Interpolation: $22 \times P_{tot}$
$8 \times P_{stat}$

Assumptions.

1) 2D flow

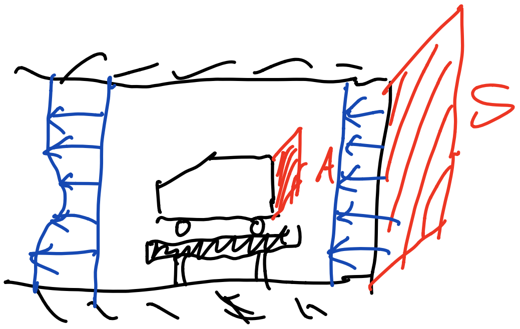
$u \gg v, w$

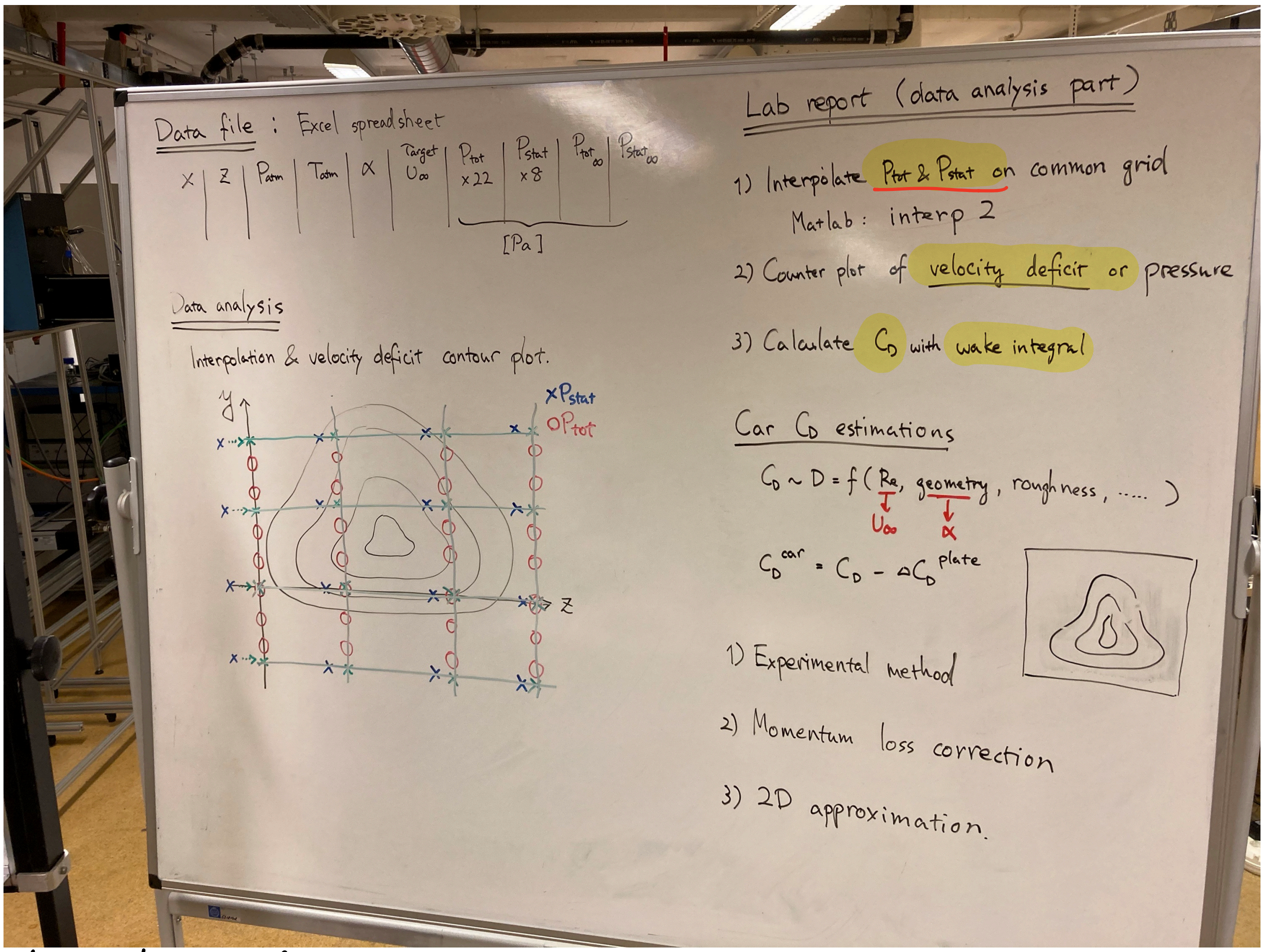
2) Incompressible flow

$\frac{U}{a} < 0.3$

3) Blockage effect

$\frac{A}{S} < 5\%$





Momentum thickness:

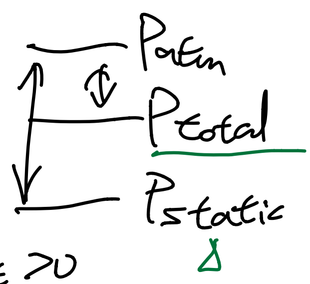
$$\theta \begin{cases} 0.664 L \, Re_L^{1/2} & \text{Laminar} \\ 0.036 L \, Re_L^{1/5} & \text{Turbulent} \end{cases}$$

$$Re = \rho \frac{LU}{\mu}$$

$$\Delta C_D^{plate} = \frac{2f}{\frac{1}{2}\rho U_\infty^2}$$

1
2

$$f = \frac{1}{2}\rho U_\infty^2 C_f$$



$\Delta p = P_{atm} - P_{tot} > 0$

$(P_{tot} - P_{atm}) < 0$

$P = 1011 \text{ mbar}$

$= 101100 \text{ Pa}$

$T = 23°C = 296 \text{ K}$

rorro@kth.se Group submission.

DRAG MEASUREMENTS THROUGH WAKE ANALYSIS (方法)

Introduction

The purpose of this laboratory demonstration is to measure the **drag** of different **simplified vehicle** shapes by means of **wake analysis**. The wake downstream of the model is measured with a **rake** consisting of **total pressure** and **static pressure probes**. The measurements will be performed by the lab assistants. The students will be engaged in the **post-processing** of the data and writing the **report**. The drag is evaluated from the measurement data, and the results should be corrected for the flat plate boundary layer that is present in the setup. In the lab-report there should also be a discussion about the approximations that are used, and the possible error sources.

Wind tunnel

The lab is performed in the **low speed wind tunnel** at the Department of Engineering Mechanics, KTH, see Fig. 1.

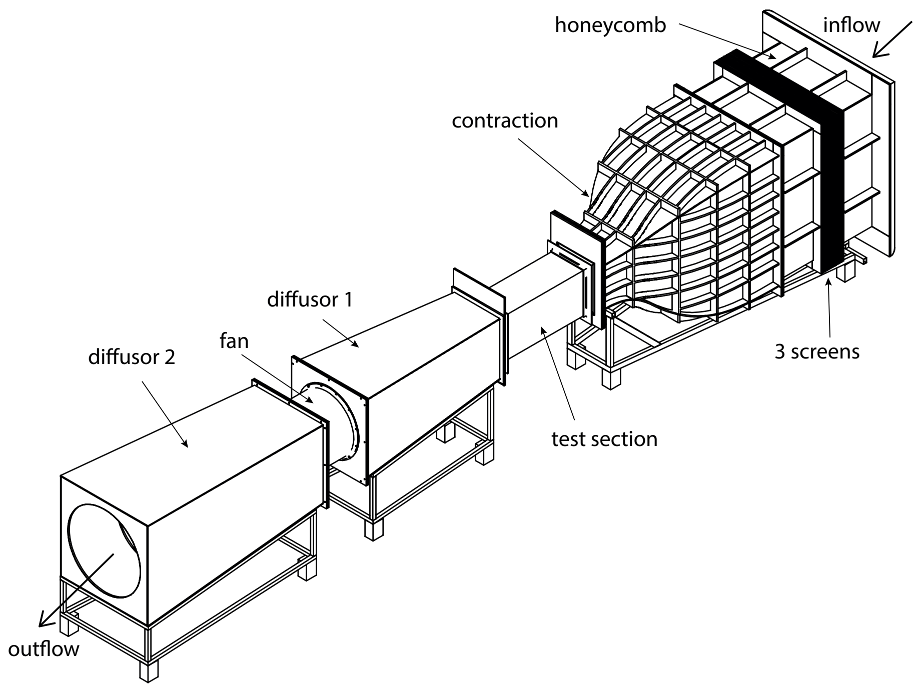


Fig.1 The low speed wind tunnel.

This is an **open type** of wind tunnel and is driven by an **rpm-regulated axial fan** (frequency driven AC motor) downstream of the test section. The width of the **test section** is 40 cm and its height is 50 cm. To maintain a good **flow quality** in the test section i.e. low levels of high-speed fluctuations and an even velocity profile, **honeycombs and screens** are used at the entrance to the **contraction**. The honeycombs direct the flow parallel to the centerline of the test section, while at the same time break down turbulent eddies. The pressure drop across the screens damps out the unevenness of the velocity profile, as well as breaking down the eddies into a smaller size. Viscous effects soon damp out the small eddies in the following **stagnation chamber**. The contraction directly upstream of the test section also provides strong damping of the relative fluctuation level and the velocity variation over the cross-section of the test section. The diffuser slows down the flow before reaching the fan.

Experimental set-up

In the **test section** the **model** is positioned on a **flat plate**, which simulate the presence of the **ground**. The plate is fixed, thus, in this lab, the effect of the relative motion between the car and the ground is not considered.

The plate with the car is positioned approximately 0.20 m above the wind tunnel floor (see Fig.2). The wake measurements will be carried out 5 car heights downstream of the car.

The **total pressure distribution** in the wake is measured by means of a rake made of **22 Pitot probes**. **8 static pressure probes** allow also an estimate of the static pressure in the wake to be obtained. The rake is mounted on a traversing equipment, which is capable to manually move the rake in the **spanwise direction**.

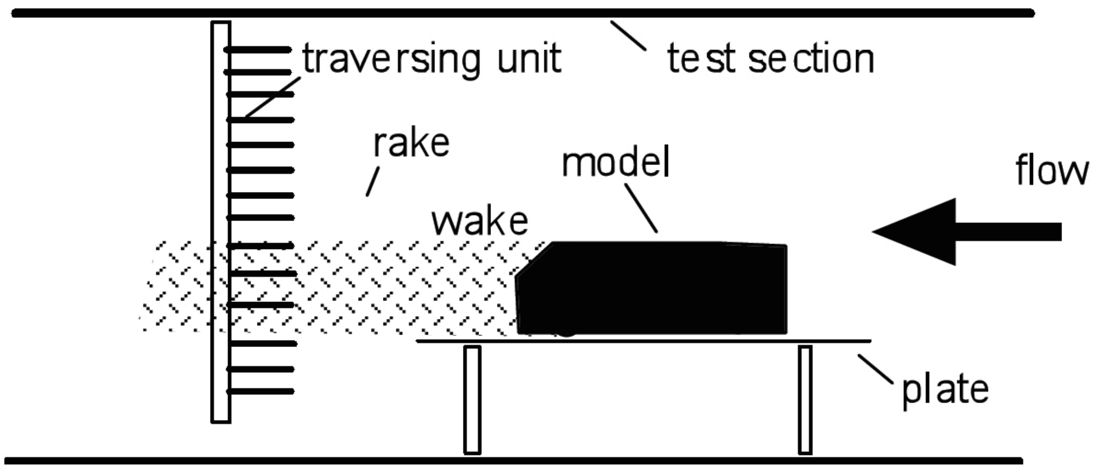


Fig.2 – Schematic of the set-up in the wind-tunnel test section

The **tubes** coming from each pressure probe of the rake are connected to a **Scanivalve**. The Scanivalve is driven by the **computer**, which through an **A/D (analog/digital converter) board** can control the steps that the Scanivalve should perform. The pressure output from the Scanivalve is connected to a pressure transducer. The transducer measures the pressures whose value is transmitted to the computer through the A/D board.
The reference speed in the wind tunnel can be calculated by means of a Prandtl tube connected to another channel of the Scanivalve.

The wake integral
The **velocity vector** in the (x,y,z)-coordinate system is defined as

$$\vec{u} = (U_\infty + u, v, w)$$

Note that the streamwise velocity component is split into the free-stream velocity (U_∞) plus the deviation from the free-stream velocity (u) – and v, w are the deviations in the same manner for y, z components. Inside the wake the deviation, u, will be **negative** since the velocity inside the wake is smaller than the free-stream velocity. The drag (D) can then be calculated from the wake integral defined as

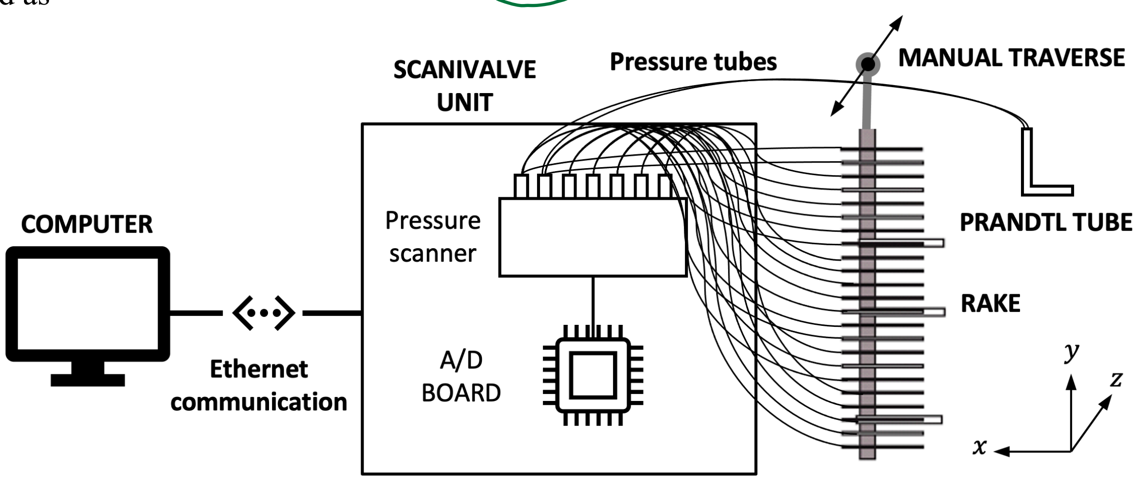


Fig. 3a – Schematic of the instrumentation set-up

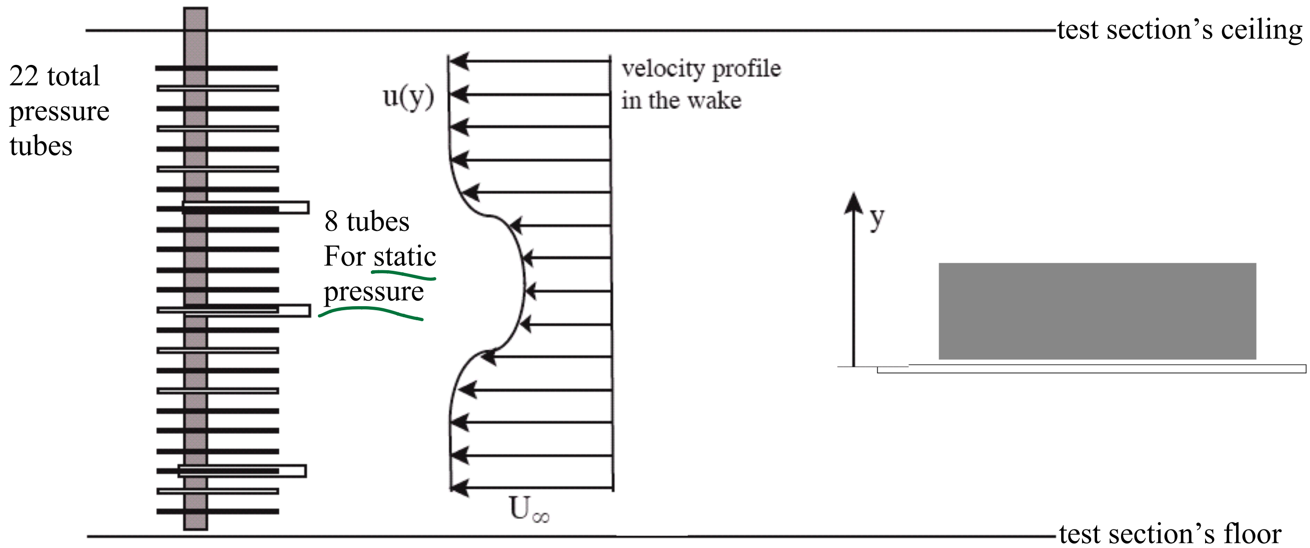


Fig. 3b – Schematic of probe positions

$$SC_D = \int_{S_3} \frac{(p_{0\infty} - p_{03})}{q_\infty} dydz - \int_{S_3} \left(\frac{u^2}{U_\infty^2}\right) dydz + \int_{S_3} \left[\left(\frac{v^2}{U_\infty^2}\right) + \left(\frac{w^2}{U_\infty^2}\right)\right] dydz \tag{1}$$

in which

$S_3 =$ measured (y,z)-plane downstream of the model

$S =$ projected area of the Ahmed body

$p_{0\infty} =$ total pressure in the free stream

$p_{03} =$ total pressure at each (y,z)-position in plane S_3

$q_\infty = \frac{1}{2}\rho U_\infty^2 =$ dynamic pressure

$u, v, w =$ velocity deviation components

Since we cannot measure the v and w velocity components with the present equipment (pressure probes) we have to make the assumption that the **third integral** is small and thus **negligible**. This will not be true in regions with strong streamwise vortices where both the v- and w-components are large. We can get an estimate of the second integral by measuring the u-component. This is possible since we can find, by means of the 8 measured points, the static pressure distribution. Please consider that the static pressure is measured at different positions than the total pressure, therefore an interpolation is required.

Boundary layer correction

The momentum loss due to the boundary layer over the flat plate is included in the measured wake, and it is desirable to make a correction in order to subtract this contribution from the measured drag. For a **laminar boundary layer** that has developed over a flat plate with length L the momentum loss thickness (θ) can be calculated from the relation

$$\theta = 0.664\, L\, \boldsymbol{Re}_L^{-1/2}$$

$$\boldsymbol{Re}_L = \frac{\rho U_\infty L}{\mu}$$

$\mu =$ dynamic viscosity of the fluid

For a **turbulent boundary layer,** it is not possible to derive a theoretical expression for the momentum loss thickness. However, as an approximation the following empirical expression for a turbulent boundary layer that has developed over a flat plate with length L can be used:

$$\theta = 0.036\, L\, \boldsymbol{Re}_L^{-1/5}$$

Lab demonstration (video)

The video will start with a description of the laboratory equipment and the experimental set-up. The vehicle model consists of a simplified car that has been used for the validation of CFD codes in predicting the aerodynamic performance of ground vehicles, called **Ahmed body**. Three different geometries, which differ in the rear part, are available: a **squareback** (model 1) and 2 types of **fastbacks** (model 2 and 3) with an angle of 25° and 35°, respectively.

Each group will receive **2 sets of measurements**, using different models or different free stream velocities.

The **output** from the measurement is an **ASCII-file** containing the measured pressures for each channel of the Scanivalve.

In order to be able to do the data evaluation you need further information:

- A list to identify each **column** in the ASCII-file with the correct pressure tube
- The **atmospheric temperature** and **pressure** measured during the experiment. You will need to calculate the **air density**
- **Plate length** (to estimate the flat plate boundary layer)
- **Dimensions** of the car to be used in the calculation of the drag coefficient (c_D)

Table 1 shows the position of the total and static pressure probes corresponding to their position in the ASCII file. The offset in the spanwise direction is given by Δz_o.

Table 1 – Total and static probe positions

Total pressure probes

Pos	1	2	3	4	5	6	7	8	9	10	11	12	13
y [cm]	19	17	15	13	11	9	7	6.3	5.5	5	4.3	3.5	3
Δz_o [cm]	0	0	0	0	0	0	0	-1	-1	0	-1	-1	0

Pos	14	15	16	17	18	19	20	21	22
y [cm]	2.3	1.5	1	-1	-3	-5	-7	-9	-11
Δz_o [cm]	-1	-1	0	0	0	0	0	0	0

Static pressure probes

Pos	1	2	3	4	5	6	7	8
y [cm]	20	16	12	8	4	0	-4	-10
Δz_o [cm]	1	1	1	1	1	1	1	1

Assignment
Take the pressure data recorded and use them to calculate the **integral** in equation (1).

> <u>Hints:</u> In order to calculate the drag coefficient, the value of the dynamic pressure should be firstly estimated by assessing the reference speed of the wind tunnel. Use the total and static pressures obtained from the wake rake to calculate the streamwise velocity deficit in the wake. For calculating the velocity deficit, it is useful to create a common grid containing YZ-coordinates in the region where both static and total pressure measurements were taken (this can be done by using the `meshgrid` function in Matlab). Use an interpolation function in Matlab (`interp, interp2` or similar) to interpolate static and total pressure values on the common grid and use the resulting data to calculate the integral in equation (1). Before the interpolation, make sure that the correct Z-coordinates are specified for the probes (remember that some of the pressure tubes in the rake had a zero offset). Also, remember to use the proper scale for the Ahmed body dimensions.

With the mean static pressure in the wake you can estimate the u-component that is used in the second integral in equation (1). Check its relative importance compared to the main contribution in the integral.

Estimate the momentum losses on the plate by assuming either a complete laminar or a complete turbulent flow. Try to comment and to explain the results obtained.

> <u>Hints:</u> Estimate the momentum loss thickness for a laminar or a complete turbulent flow (motivate your choice of flow model in the lab report). Use this to calculate the global friction coefficient over the plate and subtract the corresponding friction force from the calculated drag of the Ahmed body. This removes the drag due to the boundary layer induced by the plate. Remember to include both sides of the plate during the calculation.

<u>Experimental method:</u> You can also estimate the momentum losses from the experimental data. Near the edge of the test section, one can assume that only the wake of the plate can be seen. Remove the effect from the plate by subtracting the vertical deficit measured at one of the outermost profiles (near one of the tunnel walls) from the total wake velocity field. The experimental method can for instance be implemented by using the expressions

$$C_{D,CORRECTED} = C_{D,UNCORRECTED} - \Delta C_{D,PLATE}$$
$$\Delta C_{PLATE} = \int I_1(z = z_{edge})dy \cdot \Delta z - \int I_2(z = z_{edge})\, dy \cdot \Delta z$$

(2)

Where I_1 and I_2 are the integrands of the first two terms in equation (1),

$$I_1 = \frac{p_{0\infty} - p_{03}}{q_\infty}, \quad I_2 = \frac{u^2}{U_\infty^2} \qquad (3)$$

and $\Delta z = z_{\min} - z_{\max}$ is the spanwise measurement range.

Visualize the wake with a contour plot (using `pcolor` in Matlab or similar). Plot the velocity in the wake with and without subtracting the velocity deficit of the plate (obtained from one of the outermost profiles).

For each measurement set, report the uncorrected drag value and the drag values resulting from the two correction methods. Discuss the results.

A 2D-approximation of the Ahmed body drag can be made by first estimating the total pressure deficit along the centreline of the wake (at $z = 0$) as

$$\frac{p_{0\infty} - p_{03}(y,0)}{p_{0\infty}} \approx c_1 \exp(-c_2 (y - c_3)^2)\,, \tag{4}$$

and then calculating the drag coefficient as

$$C_D \approx \frac{p_{0\infty}}{q_\infty h} \int c_1 \exp(-c_2 (y - c_3)^2)\, dy\,, \tag{5}$$

where h is the height of the Ahmed body. Estimate the coefficients c_1, c_2 and c_3 by curve fitting in a least squares sense. Use these coefficients to calculate the approximated drag coefficient according to equation (5). Report the results and do a comparison with the drag values calculated using the other methods. What differences can be seen? Why?

Lab report

C_D

- Present a brief review of the different methods to estimate experimentally the drag coefficient of a car. What is the aim of the performed lab?
- Describe the theory used in the lab to analyze the data and assess the drag of the Ahmed body.
- State the assumptions made during the lab.
- Describe the model setup and the measurement techniques used - Process the data recorded and calculate the drag coefficient of the studied configurations.
- Apply the two different drag correction methods. Present tabulated drag coefficient values for the different configurations and show contour plots of the wake before and after the corrections.
- Compare and discuss the effect of the change in the geometry or in the measurement parameters.
- Compare the different drag correction methods. Which one is working best? Why?
- Report the drag coefficients estimated through the 2D approximation and compare the results with those obtained using the other methods.
- Check if there might be in the experimental blockage problems and in that case discuss which deviaton you should expect from the real value.

② 标准

要算别人的图吗 ①

报告什么程度
是否全部组数据吗.

Good luck!

Appendix:

Figure 4 shows the full-scale Ahmed body. To get the dimensions used in the laboratory exercise you must scale the full-scale model by 1:4.17.

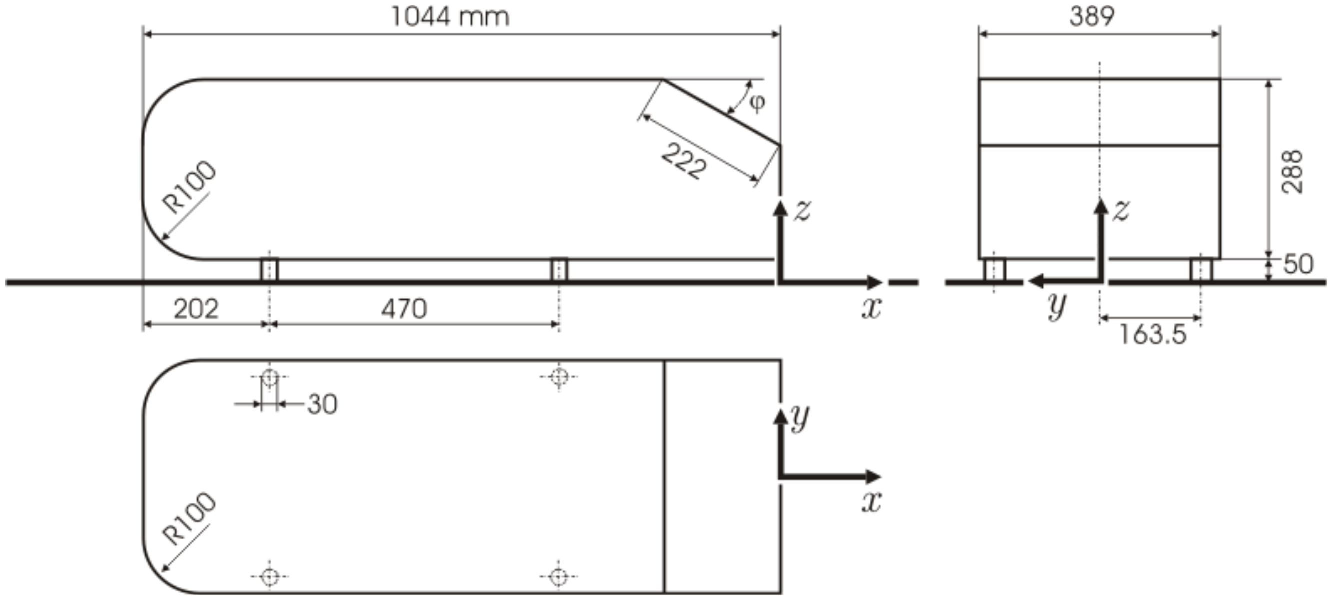


Fig. 4 – Full-scale Ahmed body dimensions