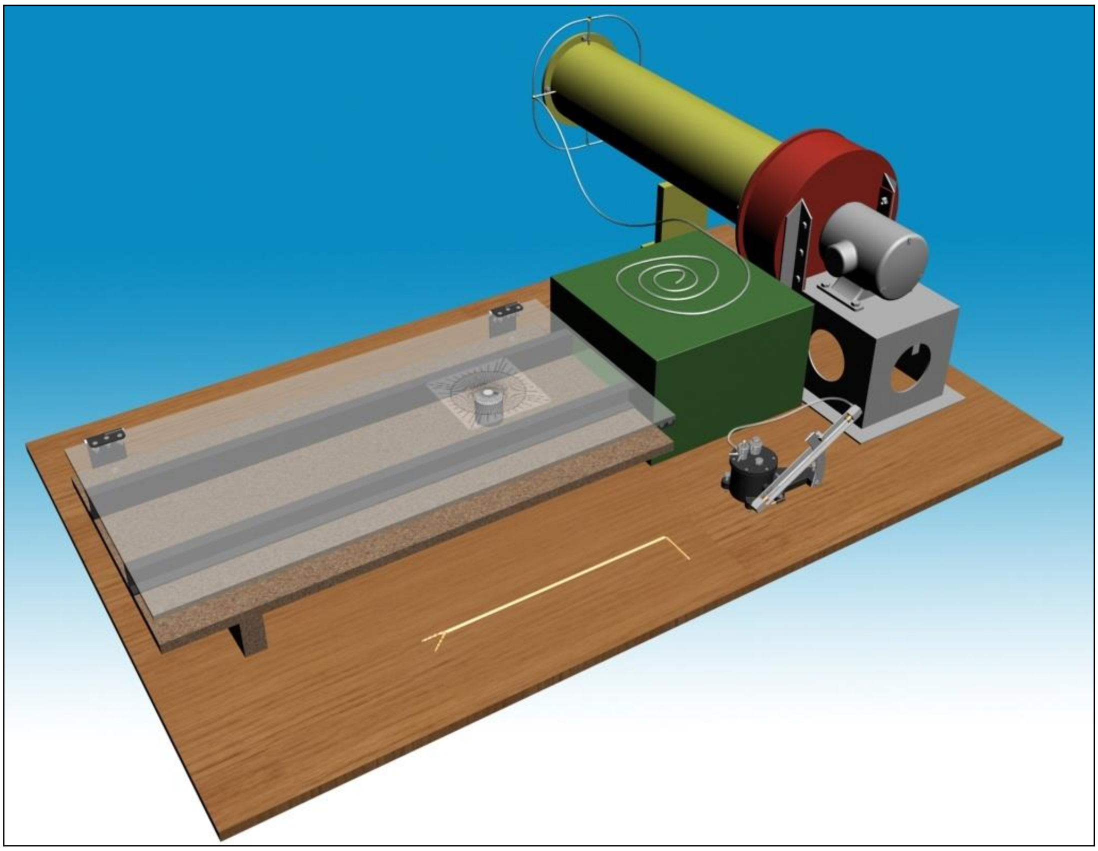


M11

EXAMINATION OF FLOWS AROUND BODIES

1. Objectives of the measurement, practical relevance

The main objective of the measurement is the analysis of the flow around bodies with different profile shapes (square pillar, circular pillar and symmetric airfoil) by the visualization of the flow field. The secondary objectives are the determination of the pressure distribution around the bodies through measurements, and the investigation of the connection between the developed flow pattern and the pressure distribution along the wall. In the laboratory report you should compute the drag coefficients based on the pressure distribution, and compare the flow patterns around the different shaped bodies.

In practice, we often need to know the characteristics of the flow field developing around bodies. The most important of these are the velocity and pressure distributions and the aerodynamical forces acting on the body. Knowing these is very important, for example in vehicle and aircraft design, and in the static investigation of buildings. A quite interesting phenomenon, which can be investigated, is the periodic fluctuation around bodies, where both the velocity and pressure field fluctuate. Therefore, the aerodynamical forces fluctuate as well, which may cause problems, if the frequency of the fluctuation is close to the mechanical resonance frequency of the body. In such cases, the amplified fluctuation may cause mechanical damage to the structure. For that very reason, the dynamical examination of the flow pattern around long bodies is also important when statically examining them.

The reader is referred to Chapter 7.6 of [1] for more information on flow fields around bodies. This laboratory examination demonstrates the basic concepts and practices of this topic.

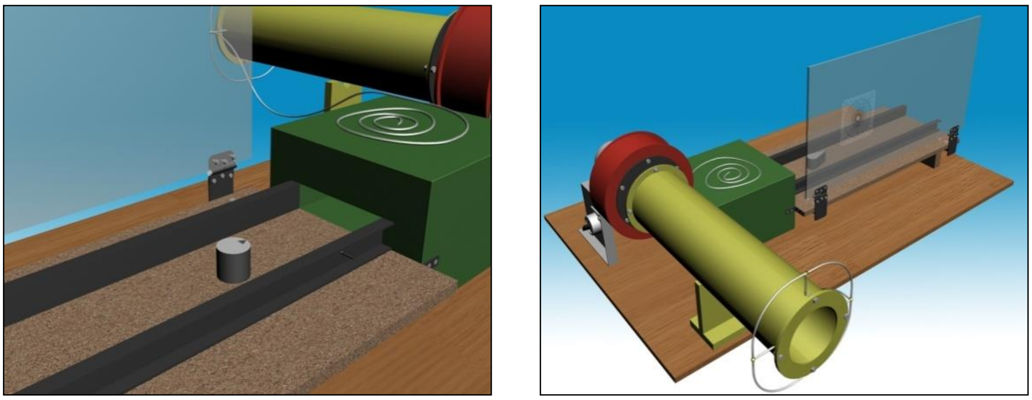


Figure 1. *3D schematic figure of the measurement*

2. Description of the measurement facility

The measurement facility, which can be used to investigate plane channel flows, contains two main parts. The first part is a miniature wind tunnel, which provides a uniform inlet velocity profile, and the second part is the adjustable measuring section. The complete measurement set-up can be seen in Figure 2. Its components listed in the order following the flow path are the following:

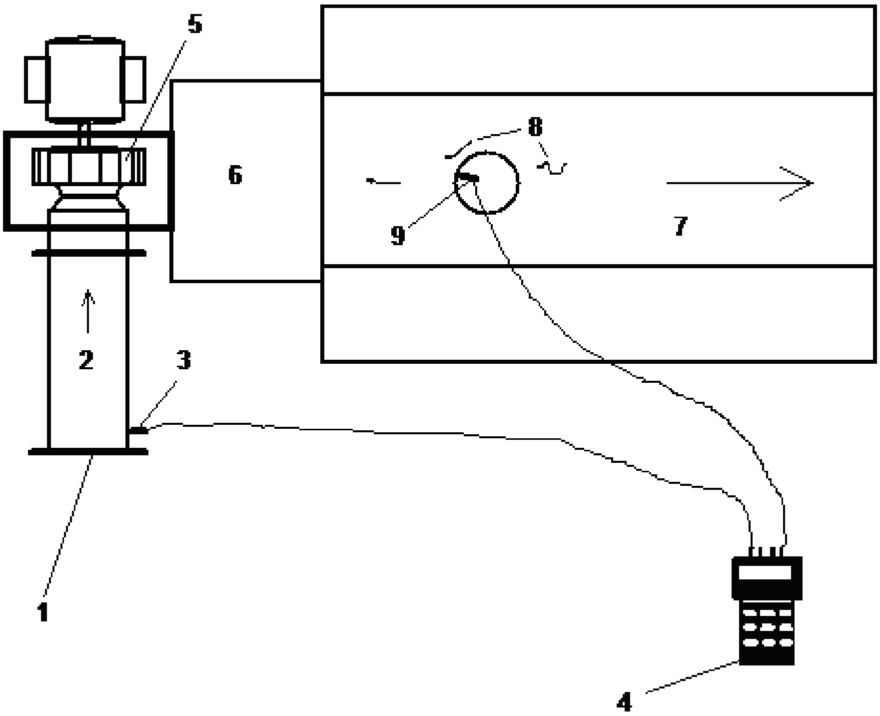


Figure 2. *2D schematic figure of the measurement*

1. Standard inlet orifice plate for measuring the flow rate.
2. Air intake nozzle.
3. Pressure tap after the inlet orifice plate, which is connected to the proper tap (in this case that is the tap denoted by “-”) of the pressure transducer by a thin rubber tube. From the measured pressure the volumetric flow rate can be calculated.

4. Two channel digital manometer.
5. Radial fan driven by a triphase asynchronous motor.
6. Flow straightener .
7. The measurement section provides the means for assembling the different channel geometries for the investigations. The almost uniform flow from the straightener is directly fed into the adjustable measurement section. The measurement section is bounded on the bottom side by a cork covered base plate (the flow visualization flags (8) can be stuck into this plate). The top of the channel consists of a transparent plexiglass plate, which can be opened. The sides consist of two adjustable plates.
8. Flow visualization flags.
9. Side walls with pressure taps on the surface.

Beside the previously described measuring facility other auxiliary devices are also needed for the measurement (e.g. barometer, thermometer, tape measure etc.). These are also provided in the laboratory.

(Note: The base and the top plates are parallel planes to each other and the sidewalls are perpendicular to them in every cross section of the channel. Therefore, by neglecting the displacement effect of the boundary layer, it can be assumed that the fluid particles are not deflected perpendicularly to the bottom and top boundary. Generally speaking, in this direction the flow variables are changing with a much smaller rate than along the other two dimensions of the measurement section. This is the observation which gives us the opportunity to investigate relatively simple two dimensional flows using this facility.)

3. Detailed description of the measurement task, basic aspects of the tests and post-processing

The extensive examination of the topics outlined in section 1 would take a long time. Therefore, within this laboratory measurement, a simplified measurement task is given, investigating either of three cross-sections:

A. *square*
B. *circular*
C. *symmetric airfoil*

3.1. Investigation of the flow pattern in the channel using a flow visualization technique; measurement of the velocity profile at the in- and outlet

The first step is to set-up the required measurement section by placing the proper side wall elements onto the base plate, and placing the measured object in the proper position in the channel. Following this, the flow visualisation flags need to be stuck into the base plate in the free-stream flow of the channel. The visualisation flags are pins with a 30-35mm length soft and fluffy thread mounted to the upper part of the pins. Taking into consideration the nature of the process, the flags need to be placed with 20-90 mm spacing. It is evident that the flags should be placed densely in the places where the flow changes significantly within a short distance and sparsely where the flow is undisturbed. It is advisable to place the threads on the pins approximately at the mean of the channel height. After the flow is started the flags turn into the local flow direction. If the flags are properly placed, the flow pattern in the channel is visualized by the many small threads. In order to document the observations, a freehand sketch or a photograph should be made of the flags. The sketch should focus on the sudden direction changes and separations which appear in the flow. It is practical to separately denote the contours of the separation bubbles on the drawings.

At the inlet section of the channel a Pitot-static probe, otherwise known as a Prandtl probe, velocity measurement should be done in order to check the uniformity of the inlet velocity profile and to calculate the approximate value of the average velocity and compare it to the value computed from the inlet orifice plate. The average velocity should be determined based on the rules of the point to point Prandtl probe measurement. In the inlet section the measurement points should be evenly distributed with 7-15 mm of spacing. Results should be presented in a table and a chart along with the average velocity values computed from the inlet orifice plate measurements.

3.2. Measurement of the pressure distribution on the body

Beside the velocity field, another important characteristic property which is present in the fluid flow is the pressure distribution. The pressure changes are in correlation with the changes in the flow pattern. Many velocity and flow rate measurement devices apply this observation (e.g. Prandtl probe, Venturi tube).

In the present experimental exercise the pressure distribution on the surface of an object placed in the flow will be examined. Following this, the connection between the pressure distribution measured on the object and the velocity distribution realized in the measurement section needs to be determined. The pressure distribution on the surface of the object can be examined by using the pressure taps on the surface of the object, and the digital manometer. One of the taps on the manometer needs to be connected to the pressure tap of the object which is to be examined, and the other needs to be connected to the pressure tap on the wall of the channel which is close to the inlet of the channel. In this way we can measure the pressure on the entire surface of the object with respect to the static pressure in the channel. Taking into consideration the equipment which is available for the measurement, the measurements on the cylinder should be executed every 5°, while the pressure taps on the square figure are distributed evenly across the cross-section. The results of the measurements should be shown in a diagram. Having acquired the pressure distribution and the flow maps, the connections between them should be investigated, with the found results being included in the report.

3.3. Determination of the drag force, the drag coefficient and pressure coefficient

During the analyses of the data, you should calculate the pressure coefficient from measured pressure values. Diagrams are required in the lab report for both the pressure difference values and the pressure coefficient values as a function of either the position or the angle of the object. The pressure coefficient can be calculated as follows:

$$c_{p,i} = \frac{p_i}{\frac{\rho_{air}}{2} v^2} \tag{1}$$

where:

$c_{p,i}$	[-]	pressure coefficient at the ith measurement point
p_i	[Pa]	pressure at the ith measurement point
ρ_{air}	[kg/m^3]	density
v	[m/s]	undisturbed flow velocity

The density of the flowing medium, and the undisturbed flow velocity can be determined using the measured data:

$$\rho_{air} = \frac{p_0}{RT_0} \tag{2}$$

$$v = \frac{q_v}{A_w} \tag{3}$$

where:

p_0	[Pa]	atmospheric pressure
R	[J/kgK]	spacific gas constant of air
T_0	[K]	temperature
A_w	[m^2]	free cross-section of the wind tunnel
q_v	[m^3/s]	volumetric flow rate

The volumetric flow rate q_v can be measured with the inlet orifice plate mounted at the beginning of the suction tube. It is assumed that the fan intake occurs through the orifice and discharges into the ambient fluid only at the channel exit. This means that the sealing in system is perfect and since the density is constant, the volumetric flow rate does not change in the device.

The volumetric flow rate can be determined by the inlet orifice plate in the following way. The relative pressure as compared to the atmospheric pressure Δp_{op} is measured at the tap following directly after the orifice plate at the beginning of the suction tube. The volumetric flow rate q_v can be computed from Δp_{op} with the following expression:

$$q_v = \alpha\varepsilon \frac{d^2\pi}{4} \sqrt{\frac{2\Delta p_{op}}{\rho_{air}}} \tag{4}$$

where:

α [-] is the contraction ratio, which depends on the area ratio of the orifice and the tube and on the Reynolds number. The value of α is determined from experimental investigations and it has been summarized in handbooks. In this measurement the contraction ratio is approximately 0.6.

ε [-] expansion number, which is assumed to be 1 in the circumstance of small pressure variation through the system, such as in this measurement.

d [m] diameter of the orifice plate.

Δp_{op} [Pa] pressure loss on the orifice plate

The experimental methods described in sections 3.1 and 3.2 can be used to make a detailed analysis of the flow around a body. Usually though, in the everyday engineering practice, it is not necessary to use such a detailed description. In such cases it is beneficial to calculate the drag force and to use only the dimensionless drag coefficient.

The drag force can be calculated from the pressure distribution, by dividing the surface of the body into sections according to the positions of the pressure measurement points around the body, thus the measurement points will be in the centers of the sections. The total force of the body, which originates from pressure, can be calculated from the sum of the forces on the different sections:

$$\underline{F} = \sum_{i=1}^{n} \underline{F_i} = \sum_{i=1}^{n} p_i A_i(-\underline{e_n}) = \sum_{i=1}^{n} p_i h_i L(-\underline{e_n}) \tag{5}$$

where:

$\underline{F}$	[N]	resultant pressure force
n	[pieces]	number of sections/points
$\underline{F_i}$	[N]	force on the ith surface section
p_i	[Pa]	pressure at the ith surface section
A_i	[m^2]	area of the ith surface section
$\underline{e_n}$	[-]	unit vector in normal direction
h_i	[m]	width of the ith surface section
L	[m]	height of the ith surface section

The x and y component of the resultant pressure force $\underline{F}$ can be determined using the well-known trigonometric identities, as Eqs. (6) and (7) show. The angles φ_i should be taken according to how it is measured at the wind tunnel, or what is shown in Figure 3. In this way, the angle 0° corresponds to the stagnation point.

$$F_x = \sum_{i=1}^{n} F_{xi} = \sum_{i=1}^{n} p_i h_i L(-\cos\varphi_i) \tag{6}$$

$$F_y = \sum_{i=1}^{n} F_{yi} = \sum_{i=1}^{n} p_i h_i L(-\sin\varphi_i) \tag{7}$$

The width of the ith surface section can be determined in different ways, depending on the measured body. If the cross-section of the body is a square, then the side of the square should simply be divided by the number of measurement points, since the bores are evenly distributed on the body's wall. If the cross-section of the measured body is circular, the side of the cyilinder can be approximated as a plane surface in the vicinity of the bores. Hence, knowing the rotation angle $\Delta\varphi$ and the cylinder radius R_c it can be calculated:

$$h_i = 2R_c \sin\left(\frac{\Delta\varphi}{2}\right) \tag{8}$$

The introduced variables can be seen in Figure 3.

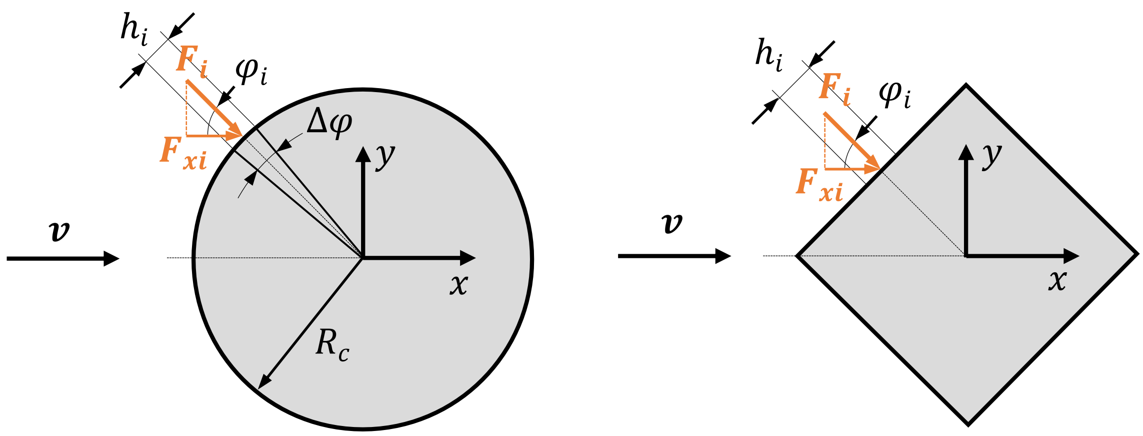


Figure 3. Interpretation of the variables in case of a circular (left) and a square (right) cross-sectional body

Having these components, we can derive any component of the total force from the results. This can be, for example, the lift force and the drag force, which are customary in aerodynamics. These are the components, which are parallel to the main stream (drag force F_d) and perpendicular to it (lift force F_l).
In the present investigation the focus is on the drag force and the drag coefficient. The drag coefficient c_d can be computed as follows:

$$c_d = \left| \frac{F_d}{\frac{\rho_{air}}{2} v^2 A_\perp} \right| \tag{9}$$

where:

F_d	[N]	drag force
ρ_{air}	[kg/m^3]	density
v	[m/s]	undisturbed flow velocity
$A_\perp$	[m^2]	projection of the body orthogonal to the flow direction

A detailed description of the volumetric flow rate measurement with an orifice plate can be found in Chapter 6.10 in [1] in English, or in Chapter 6.3.4 in [2] in Hungarian.

Table 1. contains informative details regarding the drag coefficient of three-dimensional bodies as a function of the flow direction. It may turn out that the obtained drag coefficient is higher than that seen in the literature. The reason for this is that the flow speed around the body is somewhat different compared to what is calculated in Eq. (3) as undisturbed flow velocity. The area A_w of the wind tunnel's cross-section decreases around the body by an area $A_\perp$. This results in the flow speed being higher around the body, according to continuity. This increase depends on several factors, such as the shape of the investigated body. However, the compensation for this increase is beyond the scope of this measurement.

3.4. The lab report

The content of the lab report should be similar to the present guide. First, the measurement set-up and the measurement task need to be described. The description should be brief, and it is important to write it in your own words. (Copying text from this guide or from other sources is prohibited!) After the description of the measurement set-up and measurement task, the measured data should be presented, and they should be processed according to points 3.1-3.3 of the present guide. Then, the obtained results should be evaluated. The evaluation should give an answer to the following questions:

I) What results are expected according to the literature or your own theoretical knowledge?
II) How much is the deviation from the expected results?
III) In case of significant deviation, what is the cause of it?

The hand-written measurement plan signed by the measurement supervisor, and the diagram prepared at the measurement should be scanned and attached to the end of the report.

Great care should be taken in formatting and editing the lab report. Only those reports achieve high scores which look appealing. The requirements have been presented in the pre-measurement classes, or can be found in the EXAMPLE_Lab_report.doc document [3].

3.4.1. The visualized flow around the measured body needs to be recorded and presented in the lab report.

3.4.2. Error calculation for the drag coefficient

I) The used formulas should be substituted to Eq. (9). After all the formulas are substituted, the *measured* quantities – which cause uncertainty in the results – should be directly present. After simplifying the equation, it may happen that some measured quantities disappear.

II) The $\partial c_d/\partial X_i$ derivatives should be determined. The equation obtained in point I) needs to the derivated with respect to all the X_i quantities, respectively. The particular p_i values should be considered separately, since all measurement introduces additional uncertainty to the results.
In the present measurement, the following X_i values should be considered:

$X_1 = p_0$ $\quad$ $\delta p_0 = 100\ Pa$
$X_2 = T_0$ $\quad$ $\delta T_0 = 1\ K$
$X_3 = p_i$ $\quad$ $\delta p_i = 2\ Pa$
$X_4 = \Delta p_{op}$ $\quad$ $\delta \Delta p_{op} = 2\ Pa$

III) Using the derivatives and the given δ errors, the absolute- (10) and relative errors (11) need to be calculated:

$$\delta c_d = \sqrt{\sum_{i=1}^{n}\left(\delta X_i \frac{\partial c_d}{\partial X_i}\right)^2} \tag{10}$$

$$\frac{\delta c_d}{c_d} = ? \tag{11}$$

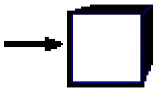
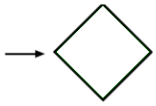
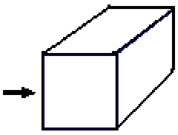
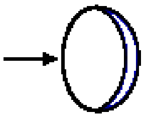
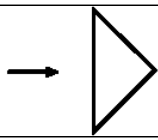
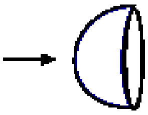
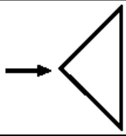
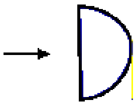
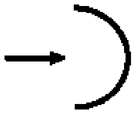
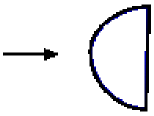
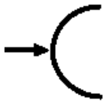
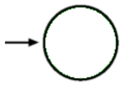
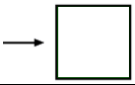
Remember that during the labs:

- Before turning any measurement device on or in general during the lab, make sure that safe working conditions are ensured. The other participants have to be warned of the starting of the machines and of any changes that could endanger the members of the lab.
- The atmospheric pressure and room temperature should be recorded before and after every measurement.
- The measurement units and other important factors (e.g. data sampling frequency, date of calibration) of every recorded value of the applied measurement devices should be recorded.
- Type and construction number of the applied measuring instrument should be included in the final report.
- Checking and harmonizing of the units of the recorded values with those used in further calculations.
- Manometers should be calibrated if necessary.
- The measurement ports of the pressure meter should be carefully connected to the correct pressure ports of the instrument.
- If inlet or outlet tubes are to be assembled with fans, connections should be airtight as escaping/entering air can significantly modify the measurement results.

Bibliography:

[1] Frank M. White, Fluid Mechanics, McGraw-Hill Higher Education, 1998.
[2] Lajos Tamás, Az áramlástan alapjai, Műegyetemi Kiadó, 2004.
[3] http://simba.ara.bme.hu/oktatas/tantargy/NEPTUN/BSc_LABOR/ENGLISH/

Table 1. Drag coefficients for a range of $Re = 10^3 - 10^5$

BODY SHAPE AND FLOW DIRECTION (3D BODIES)	C_D [-]	BODY SHAPE AND FLOW DIRECTION (3D BODIES)	C_D [-]
	1.05		1.55
	2.05		2.01
	1.42		2
	0.38		1.55
	1.17		2.3
	0.42		1.2
	0.04		1.17
			2.05