was done (i.e.α=1).

In the fvScheme file, the divergence of phi with turbulent parameter k and epsilon uses Gauss upwind scheme and the divergence of phi with U (velocity) used Gauss linearUpwind grad (U) scheme. The laplacian schemes were Gauss linear and corrected by 0.33.

5. Results and Discussions

In the regime of Laminar flow, the vorticity contour obtained at t=60s is given below. The vortex shedding can be visually observed in the wake of ellipse. The intensity of vortex shed is maximum near the cylinder and unsteady separation of flow of fluid around the body occurs. The repeating pattern of swirling vortices caused by vortex shedding is known as “Von Karman Vortex Street” effect.

(*Note: Due to refinement of mesh only close to the ellipse an elliptical core is visible at some distance from the cylinder and it does not depict the physics of the phenomena in any way.)*



The time averaged coefficient of discharge is found to be 0.813562. The surface-averaged transient variation of Cd on the Elliptical surface is plotted below in the interval of 30s<t<60s. The maximum and minimum values correspond to 1.2825 and 0.418905 respectively.

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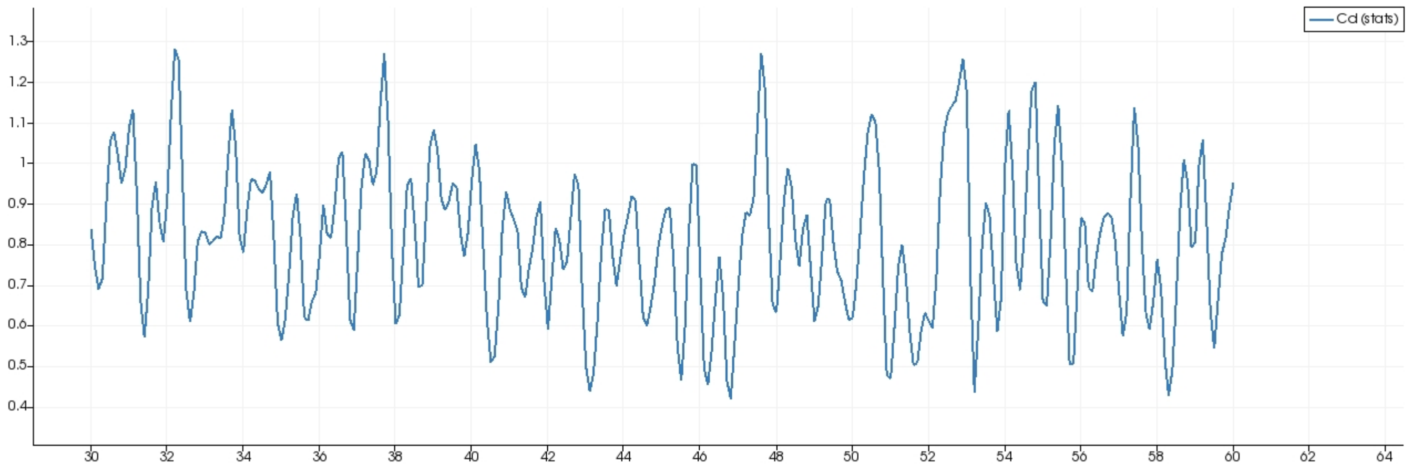
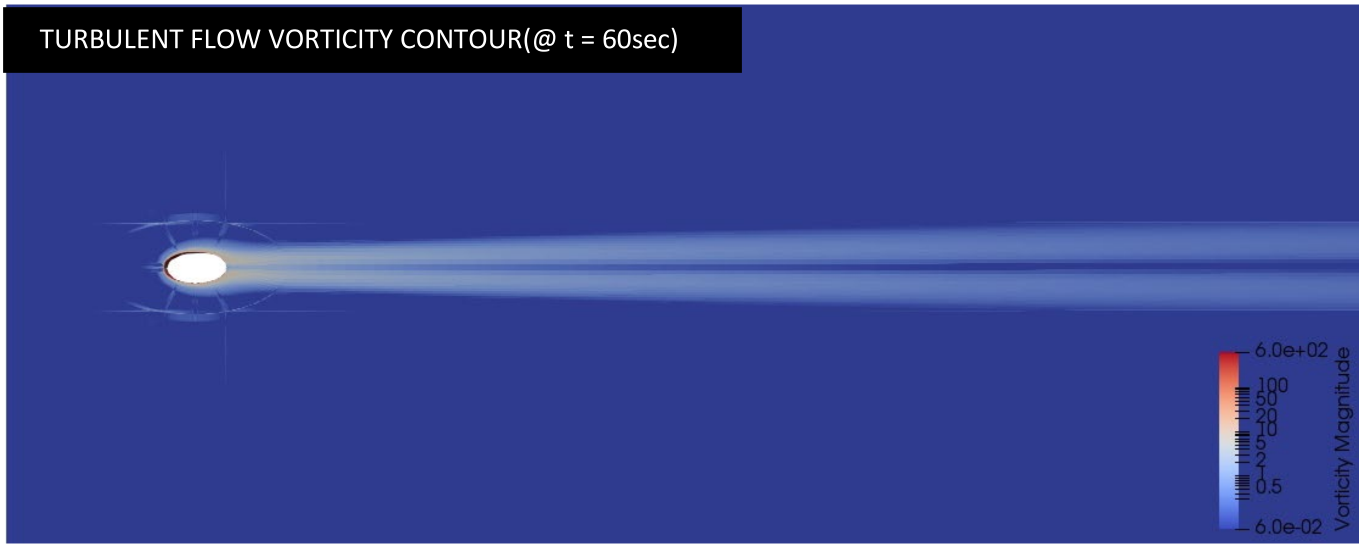
DRAG COEFFICIENT VS TIME (30s<t<60s)



The standard deviation of coefficient of discharge is calculated in the mentioned interval and it was found to be 0.183981, which represents an average variation of 22% in the value of Cd from its mean in the interval.

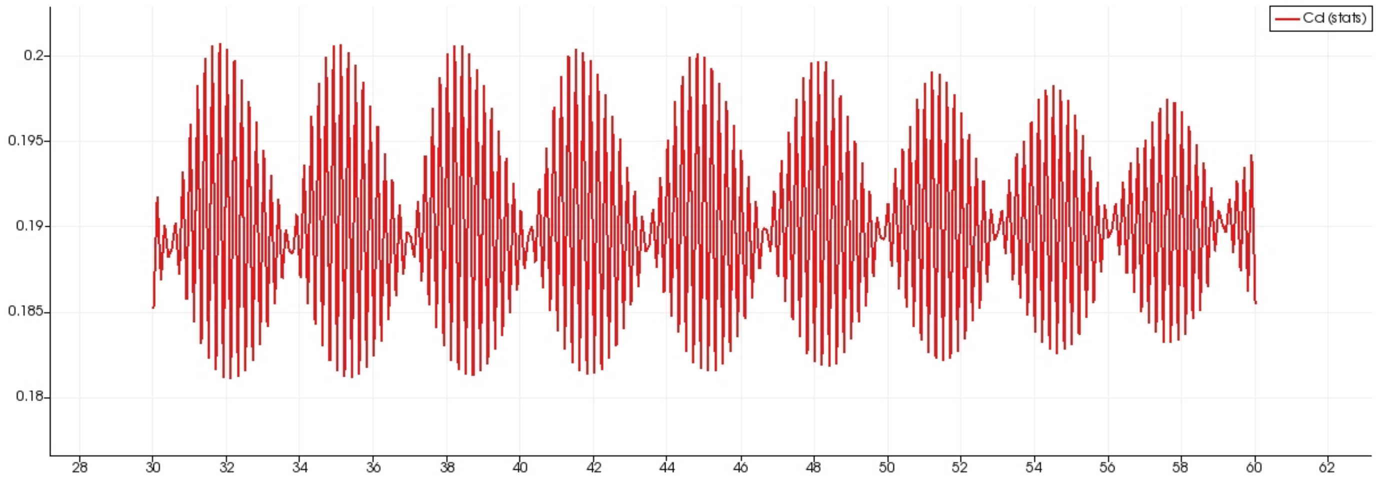
In the turbulent regime, the vorticity contour obtained at t=60s is given below. Due to the inclusion of turbulence, no vortex shedding is observed and the vortex plot seems to be normalized. In the wake of elliptical cylinder the magnitude of vorticity again is maximum and fades as the distance from the wall of cylinder increases. The two vorticity waves from above and below the cylinder seems to remain disconnected and diverge symmetrically with distance from the ellipse.

(*Note: Due to refinement of mesh only close to the ellipse an elliptical core is visible at some distance from the cylinder and it does not depict the physics of the phenomena in any way.)*



The time averaged coefficient of discharge is found to be 0.19. The surface-averaged transient variation of Cd on the Elliptical surface is plotted below in the interval of 30s<t<60s. The maximum and minimum values correspond to 0.2 and 0.181026 respectively. The standard deviation of coefficient of discharge is calculated in the mentioned interval and it was found to be 0.00623827, which represents an average variation of 3.28% in the value of Cd from its mean in the interval.

DRAG COEFFICIENT VS TIME (30s<t<60s)



The transient oscillating behaviour of coefficient of discharge about its mean value is well evident by observation of the variation plot given above. It can also be observed that amplitude attenuation of the oscillation is taking place.

It was found that the drag coefficient for Laminar flow was found to be more than turbulent flow by about 4.28 times. The value of Cd showed a highly irregular variation with time in laminar regime and the variation from mean value was also found to be significantly more than that in the case of Turbulent flow. The k-ε model is found to have shown an attenuated oscillatory behaviour in Cd along with no vortex shedding in the turbulent regime whereas in the laminar regime significant vortex shedding has been observed.

References

- McCabe, W., Smith, J., Harriott, P. and McCabe, W., 2001. *Unit operations of chemical engineering*. Boston: McGraw-Hill.