Fluid Mechanics MTF053

Flow Around a Cylinder

Hands-on Lab

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Overview

The purpose of this exercise is to introduce you to external flows, more specifically the flow around a cylinder. Although a cylinder is not geometrically complex, flows around cylinders are very complex and includes several interesting flow phenomena that will be investigated in this exercise. The laboratory work will be carried out in the Chalmers Fluid Dynamics Laboratory, which is a well-equipped world-class laboratory, including a large wind tunnel with low-turbulent flow of the highest quality.

Outline

The laboratory work will be carried out for a total of 2 hours in the Chalmers Fluid Dynamics Laboratory. The laboratory work will be presented at a later seminar. Make sure to keep detailed notes of what you do during the laboratory work to support your preparations for the group seminar. Feel free to take pictures with your mobile camera to document and illustrate. At the end of this memo there is a description of what is expected to be included in the report at the seminar. The assessment of this course element is described in more detail in Section 4.

Note! before your lab session, you should read through this document and do a hand calculation. The pre-lab calculations are described in more detail in Section 2.

Learning Objectives

The laboratory work adresses the following learning objectives of the Fluid Mechanics course:

After completing the course, the student should be able to:

- **Define** the Reynolds number for different flows
- **Categorize** a flow and have knowledge about how to select applicable methods for the analysis of a specific flow based on category
- **Explain** what a boundary layer is and when/where/why it appears
- **Explain** how to use non-dimensional numbers and the Π-theorem
- **Describe** what is characteristic for a turbulent flow
- **Explain** flow separation (for example separated cylinder flow)
- **Explain** how to delay or avoid separation
- **Understand**, **explain** and **use** the concepts drag, friction drag, pressure drag, and lift
- **Understand** and **explain** how the shape and surface roughness of an object affects drag
- **Measure** forces on an object in a flow

Related Course Literature

This lab is based on the theory covered in Chapters 5 and 7 in the course book and the corresponding lecture notes.

1 Cylinder Flow - Theory

The force F $[N]$ exerted on an object immersed in a fluid flow can be expressed as

$$F = \frac{1}{2}\rho U^2 C_D A_p \tag{1}$$

where ρ $[kg/m^3]$ is the density of the fluid , U $[m/s]$ is the fluid velocity relative to the object, A_p $[m^2]$ is the projected area of the object in the direction of the relative velocity vector, and C_D is the so-called drag coefficient, a non-dimensional coefficient that contains information about the flow situation around the object. Equation 1 can be seen as the definition of the drag coefficient (C_D).

For a given object and a given flow configuration (*e.g.* incompressible fluid flow around a cylinder), C_D can be uniquely determined as a function of one other non-dimensional parameter, namely the Reynolds number. The Reynolds number for flow around a cylinder is defined as

$$Re = \frac{\rho U D}{\mu} \tag{2}$$

where D $[m]$ is the cylinder diameter and μ $[kg/(ms)]$ is the fluid viscosity. This means that if we know Re for a given flow situation, we can find the corresponding value of C_D if we know the relation between the Reynolds number and the drag coefficient for that specific flow configuration. With C_D known, the drag force F can be calculated using Eqn. 1. Since the relationship between C_D and Re is expressed in dimensionless form, the same mapping applies to all real-world realizations of the same flow configuration (*e.g.* all cylinder flows will show the same relation between Re and C_D). Figure 1 shows how the drag coefficient C_D for a cylinder flows varies with Reynolds number.

Two things are interesting to note. The first is that the flow around a sphere and the flow around a cylinder exhibit the same basic phenomena, as seen from Figure 2 where the relation between drag coefficient (C_D) and Reynolds number (Re) is compared for cylinders and spheres. The second is that all the curves presented in Figures 1 and 2 exhibit a characteristic dip wher the Reynolds number is approximately 3.0×10^5. This phenomenon is called *drag crisis*, and is characterized by a sudden decrease in C_D over a small Reynolds number range. Since C_D contains information about the flow situation around the cylinder, it is clear that something special is happening in the flow around $Re \sim 3.0 \times 10^5$. A closer examination of the velocity and pressure fields around the cylinder in the *drag crisis* Reynolds number range (either by experiment or by computer simulations) reveals that it is the transition from laminar flow to turbulent flow in the boundary layer closest to the cylinder surface that is the root cause of this behavior.
Figure 3 shows schematically how the flow around a cylinder is affected by the flow Reynolds number. The area behind the bypassed cylinder that is affected by the cylinder's presence in the flow field is called the wake. The pressure in the wake region is lower than the pressure at the front of the cylinder leading to a net pressure force on the cylinder in the opposite direction of the flow (pressure drag). At Reynolds numbers slightly below 3.0×10^5, the wake is wide and is continuously disturbed by vortex shedding (a periodic flow fluctuation phenomenon with its origin in the region near the back of the cylinder, see Figure 3 (c)). For low Reynolds numbers, the flow in the boundary layer at the front of the cylinder is laminar. At slightly higher Reynolds numbers, the boundary layer at the front of the cylinder becomes turbulent, which increases the flow momentum close to the surface (the velocity is higher close to the

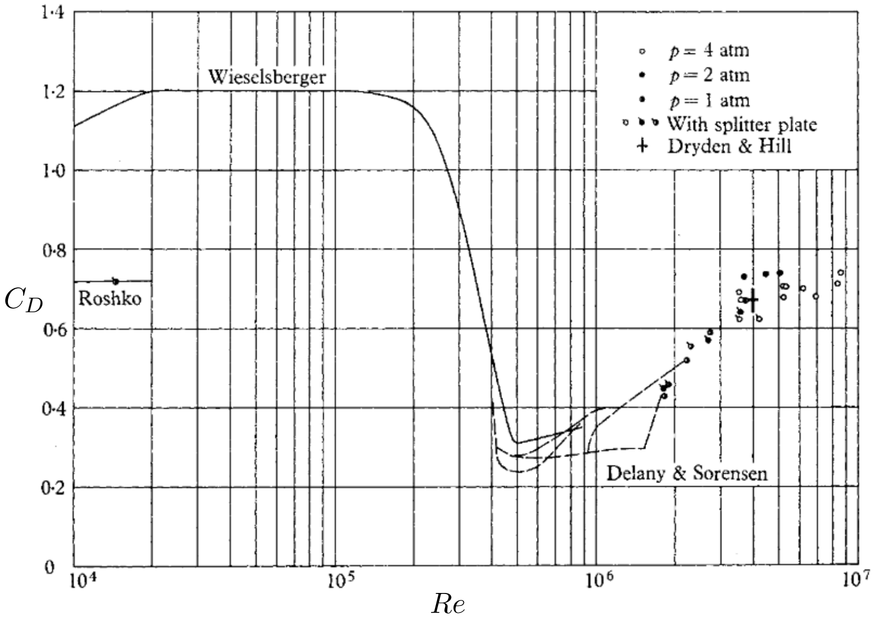

Figure 1: Drag coefficient (C_D) for flow around a cylinder as a function of Reynolds number (Re). Adopted from Roshko, "Experiments on the flow past a circular cylinder at very high Reynolds number", *Journal of Fluid Mechanics* 10, 1961.

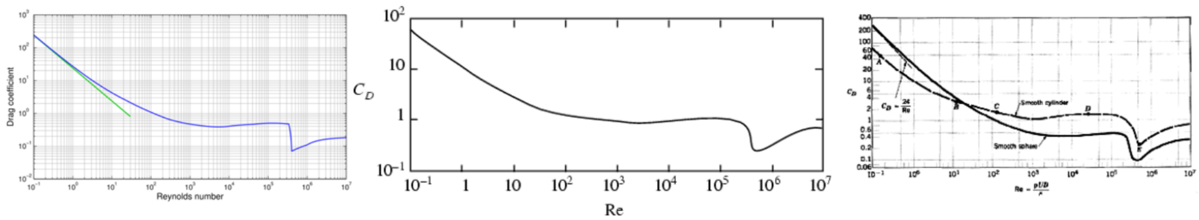

Figure 2: Drag coefficients for cylinders and spheres (left: flow around sphere, middle: flow around cylinder, right: flow around sphere and cylinder plotted in the same diagram).

surface in a turbulent boundary layer than in a laminar boundary layer), which leads to delayed flow separation and thus gives rise to a narrower wake (see the differences between situations (d) and (e) in Figure 3). Due to this abrupt change in the flow pattern around the cylinder, there is also a clear change in the force F since the size of the low-pressure wake region reduces, which is reflected in a sharp decrease in C_D.

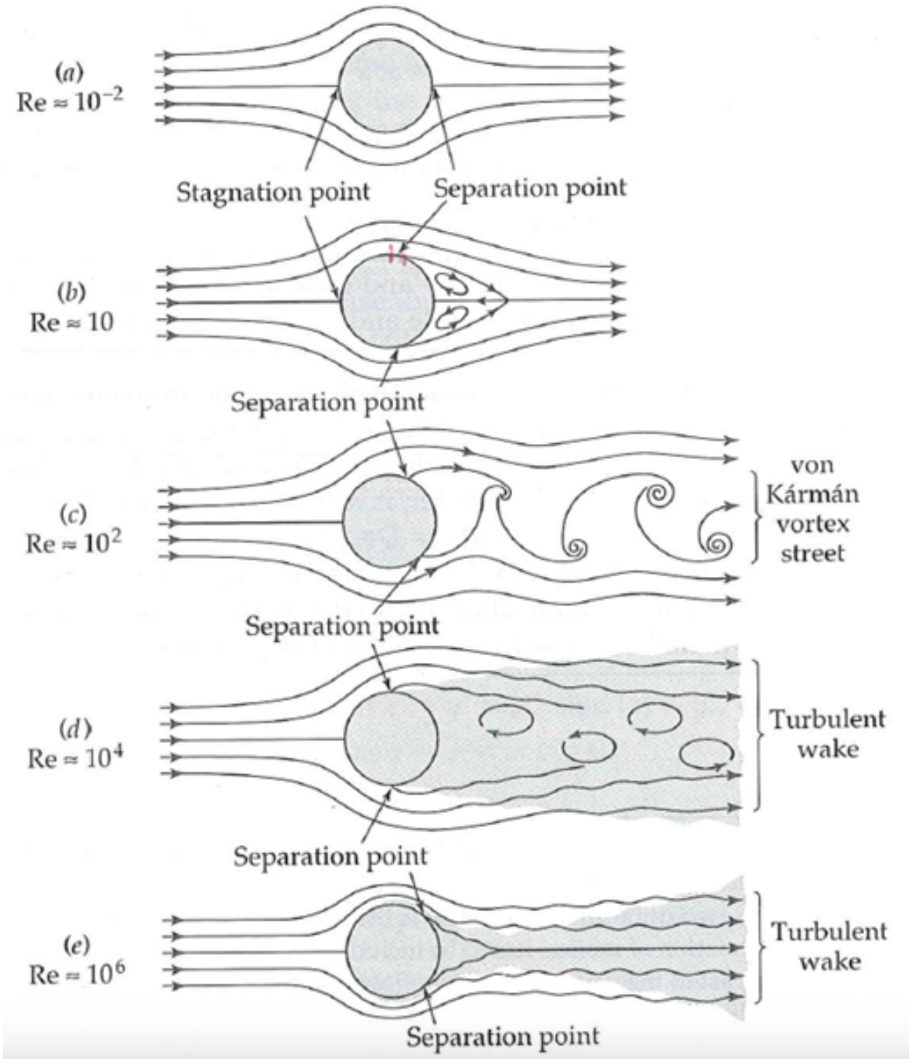

Figure 3: Flow around a cylinder - illustration of various flow regimes that are observed at different Reynolds numbers.

2 Pre-Lab Calculation

A construction company responsible for the design of a newly built bridge have received complaints that the bridge vibrates, makes noises, and tilts at wind speeds of around 10 m/s. It has also been observed that the vibrations and noises are reduced significantly when the wind speed exceeds 12 m/s. The bridge designers have given you the task to investigating the phenomenon in a wind tunnel using a 1:3 scale model. The bridge stands on cylindrical pillars with a diameter of 0.48 m and you suspect that these cylindrical foundations are the root cause of the observed vibrations at wind speeds of about 10 m/s and that the critical Reynolds number for which *drag crisis* occur has been passed if the wind speed is increased to about 12 m/s.

1. Calculate the Reynolds number for which the real bridge starts to vibrate an make noises. Assume that the environment is air at a pressure of 1 atm and a temperature of 20°C

   hints:

   - the provided pressure and temperature allows you to find proper values for the density ρ and viscosity μ
   - Eqn. 2 defines the Reynolds number

2. Estimate what velocity you need for the flow in the wind tunnel to reach the same Reynolds number (the diameter of the cylinder is now $0.48/3 = 0.16$ m). Assume that the air has the same pressure and temperature as before.

Bring your calculations to the lab

3 Hands-On Wind Tunnel Lab

Experimental Setup

The experimental setup is illustrated in the figure below. A vertical cylinder is placed inside a wind tunnel in such a way that the air flows along its curved surface. Threads that can be used for visualization of the direction of the local velocity are installed at various locations - along the sides of the cylinder and in the area where the wake should occur, see Figure 4.

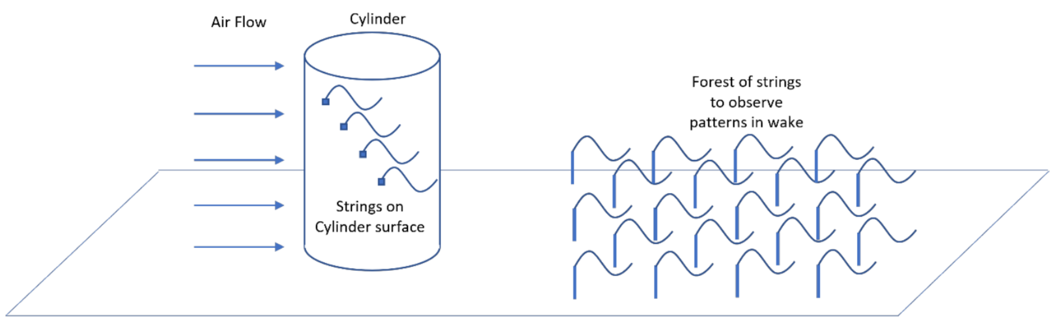

Figure 4: Experimental setup - a schematic representation of the vertical cylinder with flow visualization threads installed in the wind tunnel.

Lab Instructions - Preparations

1. Report your pre-lab calculations: what is the critical flow velocity for the experimental setup (the flow speed for which you will observe the *drag crisis* phenomenon).

2. Check the experimental setup with respect to the following factors:

   (a) The cylinder is installed on the scale

   (b) The height of the cylinder is adapted to the wind tunnel and known

   (c) Visualization threads are installed on the side of the cylinder

   (d) A sandpaper strip is attached to the back of the cylinder

   (e) A "forest" of visualization threads is placed behind the cylinder

3. Fill in values for all properties in Table 1

Property	Dimension	Value
Fluid density (ρ)	kg/m^3	
Fluid viscosity (μ)	$kg/(ms)$	
Cylinder diameter (D)	m	
Cylinder height (H)	m	
Projected area (A_p)	m^2	

Table 1: Variable values

Lab Instructions - Practical Implementation

1. Start the wind tunnel by increasing the flow speed from 0.0 to 5.0 m/s. The speed is controlled via the graphical interface on the computer. For safety reasons, it is important to start the wind tunnel at low speeds to prevent any loose objects left in the tunnel from being dragged along and damaging the tunnel or people.

2. Observe the averaged drag resistance force on the computer screen. When the reading is stable, save the values to a file.

3. Increase the flow speed in steps of 5.0 m/s and read the corresponding measured forces.

4. Observe the threads mounted on the sides of the cylinder to try to determine where on the cylinder the flow separates from the surface. Note that the separation location can be moved/changed each time you change the flow speed.

5. Observe the visualization threads in the "forest" behind the cylinder to try to determine what the wake looks like. Note that the wake's appearance (length, width and behavior) can move/change each time you change the flow speed.

6. End the measurement series when the flow speed reaches 40.0 m/s.

7. Use the measured forces, the values noted in Table 1, and Eqns. 1 and 2 to complete Table 2.

8. Rotate the cylinder so that the flow meats the rough side of the cylinder (the side with the sandpaper strip).

9. Repeat steps 1-6 and use the measured forces, the values noted in Table 1, and Eqns. 1 and 2 to complete Table 3.

Velocity (U) [m/s]	Reynolds Number (Re)	Drag Force (F) [N]	Drag Coefficient (C_D)
0			
5			
10			
15			
20			
25			
30			
35			
40			

Table 2: Smooth Cylinder

Velocity (U) [m/s]	Reynolds Number (Re)	Drag Force (F) [N]	Drag Coefficient (C_D)
0			
5			
10			
15			
20			
25			
30			
35			
40			

Table 3: Rough Cylinder

Lab Instructions - Questions for Reflection

1. Was your preliminary calculation correct for when you observed the *drag crisis*? If no, why not?
2. Did you observe any trend (with respect to Reynolds number) in where on the cylinder surface the flow separated from the cylinder? Did this observation match your expectations?
3. Did you observe any trend (with respect to Reynolds number) in how wide the wake behind the cylinder was? Did this observation match your expectations?
4. Did you observe any differences in how the flow looked around the cylinder depending on whether it was smooth or rough? If yes, describe the observed differences.
5. Did you observe any differences in when the *drag crisis* phenomenon occurred depending on whether the cylinder was smooth or rough? If yes, describe the observed differences.
6. In the lab, you changed the Reynolds number by changing the flow speed. Is this the only way? If no, what other ways can you think of?
7. Imagine a situation where a friend wants to calculate the drag resistance of a cylinder with a flow around it and asks you for help. What do you need to know about the cylinder to be able to answer the question? What do you need to know about the flow?

4 Assessment

This course element is assessed in a group session at the end of the course. At this session your laboratory work will be presented and discussed with one of the course assistants. All group members should be active in the presentation in some way. It is not important that the division between the group members is necessarily even, just that everyone is involved. Prepare slides for your seminar to be used as support for your discussion and submit your slides in Canvas before the session. Your presentation material should include the following:

1. Title slide including group number and the names of all members of the group
2. Flow around a cylinder:
   Give a brief overview of what the flow around a cylinder can look like depending on the Reynolds number. You can use the information provided in this document, lecture notes, the course book or other sources of information that you find relevant to support your discussion
3. Estimation of drag coefficient:
   (a) Show C_D as a function of Re based on your measurement data from the laboratory session for the case where the smooth side of the cylinder meets the flow.
      - Compare with similar curves in the literature and comment on any differences and/or similarities. Comment in particular on where the drag crisis occurred and whether this was in line with your expectations (and if not, what could explain the differences).
      - Comment on any observations of where on the cylinder surface the flow separated from the cylinder and how wide the wake behind the cylinder was, and state whether this was in line with your expectations (why/why not?).

   (b) Show C_D as a function of Re based on your measurement data from the laboratory session for the case where the rough side of the cylinder meets the flow.
      - Comment on the differences you observe compared to the smooth case. How can these differences (if any) be explained?
4. Reynolds number:
   Answer the following two questions:
   (a) Would it be possible to carry out the same experiment if the speed had been fixed and you had had to adjust the Reynolds number in a different way?
   (b) Suppose that one of the groups had carried out the same experiment (same cylinder) in a water tunnel instead of a wind tunnel, *i.e.* the fluid had been water instead of air as in your case. If this group had adjusted their investigated speed range so that they had covered the same Reynolds number range as you, would they have obtained the same C_D curve? Why/Why not?
5. Summary:
   This slide should contain 3 bullets where you summarize in your own words the three most important lessons that you take away from what you have done and observed.
6. References
   This slide should contain a list of the references that you have used to for your descriptions and conclusions