Measurement of the drag coefficients of different bodies in an NPL type wind tunnel

1. Aim and practical aspects of the measurement

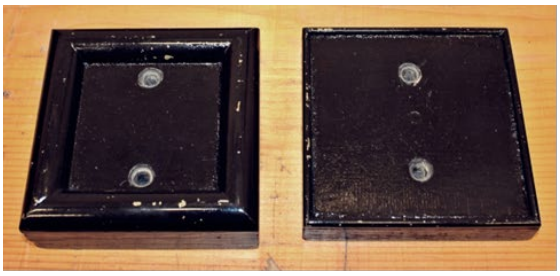
Knowing the forces and moments acting on bodies subjected to fluid flow is crucial for designing vehicles, buildings, and other structures.

In the present measurement, the aerodynamic drag of different bodies will be analyzed by measuring the drag force acting on them as the function of several geometrical parameters (slabs of different chamfer radius, perforated plates of different porosity) and the Reynolds number characterizing the flow. There are 4 series of bodies prepared for the measurement (**Fig. 1**), the edge lengths perpendicular to the flow direction are uniformly L = 100 [mm].

The available body types are:

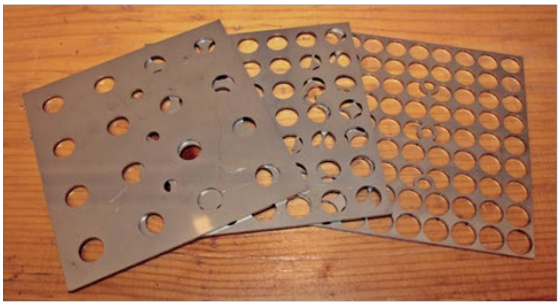
Series "A" and "B": The task is to measure the drag coefficient of slabs aligned perpendicularly to the flow direction. The slabs have different chamfer radii. (Bodies in series "A" are painted black, while the bodies in series "B" have a natural wood surface.)

Series "C" and "D": The task is to measure the drag coefficient of several steel plates with holes. In series "C", the impact of the porosity of the bodies (i.e., the ratio of the total area of the holes by the entire L^2 cross-section area of the plate) is to be analyzed. In series "D", the bodies have identical porosity, but the layout is different.

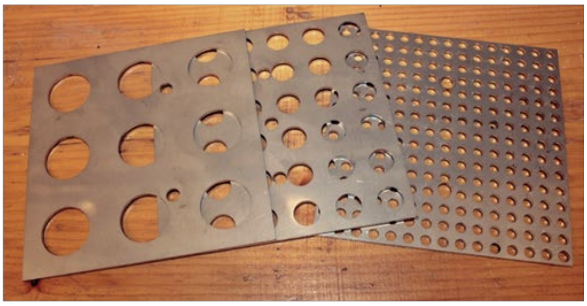


(A)

(B)



(C)



(D)

Fig. 1. *Samples of the different body types to be tested.*

2. Measurement setup

The drag coefficients of the bodies must be measured in the NPL (National Physical Laboratory) type wind tunnel of the Department of Fluid Mechanics. The NPL type refers to a closed test section wind tunnel operating in suction mode, ensuring a low wind speed (max. 15 [m/s]). Its layout is shown in **Fig. 2**. At the end of the wind tunnel, there is an axial fan is, which is driven by a DC motor, the speed of which can be controlled continuously between 0 and 1500 [1/min] using a potentiometer, between 0.0 and 10.0 positions. The uniformity and the low turbulence level of the flow are ensured by the flow straightener elements located after the bellmouth intake and the contracting geometry of the confuser section. The test section of the NPL type wind tunnel has a square cross-section of 500 × 500 [mm] and a length of 2.2 [m].

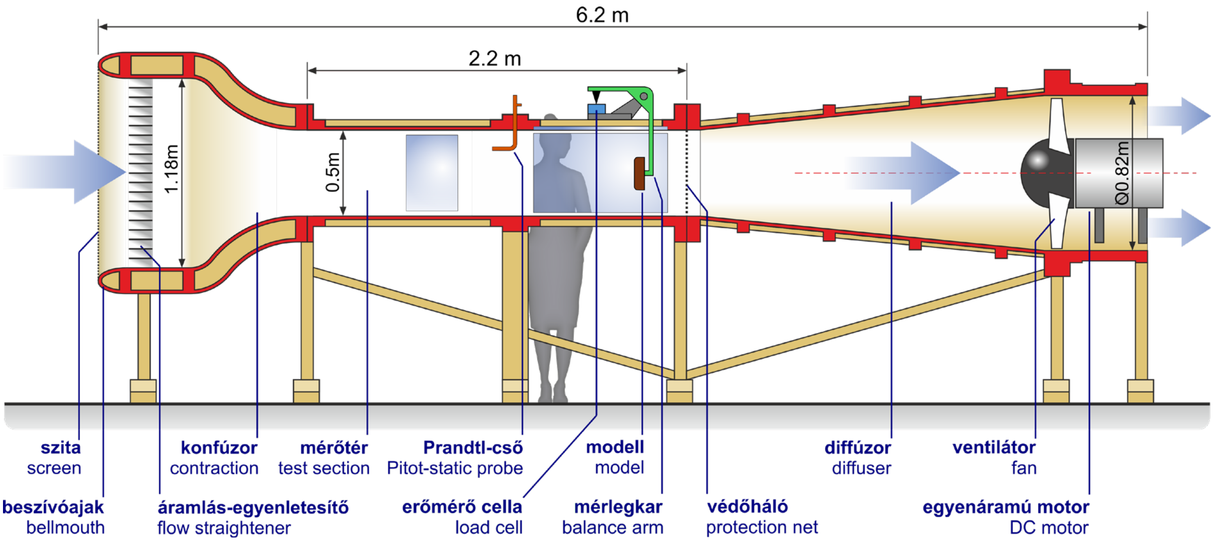


Fig 2. *The layout and characteristic dimensions of the NPL type wind tunnel.*

The air speed in the test section can be measured by a **Pitot-static probe** (also known as a Prandtl tube) mounted on the wind tunnel wall. The Pitot-static probe can be connected to a digital handheld manometer (user manual: **[1]**) using silicone tubes. The examined bodies can be mounted on the balance arm extending into the wind tunnel. The other arm of the balance rests on a **load cell**. The force measured by the load cell can be read from a digital display (digital scale).

Importantly, the force displayed on the screen is not equivalent to the aerodynamic force acting on the examined body. Moreover, the scale displays the force in kilograms, which must be converted to newtons after the measurements, during the post-processing of the results, based on the gravitational acceleration (g = 9.81 [m/s^2]).

The type of the examined bodies to test, as well as the potentiometer positions to set, are given in your individual measurement task.

3. Measurement procedure

3.1. Record the ambient temperature and barometric pressure in the laboratory before starting the measurements and after finishing them.

Use the thermometer and barometer located in the front of the lab.

3.2. Perform the calibration of the digital manometer via comparison to a Betz type manometer.

3.3. Perform the calibration of the digital scale using the available calibration weights.

The calibration must be performed using at least 2 calibration weights, in at least 4 steps*, including the zero-weight setup, when the scale should also be zeroed. Make sure that the calibration weights are placed directly above the load cell on the balance arm.

* E.g., using 0 [g], 100 [g], 200 [g], 100+200 [g] weights.

Attention: make sure that the balance arm can rotate freely around the axis and that it is not in contact with other objects that would hinder its movement before and during the measurements! In case of problems, ask your instructor for help.

3.4. Measure the force acting on the body and the balance arm together as the function of the flow rate (so-called combined measurement)!

Attach the first body to the balance arm. After zeroing the digital scale, set the first potentiometer position. When the RPM of the fan, thus the velocity in the wind tunnel, has reached a steady state, record the dynamic pressure of the flow (i.e., the pressure difference shown by the digital manometer) and the force measured by the digital scale, along with noting the current potentiometer setting.

Perform the above tasks for the remaining potentiometer positions and the remaining bodies as well.

Attention: the side door of the measurement section may only be opened (e.g., for installing a body to the arm) if the fan is not moving and air speed in the wind tunnel is zero.

3.5. Measure the force acting on the balance arm only, as the function of the flow rate (so-called blocked measurement)!

Repeat the tasks listed in Section **3.4.**, but instead of the balance arm, mount the bodies on an auxiliary arm (a lever installed on the wind tunnel floor) directly upstream of the balance arm. Make sure that the balance arm is located as close to the auxiliary arm as possible, but neither the auxiliary arm nor the body touches the balance arm (**Fig. 3b**).

3.6. Record the production or inventory number of the devices and tools used for the measurement. Take photos of the tested bodies, the measurement set-up, and the measurement process. Measure all relevant geometrical dimensions.

Make a (free-hand) sketch of the tested bodies, meeting the criteria for technical drawings, and note all dimensions. Measure the relevant geometrical dimensions of the balance arm (see **Fig. 3**).

During the post-processing of the measured data, create technical drawings of the investigated bodies based on your sketches using a graphic design or CAD software of your choice, showing all the important dimensions.

4. Post-processing and evaluation of the results

4.1. Perform the correction of the pressure values measured by the digital manometer based on the calibration of the device.

Prepare the calibration diagram based on the data pairs recorded with the Betz manometer and the digital manometer. Fit a straight trendline to the data and use its equation to correct all pressure values measured by the digital device.

The calibration curve of a device of linear characteristics can be expressed in general as

$$x_{corr} = S \cdot x_{meas} + x_{offset} \quad , \tag{1}$$

in which, x_{meas} is the measured value, and x_{corr} is the calibrated (corrected) value, measured by a verified instrument. S is the slope of the regression line fitted to the $x_{corr}(x_{meas})$ data set, and x_{offset} is the offset error of the device. If the device was zeroed before the measurement, then $x_{offset} = 0$ holds by definition.

4.2. Perform the correction of the forces measured by the load cell and the digital scale.

Prepare the calibration diagram of the digital scale. Fit a straight trendline to the data and use its equation to correct all force values measured by the digital device, similarly to task **4.1**.

4.3. Calculate the density of air based on the ambient data.

Air density can be calculated from the ideal gas law:

$$\rho = \frac{p_0}{RT_0} \tag{2}$$

In the above expression, ρ [kg/m^3] is the air density, p_0 [Pa] is its absolute pressure, and T_0 [K] is its absolute temperature. R = 287.04 [J/(kg·K)] is the specific gas constant of air. Calculate the air density based on the data recorded before and after the measurements separately and use their average as a representative value in the remaining calculations.

4.4. Calculate the air velocity and the corresponding Reynolds numbers from the measured dynamics pressures.

The relationship between the static, the dynamic, and the total pressures are given by the below equation.

$$p_{\text{tot}} = p_{stat} + p_{dyn} = p_{stat} + \frac{\rho}{2} v^2 \tag{3}$$

In the above expression p_{tot} [Pa] denotes the total pressure of the fluid, p_{stat} [Pa] denotes its static pressure, and p_{dyn} [Pa] is its dynamics pressure. The latter can be calculated from the fluid's density and its local velocity (v [m/s]); therefore, the freestream velocity in the test section (v_∞ [m/s]) can be directly expressed from the pressure difference measured by the Pitot-static probe and the digital handheld manometer by rearranging equation (3):

$$v_\infty = \sqrt{\frac{2 \cdot \Delta p}{\rho}} \,. \tag{4}$$

The Reynolds number characterizing the flow can be obtained based on the freestream velocity, the characteristic length scale of the flow ($L_{ref} \coloneqq L$), and the kinematic viscosity of the fluid:

$$Re = \frac{v_\infty L_{ref}}{\nu}. \tag{5}$$

The kinematic viscosity of air can be approximated via the below formula if the absolute temperature is known:

$$\nu = \frac{0.0103865 \cdot T_0 - 1.53699}{10^5} \quad [\mathrm{m}^2/\mathrm{s}] \tag{6}$$

4.5. Calculate the aerodynamic drag forces acting on the bodies from the measured values.

The drag force acting on the body can be calculated from the measured forces (in the combined and blocked cases) as well as the geometrical dimensions of the balance arm (see **Fig. 3.**), by writing the appropriate moment equations.

$$F_{m,b+a} \cdot l_1 = F_a \cdot l_2 + F_b \cdot l_3 \tag{7}$$

$$F'_{m,a} \cdot l_1 = F'_a \cdot l_2 \tag{8}$$

In the above equations, $F_{m,b+a}$ [N] and $F'_{m,a}$ [N] denotes the forces **m**easured by the load cell in the case of the combined and the blocked scenarios. F_b [N] is the aerodynamic force acting on the **b**ody; moreover, F_a [N] and F'_a [N] are the forces acting on the balance **a**rm. The geometrical dimensions of the balance arm are denoted by l_1 [m], l_2 [m] and l_3 [m].

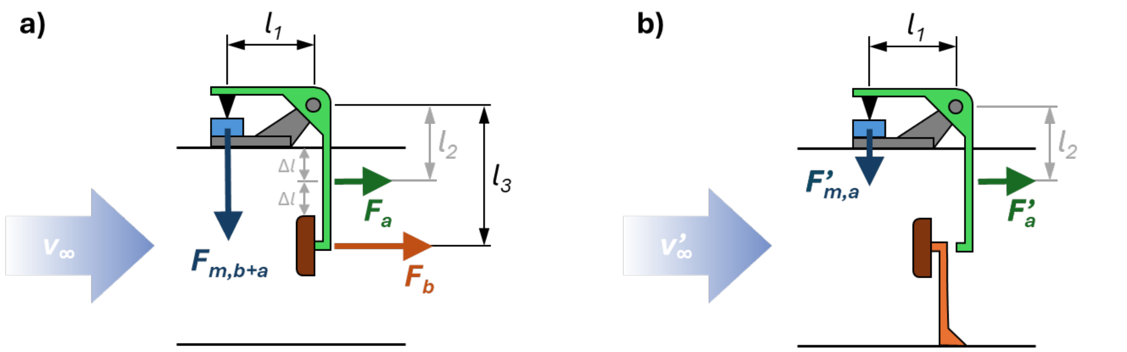


Fig. 3. *Relationship of the aerodynamic drag forces acting on the examined body (F_b) and the balance arm (F_a, F'_a) and the forces measured by the load cell ($F_{m,b+a}, F'_{m,a}$).* ***(a)*** *Combined measurement: measuring the force acting on the body and the arm together.* ***(b)*** *Blocked measurement: measuring the force acting on the balance arm only.*

As the velocity can be slightly different in the combined and the blocked measurements, even for the same potentiometer setting (**Fig. 3**: $v_\infty \neq v'_\infty$), the force acting on the arm in the blocked scenario (F'_k) must be converted to the velocity of the combined measurement (v_∞) using the below formula:

$$F_k = \left(\frac{v_\infty}{v'_\infty}\right)^2 \cdot F'_k = \frac{\Delta p}{\Delta p'} \cdot F'_k\,. \tag{9}$$

As shown in equation **(9)**, the measured value must be corrected using the ratio of the square of the velocities, as the drag force is proportional to the square of the velocity. Importantly, the ratio of the square of the velocities is equivalent to the ratio of the respective measured dynamic pressures (pressure differences measured using the digital manometer).

Based on equations **(7)** and **(9)**, the force acting on the body can be expressed as

$$F_t = \frac{F_{m,b+a} \cdot l_1 - \left(\frac{\Delta p}{\Delta p'}\right) \cdot F_a' \cdot l_2}{l_3} \tag{10}$$

Expressing F_k' from equation **(8)**, and plugging it back to equation **(10)**, the ultimate formula for the drag force acting on the body yields

$$F_b = \frac{l_1}{l_3} \cdot \left(F_{m,b+a} - \frac{\Delta p}{\Delta p'} \cdot F_{m,a}'\right). \tag{11}$$

4.6. Calculate the drag coefficient from the forces obtained in the previous task.

The drag coefficients representative of the geometries can be obtained by normalizing the drag forces.

$$c_d = \frac{F_b}{\frac{\rho}{2} v_\infty^2 A_{ref}} \tag{12}$$

In the above formula, c_d [–] is the drag coefficient, and A_{ref} [m^2] is the projected cross-section area of the body (perpendicular to the flow direction).

Use the $A_{ref} \coloneqq L^2$ assumption in all of your calculations, even if the real projected cross-section area of the body is smaller, to the changes in the drag force due to geometrical changes could translate to the drag coefficients, as well.

4.7. Conclude the measured and calculated data in a table.

Compile the measured and calibrated results (forces, dynamic pressures) and the calculated values (drag force, drag coefficient, velocity, Reynolds number) for all measurements in a single table. The table can span through a whole page, if necessary. No not forget to show the units of the quantities.

4.8. Visualize the results.

a) Create an XY chart (not a line chart!) showing the drag coefficient of the bodies as the function of the relevant geometrical parameter (fillet radius, porosity, number/size/placement of the holes). Draw separate data series for the different Reynolds numbers onto the same plot. Show the average Reynolds number characterizing each data set in the legend.

b) Create a further XY chart showing the drag coefficient of the bodies as the function of the Reynolds number. Draw separate data series for the different geometries onto the same plot. Show the geometrical parameter(s) characterizing each data set in the legend.

Important: all diagrams must be followed by a brief explanation. Conclude what is shown in the charts concisely. Analyze the dependence of the physical quantities on each other in

2-3 informative sentences and reveal cause-and-effect relationships based on your knowledge of Fluid Mechanics or based on the literature (e.g., **[2–4]**).

5. Uncertainty calculation

Based on the law of Gaussian error propagation, the total measurement uncertainty of a quantity ($\delta R \coloneqq \delta c_d$) depends on the measurement uncertainties of k pieces of independent quantities (δX_k) as follows:

$$\delta R = \sqrt{\sum_{k=1}^{n} \left(\delta X_k \cdot \frac{\partial R}{\partial X_k}\right)^2} \qquad (13)$$

During the experiment, the following directly measured quantities (X_k) are subjected to measurement error (δX_k):

- Pressures measured by the digital manometer: $X_{1,2} \coloneqq p_i \quad \delta X_1 \coloneqq \delta p_i = 2\ [\mathrm{Pa}]$
- Forces measured by the digital scale: $X_{3,4} \coloneqq F_i \quad \delta X_2 \coloneqq \delta F_i = 0.02\ [\mathrm{N}]$

5.1. Starting from equations (11) and (12), arrive to the ultimate formula for the drag coefficient, which contains only directly measured quantities and known constants.

Show this expression in the report along with a brief explanation.

If you have done everything correctly, there will be 2 forces and 2 pressures in the formula. Assume that the geometrical data do not have any measurement uncertainty.

5.2. Calculate the $\partial c_d/\partial X_k$ quantities by partially differentiating the above formula by the directly measured quantities!

Show the formulas for the four partial derivatives along with a brief explanation.

5.3. Calculate the absolute (δc_d) and relative ($\delta c_d/c_d$) measurement uncertainties of the drag coefficient by substituting into substituting to the formula of the Gaussian uncertainty propagation.

Plot the absolute and relative errors as the function of the Reynolds number in a separate chart for each, based on the data of task **4.8/b**. Show the magnitude of the absolute error using error bars on both of the charts of task **4.8**. Discuss the results in text.

6. Practical application

Find an application example of the drag coefficient that is interesting to you, carry out a short literature review on the topic, and present the Fluid Mechanics-related aspects. Recommendations:

a) Comparison of the drag coefficients of different vehicles, e.g., cars/ships/aircraft; brief analysis of the differences.
b) Description of the dependence of the aerodynamic drag and the aerodynamic power loss on the velocity. Determination of the value of the above quantities for a vehicle of your choice, for the vehicle's typical velocity.
c) Application of porous/gridded structures in environmental and building aerodynamics.
d) Comparison of the resulting drag coefficients to literature data.

e) Another topic proposed by you and previously approved by the instructor responsible for the measurement.

7. Documentation

Prepare a measurement report of 8-10 pages. Apart from the correctness of your results, pay due attention to the visual appearance of the report. The structure and style of the present document can serve as a guideline for the report, too. In case of any questions prior to submitting the report, do not hesitate to contact the instructor responsible for the measurement *on time*, and if necessary, request an appointment for an **in-person consultation**.

Importantly, check the criteria below carefully before submitting the report, as if they are not met, the report cannot be graded to more than 0 points.

- The cover page (page 0) of the report should be the standard cover page issued by the Department, filled in completely with the data of the measurement group and the measurement itself, with particular attention to the verification code proving the correctness of the calculated results.
- The report should contain the aim of the measurement, as well as the description of your individual assignment (not only its ID) and the ID and description of the examined bodies along with the figures depicting them.
- The report should contain the list of instruments used throughout the measurement, along with their production or inventory number.
- All formulas used in the post-processing must be shown in the report. Equations should not be pasted as images.
- Ideas and figures taken from other sources must be provided with references appropriately. Figures may be taken from the present document, but longer text cannot be copied continuously. Please rephrase what is written in this document so that it reflects your understanding of the methods and principles.
- Make sure that you have completed all the tasks included in the present measurement guide, especially the calibration and the uncertainty calculation!
- The hand-written notes prepared during the lab sessions, signed by the instructor(s) in charge of the measurement, should be attached to the report as an appendix (scanned, photographed). The attachment does not count in the page limit.

<u>Furthermore, the following should be considered for the formatting of the charts:</u>

- All axis titles should include the name or symbol of the represented quantity and its unit. If relevant, show the units in the legend used for identifying the different data series, too.
- The lines connecting the data points should be straight: no measurements were made between the data points, so the connectors are only meant to guide the eye.
- Choose the minimum and maximum values of the axes so that they support the conclusions you have drawn.
- Apply a logical color scheme and markers when visualizing the data consistently throughout the report.
- The color of any text on the charts should be black, and the font sizes should be (almost) the same as the body text.
- Eliminate clutter to achieve a sufficiently high “visual signal-to-noise ratio”: remove unnecessary graphic elements that decrease the understandability of the diagrams (such as

the outline around the chart, dark grid lines, unnecessary decimals, unnecessarily small ticks on the axes, excessive data labeling, artistic and 3D effects). Make sure that the title of the chart is not redundant (compare it to the figure caption), and remove it if necessary.

Further formatting requirements:

- All text must be justified (i.e., spaced from margin to margin).
- Use subscripts and superscripts consistently.
- Figures and tables should not be placed outside the margins.
- Figures, tables, and longer formulas should be written in a new paragraph.
- Figures, tables, and equations should be sequentially numbered (in separate sequences). Recommended formats: "*Fix X. Short figure caption.*", *Table Y. Table title.*", and "(Z)", respectively.

8. References

[1] User manual for the EMB-001 digital handheld manometer: http://simba.ara.bme.hu/oktatas/tantargy/NEPTUN/BSc_LABOR/MAGYAR/EMB-001_Manual.pdf

[2] Lajos, T. (2019). Az Áramlástan alapjai. Műegyetemi kiadó. ISBN 978-963-122-885-4.

[3] Daku, G., Vad, J. (eds.) (2024). Áramlástan – Előadásjegyzet dr. Vad János előadásai alapján. Akadémiai Kiadó. ISBN 978-963-664-016-3. https://doi.org/10.1556/9789636640163.

[4] Spurk, J.H., Aksel, N. (2020). Fluid Mechanics. Springer Nature Switzerland AG. ISBN 978-3-030-30258-0. https://doi.org/10.1007/978-3-030-30259-7.

Appendix: Pseudo-code for the measurement procedure (Tasks 3.5.-3.6.)

```
% Bodies and potentiometer positions (example)

bodies = [A1, A2, A3, A4, A5, A6];
potentiometerPositions = [4, 6, 8, 10];

N_bodies = length(bodies);
N_pot = length(potentiometerPositions);

%-----------------------------------------------------%
% Combined measurements: body + arm

for b = 1:N_bodies
    while(fan.RPM > 0)
        wait;
    end
    mountNextBody(bodies(b),balanceArm);
    set(scale.Force,0);

    for p = 1:N_pot
        set(potentiometerPositions(p));

        if(fan.RPM.constant == true)
            M.pDyn(b,p,1)= recordPressure;
            M.Fm(b,p,1)  = recordForce;
            M.pot(b,p,1) = potentiometerPositions(p);
        end
    end
end

%-----------------------------------------------------%
% Blocked measurements: arm only

for b = 1:N_bodies
    while(fan.RPM > 0)
        wait;
    end
    mountNextBody(bodies(b),balanceArm);
set(scale.Force,0);

    for p = 1:N_pot
        set(potentiometerPosition(p));

        if(fan.RPM.constant == true)
            M.pDyn(b,p,2)= recordPressure;
            M.Fm(b,p,2)  = recordForce;
            M.pot(b,p,2) = potentiometerPositions(p);
        end
    end
end

save(M);
```