# Drag Force Measurement for External Flow Over Objects

## ME 207: Fluid Dynamics

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# Contents

# 1 Objectives

The objective of this report is to present a comprehensive analysis of drag force measurement over a circular cylinder conducted in a wind tunnel experiment. This study aimed to characterize the drag force exerted on the cylinder by establishing the velocity profile around the cylinder and subsequently using it to calculate the drag force. The report outlines the experimental setup, methodology, data acquisition process, calculations used, and the findings obtained. Specifically, the report aims to contribute valuable data towards understanding the velocity profile around the cylinder and determining the drag coefficient under various flow conditions. By providing detailed insights into the velocity distribution and drag force characteristics, this report seeks to offer essential information for further research in fluid dynamics and engineering applications involving cylindrical structures.

# 2 Theoretical Discussion / Calculations.

For the proposed experiment, a two-dimensional planar control volume (CV) is under consideration. It is important to note that the shape of the CV cannot be a standard rectangle due to the inherent imbalance in mass flow rates—specifically, the mass flow rate outside does not equate to that inside the control volume. Consequently, adjustments are necessary, leading to asymmetrical dimensions where the left side of the CV differs from the right side to compensate the mass flow rates.

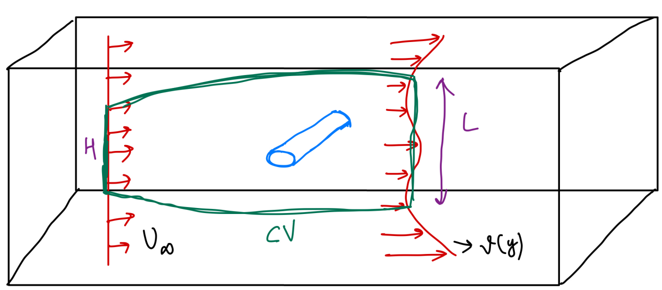



Figure 1: Control Volume selection.

To determine the drag force acting on a cylinder, we initially derived the velocity profile surrounding the cylinder. Subsequently, we conducted integral control volume analysis based on this velocity profile. Then to solve the integral equation we employed the Trapezoidal Rule of Integration to solve this numerically. Below are the mass flow rates at the inlet and outlet of the CV;

$$\dot{m}_{in} = \rho U_\infty H W$$
$$\dot{m}_{out} = \int \rho U(y) W dy$$

Where;

$U_\infty$ is velocity of the wind tunnel,

U(y) is the velocity profile at the outlet,

W is the width of our test section,

H is the length we are taking at left to compensate the mass flow rates,

$\rho$ is density of air

Using Mass conservation we get;

$$\dot{m}_{in} = \dot{m}_{out}$$

$$U_\infty H = \int U(y) dy$$
$$H = \frac{\int U(y) dy}{U_\infty}$$

Writing Momentum Equation

$$\dot{M}_{in} = \rho {U_\infty}^2 H W$$
$$\dot{m}_{out} = \int \rho U(y)^2 W dy$$

Substituting H in Momentum equation

$$\dot{M}_{in} = \rho W U_\infty \int U(y) dy$$

$$\text{Drag Force} = \dot{M}_{out} - \dot{M}_{in}$$
$$\text{Drag Force} = \int \rho U(y)^2 W dy - \int \rho W U_\infty (y) dy$$
$$\text{Drag Force} = \rho W \int U(y)(U(y) - U_\infty) dy$$

We will be solving the above integral equation with the help of trapezoidal method,

$$F_D \approx \rho \cdot W \cdot \sum_{i=1}^{n-1} \frac{(U(y_i) + U(y_{i+1}))}{2} \cdot [U(y_i) - U_\infty] \cdot \Delta y_i$$

After we have $F_D$, We will compute $C_D$ using;

$$C_D = \frac{2F_D}{\rho U_\infty^2}$$

# 3 Experimental Setup

The experimental setup is designed to measure the velocity profile of airflow within the test section of a wind tunnel. This setup is essential for understanding the distribution of velocities across different sections of the airflow, providing valuable insights ifor our calculations.

- **Test Section:** Within the wind tunnel, the test section is where the actual experimentation takes place. It is equipped with strategically placed holes at equidistant positions along the cross-section. These holes allow for the insertion of pitot tubes for measuring the local velocity at various points within the airflow.

- **Pitot Tube:** A pitot tube is employed to measure the velocity of the airflow at specific locations within the test section. This device consists of a slender tube with one opening facing the airflow and another opening perpendicular to the flow direction. By measuring the pressure difference between these two openings, the velocity of the airflow can be accurately determined.

- **Micro-Manometer:** To quantify the pressure difference and velocity sensed by the pitot tube, a manometer is utilized. The manometer provides a visual indication of the pressure difference and velocity.

- **Height Gauge:** A height gauge is employed to precisely adjust the position within the test section where velocity measurements are to be taken.

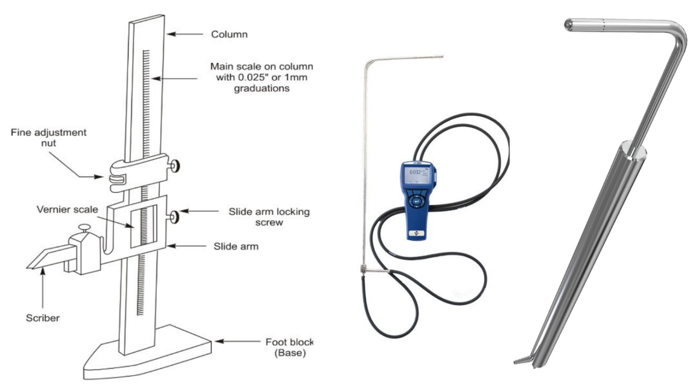
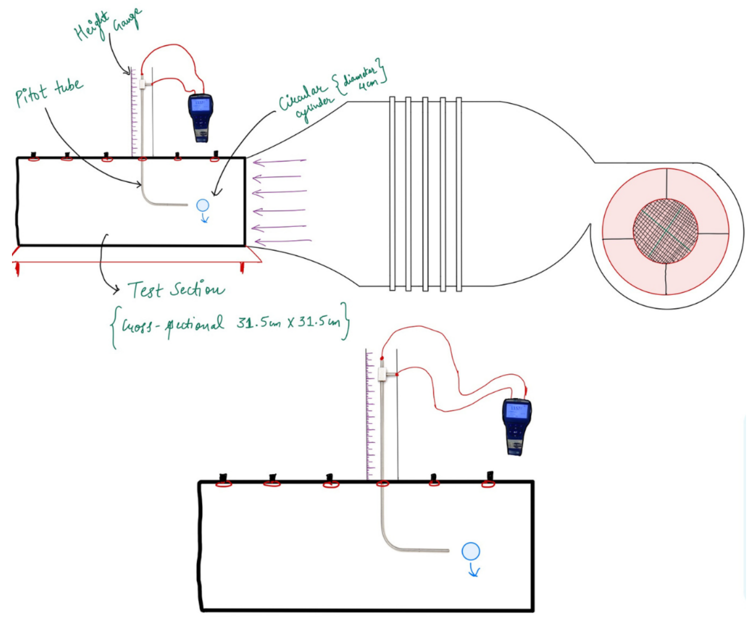



Figure 2: Pitot tube, Height Gauge and Micro-mano Meter




(a) Schematic of Experimental setup


(b) Real Experimental setup

# 4 Experimental Procedure

The experiment was conducted in the outreach lab utilizing a micromanometer for precise measurements of velocity and pressure differences. The setup involved the utilization of a pre-existing configuration (test section) affixed to the entrance of the wind tunnel. A cylindrical object matching the exact dimensions (length) of the wind tunnel's entrance was inserted into this test section.

Upon activation of the wind tunnel, the velocity profile was systematically determined. To ensure accuracy in the velocity profile measurements, the pitot tube was incrementally lowered in small increments (2mm step size) to capture data at various depths within the airflow. Maintaining symmetry, velocity values were computed for the upper half of the cylinder's axis while a representative subset of values was gathered for the lower half.

This methodology facilitated the comprehensive calculation of the velocity profile, which is crucial for the subsequent analysis and calculation of drag force. We have ignored the boundary regions to avoid any errors.

**Assumptions** :
1) The velocity profile is assumed to exhibit symmetry about the axis of the cylindrical object, allowing for representative measurements to be taken on both the upper and lower halves.
2) We ignored the boundary regions to avoid any errors.
3) It is assumed that the micromanometer and pitot tube used for velocity and pressure measurements are calibrated and accurate within the desired range of measurements.
4) The presence of the pitot tube within the airflow is assumed to have minimal impact on the velocity profile and overall flow patterns.

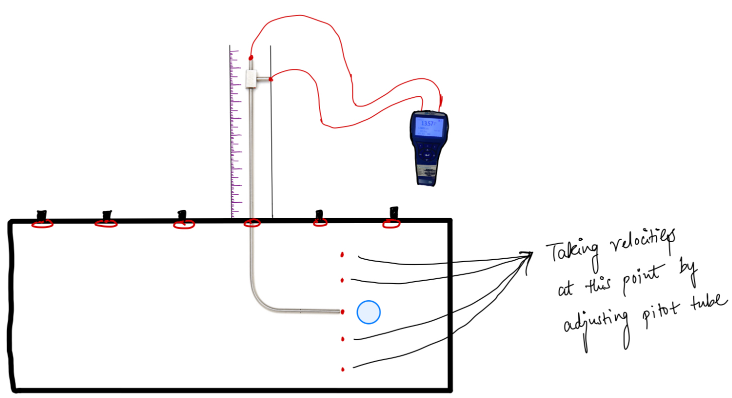



Figure 4: Procedure

# 5 Readings

The wind tunnel is activated during experimentation to generate a steady airflow within the test section. The pitot tube is then inserted into the designated holes, and pressure differentials are recorded using the manometer at various heights along the cross-section. A comprehensive velocity profile of the airflow is established by systematically adjusting the height gauge and repeating the measurements.

Table 1: Velocity points at different positions

| Velocity(in m/s) | Position |
|---|---|
| 2.2 | 0 |
| 2.2 | 1 |
| 2.76 | 2 |
| 3.465 | 3 |
| 4.085 | 4 |
| 4.615 | 5.1 |
| 4.705 | 6.1 |
| 5.005 | 7.1 |
| 5.385 | 7.6 |
| 5.62 | 8.1 |
| 6.11 | 8.6 |
| 6.415 | 8.85 |
| 6.81 | 9.1 |
| 7.11 | 9.3 |
| 7.4 | 9.5 |
| 7.56 | 9.7 |
| 7.58 | 9.9 |
| 7.6 | 10.1 |
| 7.6 | 10.4 |
| 7.65 | 10.7 |
| 7.66 | 11.1 |
| 7.7 | 11.5 |

In further **Results** section, we have used this reading to get our plots.

# 6 Results

In the experimental setup, velocity measurements were conducted at various positions within a designated plane in the test section. These measurements facilitated the construction of a velocity profile, showcasing the distribution of velocities across the examined area. The recorded readings from this velocity profile served as foundational data for subsequent calculations. Utilizing the established velocity profile, the Drag Force and Drag Coefficient were computed.

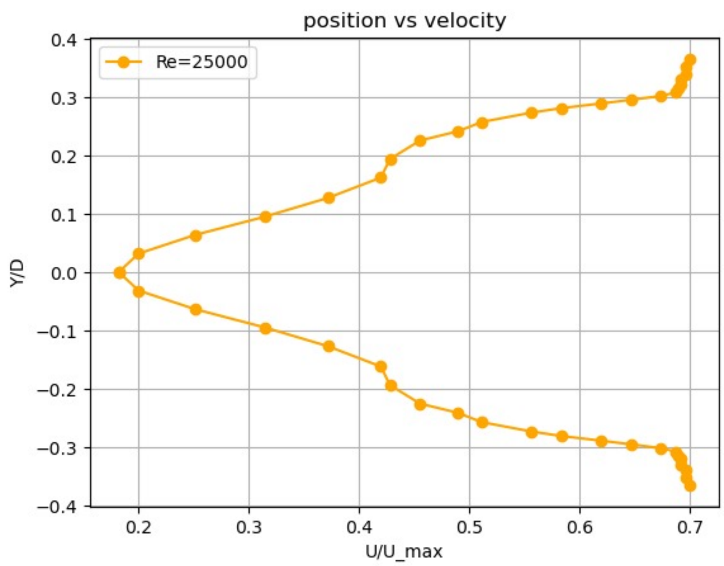



Figure 5: Velocity Profile From Table 1

```python
# Given data
vel_points = [2.0, 2.2, 2.76, 3.465, 4.085, 4.615, 4.705, 5.005, 5.385, 5.62, 6.11, 6.415, 6.81, 7.11, 7.4, 7.56, 7.58, 7.6, 7.6, 7.65, 7.66, 7.7]
position = [0, 1, 2, 3, 4, 5.1, 6.1, 7.1, 7.6, 8.1, 8.6, 8.85, 9.1, 9.3, 9.5, 9.7, 9.9, 10.1, 10.4, 10.7, 11.1, 11.5]
rho = 1.2  # Density of the fluid (kg/m^3)
W = 0.0315  # Width of the cylinder (m)
U_infinity = 7.7  # Free stream velocity (m/s)

# Convert positions from centimeters to meters
position = [pos / 100 for pos in position]

# Calculate differences in positions
delta_y = [position[i + 1] - position[i] for i in range(len(position) - 1)]

# Perform Trapezoidal Rule to approximate the integral
integral_value = sum((vel_points[i] + vel_points[i + 1]) / 2 * (vel_points[i] - U_infinity) * delta_y[i] for i in range(len(delta_y)))

# Multiply by constants to get drag force
drag_force = rho * W * integral_value
# Given data
radius = 0.025  # Radius of the cylinder (m)

# Calculate frontal area of the cylinder
A = 2* radius*W

# Calculate drag coefficient
C_D = 2 * drag_force / (rho * U_infinity**2 * A)
```

Figure 6: Code Snippet

```
print("Drag force:", drag_force, "N")
print("Drag coefficient:", C_D)
print("Reynolds number:", Re)
```

```
Drag force: 0.049495588616250016 N
Drag coefficient: 0.8833915373587453
Reynolds number: 25384.615384615387
```

Figure 7: Results

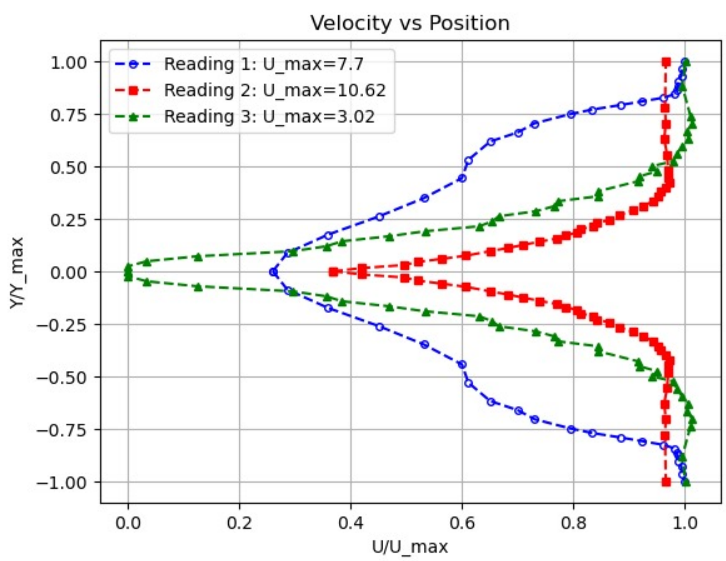



Figure 8: Different velocity profiles

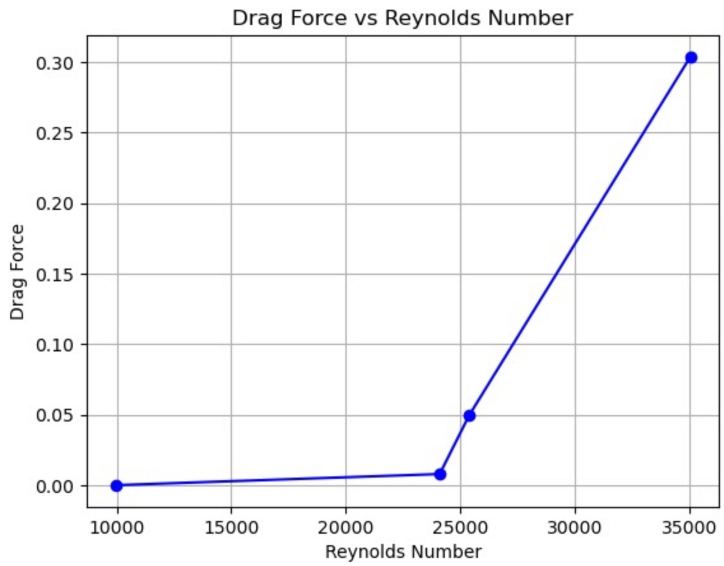



Figure 9: Results

# 7 Errors and Rectification

During our fluid dynamics project, where we aimed to calculate the drag force on a cylindrical object placed within a setup attached to the wind tunnel's mouth, several discrepancies arose. The literature value **(Yunus A. Cengel, John M. Cimbala," Fluid Mechanics, 2004** for the drag coefficient was reported as 1.2(For Laminar flow), whereas our experimental result yielded 0.9(Our was flow which was transitioning from laminar to turbulent).
Additonally,we have calculated the velocity profle for of velocity equals to 10.62 m/s, the drag coefficient was 0.303 for Reynolds number of 35000(Turbulent Flow) which was pretty much comparable to literature's (**Yunus A. Cengel, John M. Cimbala," Fluid Mechanics, 2004**) Drag Coefficent for turbulent flow, which equaled 0.3.

Several factors contributed to this variation:

$$\text{Error} = \frac{|\text{Observed value-Theoretical value}|}{\text{True value}} \times 100$$

$$\text{Error} = \frac{|0.9\text{-}1.2|}{1.2} \times 100$$

$$\text{Error} = 25\%$$

- Flow Regime: Our Reynolds number indicated a flow regime neither fully laminar nor fully turbulent, with a value of 25000. The literature drag coefficient of 1.2 was applicable to laminar flow, whereas our flow was transitioning from laminar to turbulent. This transition likely influenced the observed drag coefficient.

- Setup Attachment: The attachment of our setup to the wind tunnel's mouth was not optimal, leading to gaps that potentially affected the flow dynamics and the measured drag force.

- Mass Conservation: In our integral control volume analysis, we have used 2D analysis whereas our actual experiment involves 3D setup. This could have influenced our calculations and the resulting drag coefficient.

$$\dot{m}_{in} = 0.537 kg/s$$
$$\dot{m}_{out} = 0.442 kg/s$$

Below we have mentioned the process how we measured the mass flow rate at inlet and outlet.
To determine the mass flow rates ($\dot{m}_{in}$ and $\dot{m}_{out}$ at the inlet and outlet of the test section, a numerical integration approach was adopted due to the variation in velocity across different heights.

Utilizing the formula $\dot{m} = \rho \times A \times v$, where $\rho$ represents the density of the fluid, $A$ denotes the cross-sectional area, and $v$ signifies the velocity at a specific height, we performed numerical integration.

Given the dimensions of the mouth of the wind tunnel (length = 31.5 cm, width = 31.5 cm), the cross-sectional area ($A$) was calculated as $0.315\,\mathrm{m} \times dy$, where $dy$ represents the infinitesimal height increment.

The mass flow rate ($\dot{m}$) was then computed using the formula $\rho \times 0.315 \times \sum(v \times dy)$, where $\rho$ is the density of air and the summation involves the velocity multiplied by the infinitesimal height increment, ranging from 0 to 31.5 units.
**Conclusion: As we see $\dot{m}_{in}$ and $\dot{m}_{out}$ are not equal, this condition might have caused error in the calculation of the drag force. Since we took an important condition in our CV analysis that mass conservation holds good but which was not the case.**

- Velocity Measurement Fluctuations: The measurements obtained from the micromanometer for velocity exhibited fluctuations, introducing uncertainty into our data and calculations.

- Backward wind flow: Due to inproper isolation of setup, the wind could have obstructed and flown backward, this could lead to some discrepencies in velocity measurement.

# 8 Acknowledgment

We want to express our appreciation to Prof. Udipta Ghosh and Prof. Dilip Srinivas Sundaram for their valuable guidance and assistance during this open project. We also want to thank our TAs, Gourab Chakraborty and Inzamam Ahmad, for their valuable guidance. We are also thankful to the machine shop staff for providing us with the instruments. Their expertise and support were instrumental in the successful completion of the project. Thank you for sharing your knowledge and contributing to our learning experience.

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