MEASUREMENT 5

MEASUREMENT OF PRESSURE

1. Aims of the measurement

- To get familiar with pressure gauges.
- Pressure measurement with a U-tube (liquid column gauge) and a Bourdon gauge. Measurement of the absolute and relative pressure at two locations of a pipe system (p_n and p_s).
- Flow rate measurement with an orifice plate meter and a metering tank.
- Calibration of a Bourdon gauge.

2. Overview of pressure gauges

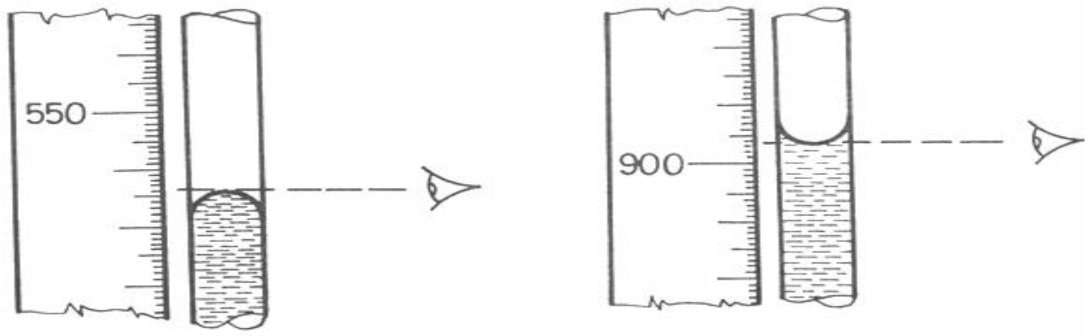
2.1 Liquid column gauge

The simplest pressure gauges are the **U-tube manometer**s. *Figure 1* shows three U-tube manometers connected to different locations of a water pipeline. Here the measuring liquid is mercury; however, it can be any kind of liquid whose density differs from the density of the working fluid. According to the principle of communicating vessels, the liquid levels are at the same height in both branches as long as neither of the branches is connected to a pressure supply. To read the difference in liquid levels, a metal or a glass **millimetre scale** is used.

Figure 1. U-tube (liquid column) gauge

The liquid level has to be read in the horizontal tangent of the liquid meniscus (the curved liquid surface), see *Figure 2*. The reading in the horizontal plane can also be assisted by a mirror placed behind the glass tube.

Non-wetting liquid Wetting liquid



h=536 mm h=904 mm

Figure 2: Curved liquid surface (meniscus)

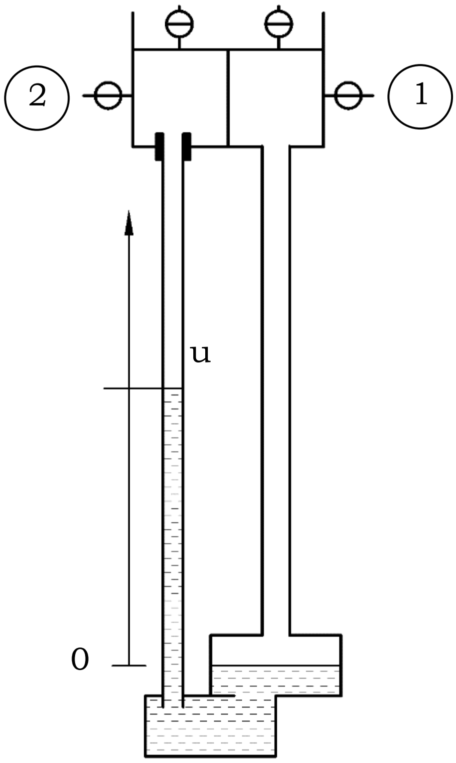


Figure 3: Well manometer

When using a liquid column gauge, the connecting tube of the manometer has to be filled with the pressure transmitting medium. This transmission medium is often the liquid in which the pressure is measured. The system can be filled with this medium with the help of a **de-airing valve** installed at the highest point of the system. Two readings are required to measure the liquid level difference for the basic U-tube manometers. The cross section of the reservoir of a **well ("single-tube") manometer** (shown in *Figure 3*) is substantially larger than the cross section of the glass "U" tube. When 1 is connected to a higher pressure location **than 2**, the mercury level in the glass tube rises so that the surface of the mercury level in the reservoir remains practically at level 0, due to the constant volume of the mercury.

A barometer for measuring the atmospheric pressure is similar in design. In this case, 1 opens to the atmosphere (p_0), and at 2 the glass tube is closed, thus there is a vacuum above the mercury column. To avoid parallax error, the reading in the horizontal plane of the liquid meniscus can be assisted by a mirror.

2.2 Metal manometers

Figure 4 Bourdon pressure gauge

Directly readable dial instruments are used in industrial applications. A Bourdon-tube gauge is a flattened and curled up, closed-end tube connected to the high pressure location (*Figure 4.*), whose curvature decreases or increases as a result of positive or negative gauge pressure, respectively. This kind of gauge can be used to measure both positive gauge pressures and vacuum. In the former case, the dial is usually made to show the gauge pressure in bar, in the latter case, a percentage proportional to the negative gauge pressure (relative vacuum) is depicted on the dial.

The displacement of the end of the Bourdon-tube is transferred to the axis of the pointer as shown in *Figure 5*.

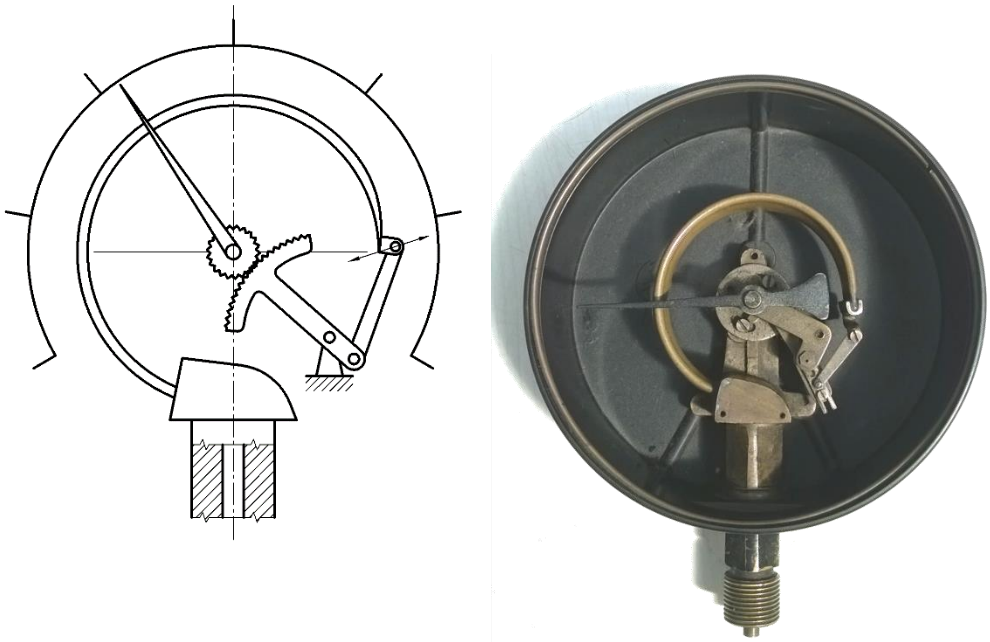


Figure 5 Interior of a Bourdon pressure gauge

2.2 Other kinds of pressure gauges

The principle of **membrane pressure gauges** is that there is a relationship between the displacement or deformation of the membrane and the p pressure causing the deflection/change. In *Figures 6* and *7*, a flat membrane and a corrugated membrane are depicted, respectively. In modern pressure gauges, the displacement or deformation of the membrane is converted into an electrical signal.

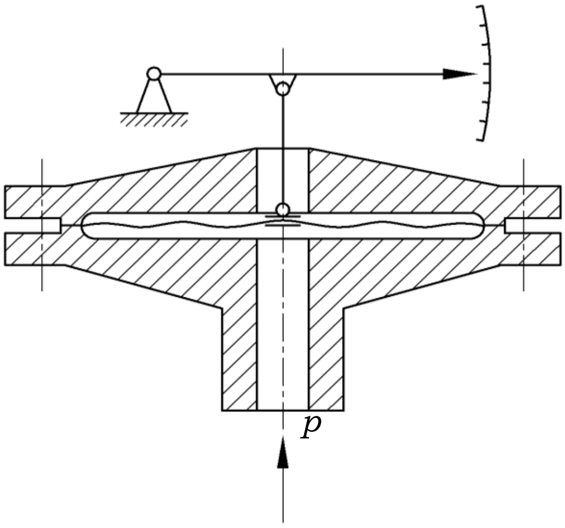


Figure 6 Flat membrane

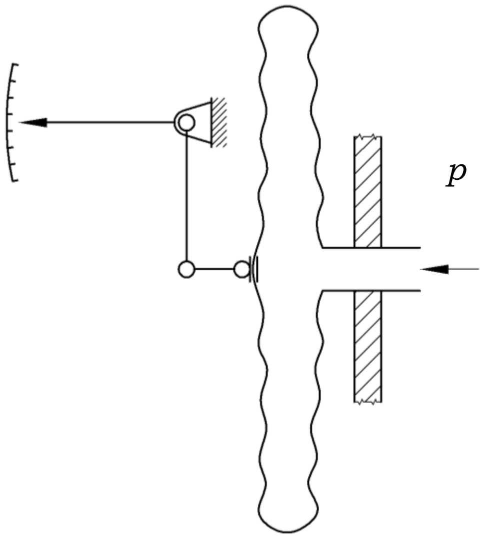


Figure 7 Corrugated membrane

3. The measurement exercises

3.1. exercise: determination of the pressures p_n and p_s in the pipeline depicted in *Figure 8* at a given Q_V volumetric flow rate. The U-tube mercury manometers marked with N and S will be used. The p_n gauge pressure is also shown by the Bourdon-tube manometer denoted with Bg (p_{nBg}).

3.2. exercise: measurement of the volumetric flow rate Q_V by using a volume meter tank (Q_{VMT}) and an orifice plate connected to the U-tube mercury manometer marked with P (Q_{OR}).

3.3. exercise: calibration of a Bourdon-tube manometer.

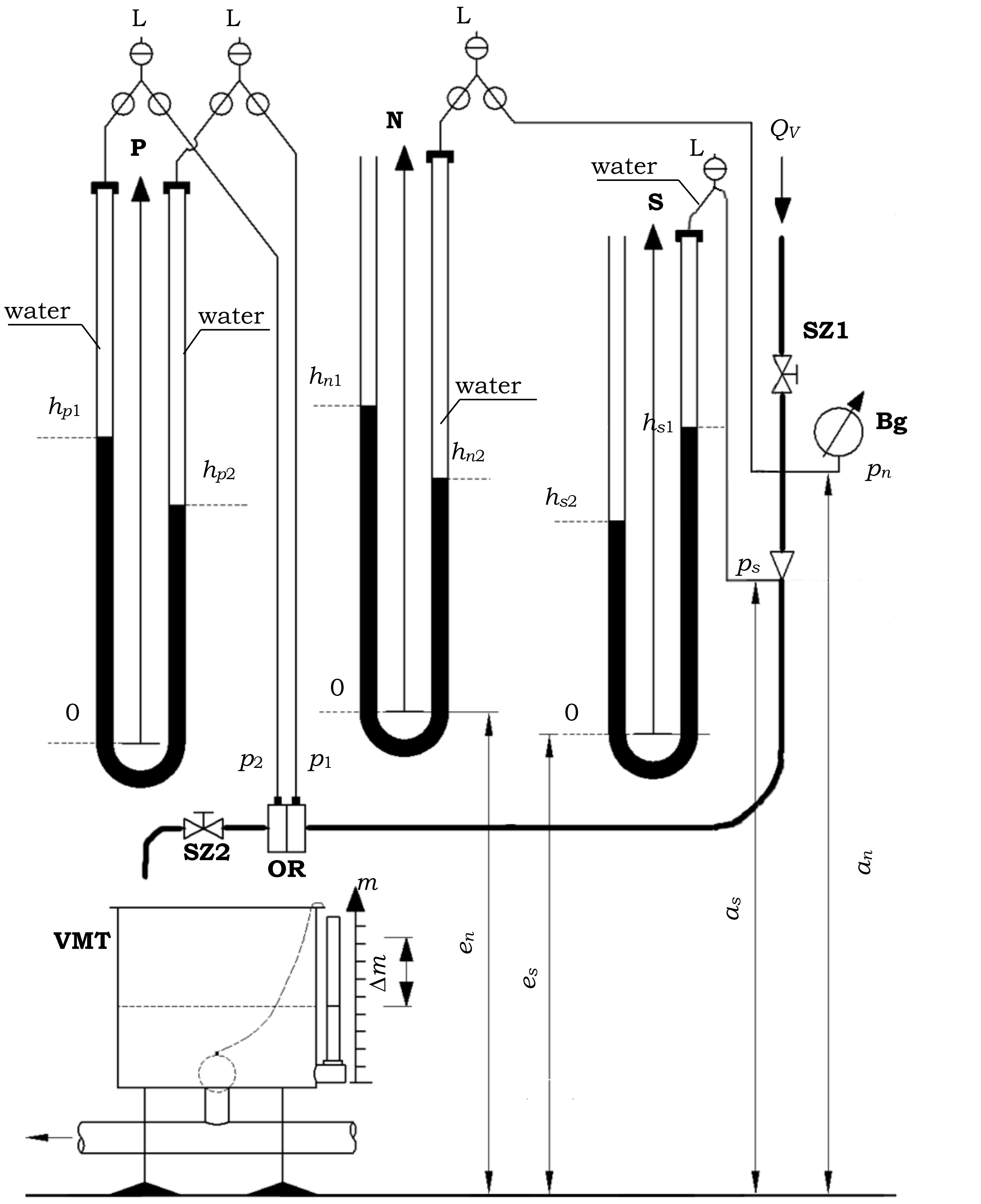


Figure 8 The measurement rig

3.1. Pressure measurement with U-tube manometer and Bourdon gauge

Valve SZ1 is used to control the volumetric flow rate, i.e. to set different measuring conditions for each student. The pressure p_n is higher than the atmospheric pressure (pressure at the outflow) due to the hydraulic resistance of the pipe section. Thus, **positive gauge pressure** can be measured here. The pressure p_s is less than the atmospheric pressure because a nozzle (streamlined contraction) is installed here, and as a result, the fluid velocity increases, causing a local pressure drop; thus, a **negative gauge pressure** can be measured here. By slightly closing valve SZ2, the pressure p_s can also be higher than the atmospheric pressure. This valve ensures that the air can escape from all four of the connecting tubes. However, it should be kept open during the measurements. During the **evaluation of the measurement**, the value of the atmospheric pressure will also be needed. The atmospheric pressure p_0 can be read in *mbar* units from a digital barometer available in the lab. Register the atmospheric pressure p_0 converted to Pa, and the altitudes a_n, a_s, e_n, e_s as „**measured constant values**". Water (ρ_V=1000 kg/m^3) and mercury (ρ_{Hg}=13600 kg/m^3) densities are considered to be constant. According to the manometer equilibrium, the unknown p_n and p_s pressures can be calculated by using the above data.

Rearrange the following equations and make the substitution.

The equilibrium condition for U-tube N:

$$p_0 + (h_{n1} - h_{n2})\rho_{Hg} g = p_n + [a_n - (e_n + h_{n2})]\rho_V g \qquad \Rightarrow p_n = \dots$$

The equilibrium condition for U-tube S:

$$p_0 = p_s - (e_s + h_{s1} - a_s)\rho_V g + (h_{s1} - h_{s2})\rho_{Hg} g \qquad \Rightarrow p_s = \dots$$

In the above equations, indices 1 and 2 refer to the higher and lower heights, respectively (**cf. Figure 8**). We read integer values in **mm**-s from the manometers, but in the numerical solution of the equations we **substitute the heights in meter units!**

Report the initial data and the results in tabular form, as well. p_{Bg} denotes the pressure read from the Bourdon-tube pressure gauge in bar.

Calculation of pressure p_n:

Measured (constant) values:

a_n = e_n =

Given (constant) values:

ρ_V = p_0 = ……….. mbar = ……………… Pa

ρ_{Hg} =

The measurement data should be recorded in the following table:

h_{n1}	h_{n2}	h_{n1}-h_{n2}	p_{nBg}	p_n absoulte pressure		p_n gauge pressure	
[mm]	[mm]	[m]	[bar]	[Pa]	[bar]	[Pa]	[bar]

Calculation of pressure p_S:

Measured (constant) values:

$a_s =$ $e_s =$

The measurement data should be recorded in the following table:

h_{s1}	h_{s2}	h_{s1}-h_{s2}	p_s absolute pressure		p_s gauge pressure	
[mm]	[mm]	[m]	[Pa]	[bar]	[Pa]	[bar]

3.2. Measuring the volumetric flow rate by using a volume meter tank and an orifice plate

The volumetric flow rate is the volume of liquid flowing through a surface per unit time, its unit is m^3/s. In engineering, it is a common task to determine the volumetric flow rate of a fluid flowing through a pipeline. The **orifice plate** is a contraction shown in *Figure 9*. The fluid flows through the plate with a higher velocity, thus its pressure decreases according to Bernoulli's equation. Between the taps before and after the plate, a well-measurable pressure difference arises. The flow rate is proportional to the square root of this pressure difference. (The derivation of this formula is very similar to that of the Venturi tube equation.)

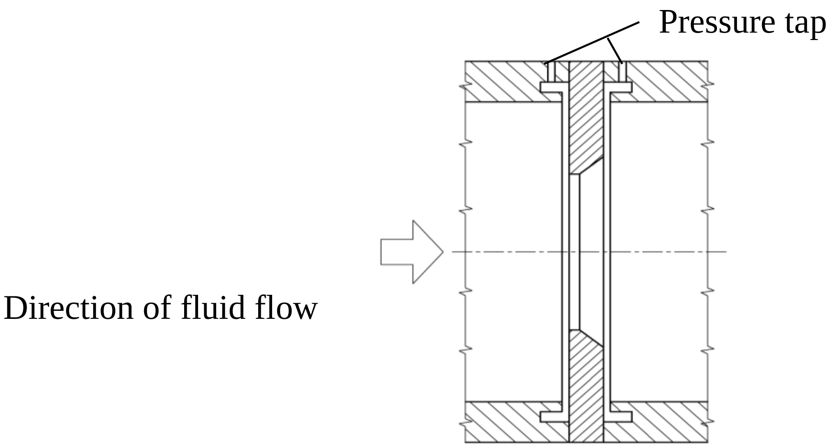


Figure 9: Orifice plate

Figure 10 shows the diagram of the orifice plate denoted by OR in *Figure 8*. In order to have an easy to handle linear relationship the square root of the liquid column height difference ($\Delta h = h_{p1} - h_{p2}$) is used, which can be **read from the manometer denoted by P**. Thus, the volumetric flow rate ($Q_{orifice}$) directly obtained after the reading of the manometer:

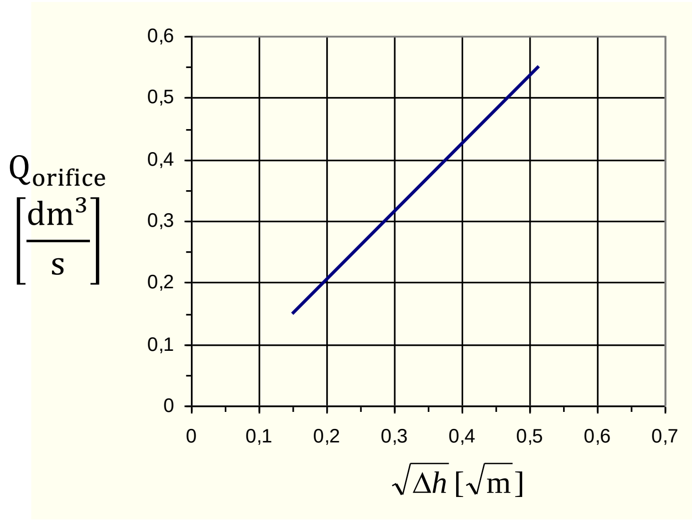


Figure 10: The volumetric flow rate – level difference relationship of the orifice plate

$$Q_{\text{orifice}}\,[dm^3/s] = 1{,}11\sqrt{\Delta h}\;[\sqrt{m}\,] - 0{,}0186$$

This volumetric flow rate can also be measured by a volume meter tank. **Volume meter tanks** can only be used when the system is open or can be opened up. The time of the liquid level rise is measured in a tank with a known cross section (*Figure 8:* **VMT**). According to the principle of communicating vessels, the level rise is observed in the glass tube connected to the tank. A scale is placed next to the glass tube. The time is measured by a stopwatch. Now the volumetric flow rate can be written as

$$Q_{\text{VMT}} = \alpha \frac{\Delta m}{\Delta t}\left[\frac{\text{dm}^3}{\text{s}}\right],$$

where α [dm^3/mm] is the constant of the tank, namely the volume of a *1 mm* thick layer of liquid in the tank

Δm [mm] is the level difference in the water evels

Δt [s] is the time needed for the level rise.

During the measurement, the level rise and the stopwatch have to be observed at the same time; therefore, it is reasonable to watch only the liquid level and **start and stop the stopwatch at round values** (e.g. round cm units), and read the time measured by the stopwatch with **units of tenth and hundredth of a second**. To reduce the uncertainty of the measurement, preferably **do not measure less than 30 seconds**. (Here, the time for at least *Δm=100 mm* rise is measured!)

The measurement data should be recorded in the following table:

h_{p1}	h_{p2}	h_{p1}-h_{p2}	$Q_{orifice}$	α	Δm	Δt	Q_{VMT}
[mm]	[mm]	[m]	[dm^3/s]	[dm^3/mm]	[mm]	[s]	[dm^3/s]

3.3. Calibration of a Bourdon gauge

Calibration means the comparison of the value shown on the gauge with an actual physical quantity. Metal manometers operate indirectly, i.e. the deformation is measured; therefore, these manometers have to be calibrated regularly to be accurate. (The word "certification" is maintained by a similar activity carried out by the authority.) The apparatus used for calibration is depicted in *Figure 11*. A plunger extending into an oil-filled cylinder is loaded with known force. Thus, the pressure *(p_t)* is known in the closed cylinder. The pressure gauge is loaded with these known pressures, which are simultaneously compared to the pressures read *(p_{read})* from the gauge. The result of the calibration is the **calibration diagram** depicted in *Figure 12*. In an ideal case – with the same scale for abscissa and ordinate – it is a straight line with a slope of 45° ("Identity function").

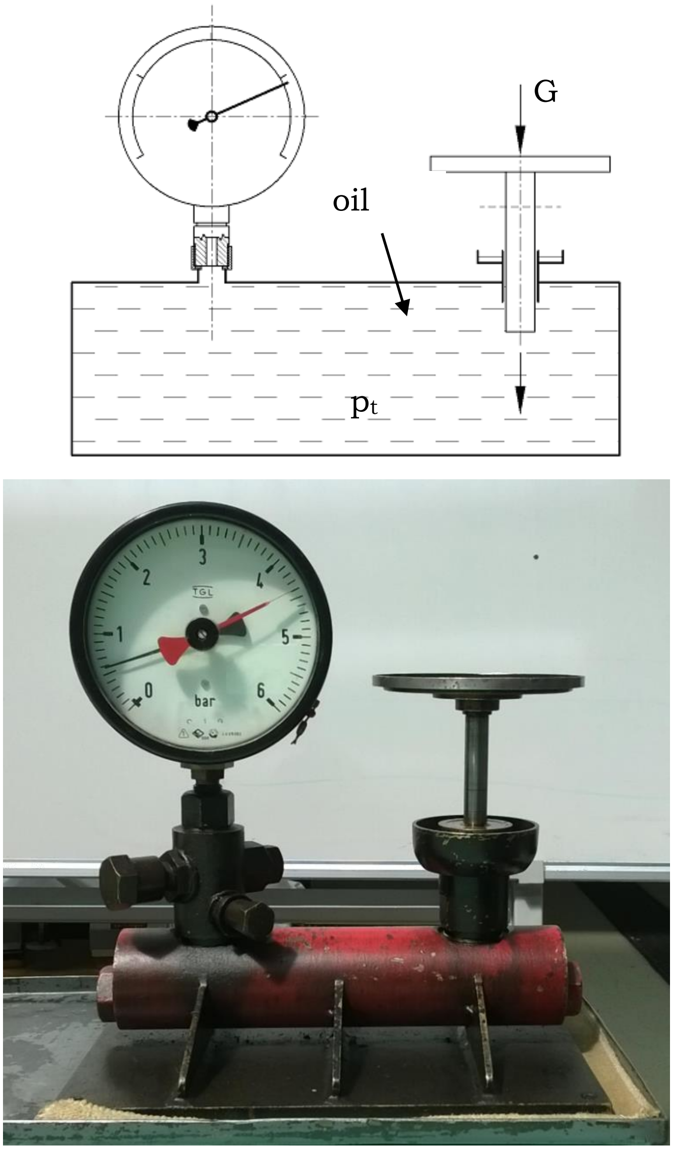


Figure 11. Apparatus used for calibration of manometer

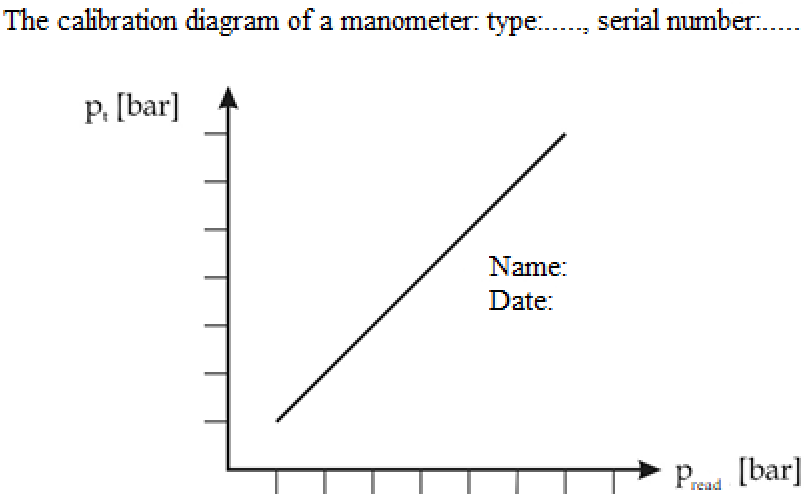


Figure 12. Calibration diagram

The ideal case means that when the Bourdon tube (spiral spring) is pressurized, it behaves the same way as it did when the dial was made. However, the spring constant of the Bourdon tube changes over time causing a **regular measurement error**. A regular measurement error can be caused by a permanent instrument error or a scale error, which **cannot be avoided** by increasing the number of measurements. The aim of creating a calibration diagram is to determine the regular measurement error.

The pressure of the fluid created by adding weights to the plunger (load pressure):

$$p_t = \frac{(m+m_0)g}{a} \text{ [Pa]}.$$

In the present measurement apparatus, the mass of the plunger is $\boldsymbol{m_0}$ **= 1 kg,** and the cross-section of the plunger rod is $\boldsymbol{\alpha}$ **= 2·10⁻⁴ m².** To increase the pressure, several steel disks of 1 and 2 kg mass (*m*) will be used. The first measuring point is when the apparatus is loaded with only the mass m_0 (plunger without disks). Approximately 8 measurement points are required. When measuring (reading the pressure value from the gauge), **rotate the tray of the plunger** to eliminate the effect of vertical piston friction.

During the measurement and evaluation, the following table should be filled out; then, the **calibration diagram** should be drawn similarly to *Figure 12.*

No.	$m+m_0$	$p_{read.}$	p_t
	[kg]	[bar]	[bar]
1			
2			
3			
4			
5			
6			
7			
8			

Preparation for the Measurement

- Bring an A4 graph paper, a pencil, a ruler and a calculator.
- Before the measurement, we shall check the proper preparation for the measurement, the knowledge and correct usage of the applied formulas during the measurement via theoretical and short numerical questions. (e.g. sample questions on the website; note that there may be different questions in the test.)
- Fill out the lab report template at home up to Section 4. (Sections 5-8 will be completed during the measurement).

Comments on the measurement description and the measurement are awaited at kklapcsik@hds.bme.hu