OpenFoam Based Analysis of Incompressible Flows Over Solid Bodies

Pragya Goyal

pragyathehuman@gmail.com

Abstract— Fluid flow around solid bodies is a common phenomenon in everyday life. The dynamics of external flows are key to understanding the generation of drag and lift forces, which are essential for enhancing the performance and efficiency of various engineering systems. This study focuses on incompressible, steady, and laminar fluid flow over three geometries: a circular cylinder, a square cylinder, and a thin flat plate. The objective is to investigate how changes in velocity and viscosity influence the resulting drag and lift forces. Numerical simulations were performed using OpenFOAM. The results were analysed for different Reynolds numbers, and the changes in drag and lift were compared across conditions.

In bluff bodies, pressure forces dominate over viscous forces. As a result, drag is primarily due to pressure differences, while the contribution from viscous forces is minimal. Lift, however, arises from pressure differences between the upper and lower surfaces due to flow asymmetry. Therefore, changes in fluid viscosity have a minor effect on drag but can significantly impact lift due to changes in the flow structures in the upper and lower surface of the bodies.

In contrast, streamlined bodies experience minimal pressure differences. For these geometries, drag is mainly caused by viscous shear, and changes in viscosity have a direct and substantial effect on drag. The influence on lift, however, is smaller due to the reduced role of pressure variations.

Keywords— Incompressible, Steady, Flow over a cylinder, Drag force, Lift Force, Flow over a flat plate

I. INTRODUCTION

One of the fundamental aspects of external fluid flow is the generation of aerodynamic forces, such as drag and lift, which result from pressure gradients and viscous shear stresses acting on the body surface. These forces are governed by various parameters, including the shape and orientation of the body, the freestream velocity and viscosity of the fluid, and its density.

Given the complexity and diversity of flow configurations, it is often impractical to tabulate drag and lift forces for every possible scenario. Instead, the use of dimensionless coefficients, such as the drag coefficient (CD) and lift coefficient (CL), offers a more generalized and scalable approach to characterize the aerodynamic performance of bodies across a wide range of flow conditions.

Therefore, this study focuses on the investigation of drag and lift forces, along with their corresponding dimensionless coefficients, under varying flow conditions such as velocity, and viscosity. This investigation further aims to analyse how flow behaviour differs between different geometries.

This paper focuses on simulating the flow of an incompressible, steady and laminar fluid over three distinct geometries: a circular and square cross-sectional cylinder, and a thin plate. These specific geometries have been chosen because they are fundamental shapes in the engineering industry. It is thus essential to know the drag and lift forces that arise when a fluid is flown over them.

Several studies have explored the behaviour of steady, incompressible flow over bluff bodies such as circular and square cylinders. These studies include those by Arthur G et al. (2000) and Kornbleuth (2016). They have simulated flow over the mentioned geometries and established benchmark data for drag and lift.

The structure of this paper is as follows: Section 3 outlines the key concepts relevant to the present study. Section 4 presents the governing equations solved using the OpenFOAM solver. Section 5 details the methodology employed. In Section 6, the results obtained under various flow conditions are discussed. Finally, Section 7 summarizes the main findings and concludes the study.

II. KEY CONCEPTS: EXPLANATIONS AND DEFINITIONS

Incompressibility: A fluid is considered incompressible if its density remains nearly constant throughout the flow.

Reynolds Number: A dimensionless number that predicts flow behaviour based on the ratio of inertial forces to viscous forces in a fluid.

Laminar Flow: When the Reynolds number (Re) is below a critical value, indicating that viscous forces dominate over inertial forces, leading to smooth, orderly fluid motion.

Stress: Force per unit area and is determined by dividing the force by the area upon which it acts.

Pressure: In a fluid at rest, normal component of a force acting on a surface per unit area or the normal stress

Viscosity: It is a fundamental property of fluids that measure the internal resistance to deformation or flow. Physically, it represents the fluid's resistance to shear or angular momentum transfer between adjacent fluid layers.

No-Slip Condition: Due to viscosity, the layer of fluid in direct contact with a stationary surface adheres to it and has zero velocity relative to the surface.

Boundary Layer: The thin region near a solid surface where viscous effects are significant and velocity changes rapidly from zero (at the wall) to the free stream value.

Drag Force: The resistance force exerted by a fluid (like air or water) on an object moving through it, opposing the motion. The drag force is due to the combined effects of wall shear and pressure forces. The wall shear force is called the friction drag. It is a strong function of viscosity. The pressure force is called the pressure drag.

Lift Force: The force generated by the fluid flow over a surface that acts perpendicular to the direction of motion or the drag force.

Flow over a bluff body leads to the formation of a wake region characterized by vortex shedding. This phenomenon causes asymmetry in the pressure distribution—both vertically and horizontally. The pressure difference between the top and bottom surfaces of the body generates lift, while the pressure difference between the front and rear (upstream and downstream) sides of the body contributes to drag.

Drag Coefficient: A dimensionless number that quantifies the amount of drag an object experiences relative to its shape and flow conditions.

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A} \tag{1}$$

Where F_D is the drag force, ρ is the density, V is the velocity and A is the area of the surface which is in contact with the fluid.

As the fluid is incompressible, the density remains constant and is thus taken to be 1.

Lift Coefficient: A dimensionless number that measures the lift generated by a body compared to the fluid density and velocity.

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A} \tag{2}$$

Where F_L is the lift force, ρ is the density, V is the velocity and A is the area of the surface which is in contact with the fluid.

As the fluid is incompressible, the density remains constant and is thus taken to be 1.

Bluff Bodies: Bodies with blunt rears. These bodies experience higher drag due to pressure forces than drag due to viscous forces

Streamlined Bodies: Bodies that experience higher drag due to viscous forces than drag due to pressure forces.

III. GOVERNING EQUATIONS

The Navies Strokes or the Governing Equations consists of mainly two equations-

- Conservation of Mass
- Conservation of Momentum

The study focuses on two-dimensional flow behaviour specifically the x and y direction. It focuses on the x-direction because the flow of the fluid and thus the forces are along the x-direction. Since the lift force acts perpendicular to the motion of the fluid, the y-direction also needs to be considered.

The z-direction components were excluded from the analysis.

A. Conservation of Mass

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{3}$$

Where u, v, w are the velocity components in the x, y and z direction. As this paper focuses on two-dimensional fluid flows, the above equation can be written as follows.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{4}$$

The rate of increase of mass inside a small fluid element plus the net rate at which mass flows out of it is zero. The mass is conserved and there is no expansion or compression in the fluid

Any change in mass within a fluid element must be balanced by the net mass flow across its boundaries. If more mass enters than leaves, the mass inside increases, and vice versa. In steady, incompressible flow, this balance ensures that the total mass remains constant over time.

B. Conservation of Momentum

The conservation of momentum follows the principle of

Force = Rate of change of momentum

x-momentum (u-component)

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \frac{-\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \rho f_x \tag{5}$$

Where $\rho$is the density and $\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right)$ is the x component of the fluid acceleration. Their product gives the force per unit volume. This has been done because mass is not directly used for fluids.

On the right-hand side of the equation, $\frac{-\partial p}{\partial x}$ represents the pressure gradient where p is the pressure. $\mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$ represents the viscosity of the fluid and accounts for the internal friction between the fluid layers. ρf_x represents the body or the external force in the x-direction.

y-momentum (v-component)

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = \frac{-\partial p}{\partial x} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \rho f_y \tag{6}$$

Where $\rho$is the density and $\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right)$ is the y component of the fluid acceleration. On the right-hand side of the equation, $\frac{-\partial p}{\partial x}$ represents the pressure gradient where p is the pressure. $\mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)$ represents the viscosity of the fluid. ρf_y represents the body or the external force in the y-direction.

In this study, ρf_x and ρf_y are assumed to be zero, as there are no external forces acting on the fluid. Additionally, since the flow is considered steady, the time derivatives $\frac{\partial u}{\partial t}$ and $\frac{\partial v}{\partial t}$ are also zero, since the fluid properties do not change with time at any point in the domain.

IV. METHODOLOGY

A. Initial Conditions

Start Time --> 0
End Time --> 30000
Time Intervals --> 100
The fluid taken for this study is air.

TABLE I
SUMMARY OF SIMULATION CASES SHOWING SHAPE, DOMAIN SETUP, FLOW CONDITIONS, AND CORRESPONDING REYNOLDS NUMBERS FOR EACH GEOMETRY

Case	**Shape**	**Domain Setup**	**Velocity (m/s)**	**Kinematic Viscosity (m2/s)**	**Reynolds Number**
Case A_1	Circular Cylinder	Diameter of 0.05m	0.054	1.5e-05	180
Case B_1	Circular Cylinder	Diameter of 0.05m	0.054	7.5e-06	360
Case C_1	Circular Cylinder	Diameter of 0.05m	0.216	1.5e-05	720
Case D_1	Circular Cylinder	Diameter of 0.05m	0.054	2.7e-08	1.0e+05

Case	Shape	Domain Setup	Velocity (m/s)	Kinematic Viscosity (m2/s)	Reynolds Number
Case E_1	Circular Cylinder	Diameter of 0.05m	30.0	3.0e-05	0.5e+05
Case F_1	Circular Cylinder	Diameter of 0.05m	30.0	1.5e-05	1.0e+05
Case G_1	Square Cylinder	Side length of 0.05m	0.054	1.5e-05	180
Case A_2	Flat plate	Length of 1.0m	0.054	7.5e-05	720
Case B_2	Flat plate	Length of 1.0m	0.054	3.75e-05	1440
Case C_2	Flat plate	Length of 1.0m	0.216	7.5e-05	2880
Case D_2	Flat plate	Length of 1.0m	0.054	1.80e-06	5.0e+04
Case E_2	Flat plate	Length of 1.0m	3.75	1.5e-04	2.5e+04
Case F_2	Flat plate	Length of 1.0m	3.75	7.5e-05	5.0e+04

C. *Control Dict File*

```
/*--------------------------------*- C++ -*----------------------------------*\
| =========                |                                                   |
| \\      /  F ield        | foam-extend: Open Source CFD                     |
|  \\    /   O peration    | Version:     4.0                                 |
|   \\  /    A nd          | Web:         http://www.foam-extend.org          |
|    \\/     M anipulation |                                                   |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "system";
    object      controlDict;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

application     simpleFoam;

startFrom       startTime;

startTime       20000;

stopAt          endTime;

endTime         30000;

deltaT          1;

writeControl    timeStep;

writeInterval   100;

purgeWrite      0;

writeFormat     ascii;

writePrecision  6;

writeCompression compressed;

timeFormat      general;

timePrecision   6;

runTimeModifiable yes;
```

```
functions
{
    forces
    {
        type        forces;
        functionObjectLibs ("libforces.so");
        outputControl timeStep;
        outputInterval 100;
        patches     (obstacle);   // name of the patch representing the cylinder
        rho         rhoInf;
        rhoInf      1.0;          // freestream density (or use actual value)
        CofR        (0 0 0);      // center of rotation, usually cylinder center
    }
}

// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //
```

D. Meshing

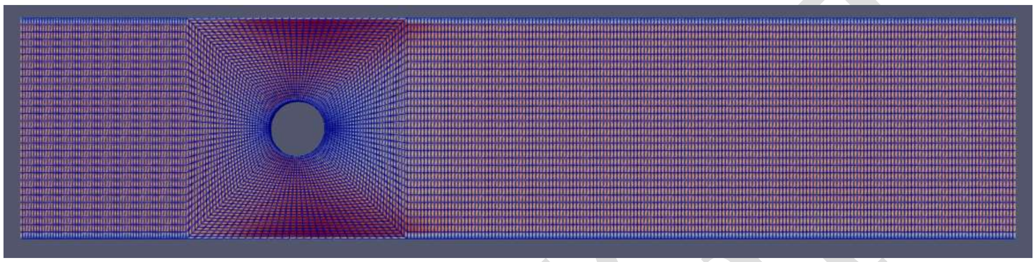


Figure 1: Meshing of the circular cylinder

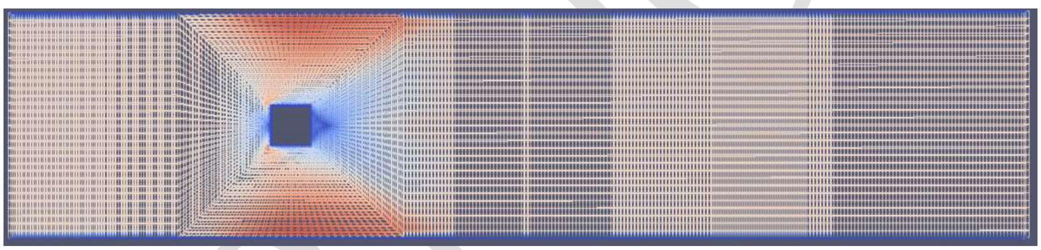


Figure 2: Meshing of the square cylinder

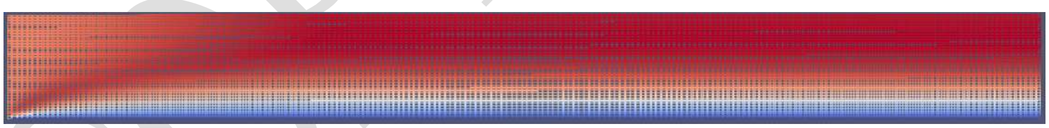


Figure 3: Meshing of the flat plate

E. Assumptions

The fluid flow considered in this study is characterized as incompressible, steady, and laminar. This means that the fluid density remains constant throughout the domain (incompressible), the flow properties at any point do not change with time (steady), and the motion of the fluid is smooth and orderly, without turbulence or chaotic mixing (laminar). These assumptions simplify the governing equations, making them suitable for accurately analysing the effects of shape, velocity, and viscosity on drag and lift forces

F. Solver

The simulations are carried out using simpleFOAM, a finite volume-based solver available in the OpenFOAM framework. This solver is primarily designed for steady-state, incompressible turbulent flows by solving the Reynolds-Averaged Navier–Stokes (RANS) equations. However, in the present study, the turbulence model was disabled in the solver settings to simulate laminar flow conditions.

In the absence of turbulence modelling, the solver solves for the pressure and velocity fields by iteratively solving the incompressible Navier–Stokes and continuity equations, capturing the laminar flow behaviour accurately.

The boundary conditions define how the fluid behaves at the edges of the domain. The inlet and outlet specify how the fluid enters and exits the domain respectively. The wall specifies how the fluid behaves at the surface of the solid. For this study, the boundary conditions are as follows-

- Inlet --> fixed velocity, zero pressure gradient
- Outlet --> zero pressure gradient, zero velocity gradient.
- Walls -->no-slip velocity condition, zero pressure gradient.

G. *Post-Processing*

ParaView was utilized for post-processing and visualization of the simulated fluid flow fields.

Case A1

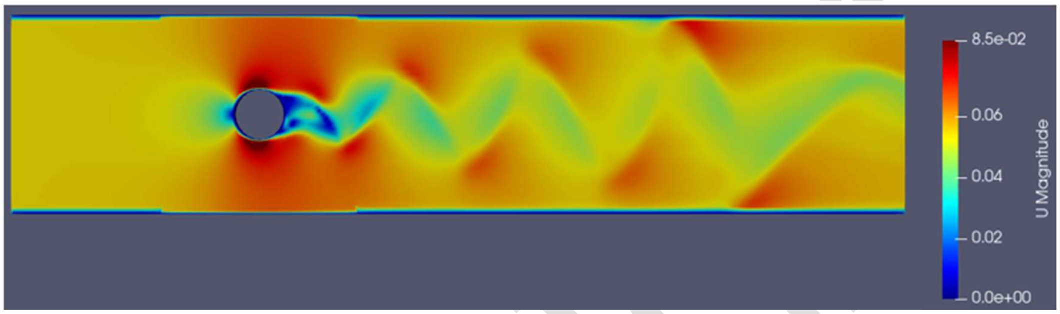


Figure 4: Velocity magnitude contour plot of flow over circular cylinder with velocity 0.054m/s and viscosity 1.5e-05m2/s

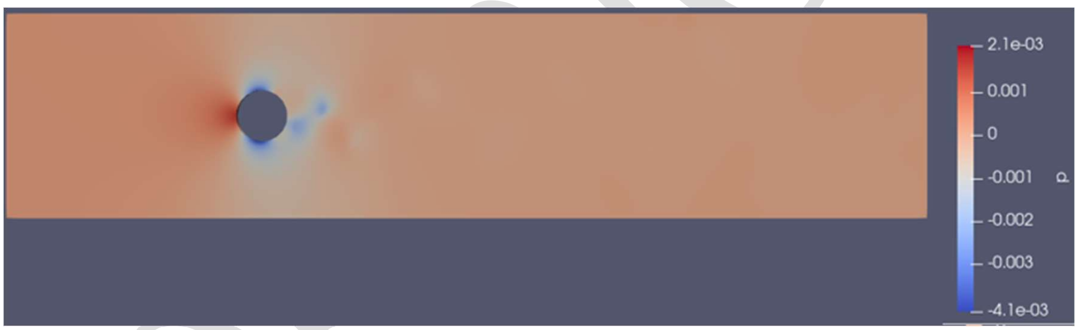


Figure 5: Pressure contour plot of flow over circular cylinder with velocity 0.054m/s and viscosity 1.5e-05m2/s

Case G1

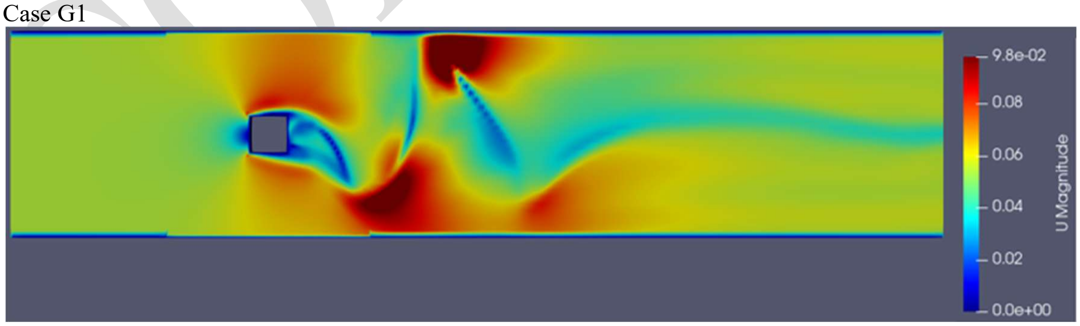


Figure 6: Velocity magnitude contour plot of flow over square cylinder with velocity 0.054m/s and kinematic viscosity 1.5e-05m2/s

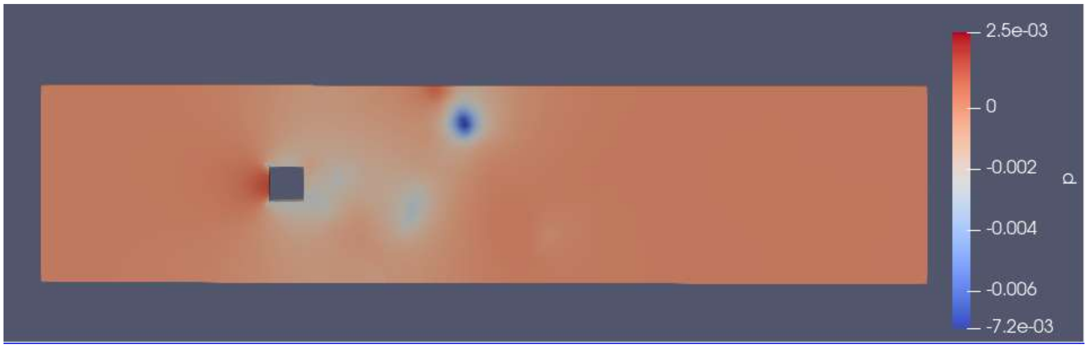


Figure 7: Pressure contour plot of flow over square cylinder with velocity 0.054m/s and viscosity 1.5e-05m2/s

Case A2

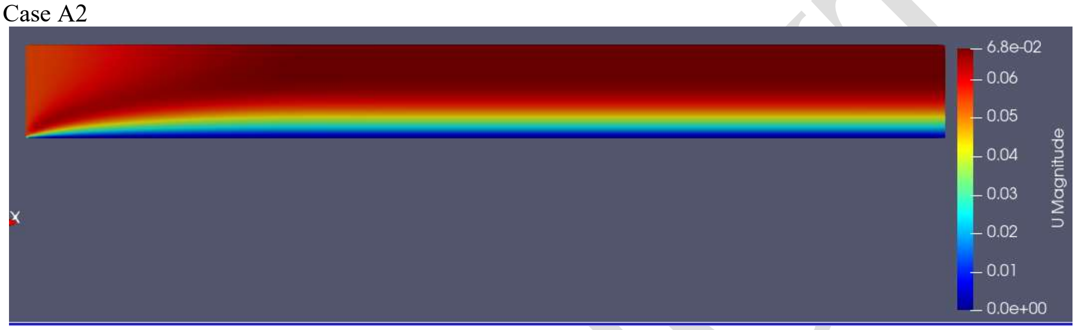


Figure 8: Velocity magnitude contour plot of flow over flat plate with velocity 0.054m/s and viscosity 1.5e-05m2/s

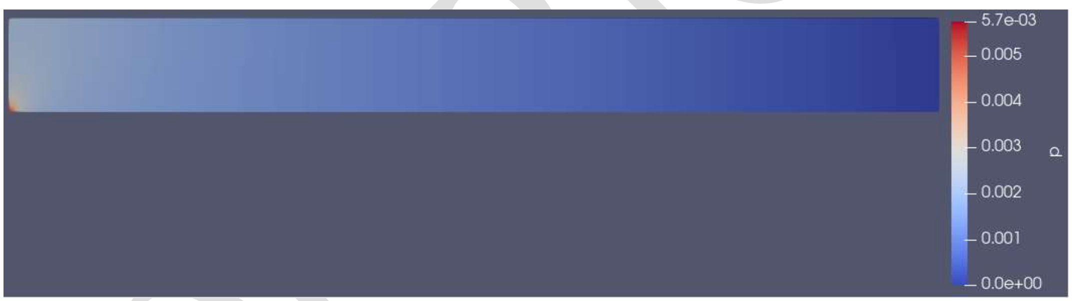


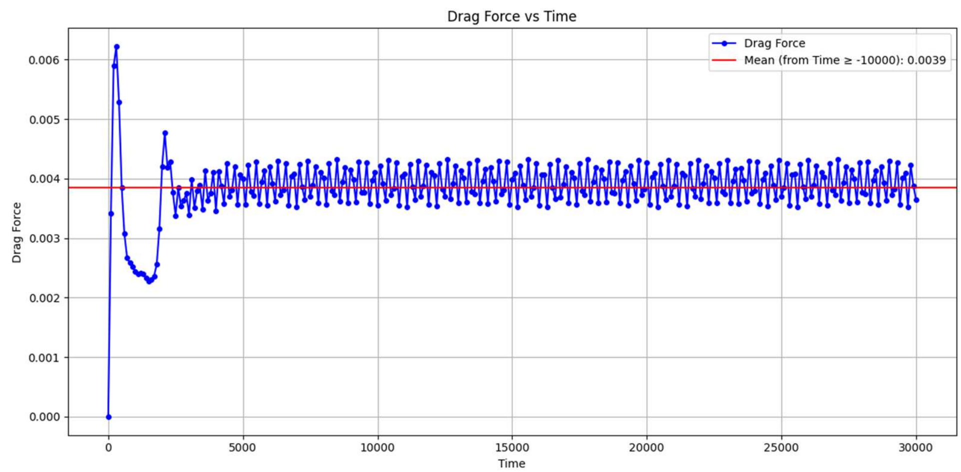
Figure 9: Velocity magnitude contour plot of flow over flat plate with velocity 0.054m/s and viscosity 1.5e-05m2/s

To analyse the forces acting on the geometries, a force output file was generated during the simulation. This file contained the pressure and viscous force components in the x, y, and z directions.

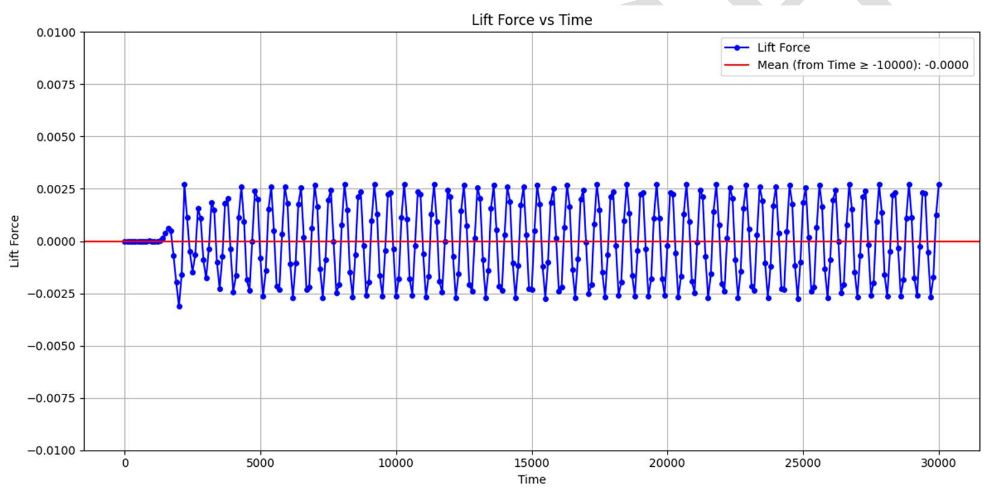
The data were extracted at fixed time intervals throughout the simulation. This made it possible to track how drag and lift forces changed under different flow conditions.

To ensure the simulation had reached a steady state, the time history of drag and lift forces and their coefficients were plotted for case B1. A mean value line was added to each graph to check for stability. Small fluctuations around the mean indicated a steady solution. A similar procedure was followed for all other cases to ensure steady-state conditions were attained.

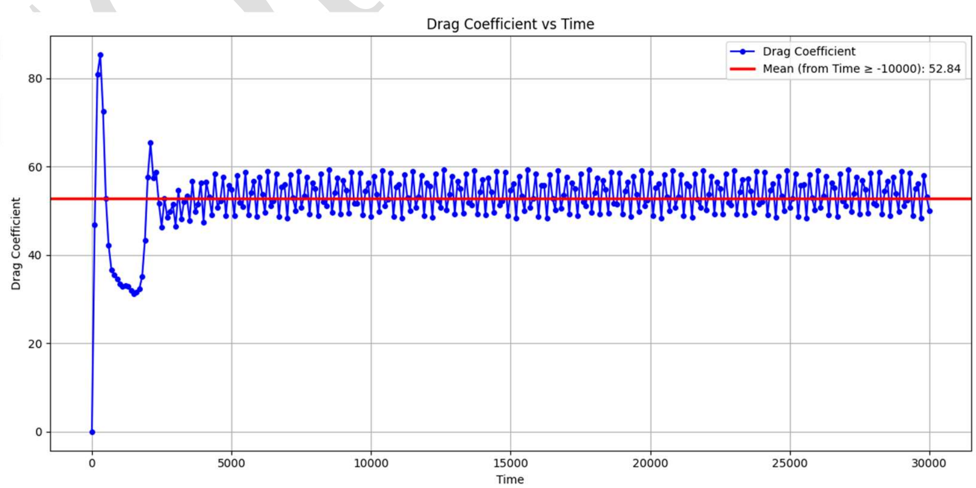
In a steady-state simulation, the values of drag, lift, and their coefficients should stay relatively constant, or closely follow the mean line.



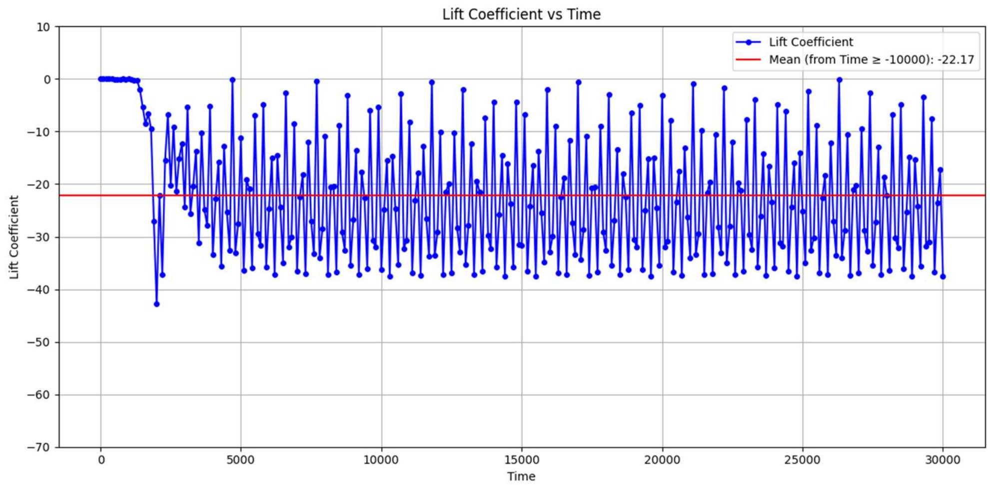
Graph 1: Variation of drag forces over time along with the mean value for flow over circular cylinder with velocity 0.054m/s and viscosity 1.5e-05m2/s



Graph 2: Variation of lift forces over time along with the mean value for flow over circular cylinder with velocity 0.054m/s and viscosity 1.5e-05m2/s



Graph 3: Variation of drag coefficient over time along with the mean value for flow over circular cylinder with velocity 0.054m/s and viscosity 1.5e-05m2/s



Graph 4: Variation of lift coefficients over time only with the mean value for flow over circular cylinder with velocity 0.054m/s and viscosity 1.5e-05m2/s

V. Results

TABLE 2

PERCENTAGE CHANGES IN DRAG AND LIFT FORCE VALUES AND THEIR COEFFICIENTS ACROSS DIFFERENT FLOW CONDITIONS AND GEOMETRIES, ALONG WITH CORRESPONDING REYNOLDS NUMBERS.

Cases	Percentage Change in Drag Force	Percentage Change in Drag Coefficient	Percentage Change in Lift Force	Percentage Change in Lift Coefficient
Case A_1 and B_1	0.72%	0.7147%	38.35%	38.34%
Case A_1 and C_1	1405.83%	-5.891%	1468.63%	-2.018%
Case E_1 and F_1	10.13%	10.10%	16.40%	16.42%
Case A_1 and G_1	126.7%	126.8%	-62.69%	-62.69%
Case A_1 and A_2	-99.95%	-100%	-99.51%	-99.98%
Case A_2 and B_2	-41.36%	-41.36%	-36.01%	-36.02%
Case A_2 and C_2	468.1%	-64.5%	574.1%	-57.86%
Case E_2 and F_2	-33.51%	-33.51%	-28.76%	-28.76%

For the circular cylinder cases, where only velocity and viscosity were varied, the drag coefficients remained nearly constant. This suggests that for bluff bodies, the drag coefficient remains approximately constant within certain Reynolds number ranges, until significant changes occur in the overall flow characteristics.

When the velocity was increased by four times, the drag force increased by approximately 16 times. This matches the expected relationship from the drag equation. For example, in the simulation, increasing velocity from 0.054 m/s to 0.216 m/s resulted in the drag force rising 14.05 times.

In contrast, for streamlined bodies like the flat plate, the drag coefficient decreases with increasing Reynolds number. As a result, even when velocity is quadrupled, the drag force does not increase by 16 times. This is because the drop in the drag coefficient partially offsets the effect of increased velocity. Hence, in the simulation results, when the velocity was changed from 0.054m/s to 0.216m/s, the drag force increased by only 468.1%.

A. *Bluff Bodies*

In bluff bodies, drag is dominated by pressure differences due to flow separation, with minimal contribution from viscous shear forces. When viscosity was halved, the Reynolds number increased, potentially altering the flow separation behaviour slightly. This caused only a minor increase in drag (0.72%) but a more noticeable increase in lift (38.35%), likely due to enhanced asymmetry in the wake structure.

In contrast, when the velocity was quadrupled, the Reynolds number increased, delaying flow separation. This led to a greater contribution from viscous forces to the total drag. As a result, the drag force increased dramatically due to a combined rise in both pressure and viscous drag. This is evident from the simulation, where the drag force rose by 1405.83% in the velocity-change case, compared to just 0.72% for the viscosity-change case.

Since Reynolds number is inversely proportional to viscosity, lowering viscosity raises the Reynolds number. At higher Reynolds numbers, pressure forces dominate, and the effect of viscosity becomes less significant.

Therefore, changes in viscosity have a smaller impact on lift. This is confirmed by the simulation, where the lift increased by only 16% in the high Reynolds number case.

These results suggest that at low Reynolds numbers, lift in bluff body flows can be sensitive to changes in viscosity due to its influence on wake asymmetry. In contrast, the drag force remains relatively stable with respect to viscosity changes, as it is predominantly governed by pressure separation, which is less sensitive to viscosity at these Reynolds numbers.

B. Streamlined Bodies

In streamlined bodies like flat plates, viscous shear is the primary contributor to drag, especially at low Reynolds numbers where flow remains attached. Simulation results support this: when viscosity was reduced, the drag force decreased by 41.36%, while the lift force dropped by 36.01%, indicating that drag is more sensitive to viscosity in such configurations. Since flat plates aligned with the flow produce minimal pressure-induced lift, lift is less influenced by changes in viscosity.

The role of the Reynolds number is critical in explaining this behaviour. At low Reynolds numbers, viscous effects dominate, so changing viscosity significantly alters drag. As observed, the drag reduction due to decreased viscosity was larger (41.36%) at low Re compared to just 33.51% at high Re, consistent with theoretical expectations. At high Re, pressure forces grow in influence, and the sensitivity of drag to viscosity diminishes.

Additionally, for both bluff and streamlined bodies, the drag and lift coefficients are computed by normalizing the forces with ρU2. When viscosity is altered, the denominator remains constant, so any change in the coefficient reflects a direct change in the force. Thus, changes in force and coefficients show similar trends. On the other hand, increasing velocity affects both the numerator and denominator. Since force often doesn't grow as fast as U2, the net effect is a decrease in the drag and lift coefficients, even when the raw forces increase. This trend is observed in the simulations.

VI. CONCLUSION

For bluff bodies, the drag and lift coefficients remained nearly constant when only flow conditions—such as velocity and viscosity were changed. This indicates that, within a certain Reynolds number range, these coefficients are primarily governed by geometry rather than by flow parameters. Notably, when velocity was increased by a factor of four, the drag and lift forces rose by approximately 15 times, which closely aligns with the quadratic dependence on velocity predicted by the drag equation. This confirms that, when coefficients remain unchanged, drag and lift forces scale with the square of velocity.

Interestingly, when viscosity was changed, the lift force varied more significantly than the drag force in bluff bodies, particularly at lower Reynolds numbers. This likely results from changes in the vortex shedding behaviour, which influence asymmetries in pressure distribution and thus lift.

In contrast, for streamlined bodies, the drag and lift coefficients showed noticeable variation with Reynolds number even when the geometry was held constant. This is because boundary layer behaviour and flow separation are highly sensitive to Reynolds number. As a result, the drag and lift forces did not scale simply with velocity, and the expected quadratic increase was moderated by changes in the coefficients. For these bodies, changes in viscosity had a stronger effect on drag than on lift, especially at low Reynolds numbers where viscous shear dominates.

Modifying the geometry produced measurable but modest changes in the drag and lift forces and their corresponding coefficients. Among the geometries studied, the flat plate generated the lowest drag and lift, consistent with its streamlined profile and minimal pressure variation.

While drag and lift coefficients are dimensionless, they are not strictly independent of flow parameters. Instead, they are functions of the Reynolds number (and Mach number in compressible flow), which encapsulate the effects of velocity, viscosity, and density. Therefore, changes in these flow parameters alter the flow structure such as separation point and pressure distribution, which may change the drag and lift coefficients. This explains the observed variation in the coefficients despite their theoretical non-dimensional formulation.

REFERENCES

[1] Xu, Zhun, Shiqiang Wu, Xiufeng Wu, Wanyun Xue, Fangfang Wang, Ang Gao, and Weile Zhang. 2023. *Analysis of Flow Characteristics around a Square Cylinder with Boundary Constraint*, *Water* 15, no. 8: 1507. Available: https://doi.org/10.3390/w15081507

[2] Kornbleuth, Josh. 2016, *Flow Around a Circular Cylinder: A CFD Study with OpenFOAM*, Boston University, Undergraduate Fluid Mechanics and Aerodynamics Laboratory. Available: https://www.bu.edu/ufmal/files/2016/12/Kornbleuth_FlowAroundCylinder.pdf

[3] Arthur G. Kravchenko, Parviz Moin. 2000, *Numerical studies of flow over a circular cylinder at R_D=3900*, Department of Mechanical Engineering, Stanford University, Stanford, California 94305. Available:

https://pubs.aip.org/aip/pof/article-abstract/12/2/403/254179/Numerical-studies-of-flow-over-a-circular-cylinder?redirectedFrom=fulltext

[4] Yunus A. Cengel, John M. Cimbala. *Fluid Mechanics: Fundamentals and Applications*, Fourth Edition, Mc Graw Hill Education, 2018.

[5] Asmaa Hadane, *OpenFOAM Tutorial: Simulation of the flow around a cylinder,* Youtube Video 34:32, 2 Feb, 2021. Available: https://youtu.be/Udt3RhkbgKw?si=W60KiY0brzKUwIcH