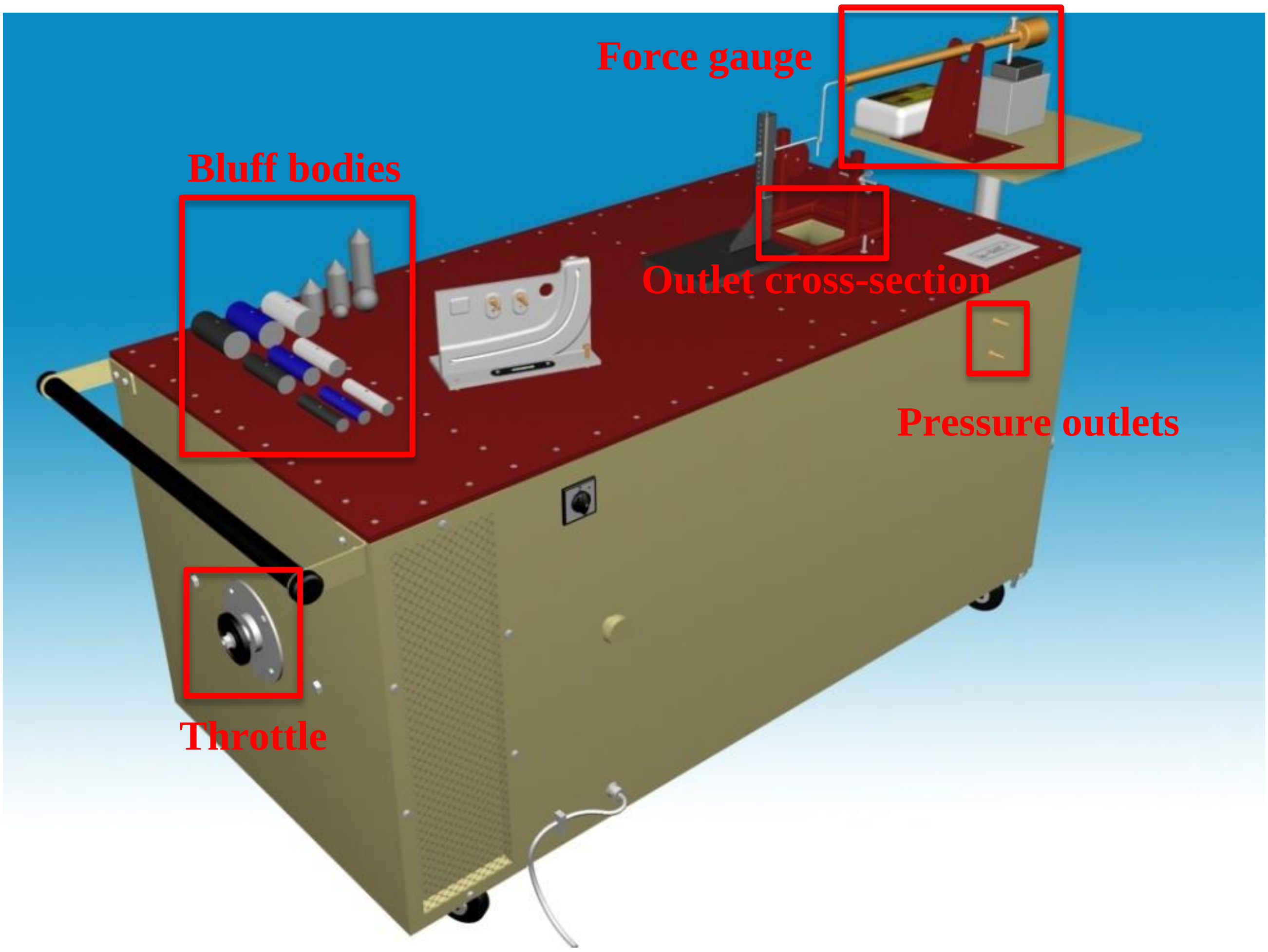


M01 measurement

INVESTIGATION OF THE DRAG COEFFICIENT OF BLUFF BODIES

I. Aim of the measurement

Determination of drag forces acting on different, but comparable in some properties, bluff bodies at various speeds through pressure measurements. The measurement aims to investigate the dependence of the drag coefficient on the Reynolds number and on compared properties of the bluff bodies.
(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. An example would be an arrow.)

II. Preparation for the measurement

After a thorough **study of this measurement guide, prepare the measurement work plan with tables in which the data to be measured can be recorded.** The preparation of the tables is very important, since the time during the measurement will be short and the prepared tables help to record the data quickly.

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

1. Theoretical background

Bodies (e.g. buildings, vehicles) in the fluid flow are affected by aerodynamic forces. The component of this force parallel to the direction of undisturbed flow is called the drag force. The F_e drag force depends on the v_∞ velocity of undisturbed flow, the A surface of the body (perpendicular) and the shape of the body (c_e characterized by the drag coefficient), i.e.,

$$F_e = \frac{\rho}{2} v_\infty^2 A c_e,$$

where the $\frac{\rho}{2} v_\infty^2$ group is, by definition, the dynamic pressure, i.e.,

$$p_{din} = \frac{\rho}{2} v_\infty^2.$$

The F_e drag force is therefore directly proportional to the p_{din} dynamic pressure, in addition to the A surface of the body, and to the c_e dimensionless drag coefficient

$$F_e = p_{din} c_e A.$$

The A surface of the body for bluff bodies is the area of the projection of the body perpendicular to the flow. According to experience and theoretical considerations, the c_e drag coefficient of various bluff bodies, in the flow speed and size range to be examined, depends on the exact shape of the body, its angular position relative to undisturbed flow, its surface roughness and the Reynolds number, i.e.

$$c_e = f(shape, position, roughness, Re).$$

The Reynolds number is a dimensionless group defined by the flow velocity (v_∞), the characteristic size of the body (L) and the density of the fluid (ρ), and dynamic viscosity of the fluid (μ).

$$Re = \frac{v_\infty L \rho}{\mu}.$$

The two material constants (density and dynamic viscosity) are usually combined and called kinematic viscosity (ν)

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

Dynamic viscosity refers to how much shear force the fluid resists to at a given speed. Then the inertial mass of the fluid does not play a role, since there is no acceleration, we are talking about a steady state.

In the case of kinematic viscosity, the inertial mass is also taken into account. It is characterized by e.g. how quickly eddies of a given size in a disturbed fluid decay when left alone.

Air is an ideal gas with a good approximation, so the air density can be obtained from the ideal gas law

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

p_0 : the static pressure, approx. 100 [kPa], the exact value can be read from the instrument on the laboratory wall

T: absolute temperature (unit [K]). The temperature can be read from the thermometer on the lab wall in [°C].

R_{air}: the **specific gas constant** for air is 287.1 [J/(kg K)]. (Not to be confused with the universal gas constant, which is R = 8.3144626 [J/(mol K)]. The conversion number between the universal and specific gas constant is the molar mass of the given gas, which in the case of air is 0.02896 [kg/mol].)

The dynamic viscosity of ideal gases can be considered independent of pressure, but increases with absolute temperature. For air the dynamic viscosity is 18.2E-6 [Pa s] at 20 [°C].

2. Description of the measuring devices

The mobile measurement car. Measurement and adjustment of dynamic pressure

The air flow is created with a portable wind tunnel with an open measuring area. The uniform velocity distribution of the exiting air is ensured by the confusor, filter layer and guiding grid placed in front of the exit opening.

There is a pressure outlet in front of the confusor and at the exit cross-section, to which we must connect our pressure measuring instrument. The pressure difference measured here gives the dynamic pressure. However, we need the dynamic pressure in the vicinity of the bodies placed in the flow, which is given by the following empirical relation

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

where Δp the dynamic pressure can be measured between the pressure outlets of the measuring cart and p_{din}at a height of 140 mm in the middle of the outlet cross-section. This is used to calculate the desired dynamic pressure during the measurement.

The dynamic pressure is controlled by throttling the fan on the suction side. The choke mechanism is visible through the plexi-glass window on the top of the car, and can be manually adjusted with a wheel on the side. The throttling is solved by a movable circular plate in front of the suction cross-section, which can be adjusted via a spindle mechanism. When completely closed, we can set almost 0 Pa, while opening the cross-section continuously, the pressure increases drastically with the first 10 revolutions of the wheel to 90% of the maximum value, and slowly increases with another 8 revolutions until the fully open position.

The wheel can be moved **without a big effort**. Be very careful **not to overtighten the spindle** near the end positions, because it may break! (It works similarly to the water tap: closes by turning to the right!)

Measuring the drag force

The bodies must be mounted on the load cell for the measurement. At the end of the measuring stem, the M5 spindle is wound into the threaded hole of the body and countersunk with the nut. The other end of the measuring stem is attached to the end of the force gauge, where it is held by a small neodymium magnet. The whole thing is designed so that the operation is simple, but the force gauge cannot be overloaded by an accidental wrong move. The force gauge is protected from flow by a cover. The whole thing is designed in such a way that the measurement result can be as accurate as possible.

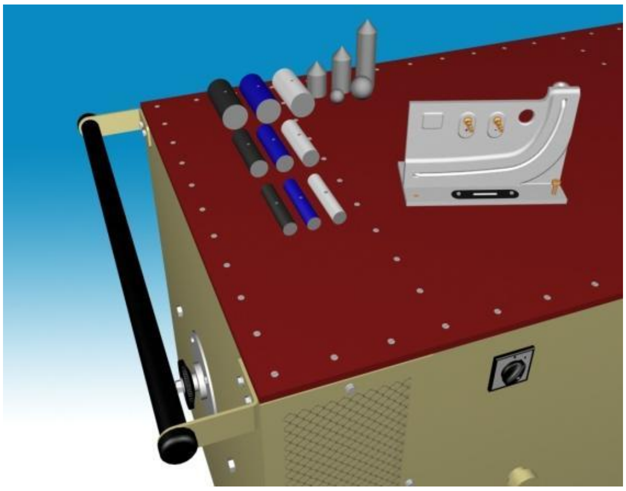
Possible sources of error:

- The flow also gets into the force gauge, and its force is also shown in the result. The casing serves to exclude this.
- The force gauge (+covering) is close to the tested body, so it interferes with the flow, which modifies the force. To reduce this, we placed the force meter behind the body, at a decent distance from it. (long stem holds the body to be measured)
- The long measuring stem is not covered, unfortunately it can also be affected by flow force. Therefore, the measuring stem is thin, smooth, and parallel to the direction of flow (or the direction of sensitivity of the force gauge).

We try to minimize the measurement error based on the above considerations and designs.

Since the examined flows are turbulent, a fluctuation can also be experienced in the force signal. To reduce this, moving averaging is set in the force meter program.

The moving average means that in this case it measures one piece of data every tenth of a second, fits them into a time series, and always shows the average of the latest N samples on the display.



1 . Fig. Measuring trolley, movable wind tunnel

2 . Fig. Force measuring stand with the measuring stem hanging from it and a cylinder on it. The shiny tube is the windshield, inside it is the load cell/force gauge.

3 . Fig. Cylindrical body on the measuring stem. The steel component glued to the left end of the stem ensures a stable connection to the magnet, but also the ability to tilt it.

III. The measurement

1. Recording of basic data

The shape, dimensions, roughness of the selected bodies and the applicable **flow direction** must be recorded in the measurement plan. The dimensions of the bodies must be measured with a caliper.
The type and serial number of the measuring devices (measuring cart, pressure gauge, force measuring gauge) must be recorded in the measurement plan.
Finally, read the wall instruments in the lab **for temperature and air pressure values** of the room.

In the measurement plan, there should be an empty column for each data to be recorded, that helps to avoid forgetting some data.

2. Calibrations

Calibration of the pressure gauge

We can calibrate the digital manometer using the Betz manometer. Both instruments must be zeroed. The positive inputs (on both pressure gauges) must be connected to the fully extended syringe. You don't have to worry about negative inputs, the reference point for both instruments will be the ambient pressure.
During calibration, the pressure can be changed between 0 and 500 [Pa] by adjusting the syringe per 50 [Pa]. The values must be recorded in a table: h_{Betz} [mm] and p_{dig} [Pa] (1 water column mm ≈ 10Pa).

Calibration of the load cell/force gauge

The calibration of the force measuring cell/gauge must be performed **with the wind tunnel switched off**. After the force meter has been zeroed, the provided measuring weight must be hung on the force meter and the displayed value must be read.

3. Starting and testing the car, measuring the maximum and minimum pressure

Connect the **pressure gauge** to the pressure outlets of the car and **zero it when the wind tunnel is completely off**. Start the fan with the outlet uncovered. In throttled conditions, the minimum flow speed can be set and the associated pressure difference can be determined. By opening the throttle, the maximum flow speed can be set and the corresponding pressure difference recorded! (This will determine the lower and upper limit of the speed range that can be covered.)

Before measuring, it is advisable to check the pressure-transmitting silicone pipes to make sure they don't have small cracks or tears. Critical points are the places of connection to the pressure outlets. The inspection can be carried out by visual inspection.

4. Preparation of the measurement program, determination of target pressures

The assignments, in general, require measurements on the same velocities or *Re numbers*. On the other hand, only pressure values can be measured on the measuring trolley. Therefore, it is necessary to decide in advance (knowing the dimensions and properties of the bodies to be measured) and record in a table what value will be needed on the pressure measuring device at the given measurement point. The pressure values recorded in the table are called target pressures. The determination of these values is understood as the preparation of **a measurement program** .

Below we provide the way to set the given speed, or how can the target pressure values be determined from the Re-numbers.

- We measure the gauge-car pressure corresponding to the maximum flow speed.
- 90% of the pressure corresponding to the maximum flow speed will be the maximum pressure p_{max} set by us.
- 16th part of p_{max} is the minimum pressure p_{min} .

We will work in this pressure range. Based on p_{max} , p_{min} , we calculate the achievable minimum and maximum flow speeds using the formulas above.

If we have to measure **at several speed points** , the corresponding dynamic pressure values can be specified from those, from which the necessary car pressures can be derived. (The latter will have to be adjusted by turning the throttle.)
(The points should always be equally distributed on a logarithmic scale. That is, the *quotient of adjacent values* should be constant, not the difference.)

If, on the other hand, **the same *Re* numbers are prescribed for 3 bodies of different sizes**, the largest and the smallest *Re* number that can be realized with all three bodies must be calculated.
Re number increases with the size of the bodies, so Re_{max} is the most difficult to achieve with the smallest body. So Re_{max} is calculated with the smallest size and maximum flow speed.
We proceed similarly to the calculation of Re_{min}, i.e., we calculate with the largest body and smallest flow speed. We choose additional values between the Re_{min} and Re_{max}, these are our *Re* numbers to be used. The associated speeds, dynamic pressures, car pressures are calculated using the known formulas.

5. Quick check

On the basis of the above, the target pressures are known in any case, the setting of which can be checked with the pressure gauge. The preliminary calculations are correct if all the target pressures fall between Δp_{max} and Δp_{min} .

6. Execution of the measurement program

A row in the table of measurements contains the following data:

- Body shape, serial number.
- Typical body size.
- The Δp_{target} is the target pressure of the measuring car (pre-calculated) [Pa].
- The $\Delta p_{measured}$ is the measured gauge-car pressure (adjusted by throttle) [Pa].
- The measured force value [N].

Recommended sequence of operations for a body:

- Throttle adjustment for minimum flow speed.
- (Disabling the channel, we wait until it stops.)

- Mounting the body on the force gauge, positioning the body in the axis of the outlet.
- Reset both force and pressure gauges.
- Turning on the wind tunnel.
- You have to wait for the steady state to settle (5-10 seconds), then the instruments can be read. Record the readings, then set a new pressure and so on.

At the end of the measurements, record the atmospheric temperature and pressure of the room again.

What else should we pay attention to during the measurement?

1. Work health and safety:

Do not try to divert or cover the wind from the activated wind tunnel with the cover, because it is dangerous!
We place only the most necessary things on the surface of the table! Do not leave stationery or other small objects on the table, which could be blown away by the air current and fall or cause injury!

2. Checking the pressure measurement:

Make sure to read the channel that is connected! Check the correct connection of the instrument!

3. Force measurement error possibilities:

Don't forget to reset the force meter when changing bodies, because the bodies have different weights!
Let's make sure that the balance (within measurement uncertainty) shows 0 N with a perfectly stationary wind tunnel!
Since the switched-off wind tunnel stops only slowly, in this case we can divert the weak flow by simply covering the opening of the wind tunnel with a rigid sheet (e.g. a folder).

7. Checking the recorded data

We check the recorded data to make sure there are no gaps or suspicious values even at first glance. We check that there is no big difference between the target values and the realized values.

On the millimeter-paper, we plot the values read from the force gauge as a function of the pressure. The points are fitting a different slope for each body, but must fit on (almost) straight lines starting from the origin.

8. Finishing the measurement

Handing over the handwritten form of the measurement report to the instructor for signature. The instructor can check the inventory of the equipment belonging to the measuring stand.

The **handwritten report**:

- The title, time and date of the measurement, the name of the students performing the measurement and the Neptun code should be included on the title page!
- Each sheet should include the page number and date, as well as the name of the instructor in charge of the measurement.

- All pages containing information (measured data, sketch, formula) that will be used later during the evaluation must be part of the report, including the title page and millimeter-paper diagram!
- Papers containing multiple written data (drafts) do not need to be submitted.
- Upon acceptance of the report, the instructor signs each page arranged for submission.

IV. Evaluation, preparation of report

1. Evaluation of the measurement task

Table 1. Measured and derived geometric data of bodies.

Table 2. Calculation of the environmental constants: we calculate the air density and viscosity based on the arithmetic averages of the data taken at the beginning and end of the measurement. We record the results in a table.

Table 3. Calibration of the pressure gauge : After recording the raw data, convert the water column values read on the Betz manometer to [Pa]:

$$\Delta p_{Betz} = \rho_{víz} g h_{Betz} .$$

These values are represented on a diagram as a function of the values read on the digital pressure gauge. Show the regression line of the points on the diagram and write out the equation of the line

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

Since the pressure measuring instrument has an immediate zeroing option, which we used several times at the beginning and even during the measurement, the Δp_{0dig} constant of the regression line is not informative for us. The slope of the regression line k_p will be considered the calibration factor of our digital pressure gauge.

Table 4. Calibration of the load cell : the ratio of the calculated weight of the calibration mass and the average of the measured values is the calibration factor of the force gauge:

$$k_F = \frac{mg}{\frac{1}{n}\Sigma F_{dig,i}} ,$$

where *n* is the number of calibration points.

5. Table. Table for processing measurements:

It is advisable to include the processing of all measurement data in a single, large table, and to arrange the data in such a way that measurement data measured with one body, at one speed, and all data resulting from their processing are in one row. It is advisable to arrange the data belonging to a body directly below each other, in increasing order according to speed, so it is best to provide diagrams.

A row contains the following columns:

- body shape, serial number,
- typical body size,

- characteristic dimensions of the body,
- the Δp_{target} measuring car pressure target value (calculated in advance) [Pa],
- $\Delta p_{measured}$ is the car pressure (adjusted by throttle) [Pa],
- dynamic pressure [Pa]:
  - $p_{din} = K\Delta p,\ K = 0{,}908$,
- flow speed [m/s],
- Reynolds number,
- the measured force value [N],
- drag force after calibration [N]:
  - $F_e = k_F F_{mért}$.
- drag coefficient.

Finally, the error calculation is also in the same line:

- the data and members required for error calculation (in several columns),
- the absolute error of the drag coefficient,
- the relative error of the drag coefficient.

See below for error calculation.

Diagram 1. Calibration of the pressure gauge.

Diagram 2. The calculated drag forces are a function of the calculated dynamic pressure.

Diagram 3. The calculated drag coefficient values on a common diagram.
Each body is plotted with a separate line as a function of the Reynolds number. The absolute errors of the drag coefficients should also be indicated with error bars.

Evaluation of the results

Interpret the obtained results based on the theory, record our findings in the report, and present them at the presentation. Compare the results with the values found in the textbook or with other literature. Evaluate the impact of calculated errors on the uncertainty of the conclusions.

2. Error calculation of the drag coefficient

When calculating the error, start from the calibrated data. According to the previously established relationships

$$c_e = \frac{F_e}{\frac{\rho}{2}v^2 A} = \frac{F_e}{p_{din}A} = \frac{F_e}{K\Delta p A}.$$

It is assumed that the measurement error in the *K* constant and in the cross-section of the measured dimensions of the body (also in the calibration factors) is negligible. Then the drag coefficient is a function of two independent quantities

$$c_e = f\left(F_e, \Delta p\right),$$

where F_e is the measured drag force and Δp is the measured pressure difference. So, when determining the partial derivatives, the function c_e must be derived according to these variables.

The following values can be taken as the absolute errors of the above quantities $\delta\Delta p = 2Pa$ and $\delta F = 0.0004N$.