Budapest University of Technology and Economics
Department of Fluid Mechanics

BSc M01 Measurement Guidelines

INVESTIGATION OF DRAG COEFFICIENT ON BLUFF BODIES

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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 the Reynolds number and the compared properties, which is to be determined during the measurement.

(A body is called **bluff** if the drag force on it comes from the pressure difference between the front side and the back - mainly. The shear force is relatively small. For thin, aerodynamic bodies the opposite is true.)

2. Preparation for the measurement

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

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

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. 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 is:

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

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

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

For bluff bodies the specific area is the area of the projection of the body that is 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):

$$c_d = f(\text{shape, position, roughness, Re})$$

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

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

The specific dimension (or length) is the smaller of 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 (μ) is almost independent of temperature. The air is ideal gas – practically. The density (ρ) can be calculated according to the ideal gas law based on the measured temperature and pressure in the laboratory:

$$\rho = \frac{p_0}{R_{air} T}$$

4. Description of the measurement devices

4.1. **Mobile measurement table (car)**

It is practically a mobile, open test-section wind tunnel. The uniform outflow is produced by a large high pressure tank (the body of the car), and a confusor. Before the confusor a filter layer and a guiding grid make the velocity profile even more flat.

It also provides 2 pressure taps to help the velocity measurement. The manometer has to be connected to the taps. The indicated pressure should be corrected by a constant factor to get the dynamic pressure.
According to a former calibration (performed with a Prandtl tube) the following relation is valid:

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

The dynamic pressure can be 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 turns a spindle and translates a circular plate in front of the suction. If the inlet is totally closed, nearly 0 Pa pressure (or zero velocity) can be achieved. For the first 10 revolutions of the control wheel the pressure drastically increases until 90% of the maximum achievable pressure, then for another 8 revolutions the pressure increases slowly until the maximum.
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. Measuring the drag force

The drag force acting on the tested body is measured by a force gauge (force measuring cell + display). The body is screwed on a thin-and-smoothed shaft (steel, dia=4mm) The other end of the shaft is completed by a small steel part that can be fitted to the force cell. On the measuring end of the cell a special magnetic socket is fastened. It makes the work easy, and a magnet limits the force loading the cell. (the cell is sensitive and vulnerable)
The whole force cell is covered by an aluminium tube (dia=28mm) to protect is against accidents AND the wind. We want to measure the drag force on the tested body alone – without other forces. After screwing the body on the shaft, they should be attached onto the socket and the grey PVC cap should be replaced. It alse protects the cell and the socket against the wind.

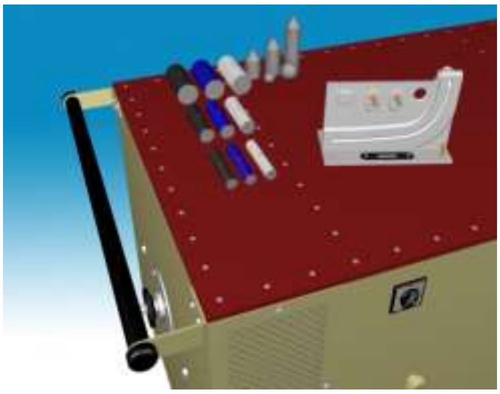

Figure 1: The mobile wind tunnel (measuring car)

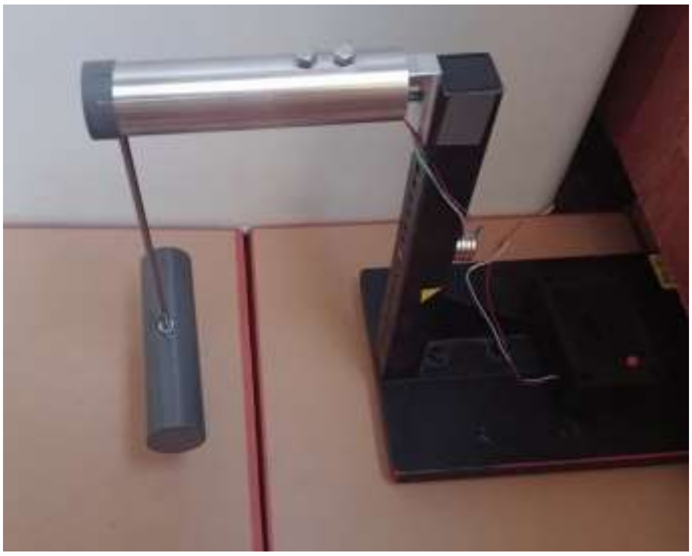

Figure 2: The black scaffolding holds the force cell (hidden in the thick alu tube).
At the left side a body (a cylinder in this case) is “hanged” onto the force cell by a thin shaft.

Figure 3: The shaft and the body under test

Measurement steps

Recording basic data

Make notes on the data of the selected bodies (shape, dimensions, roughness values). Also record the flow direction compared to the body, the type, serial no. of the used equipment (manometer, force measurement device, etc.). Write down the temperature and pressure values indicated by the equipments placed on the laboratory wall.

Calibration of the manometer

(described earlier)

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!

Zeroing

Connect the manometer to the pressure taps on the side of the car and zero it. (the fan should be switched off)

Determination of the measuring limits

Start the fan, measure the maximum pressure can be reached by the fan. Call it $p_{abs\ max}$

(Actually, for measuring the maximum pressure even an uncalibrated manometer is sufficient.)

Multiple it by 0.9.

$$p_{max} = 0.9*p_{abs\ max}$$

That p_{max} pressure will be the highest one we will try to set by the choke. (The 0.9 factor gives us a safety headroom.)

Let us choose the planned minimum pressure is:

$$p_{min} = p_{max} /25$$

It determined by the limited resolution of the manometer and the force gauge. If you are inclined and feel strength to do careful measurements with low wind you can chose a smaller p_{min} e.g. p_{max} /50.

The v_{min} and v_{max} can be calculated from them using the equation : $p_{dyn} = \frac{\rho}{2} v^2$

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 can specify either the similarity of velocities or the 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 on 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.

Planning for same prescribed velocities

Divide the $p_{min} - p_{max}$ interval into equal parts. But the equal means that the ratio of the adjacent values should be equal, NOT the difference.

Obviously the equally spaced pressures will result in equally spaced velocities too.

(The actual velocities will be calculated afterwards, at home during the evaluation.)

For same Re numbers

Let's imagine for example three bodies of different size and 8 different Reynolds numbers. The velocities in this case must be altered for every point (24 pressure values).

The question is: which range of Re-numbers can be reached with the (previously determined v_{min}-v_{max} interval AND the given body sizes.

Obviously, a high Re-number is easier to realize with larger bodies. That is why the smallest body will present a limitation. That's why the L_{imn} should be used with v_{amp} (and the viscosity) to calculate Re_{mix}. Similarly, R_{ain} should be calculated with v_{ein} and L_{ax}.

As a result, we got a Reynolds interval that can be achieved for all the bodies (in the prescribed velocity interval)

Finally, the Re interval has to be divided equally-spaced (on a logarithmic scale). For example in a case of 8 Re numbers the $Re_1 = Re_{min}$; $Re_8 = Re_{max}$ and Re_2 …Re_7 are distributed in between, and the ratio of the neighbouring ones is always constant.

Quick check: Calculate all the 24 velocities in excel). If their minimum equals to v_{ein} and maximum to v_{amp} : you can have a coffee…. or…. you can start the measurement.

Calibration of the force measuring cell

- Zero the cell (without wind)
- Hang the calibration weight onto the measuring shaft
- Read and record the indicated force value

Repeat the measurement 5 times.

4.3) Executing the measurement plan

A possible way of sharing the tasks:

1 person sets the choke on the tunnel, 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 force cell, 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
- The prescribed pressure [Pa]

- The realised pressure value (it can differ slightly from the prescribed one) [Pa]
- Measured force [N]

Suggested measurement order:

1. Wind OFF.
2. Apply the selected body on the force cell,
3. wait until the motor comes to a halt entirely.
4. Zero both the force and the pressure gauges.
5. Wind ON
6. set the smallest pressure (we will start[1] from the small winds)
7. wait 10-15s setup time
8. Measure and record the force and the pressure.
9. set the next pressure (adjusting the choke)
10. Goto 7 (if not ready yet)
11. end.

Do the same for all bodies.

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

[1] Now, at the beginning (not far from zeroing) the zero error is the smallest. (Later it will increase with time.) So this is the best opportunity to measure the smallest pressures and forces, they are the most sensitive to zero error.

Pay attention to the following points:

Work safety:
Do not try to alter the flow direction with a cover when the fan is running!
Remove the unnecessary things from 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 used plastic tubes for damages!
While changing bodies, make sure that the fan is switched off. (and always use every opportunity to zero the manometer)

Force measurement:
Make sure that the cell measures 0 N for switched off fan (within measurement error limits). Zero the device after changing the body!

Setting and recording the pressure values:
Always record the measured pressure difference! The pre-calculated goal pressures are not sufficient, (not accurate enough)!
The pressure can be set easily within a 5% of the reading values. This accuracy is enough for the pressure setting, but not enough for the measurement.
Take into consideration that the pressure stabilizes after 5-10 seconds when you change the choking.

4.4) **Checking data**
Check the recorded 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[N]).

The points should lie on straight lines of different slope starting from (0;0) for the different bodies. This way a fast check can be made if there are any obvious errors in the measured data (miswriting a digit, no zeroing in the beginning, …)

4.5) Cleaning, completing the handwritten documentation
Clean up and place everything back in the box!
Requirements of the handwritten 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 the title page and the mm-paper diagram as well! Redundant data is not to be included!
For accepted documentation the instructor must sign every sheet of 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 recorded. Based on the average, calculate the density and viscosity.

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

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

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:

$$p_{Betz} = k_p\, p_{dig} + \text{offset}$$

The offset is practically zero and it can be neglected, because the digital manometer will be zeroed every now and then. The k_p constant is the calibration factor of the digital manometer.

Table 4. Calibration of the force measuring cell

$$k_F = \frac{m_{cal} g}{\frac{1}{n}\sum_i F_{dig\_i}}$$

Where m_{cal} is the mass of the calibration weight, F_{dig_i} is the indicated values by the force measuring device. ($g=9.806 m/s^2$ in Budapest)

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 (and read).
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 by velocity in an increasing order, thus the diagrams are easier to make, and it is easier to look through data.
One row should contain the following data

- Name of the body, qualitative size (large, medium, etc.)
- aimed pressure
- indicated pressure
- dynamic pressure (calibrated, corrected)

- indicated force
- dynamic force (calibrated)

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

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

The **calibrated force** can be calculated from the value measured on the digital force measuring cell:

$$F_{body} = k_F\, F_{dig}$$

F_{dig} the reading value on the device, k_F is the calibration factor (hopefully not differing from 1 heavily)

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

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

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 body with different data as a function 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:

$$c_d = \frac{F_d}{\frac{\rho}{2} v^2 A} = \frac{F_d}{p_{dyn} A} = \frac{F_d}{K \Delta p A}$$

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:

$c_e = f(F_d, \Delta p)$

Where:

F_d is the drag force

Δp is the pressure reading from the digit manometer.

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

$$f(X_1, X_2) = \frac{F_e}{\Delta p K A}$$

The absolute errors of the needed variables:

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

$$\delta F = 0.0004 N$$

You are free to modify these values in case you experienced higher or lower uncertainties during the measurements. But never forget to write them down – with some explanation.