FOSSEE, IIT Bombay
OpenFOAM Research Migration Project
April 13, 2023

CFD analysis on Flow over cylinder and impact of no. of sides and orientation of cylinder on the drag in a Laminar flow

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Abstract:

Fluid flow over a surface have always fascinated the research community because they are ubiquitous in nature, nature always presents the finest examples for any engineering problem, in this case we have seen fish swimming in water, the shape of fish is classic example of streamlined body and nature have always made fish with that shape so as to reduce its drag and travel effectively. Flow over cylinder is a class of problems which has immense applications in nature, with the development of CFD it possible to model the flow dynamics of these class of problems with quite ease.

This report will drive through the effects of no. of sides on the important parameter (drag, lift) for 2 different cases namely steady flow (Re<40) and Unsteady flow (Re>40), also the essence of streamlining is briefed. The report ends with certain conclusion drawn from the study and mentioning the future scope of the same.

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1. Introduction:

Flow across a cylinder is always a problem where the researchers has focused on due to its wide applicability in practical purposes.

The applications include flow across a high-rise building, flow across a bridge etc. The parameters to focus on includes the drag and lift coefficients, angle of attack of flow to the cylinder, studying these parameters enables us to get an idea of Drag forces the cylinder resists when placed in a flow field, alternatively for moving objects in a flow field we can model by relative analysis of considering flow moving with same velocity in opposite direction and stationary object, the examples of this include flow over train ,ships etc.

Various study of flow over cylinder are available in research but most of them extensively focusses on square and circular cylinders, but the effect of increasing the sides of obstacle has not been analysed and the idea behind the transition from square (4 sides) to circular (infinite sides) has not been put forward.

In this study, the primary goal is to study this effect of sides transition and analyse its impact primarily on Drag coefficient (Cd) for 2 cases namely, Steady flow situation (Re<40) and Unsteady case situation (Re>40), also the idea behind introducing Streamlined body is presented in brief.

2. Geometrical Details:

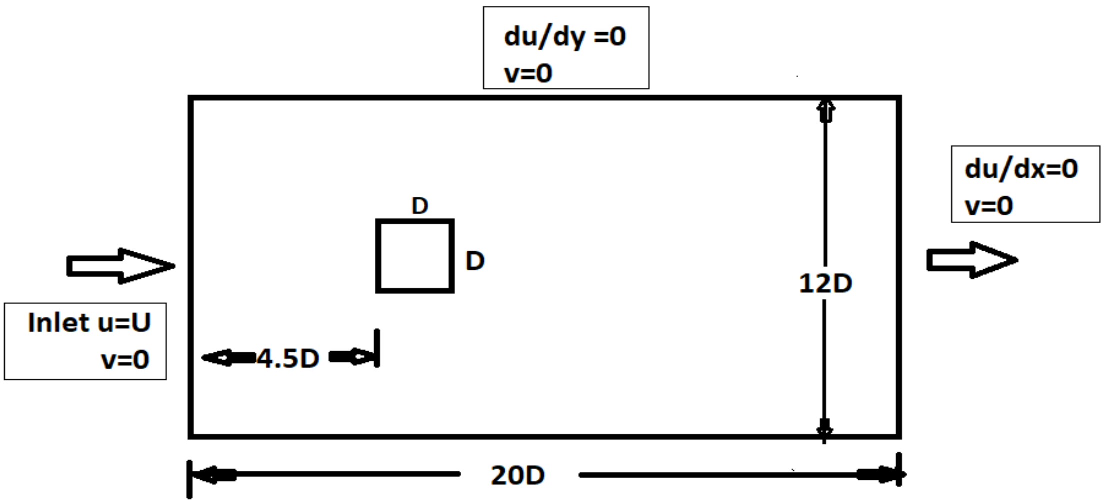


Figure 1: Computational Domain used for the analysis [1]

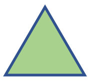
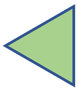
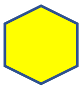
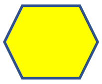
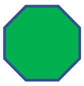
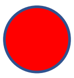
Mentioned here is the Detailed geometrical analysis for the domain used and boundary condition used for simulation, the mentioned domain is for square cylinder but we just move on similar lines for other obstacle shapes, except Circular cylinder where every parameter are same except the domain width, this is done as most of papers in research proposed H/D of more than 15 for circular cylinder to counter the effect of wall especially in circular cylinder.

Reynolds number in this study is defined as, $Re = \frac{uD}{\vartheta}$

Where D is defined as the height of cylinder.

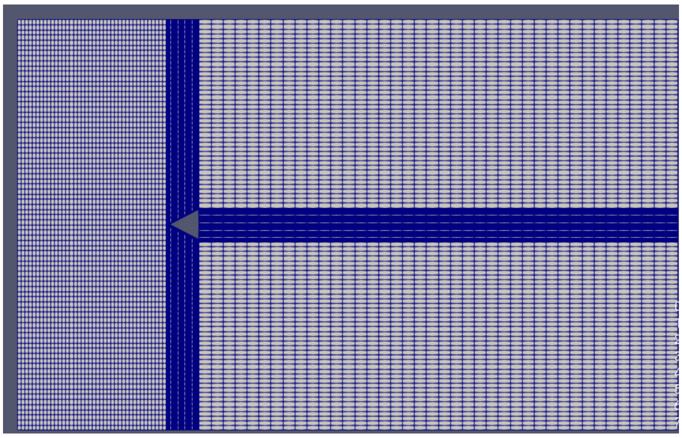
The Solver used to model this problem is **icoFoam.**

Table 1: The various Geometries modelled

Sr no	**Cylinder shape**	
1		Triangle 2
2		Triangle 1
3		Square
4		Hexagon 2
5		Hexagon 1
6		Octagon
7		Circle
8		Near Streamline shape

3. Simulation Procedure:

3.1 Meshing in openFoam



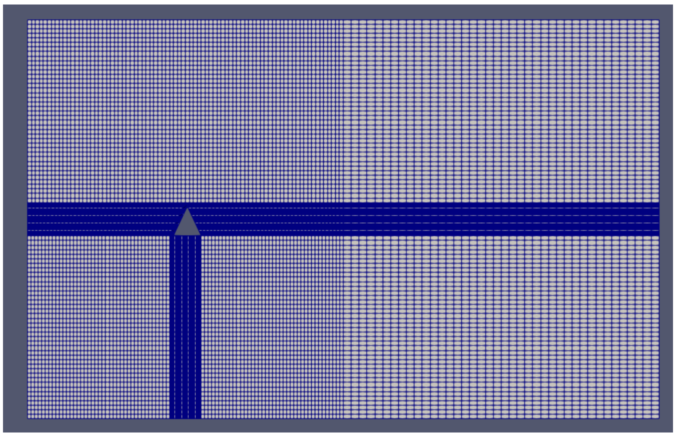


Figure 2: Meshing Strategy for Triangular obstacles

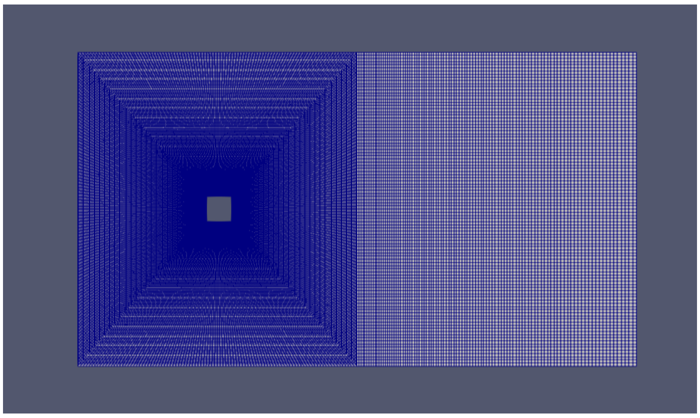
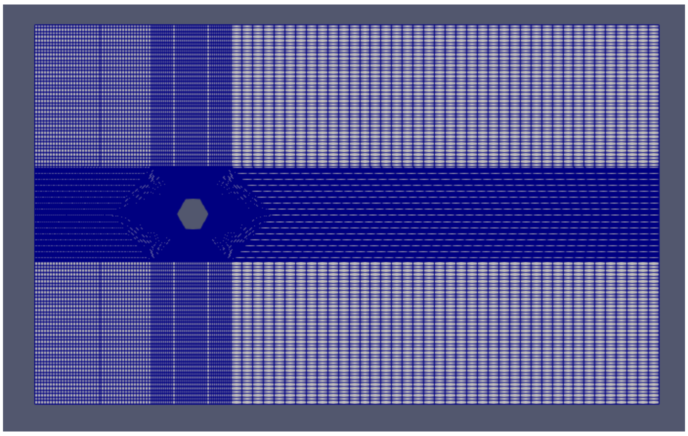


Figure 3: Meshing Strategy for square obstacle



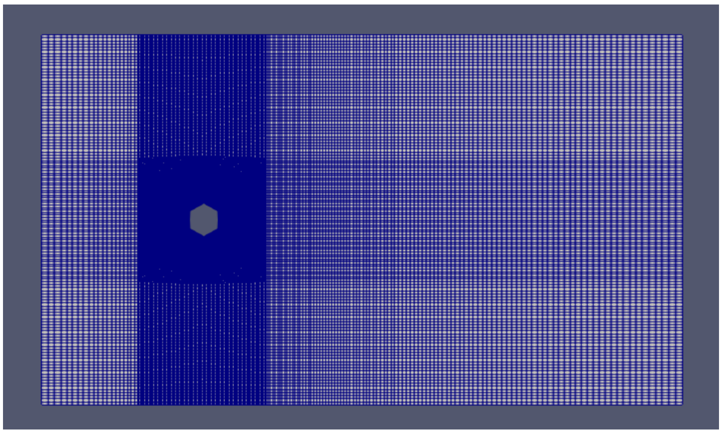


Figure 4: Meshing Strategy for Hexagonal obstacles

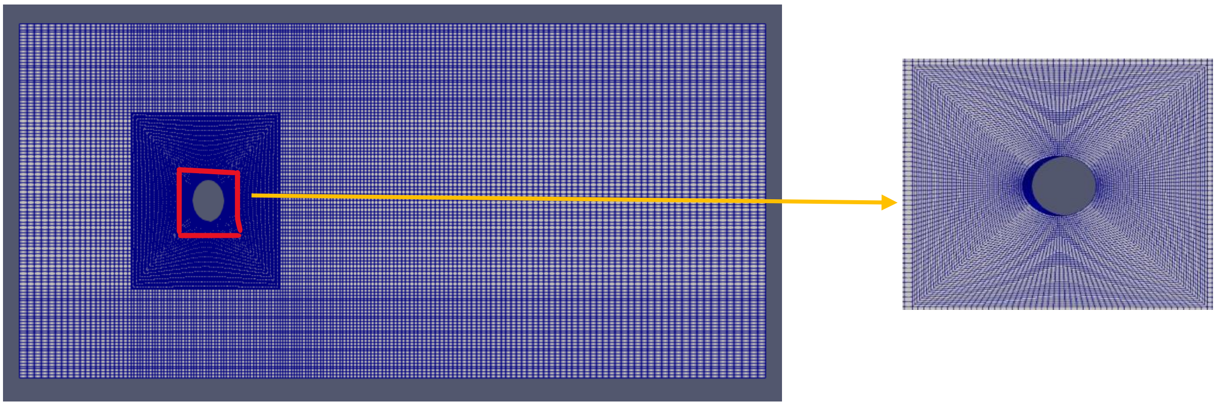


Figure 5: Meshing Strategy for Circular obstacle

3.2 Solver Used:

icoFoam solver is used for analysis, it is an incompressible, transient solver. Here we intend to solve for laminar region so we have chosen icoFoam solver, a point here to be noted that the Courant number should be closely monitored as it is sensitive to courant number.

Here additionally we have introduced a function in controldict file for calculating drag and lift coefficients.

The governing Equations used are:

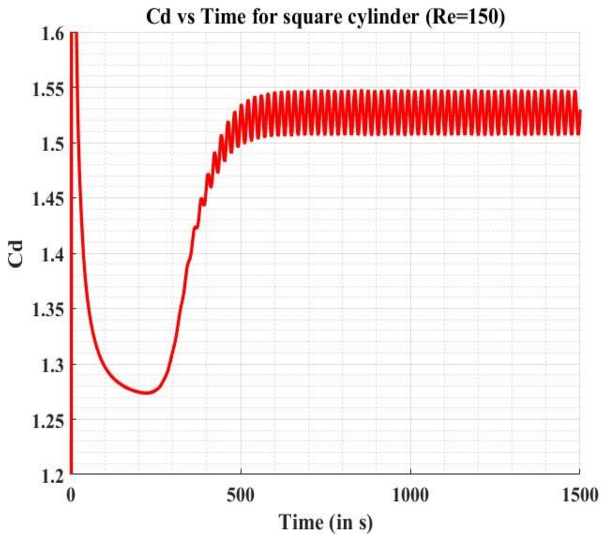
Continuity Equation: $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$ (1)

X Momentum Equation: $\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \vartheta\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{1}{\rho}\frac{\partial P}{\partial x}$ (2)

Y momentum equation: $\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \vartheta\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{1}{\rho}\frac{\partial P}{\partial y}$ (3)

4. Validation:

The validation of the study is done for Steady flow (Re=40) and Unsteady Flow (Re=150) for flow across a square cylinder against standard results in the literature



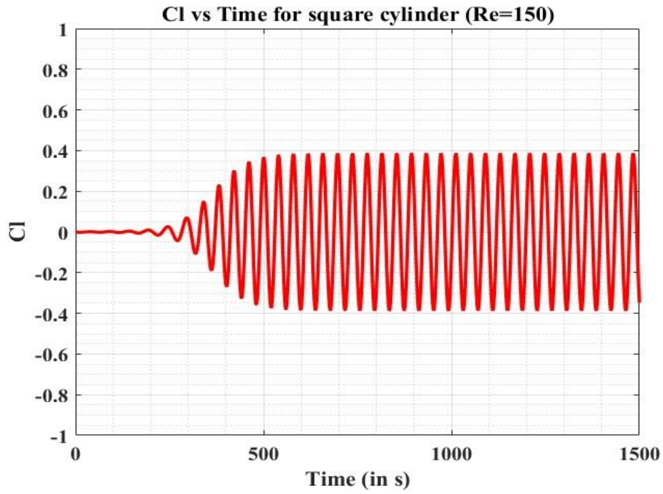


Figure 6: Variation drag and lift for Re=150 (For validation)

Table 2: Validation of results (Cd,Cl) for Re=150 for flow over square cylinder

CURRENT WORK (For Re=150)	**(Franke et al, 1990)[1]**	
	For Re=150	Error(in %)
Cd(max cycle)=1.55 Cd(min cycle)=1.51	Cd=1.56	-1.92
Cl(in cycle)= ±0.388	Cl=±0.38	2.10

5. Results and Discussion:

For Flow over cylinder, usually there are 2 major cases in Literature, steady flow case (Re<40) and Unsteady Flow case (Re>40). Here we will analyse and discuss results for both the cases.

5.1 Steady Flow case:

For Steady flow here Reynolds number considered is Re=40.

The important parameters that are compared for all the different cylinders are:

a) **Drag Coefficient**: It usually is the non-dimensional measurement of amount of shear force experienced by the body when a fluid is flowing over the body.

b) **Recirculation Length (RL)**: When a fluid flows over a body, there is a low pressure region just downstream to the body, due to which there is a recirculation zone i,e velocity of fluid becomes negative (flows in opposite direction), The recirculation length is defined as the length along flow direction from the cylinder end to the point where velocity changes direction of flow (positive velocity).

Here mentioned is the example to demonstrate Recirculation length,

We can see from the Figure 7 that when a flow is passed a vertical flat plate, its velocity is zero at the walls of the plate and it becomes negative and after a particular distance it regains its velocity in positive direction, this distance between the transition is termed as recirculation length.

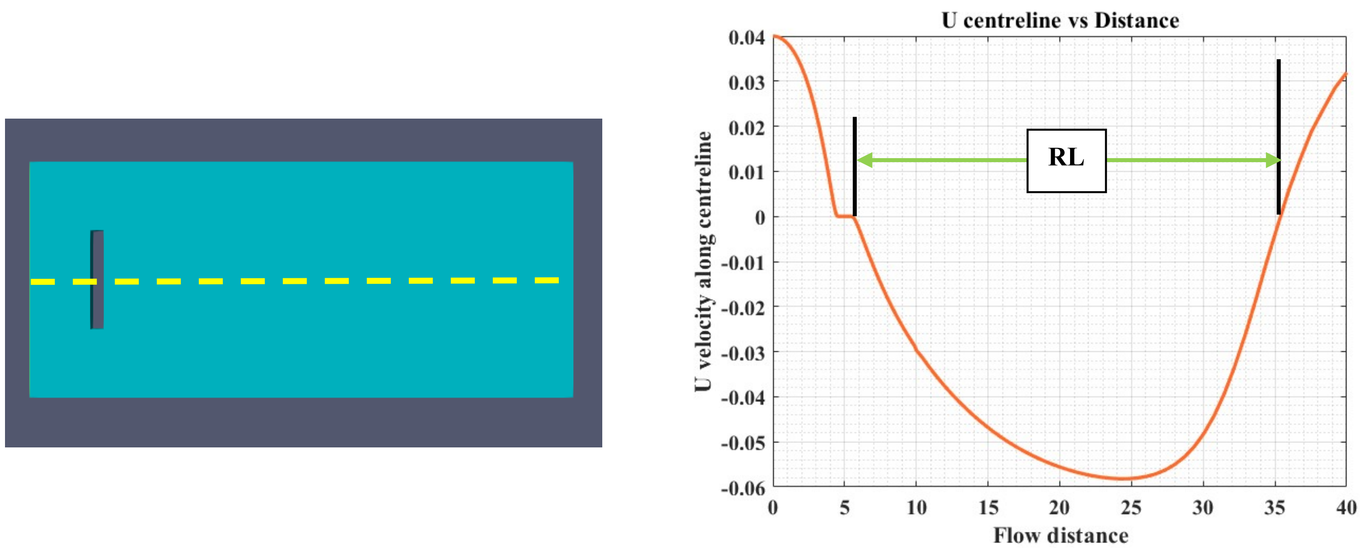


Figure 7: The U centreline Velocity variation for a flow across a vertical flat plate with flow distance

Figure 8 shows variation of Drag coefficient with time for various shapes, as the Re=40 (steady case) drag coefficient becomes almost constant after some time, from this graph we can observe that square has the highest Drag coefficient as compared to all other shapes, leaving Triangle as we increase the no.of sides of the object the drag coefficient decreases, with 1 exception i,e Hexagon_1 which have the lowest drag coefficient among all the shapes, the reason for the same will be illustrated in further sections.

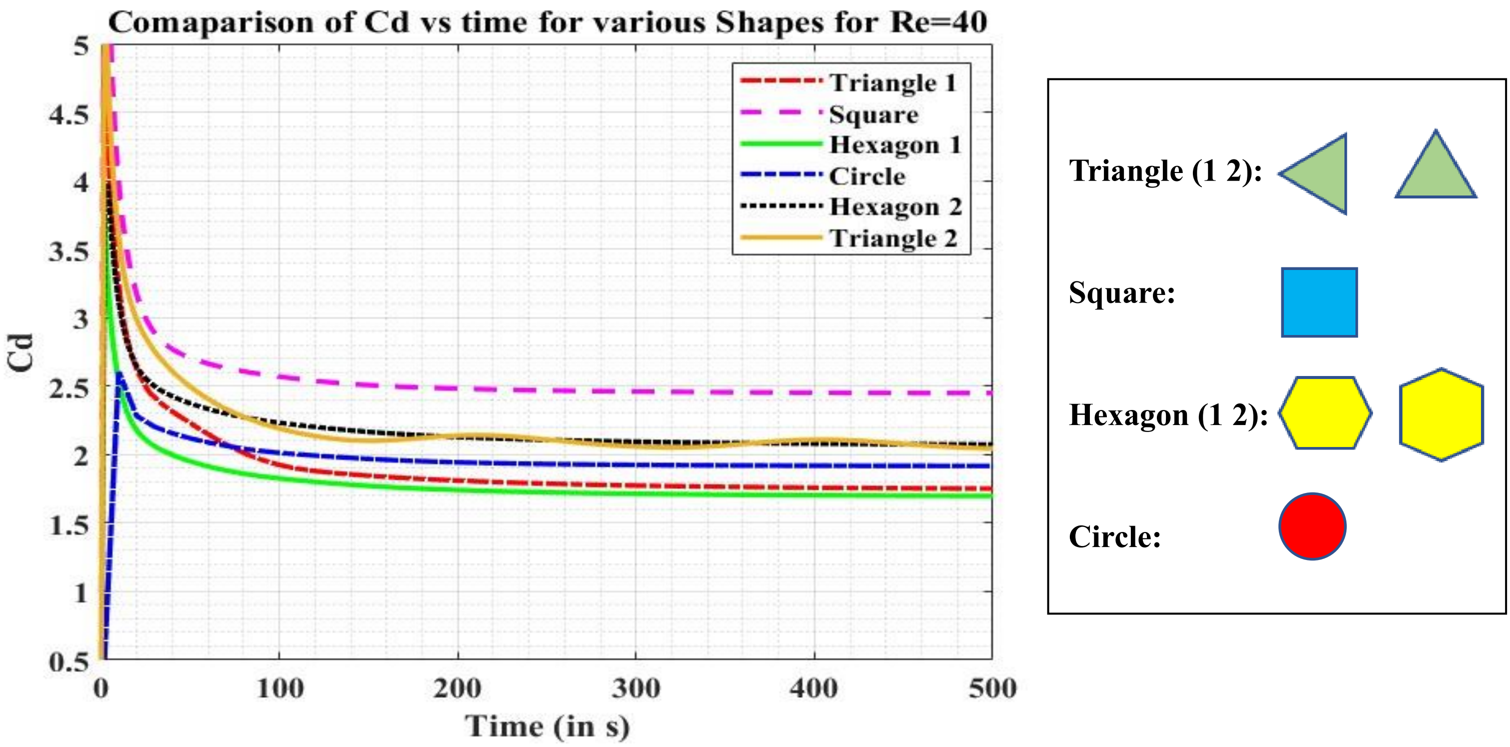


Figure 8: Comparison of drag coefficient for various shapes (Re=40)

5.1.1 Comparison with Streamlined Shaped body:

In the previous comparison we saw that Hexagon_1 has lowest drag coefficient as compared to all other shapes, so here an attempt is made to explain the reason behind the result, by trying to streamlined an object. Figure 8 a shows s detailed profile of streamlined body, here we can observe that at the region of fluid striking it has a uniform splitting surface which pushes the fluid equally over both sides of the shape, The top portion is kind of flat at the beginning and has a uniform downward inclination. Figure 8 b shows a modelled shape following the path of the streamlines.

Also, the thing to note and observe is the only object modelled above which satisfies this condition is Hexagon_1 and so it has the least Drag coefficient as compared to all other objects.

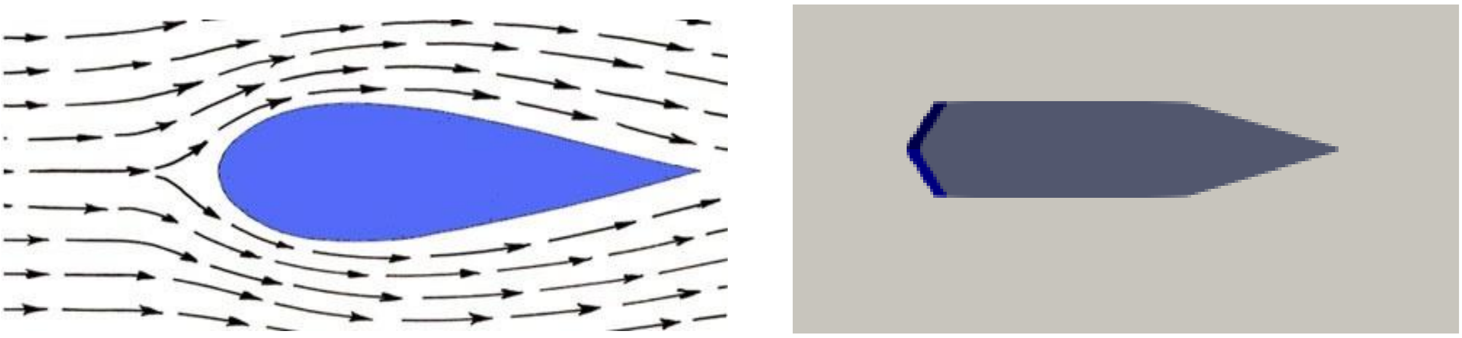
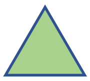
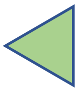
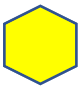
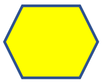
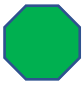
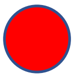


Figure 9: a) Streamlined body b) modelled shape similar to the streamlined body

Table 3 displays the Drag coefficient for different shaped cylinders at Re=40, with square having the maximum drag coefficient to Hexagon_1 having the minimum drag coefficient. A point that can be noted here is for the circular cylinder value of Cd in research papers varies from 1.55 to 1.91, due to different domains and the selection of boundary conditions.

Table 3: Drag coefficient for various shapes at Re=40

Sr no	**Cylinder shape**		**Drag Coefficient**	**RL (m)**
1		Triangle 2	2.07	-
2		Triangle 1	1.75	3.0
3		Square	2.22	2.2
4		Hexagon 2	2.067	2.1
5		Hexagon 1	1.695	-
6		Octagon	2.007	-
7		Circle	1.77	1.7
8		Near Streamline shape	0.504	0.75

5.2 Unsteady Flow case:

For unsteady flow here Reynolds number considered is Re=150.

The important parameters that are compared for all the different cylinders are:

a) **Drag Coefficient**: It usually is the non-dimensional measurement of the amount of shear force experienced by the body when a fluid is flowing over the body.
b) **Lift Coefficient:** It is the non-dimensional measurement of amount of force experienced by body in direction perpendicular to the flow.
c) **Strouhal Number(St):** It is a non-dimensional number corresponding to the frequency of vortex sheading in Unsteady flow for the bluff bodies.

$$St = \frac{fD}{U} \tag{1}$$

Where f is frequency of vortex shedding

D is diameter of the cylinder

U is free stream velocity

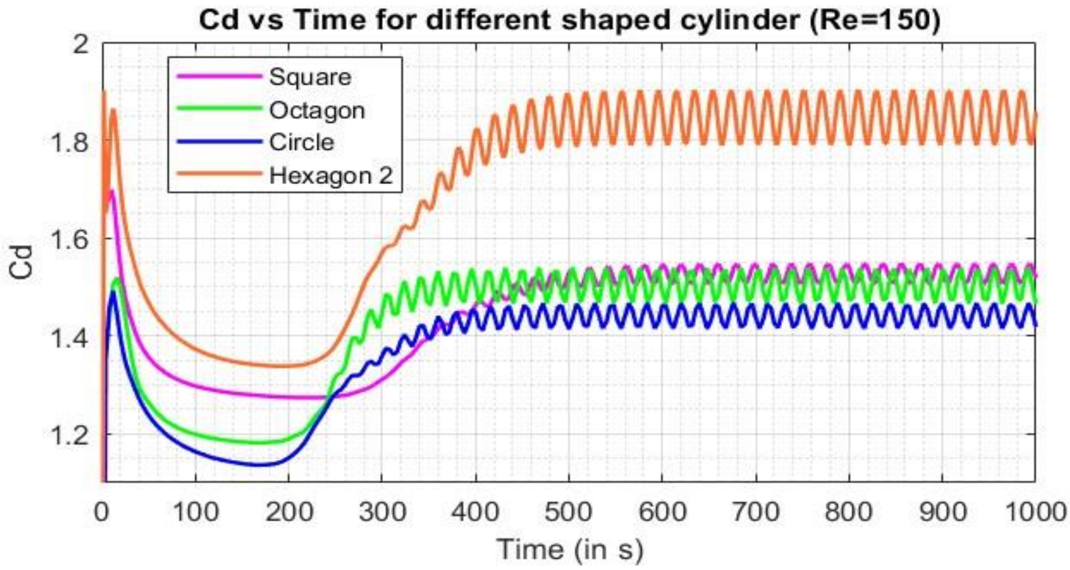


Figure 10: Comparison of Cd for various shapes of cylinder

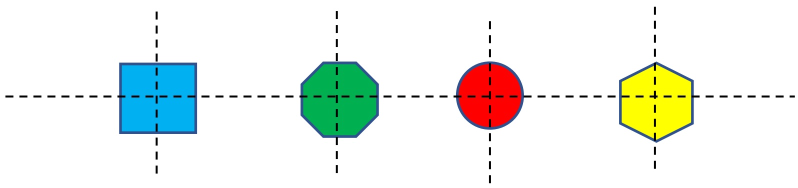


Figure 10 shows the drag coefficient of different cylinder shapes at Re=150, leaving Hexagon_2, as the no.of sides increases the drag coefficient reduces from square to circle. Hexagon_2 here shows a fairly high drag coefficient value as compared to other shapes, firstly comparison of hexagon_2 with other shapes is not a wise comparison, there are 2 reasons firstly hexagon has different dynamics as compared to other shapes because it's not fully symmetrical as opposed to other mentioned shape which are fully symmetrical, secondly defining Reynolds number is also difficult because regular hexagon doesn't have same width along both perpendicular directions.

Here for comparison, we can only use regular figures of side N satisfying $(N\%4 = 0)$.

So (N=4,8,12,16...) can be used as they are completely symmetrical.

5.2.1 Strouhal Number (St)

Strouhal Number defines the frequency of vortex formation, it is a very significant parameter in Unsteady flow cases, Monitoring the strouhal number is critical in cases as if the frequency of vortex shedding matches with the natural frequency of the system then it may cause disastrous effects on the structures, one such example is Tahoma Bridge failure in 1940.

For calculation of Frequency of vortex we track the Lift coefficient in a cycle and find the time of repetation of the cycle, $f = \frac{1}{T}$

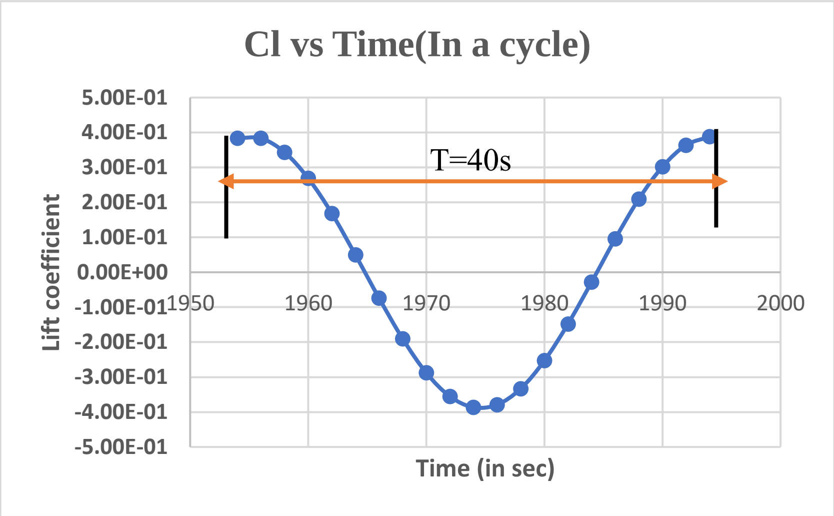


Figure 11: Determining the time period of oscillation for square cylinder

5.2.2 For Near Streamlined Body:

Figure 12 shows for a near streamlined shape for Re=150 we still see a steady profile while for other shaped cylinder, we see an unsteady flow, this may be because of the streamlined shape the initiation of vortex may start at a higher Reynolds number, also we observe a smaller value of Cd=0.27 for this case.

For an Ideal streamlined body the value of the drag coefficient lies even less than 0.1, In racing cars even a 5% improvement in drag coefficient can improve fuel efficiency drastically, so constant efforts are made by leading automobile companies to design the vehicle for better aerodynamic performance.

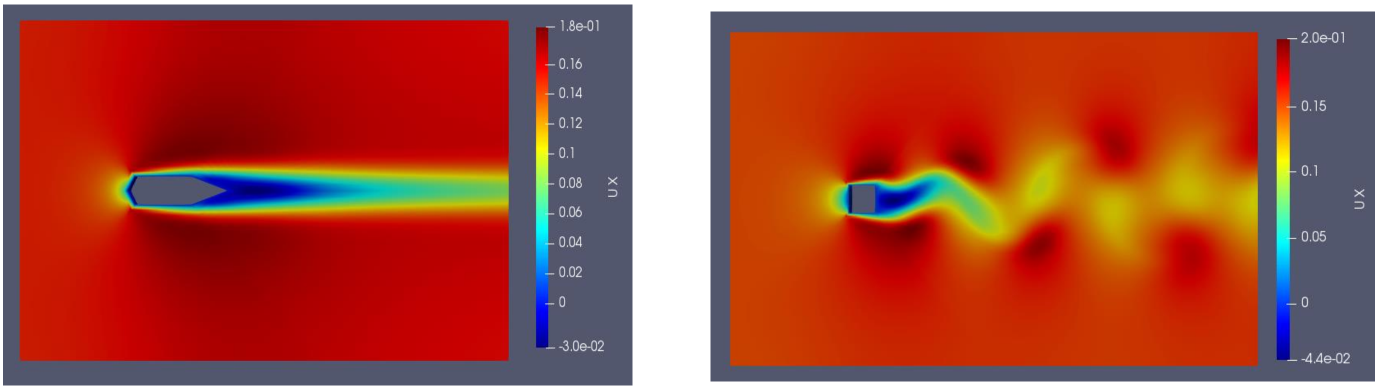


Figure 12: Comparison of velocity contour for a) Near streamline shape b) Square cylinder for Re=150 at t=500s

Figure 13 shows the variation of Cd and we can see that its value is a constant wrt time similar to the steady case, while for other shapes it varies with time periodically as shown in Figure 10.

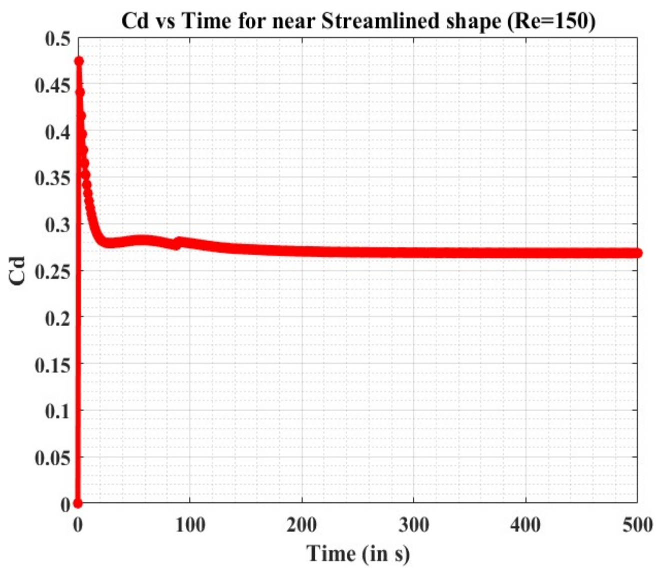
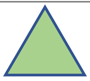
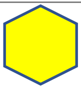
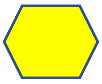
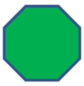
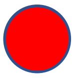


Figure 13: Cd variation with time for near streamlined shape

Table 4: Comparison of Drag and Lift for various shaped cylinders(Re=150)

Sr no	**Cylinder Shape**		**Drag Coefficient(Cd)**	**Lift Coefficient(Cl)**	**Strouhal Number**
1		Triangle 2	2.26	(-0.78,-2.1)	0.175
2		Square	1.53	±0.39	0.167
3		Hexagon 2	1.85	±0.85	0.175
4		Hexagon 1	1.42	±0.48	0.175
5		Octagon	1.48	±0.65	0.185
6		Circle	1.43	±0.54	0.175
7		Near Streamline shape	0.27	-	-

5.3 Variation of Cd with change in Reynolds number

In the previous sections, we looked drag coefficient and related important parameters for the same Reynolds number, here we will change the Reynold number for steady and unsteady cases and compare the variation of Cd with the Reynolds number for mainly 2 shapes square cylinder and circular cylinder.

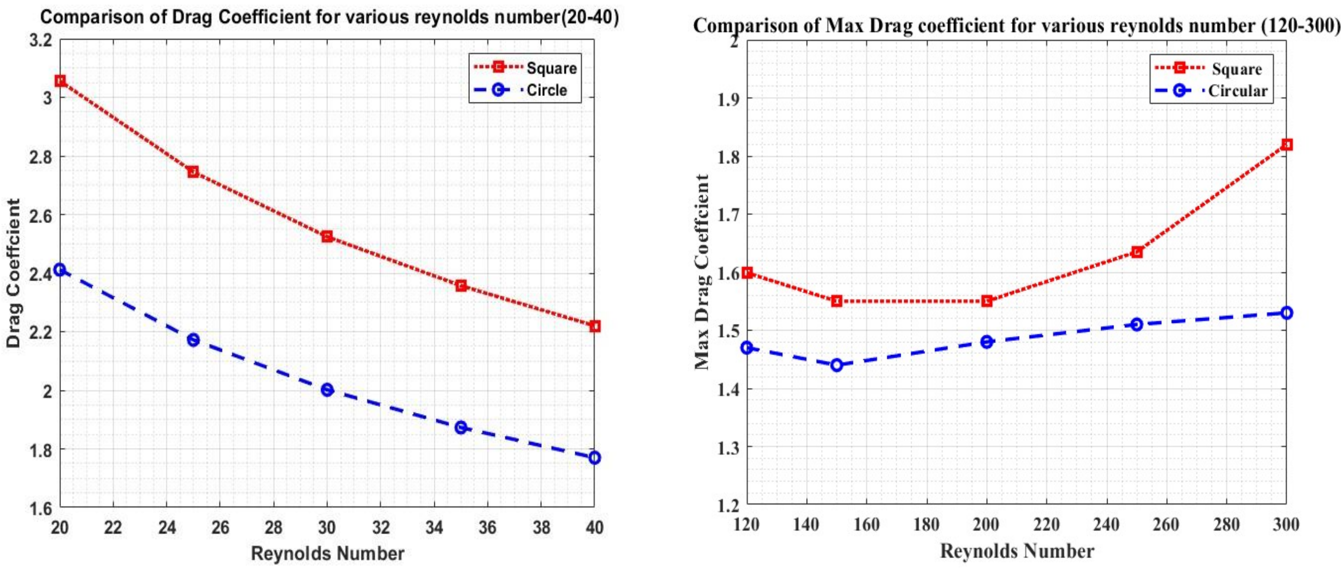


Figure 14: Comparison of maximum Drag coefficient for a square and circular cylinder for a range of Reynolds number a) steady b) unsteady

Figure 14 compares the Cd variation over a range of Reynolds number and we can see that any Reynolds number in the range circular cylinder always has lower drag as compared to that of square cylinder.

Here we can conclude that for a stationary object in a moving flow field circular cylinder is quite better in terms of hydrodynamic performance then a square cylinder.

6. Conclusion and Future Scope:

Flow over cylinder was modelled and analysed for various possible shapes and we have made the following conclusions

1) For the flow of Re<40 we have a steady flow situation and for low Reynolds number the viscous drag dominates, and we observed that on increasing sides of the cylinder, the drag coefficient drops barring a single exception of Hexagon_1, whose surfaces follow path lines of streamlined body.
2) For the unsteady case we looked at Re=150, as the Reynolds number increases the viscous drag dominance tends to decrease and we see a drop in Cd for almost all shapes, Here also we see a dropping nature of drag coefficient as sides increase except Hexagon_2 which is not fully symmetrical as other shapes and here we concluded that a cylinder with N sides satisfying (N%4 =0) can be used for comparisons.
3) A near streamline-shaped cylinder was modelled for both cases and we concluded that in both cases it shows a lower value of drag coefficient as compared to other cylinders.
4) We compared square and circular cylinders for various ranges of Reynolds number and found that circular have always least drag coefficient as compared to square.

This work can be continued as follows,

1) In nature not all flows are laminar, turbulent flows are widely encountered and the present work can be extended for modelling turbulent flows across the above-mentioned cases and the impact of the current work can be elevated.
2) The current work can be extended for a very lower Reynolds number (Re<1) as there significance in biological studies is of great importance.

References:

1) Franke, R., W. Rodi, and B. Schönung. "Numerical calculation of laminar vortex-shedding flow past cylinders." *Journal of Wind Engineering and Industrial Aerodynamics* 35 (1990): 237-257.

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