# M3

# MEASUREMENT OF AERODYNAMIC FORCES ACTING ON A CYLINDER IN A CLOSED DUCT

## 1. The aim of the measurement

The aim of the measurement is to investigate the aerodynamic forces $\underline{F}$ ($F_x$, $F_y$) acting on cylinders of different diameters, that are perpendicularly mounted into a miniature wind tunnel with rectangular cross section. The force is determined with the assumption that the wall shear stress value on the cylinder is negligible compared to the pressure forces (this is a rather good approximation in the case of bluff bodies in a high Reynolds number flow). During the experiment the pressure distribution on the surface of the cylinder is measured and the pressure coefficient $c_p$, the drag coefficient $c_d$ and the lift coefficient $c_l$ are evaluated. With this measurement facility, the effect of cylinders non-symmetrically aligned in the duct, can also be investigated, in terms of the pressure distribution and aerodynamic forces.

## 2. Description of the measurement facility

A miniature wind tunnel is used for this measurement task. The sketch of the table sized facility can be seen in Figure 1. The air is delivered by a centrifugal fan, which is installed into the mobile unit. The air velocity is controlled by a throttle valve on the suction side of the machine. The maximum velocity is approximately 32 m/s in the outlet section of 150x150mm

duct. The outlet velocity (denoted by „v") can be calculated by substituting the reference pressure value ($\Delta p_{ref}$) (measured on the taps located at the side of the machine base) into the calibration formula depicted on the top of the device. The value of the calibration constant ("K") has to be checked, by a Prandtl-probe velocity measurement, at beginning of the experiment.
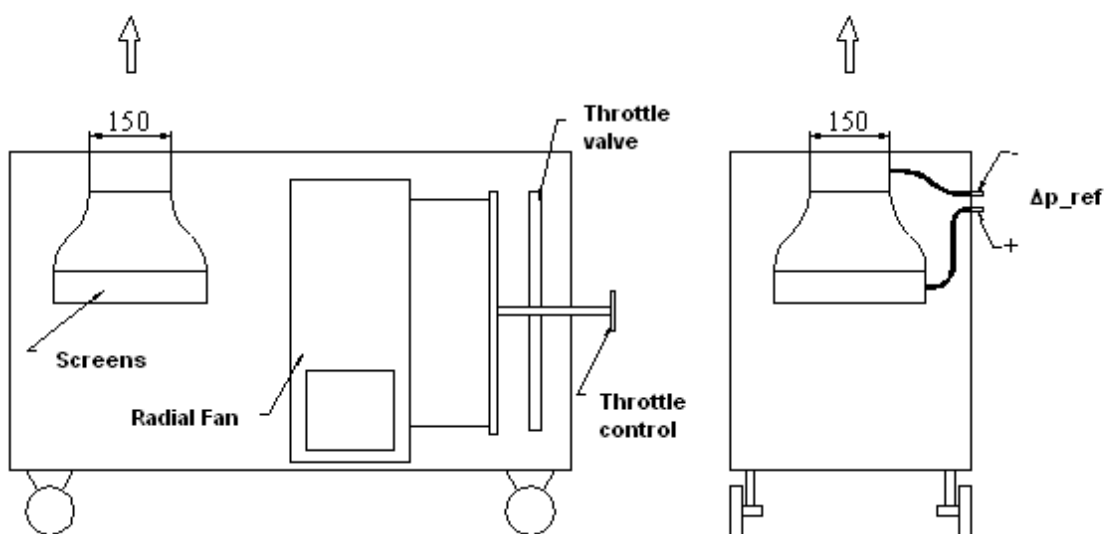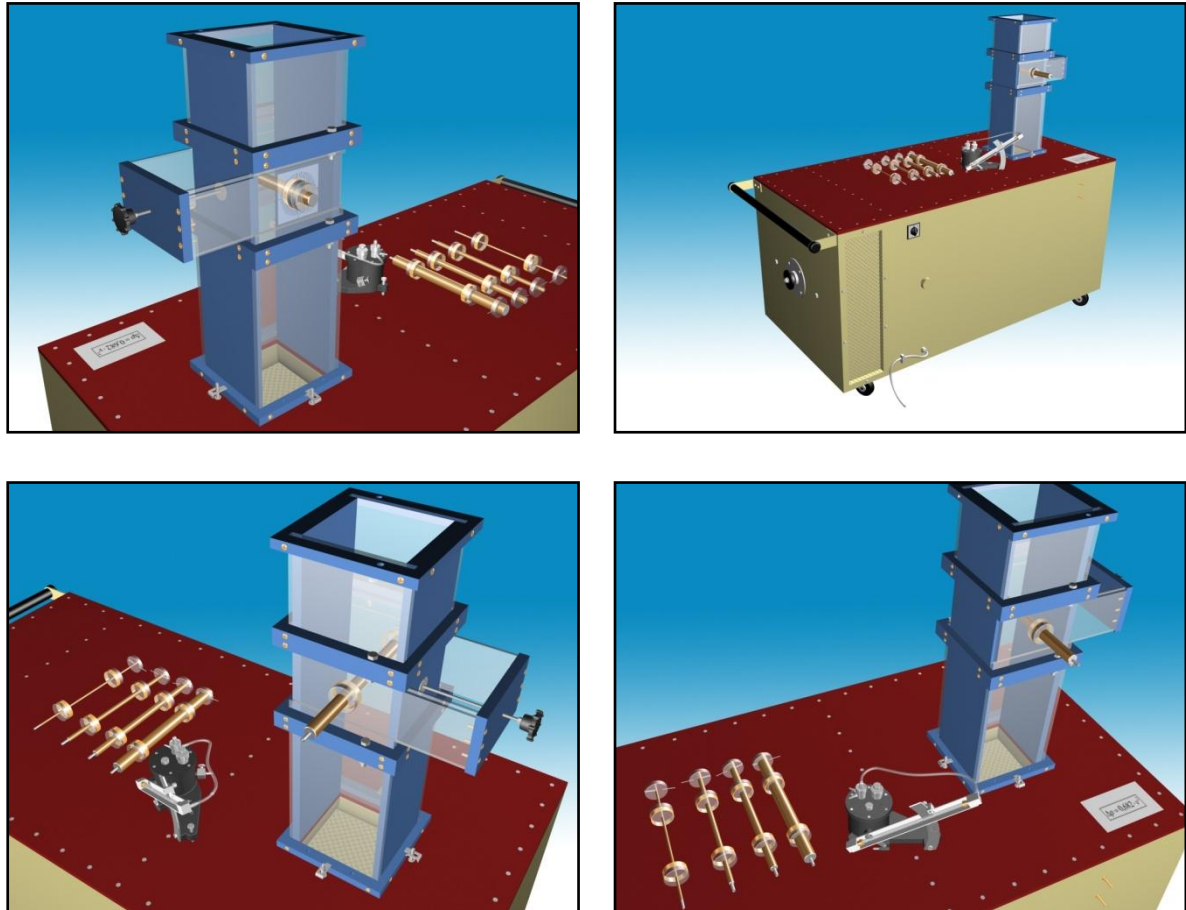


**Figure 1.** Sketch of the measurement device

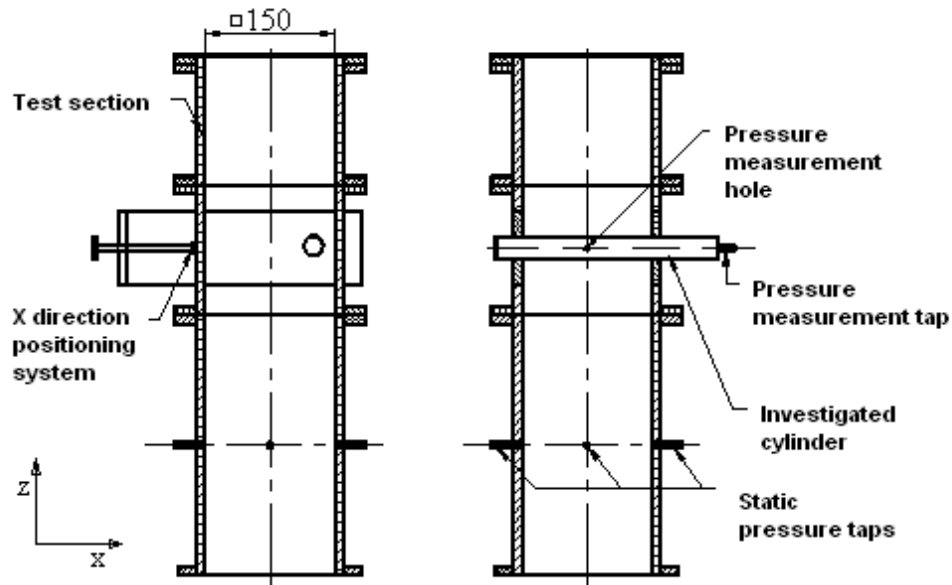The cylinders to be measured can be placed into the uprightly, closed, rectangular test section, shown in Figure 2.



**Figure 2.** The closed test section

The test section contains three elements, the order of which can be changed. In this way, the length of the test section before and after the cylinder can be varied. One of the test section elements is built in such a way, that the measurement cylinders with different diameters can be placed perpendicularly into the flow. This piece of channel is equipped with a manual movement mechanism, which is able to modify the position of the cylinder in the direction which is perpendicular to its axis. The movement of the cylinder in the direction which is parallel to its axis is also possible. A small pressure measurement hole can be found on every cylinder's surface, which is connected to the pressure tap at one end of the cylinder. The other end of the cylinders is closed. In this way we can measure the local static pressure on the surface of the cylinder. In the measurement we are interested in the difference of that static pressure and the static pressure in the wind tunnel duct. In order to measure the static pressure in the duct four pressure taps have been installed on the walls of the wind tunnel. These taps are joined by a silicone tube, by which the average static pressure on the duct walls can be measured, using a manometer.

## 3. Theory of the measurement

The source of the aerodynamic forces acting on a body can be divided into two main parts. One of them is due to the pressure distribution on the surface of the body, while the other is a result of the surface skin friction. In real (viscous) fluid flows the Bernoulli-sum along the streamlines decreases near solid surfaces, therefore forming a wake behind the body, where the velocity distribution (and also the pressure distribution due to the curved streamlines) is different from the one observed in an inviscid flow case. The value of the pressure drop highly depends on the Reynolds-number, which can characterize the flow pattern. In the case of this measurement set-up, the typical Reynolds number is in the range of $10^3$-$10^5$. This means that here the inertial forces are the dominant ones, and the vortex pair formed behind

the cylinder is periodically detached. (This is the so called Kármán-vortex street) In the vicinity of the vortices the velocities are relatively high and the pressure is low. The drag force on the cylinder is basically a result of the low pressure zones caused by the vortex shedding behind of the bod.

The high drag forces can also be explained by the high kinetic energy level of the separated vortices, which is dissipating into heat behind the body. (If we investigate this in an absolute system, we need to invest a relatively large amount of work in order to move the cylinder in a stationary flow, covering the high kinetic energy loss of the flow, which is producing heat.)

In the case of an asymmetric cylinder alignment, we need to account for the effect of the wall. As we are moving the cylinder toward the wall, the symmetry of the flow pattern is vanishing, the velocity and the pressure distribution is changing, and there will be forces acting in the direction perpendicular to the flow. The magnitude of this force depends on the asymmetry of the flow pattern, and therefore the distance of the cylinder from the wall. The investigation of this dependency is also one of the aims of the measurement.

## 4. Description of the measurement task

*Velocity and pressure measurement*

The measurement of the fluid velocity in the test section via the reference pressure measurement has already been discussed in Section 2.

The pressure distribution on the surface of the cylinder can be determined by rotating the single pressure measurement point around the axis of the cylinder. (This is achieved by rotating the entire cylinder in the mount.) The appropriate step size is about 5° - 10 ° between 0° and 360°. For the measurement of the angle a protractor is mounted on the device, around the cylinder. In this way we will have *n* measurement points around the perimeter of the cylinder and for every point a sub surface $A_i$ of the cylinder can be assigned.

Possible measurement tasks:

- Pressure distribution of one specific cylinder measured at four different Reynolds numbers (by changing the velocity)

- Pressure distribution on four different diameter cylinders at a constant Reynolds number.

- Pressure distribution on one specific cylinder, at four different distances from the channel side wall.

It should be mentioned that the sign of the pressure can change during the measurement (both overpressure and depression can be found along the perimeter of the cylinder as compared to the channel static pressure)

*Further measurement parameters*

The atmospheric pressure and laboratory temperature should be measured at the beginning and at the end of the measurement. This is necessary for the calculation of air density.

The geometric parameters of the measurement facility, the factory numbers and state of the measurement devices should also be recorded.

## 5. Post processing and comparing the results to the literature data

During the post processing the manometer deflections should be converted into pressure values (When the EBM-001 digital manometer is used then this is not needed). From the

static pressure difference measured on the cylinder and on the channel wall the pressure coefficient should be computed and plotted against the angle.

$$c_{p,i} = \frac{\Delta p_i}{\frac{\rho_{air}}{2} \cdot v^2}$$

(1)

where

$c_{p,i}$     [-]                     Pressure coefficient at the position i

$\Delta p_i$     [Pa]                    Pressure difference between the cylinder and duct wall at the position i
$\rho_{air}$     [kg/m$^3$]              density of the fluid (air)
v     [m/s]                   flow velocity

$$F_y = \sum_{i=1}^{n} F_{iy} = \sum_{i=1}^{n} \Delta p_i \frac{D\pi}{n} h \sin \Phi_i$$

The force ($\underline{F}$) acting on the cylinder should be determined by numerical integration, along with its components ($F_x$) in the flow direction, and ($F_y$) perpendicular to the flow direction,

$$\underline{F} = \sum_{i=1}^{n} \underline{F_i} = \sum_{i=1}^{n} \Delta p_i A_i \left( -\underline{e_n} \right)$$

(2)

$$F_x = \sum_{i=1}^{n} F_{ix} = \sum_{i=1}^{n} \Delta p_i \frac{D\pi}{n} h \cos \Phi_i$$

(3)

$$F_y = \sum_{i=1}^{n} F_{iy} = \sum_{i=1}^{n} \Delta p_i \frac{D\pi}{n} h \sin \Phi_i$$

(4)

where

$\underline{F}$     [N]     Force acting on the body
n     [db]     Number of measurement points
$\underline{F_i}$     [N]     Force acting on the sub surface i

$\Delta p_i$     [Pa]     Pressure difference measured in the sub surface i
$A_i$     [m$^2$]     Area of the sub surface i
D     [m]     Diameter of the cylinder
h     [m]     Height of the cylinder
$\underline{e_n}$     [-]     Surface normal (unit vector)

$\Phi_i$     [°]     Angel between the measurement point i and the x axis
$F_x, F_y$     [N]     Force components in the x, y directions respectively
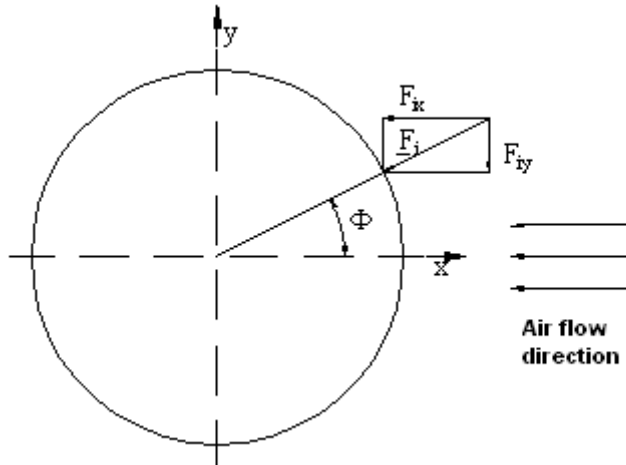
For the details see Figure 3..

**Figure 3.** Calculating the forces

The force acting in the flow direction $F_x$ is called drag, while the perpendicular component $F_y$ is called lift. From these force components we can calculate the drag coefficient $c_d$ and the lift coefficient $c_l$, respectively.

$$c_d = \frac{F_d}{\frac{\rho_{air}}{2} \cdot v^2 \cdot A_{cylinder}} \tag{5}$$

$$c_l = \frac{F_l}{\frac{\rho_{air}}{2} \cdot v^2 \cdot A_{cylinder}} \tag{6}$$

where

| | | |
|---|---|---|
| $c_d$ | [-] | drag coefficient |
| $c_l$ | [-] | lift coefficient |
| $F_d$ | [N] | drag |
| $F_l$ | [N] | lift |
| $A_{cyliner}$ | [m$^2$] | Cross section of the measured body perpendicular to the flow |

It is advisable to compare the measured drag coefficient values to the data in the literature.

When the larger cylinders are measured in the duct, the flow pattern is significantly different from the one which can be obtained if the cylinder would be placed in an infinitely large flow field. The measurement results depend on the duct size. The flow differs more from that in the infinite flow field type situation as the diameter of the cylinder increases. This phenomenon is the called blockage and should be accounted for in the measurement results by a correction factor. For the drag coefficient, the following correction can be applied.

$$\frac{c_{d,c}}{c_d} = \left( \frac{1 - G(S/C)}{1 + 0.822(S/C)^2} \right)^2 \tag{7}$$

where

$c_{d,c}$    [-]      corrected drag coefficient
$c_d$     [-]      measured drag coefficient
G      [-]      empirical constant, for cylindrical bodies it is G=0.3 according to the literature
S      [m$^2$]    Cross section of the measured body perpendicular to the flow
C      [m$^2$]    Cross section of the wind tunnel perpendicular to the flow

The corrected drag coefficient in case of Re>3·10$^5$ is approximately $c_d$≈0,3. For lower Reynolds number $c_d$=1,2 can be a good approximation. There is a narrow transitional region between the two values where the drag coefficient values can be estimated from Figure 4.
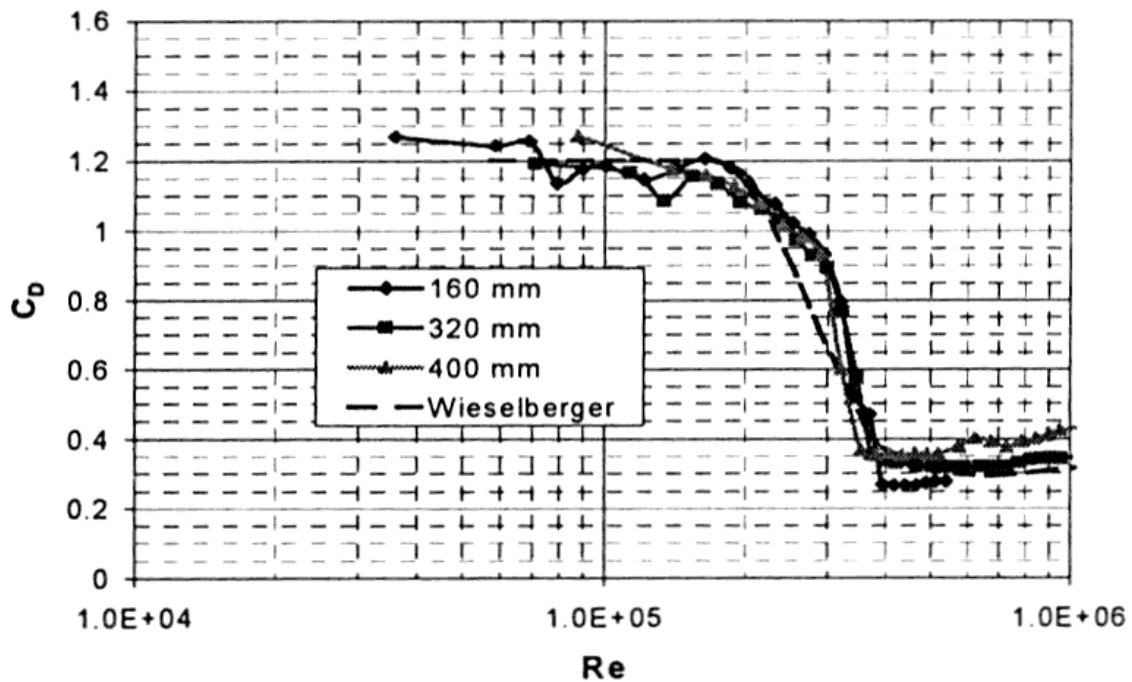


**Figure. 4 Drag coefficient** $c_d$ as a function of the Reynolds number, for different cylinder diameters $d$=160, 320, 400 mm

## 6. Measurement error calculation:

The measurement error calculation needs to be done, as described below, for the drag coefficients of the cylinders.

Expression for the drag coefficient:

$$c_d = \frac{F_d}{\dfrac{\rho_{air}}{2}v^2 A_{cylinder}} = \frac{\displaystyle\sum_{i=1}^{n}\Delta p_i \frac{D\pi}{n}h\cos\Phi_i}{\dfrac{\rho_{air}}{2}\dfrac{2K\Delta p_{ref}}{\rho_{air}}A_{cylinder}} = \frac{\displaystyle\sum_{i=1}^{n}\Delta p_i \frac{\pi}{n}\cos\Phi_i}{K\Delta p_{ref}}$$

(„K" is the calibration constant for the velocity of the wind tunnel)

Evaluation of the absolute measurement error:

$$\delta c_d = \sqrt{\sum_{i=1}^{n}\left(\delta X_i \cdot \frac{\partial c_d}{\partial X_i}\right)^2}$$

The relative error:

$$\frac{\delta c_d}{c_d} = ?$$

where $X_i$ are the measured quantities. The approximate absolute error of them:

| | | |
|---|---|---|
| $X_1=\Delta p_i$, | error of the pressure measurement | $\delta \Delta p_i = 2 Pa$ |
| $X_2=p_0$, | error of the atmospheric pressure measurement | $\delta p_0 = 100\ Pa$ |
| $X_3=T_0$, | error of the temperature measurement | $\delta T_0 = 1K$ |
| $X_4=\Delta p_{ref}$, | error of the reference pressure measurement | $\delta \Delta p_{ref} = 2 Pa$ |
| $X_5=\Phi_i$, | error of the angle measurement | $\delta \Phi_i = 2°$ |

## 7. Diagrams to be included in the report:

- Pressure coefficient ($c_p$) distribution on the cylinder surface as a function of the angle.
- Drag and lift coefficients of the cylinders with different diameters in the function of the Reynolds number or distance from the duct wall, including absolute and relative error values.

### *Remember that during the labs:*

- Before turning any measurement device on, or in general during the lab, make sure that safe working conditions are ensured. The other participants have to be warned of the starting of the machines and of any changes that could endanger the members of the lab.
- The atmospheric pressure and room temperature should be recorded before and after every measurement..
- The measurement units and other important factors (e.g. data sampling frequency, data of calibration) of every recorded value of the applied measurement devices should be recorded.
- Type and construction number of the applied measuring instrument should be included in the final report.
- Checking and harmonizing of the units of the recorded values with those used in further calculations.
- Manometers should be calibrated if necessary.
- The measurement ports of the pressure meter should be carefully connected to the correct pressure ports of the instrument.
- If inlet or outlet tubes are to be assembled with fans, connections should be airtight as escaping/entering air can significantly modify the measurement results