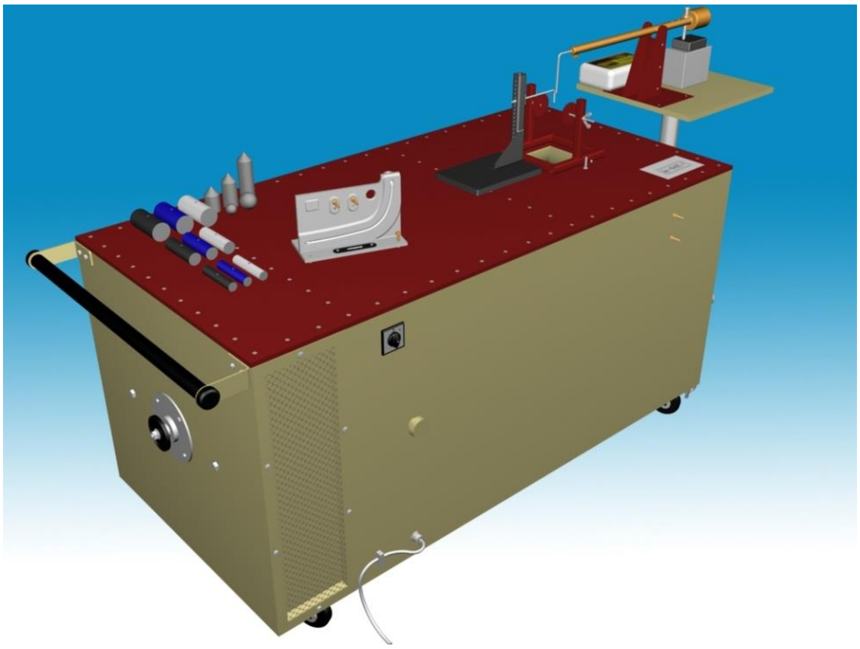
Budapest University of Technology and Economics

Department of Fluid Mechanics



BSc M01 Measurement Guidelines

INVESTIGATION OF DRAG COEFFICIENT ON BLUFF BODIES

Valid: 2015/16. II. semester

Home preparation

1. Aim of the measurement

Determination of drag coefficient on different, but comparable in some properties, bluff bodies by measurements. The drag coefficient is dependent on Reynolds number and the compared properties, which is to be determined during the measurement.

2. Preparation for the measurement

Examine the measurement guide carefully and prepare a work plan for the measurement with tables in which measured data can be registered.

For Hungarian speaking students, chapters 11.1 – 11.3 from the book “Lajos Tamás: Az áramlástan alapjai” can give useful informations.

3. Theoretical background

Investigating a body placed in a fluid flow (e.g. buildings, vehicles), it can be concluded, that aerodynamic forces act on the body. The component which is parallel to the undisturbed flow is called the drag force. For bluff bodies the drag force is a result of the pressure difference between the windward and leeward side, the effect of the wall shear stress can be neglected (for aerodynamic bodies the opposite is true). The drag force is dependent on the flow velocity, the dimensions and shape of the body. The equation is the following:

$$F_d = \frac{\rho}{2} v^2 c_d A$$

where the dynamic pressure of the undisturbed flow by definition is:

$$p_{dyn} = \frac{\rho}{2} v^2$$

The drag force is linearly dependent on the dynamic pressure, the specific area of the body and the non-dimensional drag coefficient:

$$F_d = p_{dyn} c_d A$$

For bluff bodies the specific area is the area of the projection of the body perpendicular to the flow. Based on experience and theory, the drag coefficient of bluff bodies measured in the current velocity and dimension intervals is dependent on the following: shape of the body, position relative to the undisturbed flow, surface roughness, Reynolds number (Re):

$$c_d = f(shape, position, roughness, Re)$$

The Reynolds number is a non-dimensional group, which is characterised by the flow velocity (v), specific dimension of the body (L) and the kinematic viscosity of the fluid (ν):

$$Re = \frac{vL}{\nu}$$

The specific dimension (or length) is the smaller from the two lengths of the specific area (or the diameter for circular area). The kinematic viscosity is the ratio of the dynamic viscosity and the density:

$$\nu = \frac{\mu}{\rho}$$

The dynamic viscosity depending on temperature can be determined according to an empirical equation (for the investigated flow velocity and dimension intervals) and can be verified by diagrams. The density can be calculated according to the ideal gas law based on the measured temperature and pressure in the laboratory:

$$\rho = \frac{p_0}{RT}$$

4. Description of the measurement devices

4.1. Measurement table (car). Setting and measuring the dynamic pressure

The flow is provided by an open test section mobile wind tunnel. The uniform outflow velocity is ensured by a confusor before the outlet section, filter layer and a guiding grid.

There are pressure taps at the inlet and the outlet cross sections of the confusor, where the manometer should be connected. Similar to a Venturi tube, **the difference in pressure between the two points is nearly the dynamic pressure at the outlet of the tunnel**. According to calibration measurements (performed with a Prandtl tube) **the following relation is valid**:

$$p_{dyn} = K\Delta p, K = 0.908$$

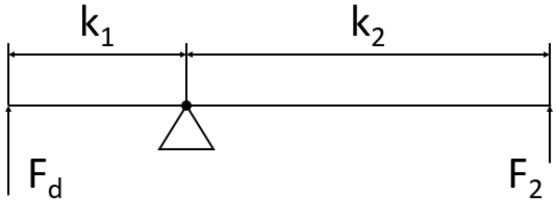
The dynamic pressure is controlled by the choke at the suction side of the fan. The choke mechanism can be seen through the window on top of the car, and can be adjusted by a wheel on the back of the car. The wheel translates a circular plate in front of the suction cross section through a spindle mechanism. **If the inlet is totally closed, nearly 0 Pa pressure can be achieved. For the first 10 revolutions of the control wheel the pressure drastically increases until the 90% of the maximum achievable pressure**, then for another 8 revolutions the pressure slowly increases until the fully open case.

The wheel can be turned without much effort. <u>Do not try to force the wheel in the end positions, because it can break!</u>

4.2. Force measuring scale

The drag force acting on the bodies is measured by a two-armed scale, which is connected to an electronic force measuring cell. The measured body can be applied on the end of the longer arm, the shorter arm applies load on the force measuring cell.

As the scale acts as a two-armed lifting device (the forces on the two ends are in equilibrium through the two arms of the scale → the momentum on the joint of the arm is zero, thus $F_d k_1 = F_2 k_2$)**, the momentum equilibrium must be applied when the resulting force is to be calculated**:



$$F_d = F_2 \frac{k_2}{k_1}$$

The measured force on the measuring cell is higher than the real force acting on the body, because of the ratio of the arm lengths.

4.3. Measuring the drag force

During the measurement the scale arm is also in the flow, therefore a drag force is acting on it too which is also measured. This drag force is greatly influenced by the flow behind the measured body. This force must be subtracted from the results, because only the force acting on the body is important for the measurement. **The steps to eliminate this force are the following**:

0) **Nulling the force measuring device at switched off wind tunnel.** This way the weights of the measurement setup are eliminated.

1) **For the first measurement, the body is applied on the measuring arm and placed in the flow**. This way the force acting on the body and the measuring arm is measured.

2) **For the second measurement the body is applied on a separate stand in a way to preserve the original setup (in step 1) as much as possible**. It is important that the body and the scale arm do not touch! This way the drag force on the scale arm can be measured.

3) **Now the force acting on the body can be calculated by subtracting the force measured in step 2 from the force measured in step 1:**

$$F_d = F_{d,body+arm} - F_{d,arm}$$

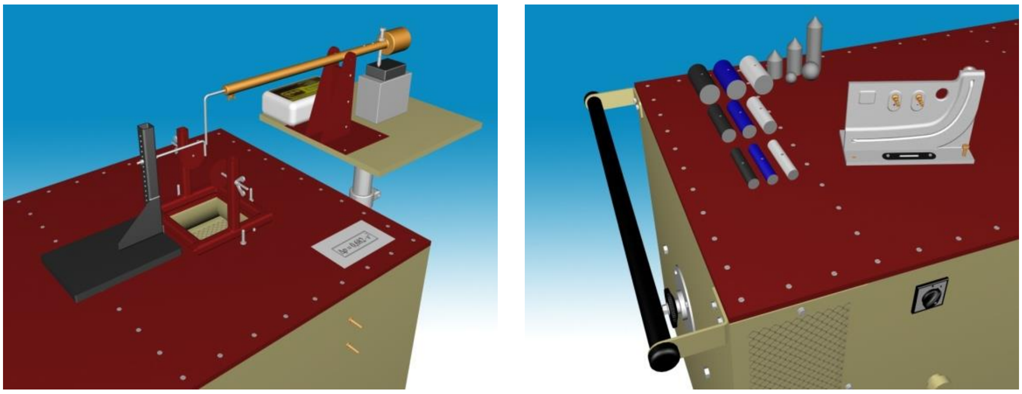


Figure 1: The mobile wind tunnel (measuring car)

Measurement steps

4.1 Registering basic data (two parallel individual tasks)

1a) The data of the selected bodies are to be registered (shape, dimensions, roughness values). Also register the flow direction compared to the body. Register the type, serial no. of the used equipment (manometer, force measurement device, etc.). Write down the temperature and pressure values read from the equipment placed on the laboratory wall.

1b) Starting the fan, minimum and maximum pressure measurements.

Examine the tubes used for pressure measurement for damages. If the tubes are damaged, the measurement data will be incorrect and only repeating the whole measurement will help!

To measure the minimum and maximum pressures the use of the uncalibrated manometer is sufficient, because these are just informative values. **Connect the device to the pressure taps** on the side of the car and **null it for the switched off fan**. **Start the fan and with the wheel try the whole interval of the choke and register the maximum difference of the pressures measured. This will indicate the upper limit of the applicable velocity interval.**

4.2 Calibration and measurement planning (three parallel individual tasks)

2a) Calibration of the manometer: the digital manometer can be calibrated to the Betz micromanometer. Between the 0 point and the maximum measured pressure calibrate the device in 5 points (h_{Betz} $[mm]$; p_{dig} $[Pa]$). Use values which can be easily set on the Betz manometer (integer water column [mm] values).

2b) Calibration of the force measuring cell: after the nulling of the cell place the provided calibration weight on top of the measuring needle and register the measured value. Repeat the measurement 5 times. Measure and register the lengths of the arms of the scale.

2 c) Measurement planning, determining the desired pressures

According to the dimensions of the bodies and the pressure interval of the wind tunnel a measurement plan must be made. The needed pressure values must be determined which can be set during the measurement with the control wheel of the tunnel.

The measurement exercise specifies either the similarity of velocities or Reynolds numbers. On the car only pressure can be measured and set. The emphasis is not on exact values, but on the similarity of these for the different bodies. Methods are given here how to determine pressure values according to the velocity or Re numbers in a way that they will be realizable within the limits of the wind tunnel and body shapes/dimensions. The exact values for the velocities and Re numbers will be calculated afterwards in the documentation.

2 c 1) For same prescribed velocities

Divide the measurement points nearly uniformly in integer pressure values. Avoid lower than 20 Pa and higher than the 90% of the maximum pressure values. The actual velocities will be calculated afterwards in the evaluation.

2 c 2) For same Re numbers

E.g. three different sized bodies on five different Reynolds numbers. The velocities in this case must be altered in every point (15 pressure values). In this case the pressures can be registered in a 3 rows x 5 columns table. The columns represent in increasing order the Reynolds numbers, the rows represent the different bodies in increasing specific dimension order.

1.) **Take the body with the largest specific dimension and the lowest Reynolds number, this cell will have the lowest pressure. Set this to e.g. 20 Pa,** because it can be easily set with tolerable measurement errors.

2) **Take the body with the lowest specific dimension and the largest Reynolds number. This cell will have the largest pressure. Set this to the 90% of the maximum pressure**.

3) **From the lowest pressure, calculate the other pressures in the same column, meaning for the same Reynolds numbers**. Assuming that the density, kinematic viscosity and the calibration constant are constant during the measurement, **the pressures can be calculated as the following formula** (based on the definition of the Reynolds number and dynamic pressure):

$$Re_1 = Re_2 \rightarrow \Delta p_2 = \Delta p_1 \left(\frac{L_1}{L_2}\right)^2$$

Quick check: for same Re, the bigger body always has lower dynamic pressure.

4) **Now the pressures are known for the highest and lowest Re numbers for the largest body. Between these two values uniformly distribute the other pressure values in integer values.**

5) With the Eq. in point 3) **calculate the pressures in the other columns starting from the values calculated in point 4)**.

We are done, let’s start the measurement!

4.3) Executing the measurement plan

Suggested task division for 4 person:

1 person sets the choke on the car, checks the pressure values on the manometer.

1 person checks the force measuring cell and the manometer and registers the values.

1 person applies the bodies to the scale arm or the separate stand, starts and shuts off the fan.

1 person supervises the measurement plan and the progress, communicates the body shape and configuration to be measured and the pressures to be set.

In the measurement table one row should contain the following data:

Shape of the body, serial no.

Specific dimension of the body

Measuring arm or separate stand configuration?

The realised pressure value (in a small extent it can differ from the prescribed) [Pa]

Measured force [N]

Suggested measurement order:

1st body:

Wind tunnel switched off, manometer nulling.

Apply body on scale arm, force measuring device nulling, starting the fan.

Measurement of the body in order of increased choking (decreasing pressure), then switch off fan.

Apply body on separate stand, force measuring device nulling, start the fan.

Measurement of the body in decreasing order of choking (increasing pressure), then switch off fan.

Same for 2nd, 3rd, … bodies.

At the end of the measurement register the temperature and pressure in the laboratory again!

Pay attention to the following:

Work safety:

Do not try to alter the flow direction with a cover when the fan is running!

Only place the most necessary things on the table! Do not leave pens, pencils, etc. on the table, which can be blown away by the flow therefore causing an accident!

During pressure measurement:

Use the appropriate channel, which is connected to the manometer! Check if the connection is appropriate!

Examine the plastic tubes used for the pressure measurement for damages!

When changing bodies, make sure that at switched off fan the pressure difference is 0 Pa with a max. difference of $\pm$2 Pa.

Force measurement:

Make sure that the cell measures 0 N for switched off fan (within measurement error limits). Null the device for every body change!

Using the separate stand:

Do not let the stand touch the scale arm and make sure to set up the same configuration as with the scale arm as much as possible!

Setting and registering the pressure values:

Register the measured pressure difference, the calculated goal pressure values are not sufficient!

The pressure can be set within a 5 Pa limit for high pressures and 1 Pa for low pressures. Take into consideration that the pressure stabilizes after 5-10 seconds when you change the choking.

4.4) Checking data

Check the registered data if there are missing or unrealistic values.

Check the goal and achieved pressure values if there are any discrepancies.

Diagram on a millimetre paper:

The measured data can be checked by drawing a diagram on a millimetre paper ($p_{dig}[Pa]; F_{d,body+arm}[N]$). The points should lie on different slope straight lines starting from (0;0) for different bodies. This way a fast check can be made if there are any obvious errors in the measured data (miswriting a digit, no nulling in the beginning, …)

4.5) Cleaning, hand written documentation

Clean up and place everything back in the box!

Requirements of the hand written documentation:

Show the title of the measurement, time and date, names of the group, NEPTUN code and signature on the title page.

Page number and date on every page and the name of the instructor!

Every paper which contains information, which you would like to use for evaluation (measured data, sketches, equations) **must be the part of the documentation,** meaning also the title page and the mm-paper diagram! Redundant data is not to be included!

For accepted documentation the instructor signs every paper which is to be submitted.

Evaluation

5. Evaluating the measurement data

Table 1. Measured and calculated data of bodies

Table 2. Calculating the density and viscosity: At the beginning and at the end of the measurement temperature and pressure data of the laboratory was registered. Based on the average calculate the density and viscosity. Register in the table.

Table 3. Calibrating the manometer: show the raw data, then calculate the pressure from the Betz manometer: water column mm to Pa

$$\Delta p_{Betz} = \rho_{water} g h_{Betz}$$

Show a diagram of these values against the digital manometer values. Put a regression line on the points and show the equation of the line:

$$\Delta p_{Betz} \cong k_p \Delta p_{dig} + \Delta p_{0,dig}$$

The $\Delta p_{0,dig}$ can be neglected, because the digital manometer is capable of instant nulling. The k_p constant is the calibration factor of the manometer.

Table 4. Calibration of the force measuring cell

$$k_F = \frac{m_{cal} g}{\frac{1}{n} \sum F_{dig,i}}$$

Where m_{cal} is the mass of the calibration weight, F_{dig} is the force from the measuring cell.

This is only to correct the measurement error of the scale, not for the correction of the arm lengths!

Table 5. Evaluation of the measurements.

It is advised to have all the measurement data in one table, this way the cell definitions are easier to make.

It is also advised to organize the data in a way, that measured and calculated data for one body and one velocity is in one row.

Data for one body should be organized under one each other in order of increasing velocity, thus the diagrams are easier to make and it is easier to see through data.

One row should contain the following data

- Name of the body, qualitative size (large, medium, etc.)
- aimed pressure
- realized pressure for body + scale arm configuration
- realized force for body + scale arm configuration
- realized pressure for separate stand configuration
- realized force for separate stand configuration

- average calibrated pressure difference
- calibrated force for body + arm configuration
- calibrated force for separate stand configuration

- dynamic pressure
- drag force
- velocity
- specific dimension of the body
- Reynolds number
- specific area of body
- drag coefficient

- data for drag coefficient error calculation (multiple columns)
- absolute error of drag coefficient
- relative error of drag coefficient

The average calibrated pressure difference is to equalize the difference when the pressure is set again for the elimination calculation and also to correct the value with the calibration factor.

$$\Delta p = k_p(\Delta p_{dig,body+arm} + \Delta p_{dig,arm})/2$$

The calibrated force **(measured on the longer arm of the scale) can be calculated from the value measured on the digital force measuring cell:**

$$F_{body+arm} = k_F F_{dig,body+arm}$$

$$F_{arm} = k_F F_{dig,arm}$$

The dynamic pressure is corrected with the correction factor of the wind tunnel:

$$p_{dyn} = K\Delta p; K = 0.908$$

The drag force:

$$F_d = F_{d,body+arm} - F_{d,arm} = \frac{k_2}{k_1}\left(F_{body+arm} - F_{arm}\right)$$

The velocity, Reynolds number and drag coefficient are calculated according to the definitions. For the drag coefficient the dynamic pressure is directly used.

For the error calculation see the appendix.

Diagram 1. Calibration of the manometer

Diagram 2. Calculated drag forces as a function of calculated dynamic pressure.

Diagram 3. Calculated drag coefficient in one diagram for every bodies with different data as a fuction of Reynolds number. Also show the absolute error!

Evaluation.

Compare the results to theoretical data, write the conclusions in the documentation, prepare a presentation about the results. Compare the results to literature data. Evaluate the errors separately and draw conclusions about the effects of them on the uncertainty of your conclusions.

Appendix. Error calculation of the drag coefficient.

For sake of simplicity, the calculations are based on already calibrated data.

Based on former equations:

$$c_d = \frac{F_d}{\frac{\rho}{2} v^2 A} = \frac{F_{d,body+arm} - F_{d,arm}}{p_{dyn} A} = \frac{\frac{k_2}{k_1}\left(F_{body+arm} - F_{arm}\right)}{K \Delta p A}$$

We assume that for the constant group and for the specific area (and also for the calibration factors) the measurement error is negligible. This way the drag coefficient is the function of three independent variables:

$$c_d = f(X_1, X_2, X_3)$$

Where:

$X_1 = F_{body+arm}$ → The calibrated, measured body + arm drag force (before correcting with arm lengths)

$X_2 = F_{arm}$ → The calibrated, measured drag force on the arm (before correcting with arm lengths)

$X_3 = \Delta p$ → The calibrated average pressure difference

So for the partial derivatives the following function can be used:

$$f(X_1, X_2, X_3) = \left(\frac{k_2}{k_1 K A}\right) \frac{\left(F_{body+arm} - F_{arm}\right)}{\Delta p}$$

The absolute errors of the needed variables:

$$\delta \Delta p = 2\ Pa$$

$$\delta F = 0.02\ N$$