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THERMODYNAMICS LAB (ISE)

Pressure Measurement

Pressure Measurement Experiments

Introduction

Pressure is a state property and describes the state of a thermodynamical system. It is defined as a force per area unit. It may be expressed as a Gauge, Absolute, Negative gauge or Vacuum reading. Although pressure is an absolute quantity, everyday pressure measurements, such as for tire pressure, are usually made relative to ambient air pressure. In other cases measurements are made relative to a vacuum or to some other ad hoc reference. When distinguishing between these zero references, the following terms are used:

- **Absolute pressure** is zero referenced against a perfect vacuum, so it is equal to gauge pressure plus atmospheric pressure.

- **Gauge pressure** is zero referenced against ambient air pressure, so it is equal to absolute pressure minus atmospheric pressure. Negative signs are usually omitted.

- **Differential pressure** is the difference in pressure between two points.

Atmospheric pressure is typically about 100 kPa at sea level, but is variable with altitude and weather. If the absolute pressure of a fluid stays constant, the gauge pressure of the same fluid will vary as atmospheric pressure changes. For example, when a car drives up a mountain (atmospheric air pressure decreases), the (gauge) tire pressure goes up. Some standard values of atmospheric pressure such as 101.325 kPa or 100 kPa have been defined, and some instruments use one of these standard values as a constant zero reference instead of the actual variable ambient air pressure. This impairs the accuracy of these instruments, especially when used at high altitudes. One Pascal is the pressure which is exerted by a force of 1 Newton on 1 m^2 area (the force acting perpendicular to the surface), i.e. $1\ Pa = 1\ N/m^2 = 1\ kg/(m \cdot s^2)$. Pascal (Pa) is the SI unit of pressure. Figure 1.1 shows some other common units and the conversion factors. As with most measurements, pressure measurement methods have varying suitability for different applications. Measurement engineers need to be familiar with several techniques in order to select the one that is most appropriate for their specific requirements.

1 Calibration of a manometer

1.1 Description

A dead weight tester (piston gauge) should be used for primary calibration of pressure measuring instruments. Different pressures will be generated by turning a jackscrew that reduces the fluid volume inside the tester. The difference between the applied pressure on the piston manometer and the display of the device under test (e.g., Bourdon gauge) will be determined and graphically shown.

1.2 Physical Principles

This device, shown in Figure 1.2 uses calibrated weights (masses) that exert pressure on a fluid (usually a liquid) through a piston. Deadweight testers can be used as primary standards because the factors influencing accuracy are traceable to standards of mass, length, and time.

The piston gauge is simple to operate; pressure is generated by turning a jackscrew that reduces the fluid volume inside the tester, resulting in increased pressure. When the pressure generated by the reduced volume is slightly higher than that generated by the weights on the piston, the piston will rise until it reaches a point of equilibrium where the pressures at the gauge and at the bottom of the piston are exactly equal. The pressure in the system will be:

$$p = \frac{(G_K + G_A) \cdot g}{A}$$

[G_K = Mass of the piston, G_A = Additional masses (weights) put on the piston, A = Cross-sectional area of the piston, g = Acceleration due to gravity].

For the calibration of a Bourdon gauge, as shown here, the pressures from 1 to 70 bar can be applied with the help of a hand pump [Druckpresse]. Both the device under test (Bourdon gauge) [Prüfling] and the piston manometer [Kolbenmanometer] are connected to the pressure cylinder [Druckzylinder] through appropriate connections, stop valve [Absperrventil] and a reservoir [Behälter] for collecting the extra oil [Drucköl]. The display of the device under test (e.g., Bourdon gauge) will be read ant the difference between the applied pressure on the piston manometer and this display can be determined and graphically shown.

1.2.2 Bourdon guage (manometer)

The Bourdon pressure gauge, shown in Figure 1.3, uses the principle that a flattened tube tends to change to a more circular cross-section when pressurized. Although this change in cross-section may be hardly noticeable, and thus involving moderate stresses within the elastic range of easily workable materials, the strain of the material of the tube is magnified by forming the tube into a C shape or even a helix, such that the entire tube tends to straighten out or uncoil, elastically, as it is pressurized. Eugene Bourdon patented his gauge in France in 1849, and it was widely adopted because of its superior sensitivity, linearity, and accuracy. In practice, a flattened thin-wall, closed-end tube is connected at the hollow end to a fixed pipe containing the fluid pressure to be measured. As the pressure increases, the closed end moves in an arc, and this motion is converted into the rotation of a (segment of a) gear by a connecting link which is usually adjustable. A small diameter pinion gear is on the pointer shaft, so the motion is magnified further by the gear ratio. The positioning of the indicator card behind the pointer, the initial pointer shaft position, the linkage length and the initial position, all provide means to calibrate the pointer to indicate the desired range of pressure for variations in the behavior of the Bourdon tube itself. Figure 1.4 shows the technical details.

Bourdon tubes measure gauge pressure, relative to ambient atmospheric pressure, as opposed to absolute pressure; vacuum is sensed as a reverse motion. When the measured pressure is rapidly pulsing, such as when the gauge is near a reciprocating pump, an orifice restriction in the connecting pipe is frequently used to avoid unnecessary wear on the gears and provide an average reading. Typical high-quality modern gauges provide an accuracy of ±0.066% of full scale (Wallace & Tiernan, Günzburg, Donau) in the pressure range 5 to 10^4 bar of scan.

1.3 Experimental set up

The experimental set up shown in Figure 1.2, consists of a piston manometer [Druckkolben-manometer of firm Bodenberg. The cross sectional area of the piston is 1/16 in^2.

14 weights are available to produce a pressure in the range 1 to 70 bar. The pressure developed by putting the weights on the piston will be sensed through the hydraulic oil (Weißöl B 2) by the device under test [Prüfling], a gauge [Röhrenfedermanometer] of firm Dreyer & Co., Hannover, suitable for the measurement range of 0 to 60 bar and having an accuracy of 0.6 % of the full scale. During the measurement the filling level in the cylinder should be adjusted with the help of hand press [Druckpresse] in such a way that neither any weight is put on the cylinder nor the stroke limiter [Hubbegrenzung] of the cylinder touches the end marking.

1.4 Experimental procedure

1. Open the valve of oil reservoir [Druckölvorratsbehälter] so that some oil flows into the connecting tube.

2. Turn the hand press [Druckölpresse] left up to the end. The piston reaches its lowest position (lower end).

3. Close the valve of oil reservoir so that on moving the hand press [Druckölpresse] the oil does not enter the reservoir.

4. Put the weights on the piston head [Kolbenkopf] according to the scheme given in protocol. This is given directly in bar.

   The cross-sectional area of piston is 1/16 in^2 and hence the weight that shows a pressure of 1bar is 412 g.

5. Turn the hand press screw to the right so that the oil is pressed into piston and it is lifted up. The hand press is turn so long that the weights on the piston head are lifted about 2 mm. Check this by looking on the piston head.

6. Turn the weights and put the piston in rotation. This will clear the friction and avoid the error due to friction between piston and its casing. The small resistance during the turning of weights is also a check that the piston floats and does not sit.

7. Read the value shown on the manometer taking care that it is read from the same height. Write the value in the protocol sheet 1.

8. Lower the weights so that they sit on the cylinder. The weights are lowered by turning the hand press screw in the left direction.

   Repeat the steps 4 to 8 till all the measurements are completed.

9. Turn the hand press screw to the left up to the end.

10. Remove the weights.

11. Open the valve to the reservoir.

12. Calculate the relative percentage error from the differences between the two values and write in the protocol sheet for the two measurement series.

	N/m^2	at	atm	Torr	kp/m^2	bar
1 N/m^2 = 1 Pa	1	$1.0197 \cdot 10^{-5}$	$9.869 \cdot 10^{-6}$	$7.5006 \cdot 10^{-3}$	0.10197	$1.0 . 10^{-5}$
1 kp/cm^2 = 1 at	$9.807 \cdot 10^{4}$	1	0.9678	$7.3556 \cdot 10^{2}$	10^{4}	0.9807
1 atm = 760 Torr	$1.013 \cdot 10^{5}$	1.033	1	760	$1.0332 \cdot 10^{4}$	1.0133
1 Torr = 1 mm Hg	$1.33 \cdot 10^{2}$	$1.3595 \cdot 10^{-3}$	$1.3158 \cdot 10^{-3}$	1	$1.3595 \cdot 10$	$1.3332 \cdot 10^{-3}$
1 kp/m^2 = 1 mm WS	9.807	$1.0 \cdot 10^{-4}$	$9.6784 \cdot 10^{-5}$	$7.3556 \cdot 10^{-2}$	1	$9.8066 \cdot 10^{-5}$
1 bar = 10^6 dyn/cm^2	$1.0 \cdot 10^{5}$	1.0197	0.9869	$7.5006 \cdot 10^{2}$	$1.0197 \cdot 10^{4}$	1

Abbreviations used:
N = Newton, Pa = Pascal, at = techn. atmosphere, atm = physical atmosphere, WS = Water column, Hg = Mercury column

American and english units:

	N/m^2	Torr	bar	Psi
1 psi = 1 lbf/sqi	$6.895 \cdot 10^{3}$	51.72	$6.895 \cdot 10^{-2}$	1
1 inch WS	249.10	1.8683	$2.490 \cdot 10^{-3}$	$3.6 – 10^{-2}$
1 inch Hg	$3.378 \cdot 10^{3}$	25.4	$3.383 \cdot 10^{-2}$	0.489
1 lbf/ft^2	47.89	0.3592	$4.79 \cdot 10^{-4}$	$6.9456 \cdot 10^{-3}$

psi = pounds per square inch, lbf = pound force (force unit), ft = feet = 12 inches

Figure 1.1 Some important pressure units and their conversion factors

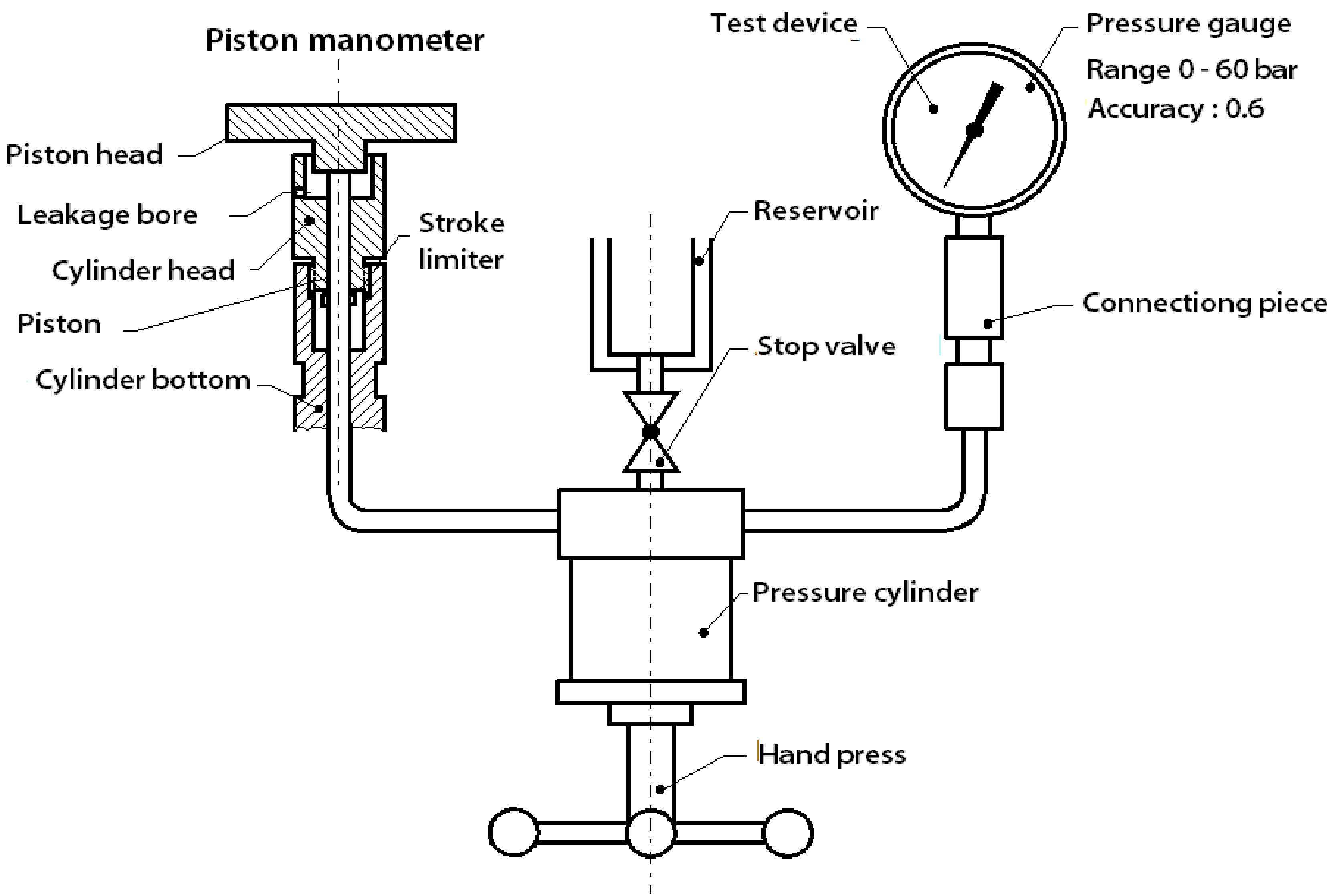

Figure 1.2 Set up for the calibration of a pressure measuring device with the help of a dead weight tester

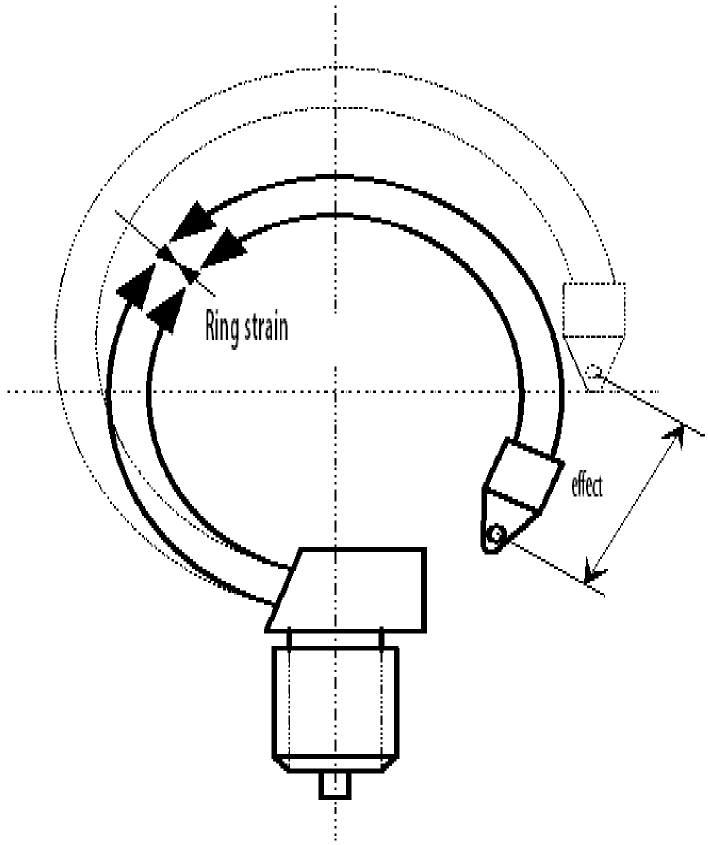

Figure 1.3 Bourdon gauge

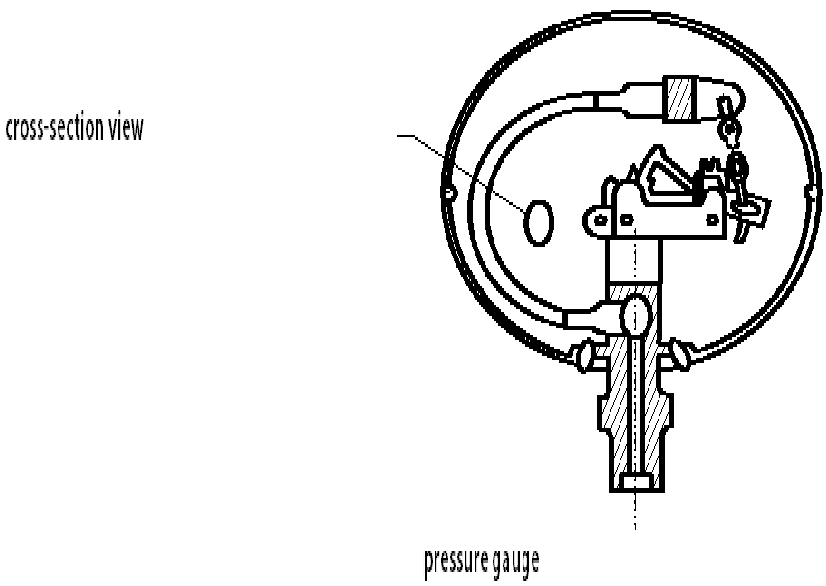

Figure 1.4 Technical details of Bourdon gauge

Protocol-1

Date: Matr.-Nr.:
Time: Name:

Experiment 1: Calibration of a pressure gauge

Piston manometer p_K [bar]	Test manometer (ascending weights) p_M [bar]	Relative error $\frac{p_M - p_K}{p_M} 100$ [%]	Test manometer (descending weights) p_M' [bar]	Relative error $\frac{p_M' - p_K}{p_M'} 100$ [%]
1				
1.5				
2.5				
5				
7.5				
10				
12.5				
15				
17.5				
20				
25				
30				
35				
40				
50				
60				

2 Measurement of vacuum (reduced pressure)

2.1 Description

Reduced pressure will be produced in a tube with the help of a rotary pump. The schematic diagram is shown in Figure 2.1. There are four different instruments connected to the measuring line: a Baro-Vacuum meter according to Lambrecht, a U-tube vacuum gauge according to Bennert, a thermal conductivity vacuum gauge and a pressure sensor vacuum gauge. Different pressures will be produced with the help of a metering valve and the values displayed by the different instruments will be recorded. The barometric pressure will also be noted and the vacuum or reduced pressure will be calculated

2.2 Physical principles

2.2.1 Introduction

Many techniques exist for the measurement of pressure and vacuum. Instruments used to measure pressure are called **pressure gauges** or **vacuum gauges**.

A **manometer** could also be referring to a pressure measuring instrument, usually limited to measuring pressures near to atmospheric. The term *manometer* is often used to refer specifically to liquid column hydrostatic instruments.

A **vacuum gauge** is used to measure the pressure in a vacuum. A general classification is:

Coarse vacuum (GV)	760 – 1 Torr
Fine vacuum (FV)	1 – 10^{-3} Torr
High vacuum (HV)	10^{-3} – 10^{-7} Torr
Ultra high vacuum (UHV)	10^{-7} Torr and below.

A wide choice of gauges is available for vacuum measurement. When choosing a gauge it is reasonable to consider first the lowest pressure to be measured. After determining the lowest pressure, the higher pressures can be determined by selecting the next gauges. A list of gauges used for various ranges are given in Figure 2.2.

Figure 2.3 explains some terms used for expressing the vacuum (low pressure).

Pressure difference
is the difference between two pressures.

Absolute pressure
is the pressure according to the definition given above. It is the pressure difference from absolute vacuum

Over pressure
is defined as the pressure difference between the measured pressure and a reference pressure (atmospheric pressure) if the measured pressure is greater than the reference (atmospheric) pressure.

Reduced pressure
is defined as the pressure difference between the measured pressure and a reference pressure (atmospheric pressure) if the measured pressure is smaller than the reference (atmospheric) pressure.

Vacuum in percent
is the ratio of reduced pressure to atmospheric pressure multiplied with hundred.

Choice of a pressure measuring instrument

When choosing a pressure gauge, not only the pressure range but also the conditions under which the measurement is to be done play important role. For industrial purposes where a danger of contamination exists, or the measuring line is not fixed so that it may come to vibrations the instruments like spring or membrane vacuum gauges or thermal conductivity instruments are recommended.

2.2.2 Liquid manometer

The well known equation from hydrostatics for the pressure exerted by a liquid column of height h and the density ρ lays down the basic principle for this family of pressure measurement instruments:

$$p = \rho \cdot g \cdot h \quad (\, g = \text{acceleration due to gravity}) \tag{2.1}$$

Liquid manometers are used for the pressure difference as well as for the absolute pressure measurements. The accuracy of the pressure measurement depends upon the accuracy in the measurement of the liquid density and the accuracy of the value of the acceleration due to gravity at that place. These values are normalized and the deviations from these should be considered.

The different corrections applied to the acceleration due to gravity and the height of the liquid column are explained below.

Temperature correction

The display of the mercury manometer is normally in Torr. One Torr is defined as the pressure exerted by 1 mm mercury column at 0°C and under normal acceleration due to gravity g = 9.80665 m/s² on its basic surface.

The components of a mercury manometer are calibrated at a particular temperature. Usually it is calibrated at 20 °C. That means the scale shows the <u>correct</u> values only at a temperature of 20 °C. At a higher temperature a lower value (e.g. 759.9 mm) from the zero point instead of 760.0 mm will be shown. This is due to the expansion of the scale which must be corrected

Same thing holds for the length of the mercury column. Only at 0 °C is the pressure exerted by 1 mm mercury column is exactly one Torr. At higher temperatures the mercury expands and the density of mercury decreases. Hence to produce a pressure of one Torr the length of mercury column is changed (say by Δl).

Generally a linear change in length is considered:

$$\Delta l = l \cdot \alpha \cdot (t - t_E)$$

l := Length under calibration conditions,
α := Coefficient of thermal expansion,
t := Actual temperature of the system (Ambient),
the system is in thermal equilibrium,
t_E := Calibration temperature.

$$l(t) = l + \Delta l$$

The change in the length of the scale:

$$\Delta l = l_S(t_{E,S}) \cdot \alpha_S \cdot (t - t_{E,S}) \tag{2.2}$$

$l_S(t_{E,S})$:= Length of the scale at calibration temperature,
α_S := Coefficient of thermal expansion of the scale (here brass)
$\alpha_S(brass) = 11 \cdot 10^{-6} \frac{1}{°C}$
$t_{E,S}$:= Calibration temperature for the scale, here 20 °C.

The change in the length of mercury column:

$$\Delta l = l_Q(t_{E,Q}) \cdot \alpha_Q \cdot (t - t_{E,Q}) \tag{2.3}$$

$l_Q(t_{E,Q})$:= Length of the scale at calibration temperature
α_Q := Coefficient of thermal expansion for mercury
$\alpha_Q = 182 \cdot 10^{-6} \frac{1}{°C}$
$t_{E,Q}$:= calibration temperature for mercury 0 °C.

The temperature correction K_t is calculated as explained below:

$l_S(t) = l_S(t_{E,S}) + \Delta l$ (Length of the scale at temperature t)

Using (2.2)

$$l_S(t) = l_S(t_{E,S})\,(1 + \alpha_S\,(t - t_{E,S}))$$

The scale will expand and hence the displayed scale value $S(t)$ will be lower. So

$$S(t) = l_S(t_{E,S})\,(1 - \alpha_S\,(t_A - t_{E,S}))$$

$$l_S(t_{E,S}) = \frac{S(t)}{(1 - \alpha_S(t_A - t_{E,S}))} \tag{2.4}$$

$l_S(t_{E,S})$ denotes the real length of mercury column at this temperature

$$l_S(t_{E,S}) = l_Q(t)$$

which is also given as

$$l_Q(t) = l_Q(t_{E,Q}) + \Delta l \tag{2.5}$$

or

$$l_Q(t) = l_Q(t_{E,Q})\,(1 + \alpha_Q\,(t_A - t_{E,Q}))$$

with (2.4) and (2.5)

$$l_Q(t_{E,Q}) = \frac{S(t)}{(1-\alpha_S(t_A - t_{E,S}))\cdot(1+\alpha_Q(t_A - t_{E,Q}))} \tag{2.6}$$

The correction is the difference between the measured value and the actual value. That is

$$K_t = l_Q(t_{E,Q}) - l_S(t) \tag{2.7}$$

Putting this value in (2.6) weg et for K_t

$$K_t = S(t)\cdot\frac{[1-(1-\alpha_S(t_A - t_{E,S}))\cdot(1+\alpha_Q(t_A - t_{E,Q}))]}{(1-\alpha_S(t_A - t_{E,S}))\cdot(1+\alpha_Q(t_A - t_{E,Q}))} \tag{2.8}$$

This may be simplified to

$$K_t = -S(t)\cdot\frac{(\alpha_Q(t_A - t_{E,Q}) - \alpha_S(t_A - t_{E,S}))}{(1+\alpha_Q(t_A - t_{E,Q}) - \alpha_S(t_A - t_{E,S}))} \tag{2.9}$$

Here the multiplication term $\alpha_Q\alpha_S$ was neglected as it is in the range of 10^{-9}.

Capillary depression

As a result of high surface tension of mercury the glass is not wetted (moistened) by the mercury and the mercury forms a convex meniscus in the tube instead of a leveled surface. Thereby the mercury height will be reduced. This must be taken into account while reading the length of the mercury column. The correction values depend on the inside diameter of the tube and on the height of the meniscus. They are ascertained empirically by comparing them with a barometer free of depression. The numerical values of the correction due to capillary depression can be taken from the Table 2.1 given below.

Table 2.1: Correction of the barometric length (mm Hg or mbar) due to capillary depression

	Capillary height (for 8 mm tube-ϕ) in mm or mbar										
	0.4	0.5	0.6	0.7	0.8	2.9	1.0	1.1	1.2	1.3	1.4
K_k (mm Hg)	0.24	0.29	0.35	0.41	0.46	0.51	0.56	0.60	0.64	0.68	0.71
K_k (mbar)	0.24	0.30	0.36	0.41	0.47	0.52	0.57	0.63	0.68	0.73	0.77

	Capillary height (for 8 mm tube-ϕ) in mm or mbar									
	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
K_k (mm Hg)	0.74	0.77	0.80	0.82						
K_k (mbar)	0.81	0.85	0.89	0.93	0.96	0.99	1.02	1.05	1.07	1.09

The correction values K_K given in the table (in mm Hg or mbar) are to be added to the barometric values.

Correction of gravity

Latitude:

The length of the mercury column also depends on the acceleration due to gravity, which changes with the geographical latitude and the height above sea level. Therefore, the barometric reading is converted to the normal gravity. At sea level below 45° of latitude the gravitational acceleration amounts to 9.80616 m/s². The normal gravity or the standard value of the gravitational acceleration is 9.80665 m/s², which is reached at sea level at approximately 45° 33′ geographical latitude. If p is the pressure measured at any geographical latitude, g_N the normal acceleration due to gravity, b_N the height of the mercury column at normal acceleration due to gravity, b_β the temperature corrected barometric column and g_β the acceleration due to gravity at any geographical place then it holds at the same atmospheric pressure on different places:

$$p = \rho \cdot g_N \cdot b_N = \rho \cdot g_\beta \cdot b_\beta \tag{2.10}$$

The correction due to gravity for that place is

$$K_\beta = b_N - b_\beta \text{ or also } K_\beta = b_\beta \cdot \left(\frac{b_N}{b_\beta} - 1 \right).$$

Using (2.10) follows:

$$K_\beta = b_\beta \cdot \left(\frac{g_\beta}{g_N} - 1 \right). \tag{2.11}$$

The acceleration due to gravity changes with the latitude according to the relation:

$$g_\beta = 9.80616 - 0{,}02586 \cos 2\beta + ...$$

So, one obtains:

$$K_\beta = \left(\frac{9.80616 - 0.02586 \cdot \cos 2\beta}{9.80665} - 1\right) \cdot b_\beta \tag{2.12}$$

(b_β is the at t = 0° C reduced barometer value)

(Geographical latitude for Duisburg = 51.5°)

<u>Height above sea level:</u>

Now the change of gravity due to the change in the height is considered. The barometric pressure decreases with the increasing height above sea level. So the air pressure values taken at different heights can, therefore, not be compared with each other. For this reason they will be reduced to a standard of reference (generally sea level). The reduction in pressure values K_H (in Torr) is calculated as follows:

$$K_H = b_H \cdot \left(e^S - 1\right) \tag{2.13}$$

where

$$S = \frac{H}{7991.15(1 + 0.00367 \cdot t_m)}. \tag{2.14}$$

Here b_H is the barometer reading (in Torr) at the height H (in meter) und t_m is the mean temperature between measuring position (temperature t° C) and sea level based on a gradient of 1 °C/100 m.
The coefficient of expansion of air is taken as 0.00367.

2.2.3 Mercury-Baro-Vacuum meter

The Baro-Vacuum meter according to Lambrecht is a combination of a barometer for the measurement of absolute air pressure and a reduced pressure measuring gauge (vacuum meter). It is a cistern barometer with an adjustable scale.

Figure 2.4 shows a schematic diagram of a baro-vacuum meter. The measurement of air pressure is made by measuring the length of the mercury column, which holds the balance to the air pressure above the point of observation as against the absolute vacuum. For this reason the zero of the scale has to be adjusted to the level in the low cistern before each measurement.

2.2.4 U-tube manometers

The height of a column of liquid, or the difference between the heights of two liquid columns, is used to measure pressure head in devices called U-tube manometers (see Figure 2.5). If a fluid is installed in an open U-shaped tube, the fluid level in each side will be the same. When pressure is applied to one side, that level will go down and the level on the other side will rise until the difference between the heights is equal to the pressure head. The height difference is proportional to the pressure and to the density of the fluid. The U-tube manometer is a primary standard for pressure measurement.

Differential pressure can be measured by connecting each of the legs to one of the measurement points. Absolute pressure can be measured by evacuating the reference side. A mercury barometer is such an absolute pressure measuring manometer indicating atmospheric pressure. In some versions, the two legs of the U are of different diameters. Some types incorporate a large-diameter "well" on one side. In others, one tube is inclined in order to provide better resolution of the reading. But they all operate on the same principle. Because of the many constraints on geometry of installation and observation, and their limited range, manometers are not practical or effective for most pressure measurements.

Although many manometers are simply a piece of glass tubing formed into a U shape with a reference scale for measuring heights, there are many variations in terms of size, shape, and material (see Figure 2.5). If the left side is connected to the measurement point, and the right is left open to atmosphere, the manometer will indicate gauge pressure, positive or negative (vacuum).

Any fluid can be used in a manometer. However, mercury is preferred for its high density (13.534 g/cm^3) and low vapor pressure. For low pressure differences well above the vapor pressure of water, water is commonly used (and "inches of water" is a common pressure unit). U-tube liquid-column pressure gauges are independent of the type of gas being measured and have a highly linear calibration. They have poor dynamic response. When measuring vacuum, the working liquid may evaporate and contaminate the vacuum if its vapor pressure is too high. When measuring liquid pressure, a loop filled with gas or a light fluid must isolate the liquids to prevent them from mixing. Simple hydrostatic gauges can measure pressures ranging from a few Torr (a few 100 Pa) to a few atmospheres (Approximately 1000000 Pa).

One manometer which is extensively used is that according to Bennert shown in Figure 2.6. It consists of a vertical standing U-tube of glass whose one arm is evacuated. The other arm is connected to an inverted U-tube. The lower end of this can be closed with the help of a valve and is connected to the pressure being measured. A scale is brought between the arms (see Figure 2.6) to measure the difference in the levels of the liquid in the two arms. It can be used to measure absolute pressures between 1 and 200 Torr.

2.2.5 Thermal conductivity vacuum meter

The thermal conductivity vacuum meter is an indirect device for pressure measurement. Generally, an increase in the density of a real gas (which also indicates an increase in pressure) increases its ability to conduct heat. In this type of gauge, a wire filament is heated by running current through it. A thermocouple or Resistance Temperature Detector (RTD) can then be used to measure the temperature of the filament. This temperature is dependent on the rate at which the filament loses heat to the surrounding gas, and therefore on the thermal conductivity. A common variant is the Pirani gauge which uses a single platinum filament as both the heated element and RTD. The operating principle of this type of instruments is that the heat loss by conduction and convection from a heated resistance wire depends on the pressure of the gas surrounding the wire. These gauges are accurate from 10 Torr to 10^{-3} Torr, but they are sensitive to the chemical composition of the gases being measured.

Under high vacuum the heat flow due to gas convection does not depend upon pressure (see Figure 2.7) and so these gauges are not useful. For higher pressures the thermal conductance changes very little with pressure.

The uncontrolled heating thermal conductivity vacuum meters can be used to measure pressures between 10^{-3} and 10 Torr whereas the controlled heating thermal conductivity vacuum meters have a range from 10^{-3} to 760 Torr. Due to low response time these may be used for controlling the pressure in various applications. The accuracy of measurement depends on the range of the instrument. The maximum error is 1 to 2% of the full scale, i.e. in lower pressure range between 10^{-2} and 1 Torr, ca. 10 % of the display. Normally air and nitrogen are used as the gases.

2.2.5 Mechanical gauges

These gauges also called Aneroid gauges are based on a metallic pressure sensing element which flexes elastically under the effect of a pressure difference across the element. "Aneroid" means "without fluid," and the term originally distinguished these gauges from the hydrostatic gauges described above. However, aneroid gauges can be used to measure the pressure of a liquid as well as a gas, and they are not the only type of gauge that can operate without fluid. Aneroid gauges are not dependent on the type of gas being measured, unlike thermal and ionization gauges, and are less likely to contaminate the system than hydrostatic gauges.

It consists of a metallic diaphragm (copper-beryllium or nickel-carbon) and is based on the principle that a flattened tube tends to change to a more circular cross-section when pressurized. Although this change in cross-section may be hardly noticeable, and thus involving moderate stresses within the elastic range of easily workable materials, the strain of the material of the tube is magnified by forming the tube into a C shape or even a helix, such that the entire tube tends to straighten out or uncoil, elastically, as it is pressurized. Figure 2.8 shows a typical instrument. The useful range is from 760 – 1 Torr, however the pressures down to 0.1 Torr may be measured where the accuracy up to 0.1 % of full scale are reached.

2.3 Experimental set up and measurement method

The experimental set up is shown schematically in Figure 2.1.

Four different instruments for pressure measurement are connected via a connecting tube: a Baro-Vacuum-meter according to Lambrecht (Firma Lambrecht, Göttingen), a U-tube-vacuum meter according to Bennert (Firma Schoeps, Duisburg), a thermal conductivity vacuum meter with controlled heating voltage (Type Thermovac TM 201 S2, Firma Leybold-Heraeus, Köln) and an Aneroid-absolute pressure gauge (Firma Wallace-Tiernan, Günzburg). The tubing is connected to a rotary pump (Type Mini of Firma Leybold-Heraeus, Köln) and will be evacuated. There is an aeration valve on the pump side of the pipe line. Air is drawn into the pipe line by opening this valve. The pressure in the pipeline can be controlled with the help of this valve when the rotary pump is running. Different pressure values can be set: 15, 10 und 5 Torr. The pressures will be set using the Aneroid pressure gauge. The setting of pressures up to 2 Torr from the given pressure is sufficient. The displays of various instruments will be read and recorded in protocol. With these measured values the absolute pressure and the vacuum in % will be calculated. The pressures should be given in Torr and N/m^2.

2.3.1 Baro-Vacuum meter

Lambrecht barometer is a combination of a barometer for the measurement of absolute air pressure and a reduced pressure measuring gauge (vacuum meter). It is a cistern barometer with an adjustable scale. Figure 2.9 shows the Baro-Vacuum meter of the firm Lambrecht schematically. There are two glass tubes which are immersed in two glass containers which are connected to each other with a glass tube (for details see Figure 2.4). The left glass tube (barometer tube) is evacuated at the upper end and is sealed (vacuum tight). The test pipe line is connected to the right tube (vacuum meter). The measurement of air pressure is made by measuring the length of the mercury column, which holds the balance to the air pressure above the point of observation as against the absolute vacuum. For this reason the zero of the scale has to be adjusted to the level in the low cistern before each measurement. The length of the mercury column can be determined by the vernier and the scale.

The length of the mercury column, which holds the balance to the present air pressure, is measured by a scale at the right side of the tube. The zero of the division coincides exactly with the point of the scale. Before each reading this point has to be adjusted to the mercury level in the cistern, so that the point and its reflected image will form a cross (X)(see Figure 2.9). The adjustment is made by the milled nut at the lower end of the scale. The metal ring at the vernier, which surrounds the tube, is adjusted by the small milled nut at the upper part of the scale in such a way that its lower edge is situated immediately above the meniscus of the mercury column. The eye must then be in the same height with the metal ring and the meniscus of the mercury. The adjustment is correct when the edges of the metal ring before and behind the tube coincide touching the meniscus of the mercury tangentially (see Figure 2.9). The last graduation mark on the scale below the zero of the vernier division indicates the entire mm. of mercury. For the reading of the tenths mm. of mercury serves the vernier. That graduation mark of the vernier, which coincides with the graduation mark of the main division indicates the tenths mm. of mercury. They must be added to the entire mm. of mercury read on the main scale. The barometric reading in Figure 2.9 is 755.3 mm. of Hg.

2.3.2 U-tube vacuum meter

The U-tube vacuum meter according to Bennert is shown schematically in Figure 2.6. It consists of a vertical standing U-tube of glass whose one arm is evacuated and sealed. The other arm is connected to an inverted U-tube. The lower end of this can be closed with the help of a valve and is connected to the pressure being measured. The glass tubes are fixed on a wooden stand. A scale is brought between the arms (see Figure 2.6) to measure the difference in the levels of the liquid in the two arms. According to the manufacturer the accuracy of this instrument is 0.5 Torr.

2.3.3 Thermal conductivity vacuum meter

It is supplied by the firm Leybold-Heraeus, and is of type TM 201 S2. It is a controlled heating thermal conductivity vacuum meter. It consists of a supply part and a measurement tube connected to it. The supply instrument contains all the electronic parts and meter with a pointer and two scales for pressure reading. The lower scale is linear and the upper logarithmic (calibrated in Torr).

An appropriate Wheatstone bridge circuit is used to make the measurements. The heat loss from the filament is also a function of the ambient temperature and in practice two gauges are connected in series to compensate for possible variations in ambient conditions. The scale is calibrated to show the logarithmic scale. The measurement range is 10^{-3} – 760 Torr with an accuracy of 1.5 % of full scale. It has a low response time. It is calibrated for air.

2.3.4 Aneroid absolute pressure gauge

A precise instrument from the firm Wallace and Tiernan is used. The measuring element is an evacuated Cu-Beryllium-C-capsule. It is a robust instrument with good temperature stability and has a very low response time. The accuracy of this instrument is 0.3 % of the full scale value.

2.4 Experimental Method

1. Turn on the thermal conductivity (Pirani) vacuum gauge and the vacuum pump.
2. Adjust the zero point of barometer scale (see Figure). For the adjustment method see "Mercury Baro- Vacuum gauge, 6. Measurement".
3. Record the barometer reading in the protocol.
4. Open the stop valve at the upper end of the vacuum meter and the U-tube manometer.
5. Close the regulating (loop) valve.
6. Observe the manometer till the pressure drops to 15 Torr.
7. Open the regulating valve slowly so that the manometer readings given in the protocol are attained (say 15 Torr). Wait until the reading is constant (± 2 Torr).
8. Adjust the left tube of the barometer as described under step 2 to the new column height.
9. Read the height of mercury column in vacuum meter tube (right tube) after the adjustment that the edges of metal ring before and behind the tube coincide touching the meniscus of the mercury tangentially.
10. Record the reading in the protocol.
11. Check the pressure at the vacuum meter. The change should not be larger than ± 0.1 Torr. Otherwise regulate the pressure again and take new reading.
12. Read the pressure gauge and record the reading in the protocol.
13. Adjust the zero point of mirror scale of U-tube vacuum meter up to the mercury column height in the left side of the tube.
14. Check the adjusted pressure at the manometer. If necessary regulate the pressure with the help of regulating valve.
15. Read the difference of mercury column height on the two sides.
16. Read the conductivity vacuum gauge and record the reading in the protocol.
17. Now adjust the pressure to another value (10 Torr).
18. Wait till the value is constant.
19. Repeat the steps 4-16.
20. Now adjust the pressure to 5 Torr and repeat the steps 4-16.

21. Open the regulating valve slowly until the mercury height in the U-tube vacuum meter attains highest value then open the valve completely.
22. Shut off the vacuum pump and conductivity meter gauge.
23. Close the valve at U-tube vacuum meter and Baro vacuum meter.
24. Evaluate the barometer readings taking into account all the corrections discussed in section 2.2.2. The corrected barometer reading in Torr is given as:

    $$b_{\mathrm{O}} = b_{\mathrm{t}} + K_{\mathrm{t}} + K_{\beta} + K_{\mathrm{H}} + K_{\mathrm{K}}$$

    b_{t} = Barometer reading
    K_{t} = Temperature correction
    K_{β} = Gravity correction, latitude
    K_{H} = Gravity correction, height
    K_{K} = Capillary height correction

    The correction term for the capillary height will be taken from table 2.1 and all other correction factors will be calculated by the formula given in section 2.2.2. The room temperature should be taken from the Lambrecht barometer reading. The latitude for Duisburg is to be taken as 51.5 ° and the height (including the place of measurement) above sea level as 40 m.
25. Draw graph showing the % deviation of values measured with different instruments from the value of the Aneroid pressure gauge (see section 2.3).
26. Calculate the vacuum in % from the values of Baro vacuum meter.
27. Give values in Pa and bar.

Protocol-2

Date: Matr.-No.:

Time: Name:

Experiment 2: Measurement of low pressure (vacuum)

Temperature:

Barometer reading [mm Hg]	Capillary height [mm Hg]	Temperatur correction [mm Hg]	Gravity Correction [mm Hg]	Height Correction [mm Hg]	Capillary Correction [mm Hg]	Actual reduced barometer reading [mm Hg]

Aneroid Vacuum meter		Baro Vacuum meter	U-tube manometer	Thermovac Thermal conductivity Vacuum meter	Vacuum	p
actual [Torr]	read [Torr]	[Torr]	[Torr]	[Torr]	(%)	[Pascal]
15						
10						
5						

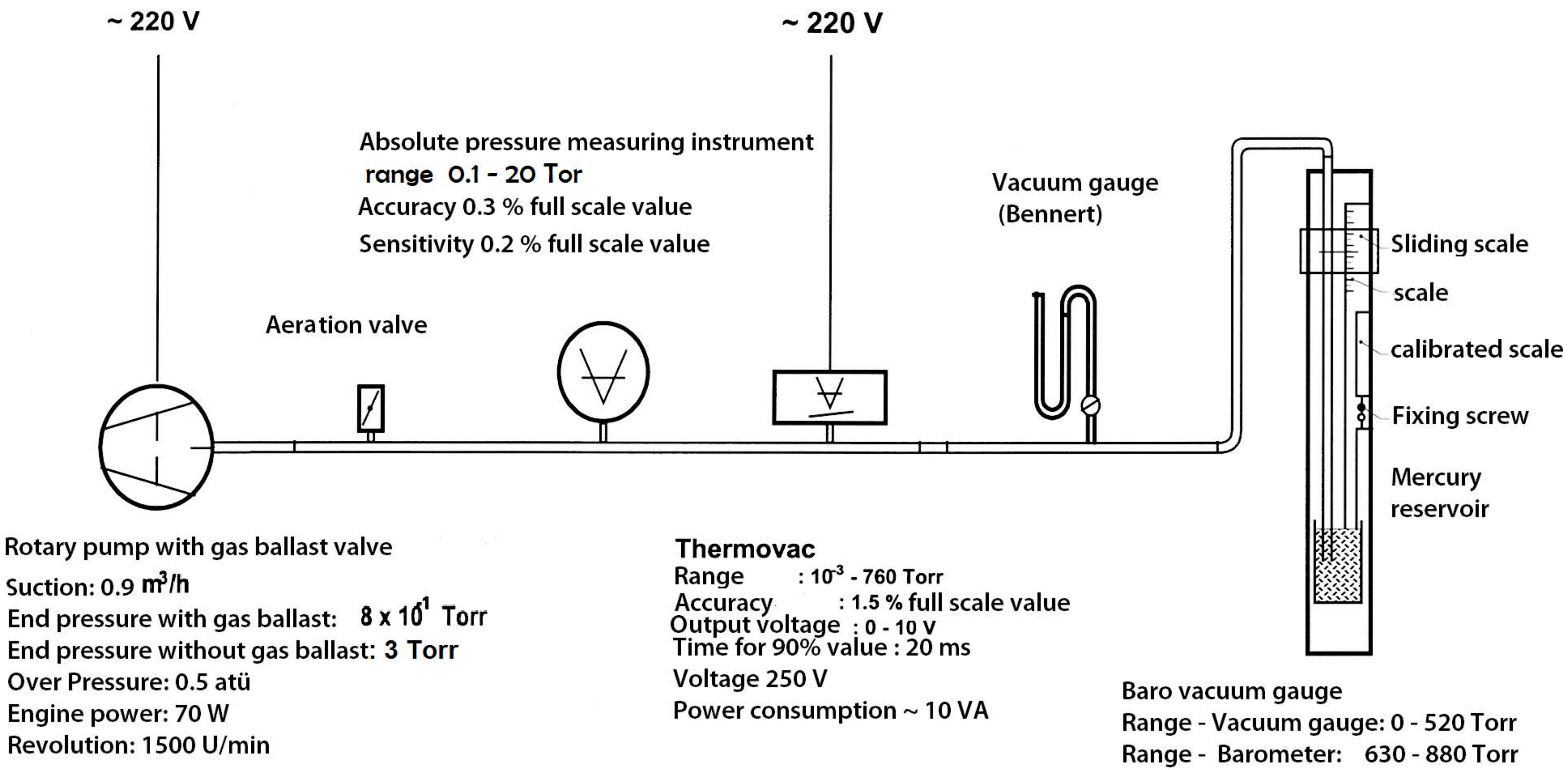

Figure 2.1 Experimental set up for low pressure (vacuum) measurement

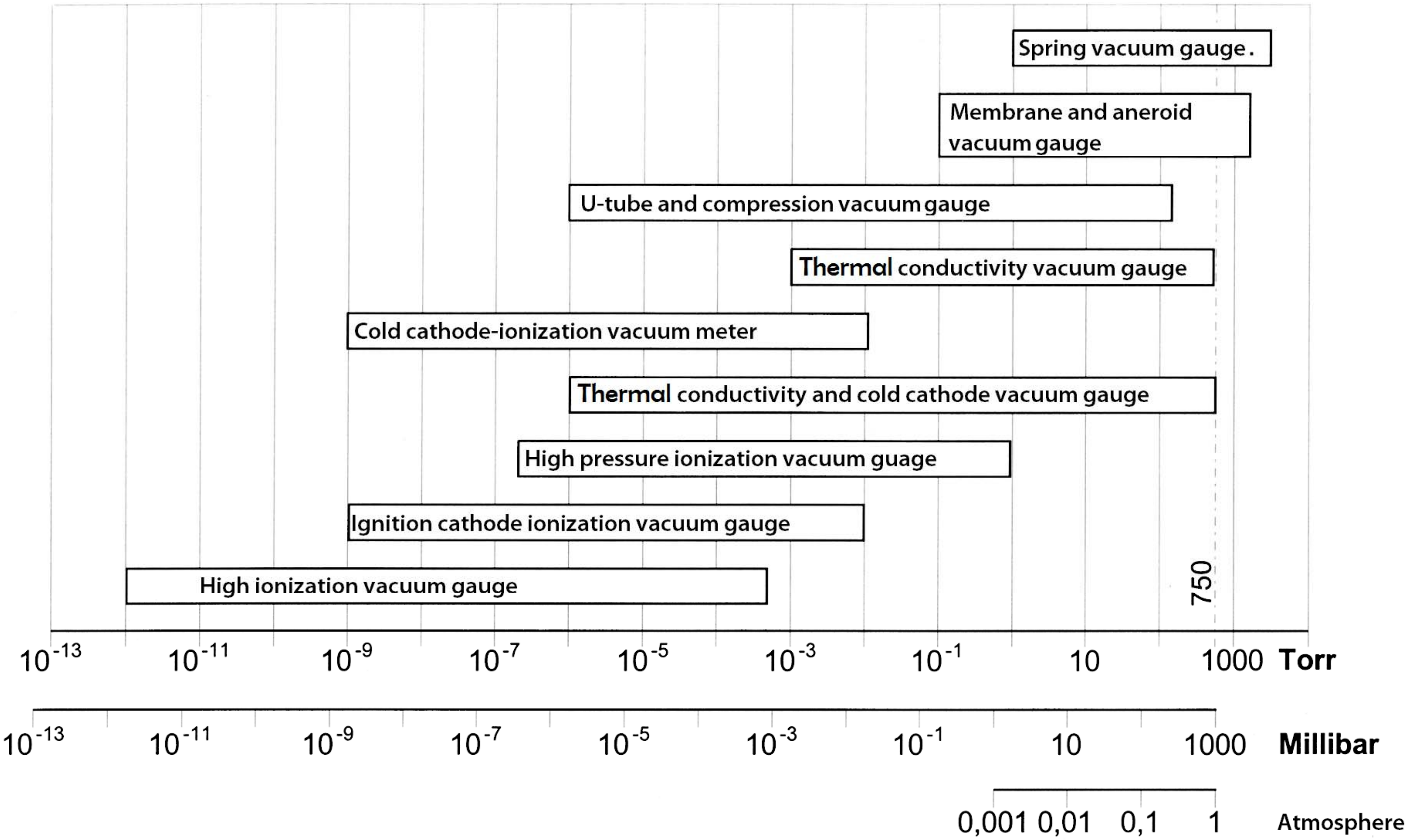

Figure 2.2 Useful ranges for different pressure measuring instruments

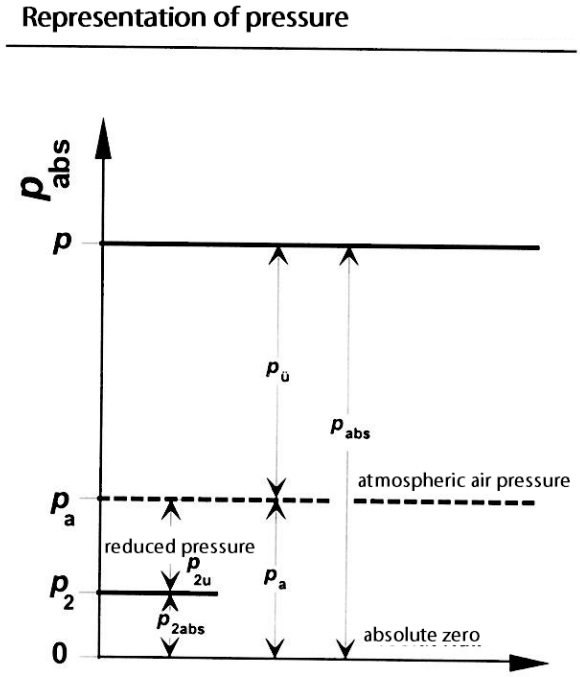

Figure 2.3 Various pressure reference points

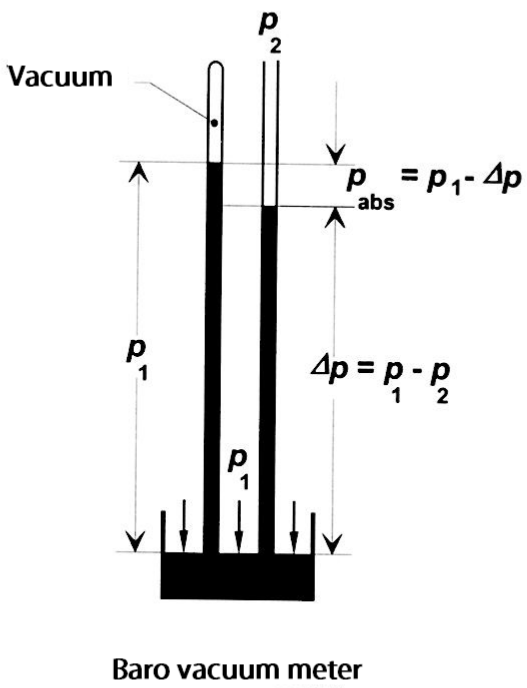

Figure 2.4 Schematic representation of a baro vacuum meter

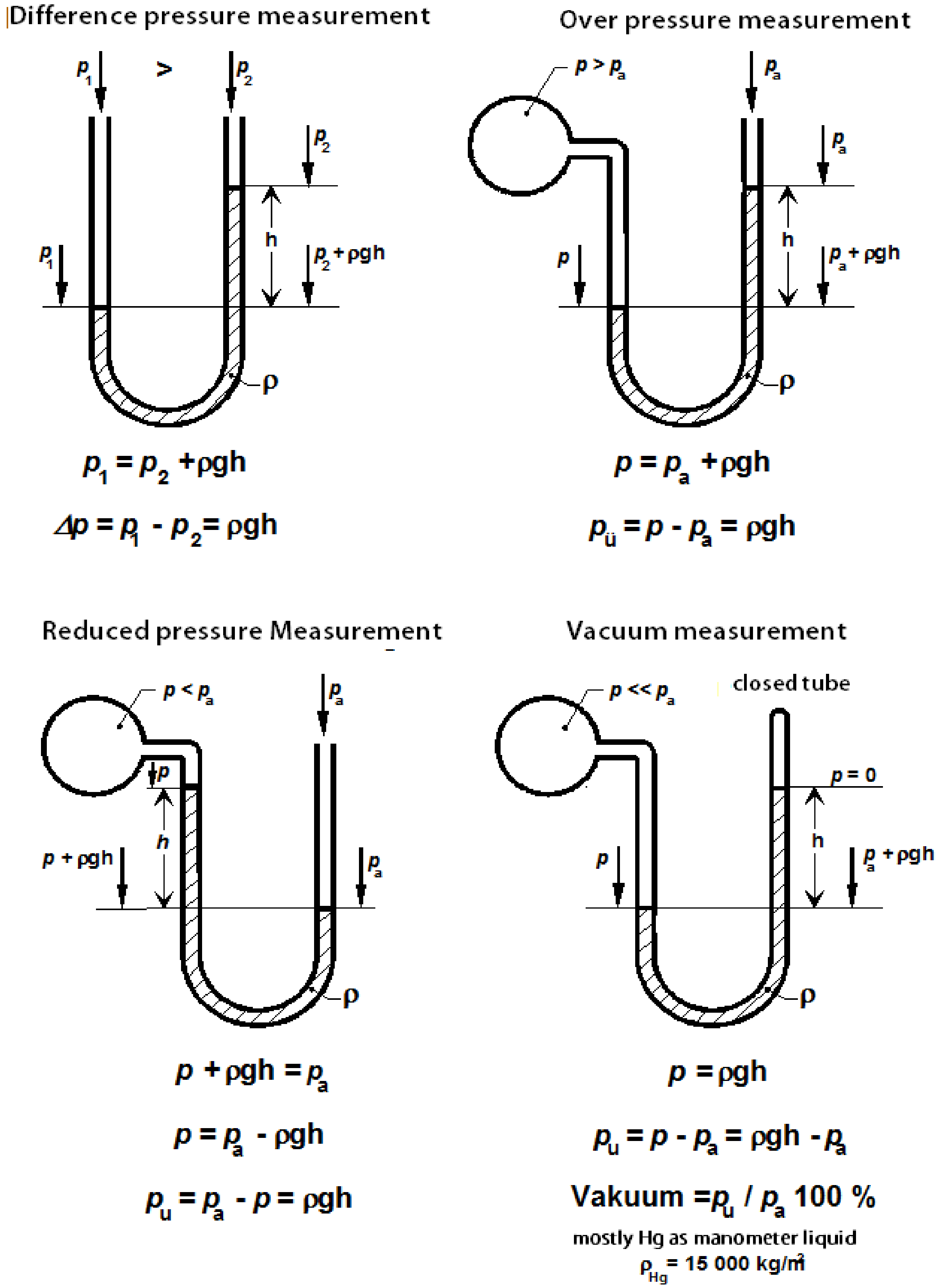

Figure 2.5 Different U-tube configurations for pressure measurements

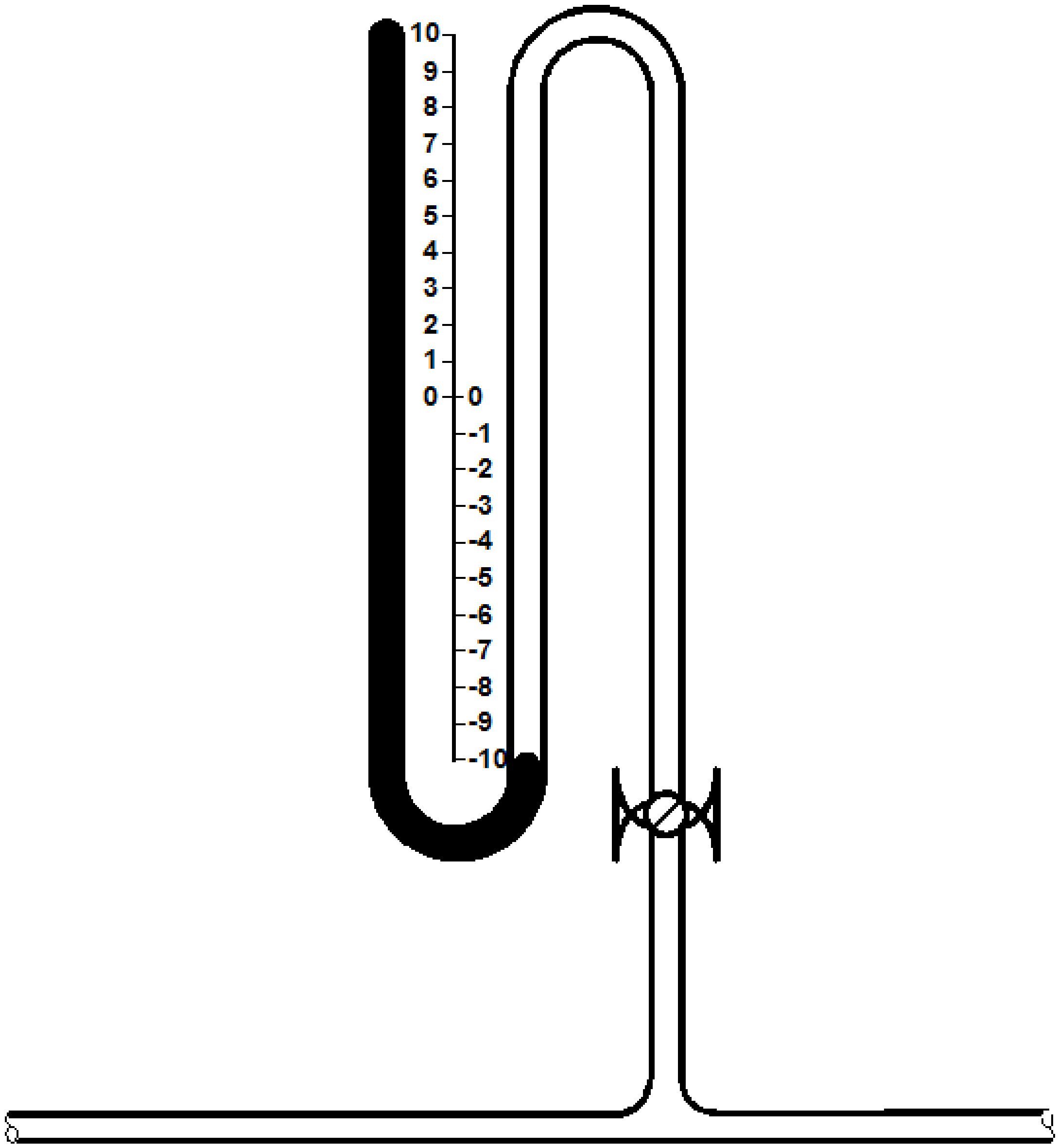

Figure 2.6 U-tube vacuum meter (Bennert)

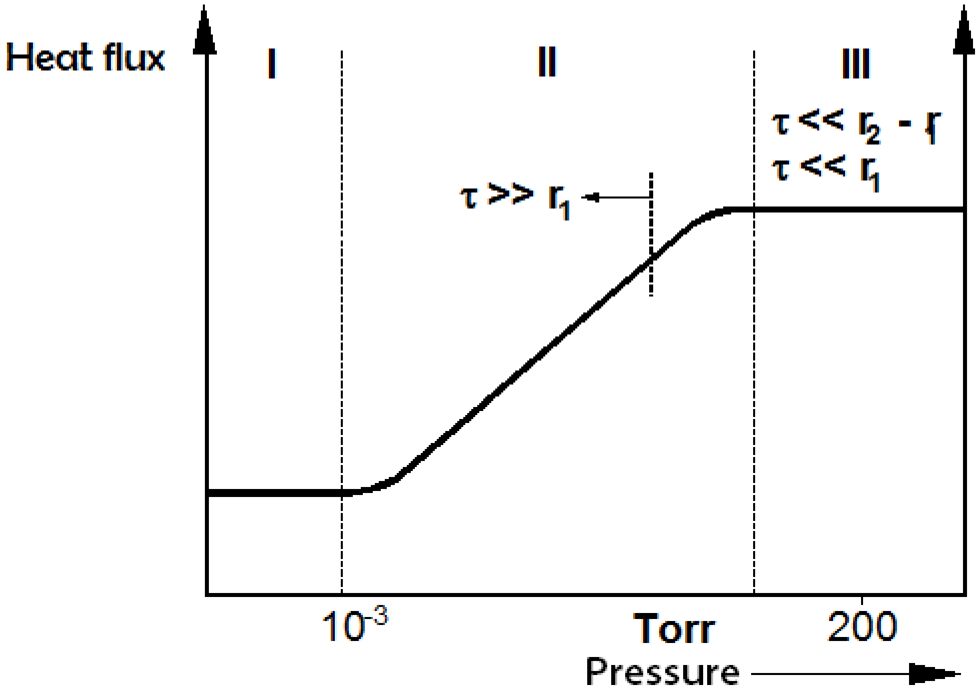

Figure 2.7 Dependence of heat flux on gas pressure for a heated wire (radius r_1) in a tube (radius r_2)

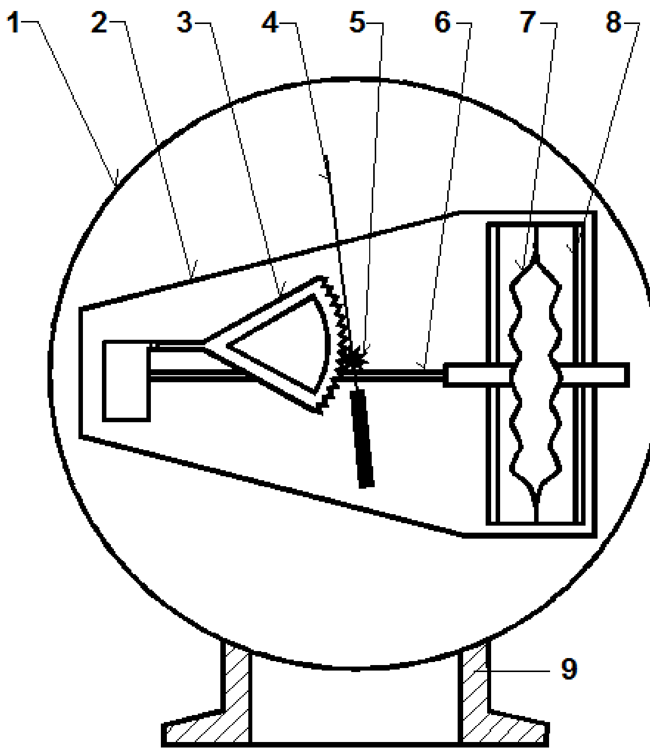

Figure 2.8 Schematic diagram of an Aneroid gauge

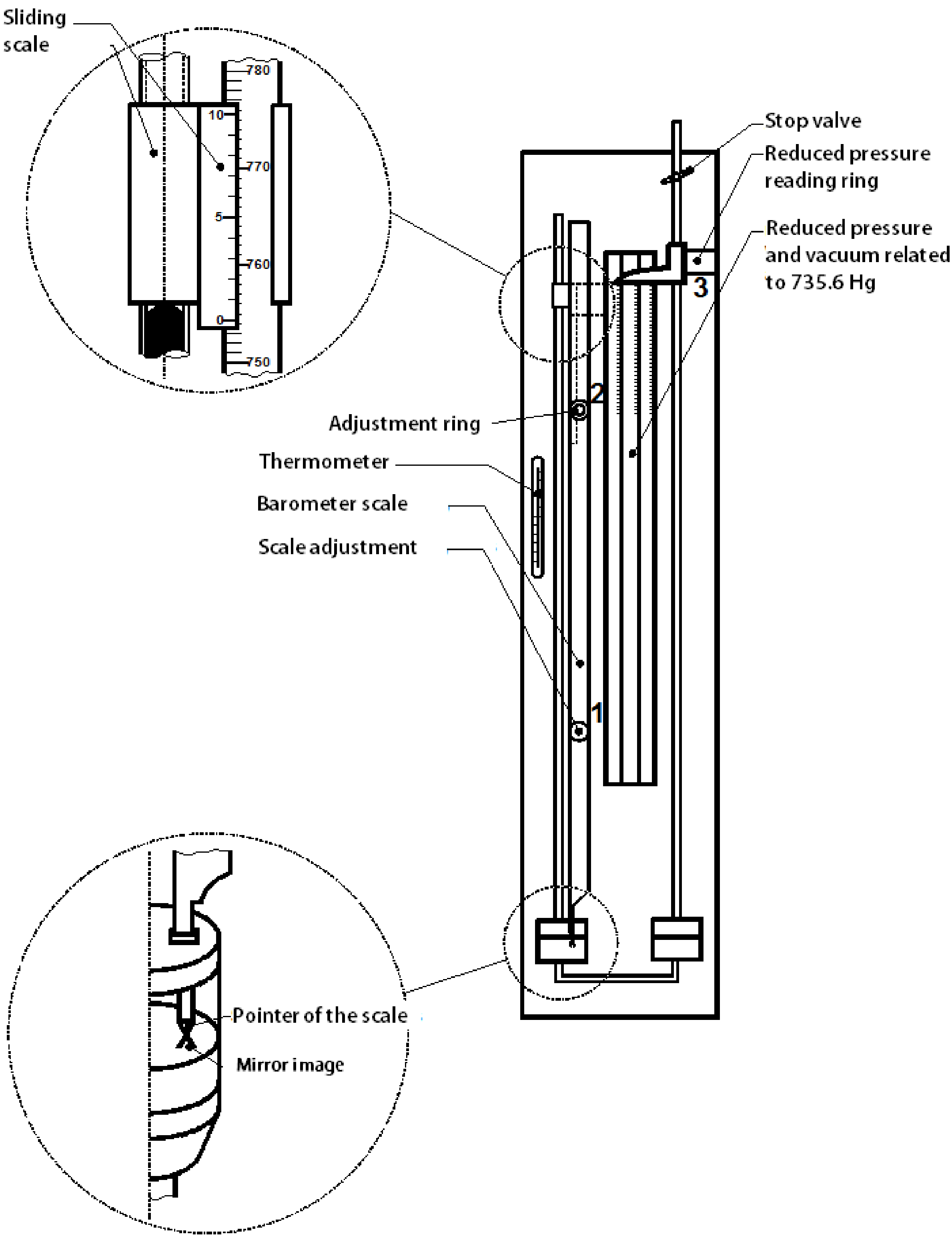

Figure 2.9 Schematic diagram of a baro-vacuum meter (Lambrecht)

3 Pressure in a flowing medium

3.1 Physical basis

3.1.1 Fluid mechanics basics

When a fluid flows through a pipe the internal roughness of the pipe wall can create local eddy currents within the fluid adding a resistance to the flow of the fluid. Pipes with smooth walls such as glass, copper, brass and polyethylene have only a small effect on the frictional resistance. Pipes with less smooth walls such as concrete, cast iron and steel will create larger eddy currents which will sometimes have a significant effect on the frictional resistance. The velocity profile in a pipe will show that the fluid at the centre of the stream will move more quickly than the fluid towards the edge of the stream. Therefore friction will occur between layers within the fluid. Fluids with a high viscosity will flow more slowly and will generally not support eddy currents and therefore the internal roughness of the pipe will have no effect on the frictional resistance.

The shear stress is directly proportional to the velocity gradient $\partial v / \partial n$ perpendicular to the direction of flow:

$$\tau = \eta \cdot \frac{\partial \mathrm{v}}{\partial n}$$

The proportionality factor η is known as the dynamic viscosity or shear viscosity. This viscosity is almost independent of pressure but depends on temperature (see Table in Figure 3.1, Figure 3.2 and Figure 3.3).

For a stationary flow condition the frictional force due to shear stress should be compensated by the forces in the direction of flow. Consider an element dl in a pipe in the direction of its axis and make the balance of forces for this element as shown in Figure 3.4 then

$$A\,dp = -\tau_w U\,dl + \dot{m}\,d\mathrm{v}$$

where A is the cross sectional area, dp the change in pressure across the distance dl,τ_W the shear stress on the wall, U the circumference, $\dot{m}$ the mass flow rate and dv the change in velocity in the direction of the pipe axis. The flow of an incompressible fluid is through a pipe of a uniform diameter is considered.

Figure 3.5 shows the building of the velocity profile in a flow through a tube. After a definite time the velocity over the complete cross section is constant

$\partial \mathrm{v}/\partial l = 0$.

The pressure drop due to friction is then given by

$$\mathrm{dp/dl} = -\tau_W \frac{U}{A}.$$

Based on a number of theoretical and experimental studies the following formula is suggested for the shear stress on wall:

$$\tau_w = \frac{\lambda}{8} \cdot \rho \cdot \overline{\mathrm{v}}^2$$

Where the proportionality factor λ is the friction factor/coefficient, ρ the density of liquid and $\overline{\mathrm{v}}$ the average velocity of flow.

The factor 4A/U is sometimes called as the hydraulic diameter d_H. So the pressure drop due to friction Δp in a tube of length *L* and uniform cross section for an incompressible medium of density ρ and average flow velocity $\overline{\mathrm{v}}$ is given as

$$\Delta p = \lambda \frac{L}{d_{\mathrm{H}}} \cdot \frac{\rho}{2} \cdot \overline{\mathrm{v}}^2$$

The force caused by the friction is $K_R = \Delta p \cdot A$.
For well formed turbulent flow on a hydraulic smooth wall the friction factor λo is calculated as
$\lambda_o = 0{,}3164 \cdot \mathrm{Re}^{-0{,}25}$

Reynolds number Re is calculated using the equation

$$\mathrm{Re} = \frac{\overline{\mathrm{v}} \cdot d}{\nu}$$

where the kinematic viscosity ν is the ratio of (dynamic)viscosity and density ($\nu = \eta/\rho$). The viscosity depends upon temperature (see Figures 3.1, 3.2 and 3.3). The viscosity of water at any temperature t °C can be calculated using the relation

$$\log\left(\frac{\eta_{20}}{\eta_t}\right) = \frac{\left[1{,}37023 \cdot (t-20) + 0{,}000836 \cdot (t-20)^2\right]}{(109+t)}.$$

The viscosity of water at 20°C (η_{20}) is 1.002 cP (1002 μPas). The density of water under atmospheric conditions is taken as 1000 kg/m^3.

3.1.2 Systematic sources of error in the measurement of pressure in flow mediums

Errors due to the position of bored hole for pressure sensor

Figure 3.7 shows five different forms of the bored holes used for pressure measurement along the tube. The effect on pressure is also shown.

3.2 Experimental set up and the procedure for the measurement of the friction factor for the tube

The pressure drop along the tube for the completely developed stream will be measured. The pressure drop will be used to determine the friction factor under different flow velocities. The experimental set up is shown in Figure 3.8.

Water from a storage tank is pumped through the pressure line with the help of a circulation pump having a constant rotation speed. An extra storage tank and an impeller water meter

[Fügelradzähler] are used to determine the amount of water used. For the fine control of the flow rate a bye pass with a valve (No. 3) is made before the water meter. The coarse control is done with the help of stop valve 1. After the water meter the flow is divided into two circuits, which may be selected with the help of the stop valve. If the stop valve 1 is open the circuit for measuring the friction factor will be opened. Water flows into the horizontally fixed tube with circular cross section having 10.1 mm diameter

After a run of about 50 times the tube diameter the running in (initialization) may be considered to be completed. The first bored hole is about 60 cm behind the beginning of the tube and is the place where the tube flow is totally built up. A vertical ascending tube to measure the pressure is fixed on the bored hole. At a distance of 40 cm from each other there are two more ascending tube manometers fixed on the bored holes.

The primary pressure will be adjusted with the help of valves 1 and 3 such that higher limb 8arm) of the water level in first manometer a mark of 450 mm (or 350 mm or 250 mm) shows. The time of flow for 20 liter of water will be noted and also the scale of the U-tube manometer. These values will be used to calculate the friction factor in the tube with the help of given formula. Also the Reynolds number and the pressure drop per meter will be calculated.

At the end the relative deviation $(\lambda_M - \lambda_T)/\lambda_T$ between the experimentally determined friction factor λ_M and the theoretically calculated friction factor λ_T for hydraulic smooth tube (read from Figure 3.6) will be calculated.

After the copletion oft he experiment the errors arising due tot he wrong forms and positions bored holes will be discussed.

3.3 Measurement Procedure

1. Open the bye pass valve 3 completely.
2. Open the stop valve 1.
3. Start the circulatory pump (position 1).
4. Adjust a value of about 450 mm on the left manometer side using valves 1 and 3.
5. Start recording the time with a watch for determining the velocity of flow.
6. Note the manometer reading and record in the protocol during the time interval.
   Read the height of the liquid in the three ascending tubes and record in the protocol.
7. Stop the watch when the water meter shows a flow of 20 liter water and note the time.
8. Reduce the flow rate with the help of valve 1 such that the left arm of the manometer tube shows a value of 350 mm.
9. Repeat the measurements from step 5 to 7.
10. Adjust the height to 250 mm as described under step 8 and repeat steps 5 to 7.
11. Calculate the average flow rate (rate of liquid flow) from the volume and time measurements and using the pipe dimensions according to

$$\bar{v} = \frac{V}{tA}$$

    where $\bar{v}$ is the average velocity, V the volume flow during time t through the tube of cross sectional area ($A = \frac{1}{4}\pi d^2$, with tube diameter d = 10,1 mm). Take care of the correct units.

12. Calculte with tube diameter d built up Reynolds number (Re = $\frac{\overline{\mathrm{v}} \cdot d}{\nu}$, use correct units).
13. Take the average of the pressure values recorded during the measurements.
14. Calculate the friction factor for the tube λ using the difference between the two pressure values (e. g., $\Delta p = p_1 - p_2$ or $\Delta p = p_1 - p_3$ where p_1, p_2, p_3 are the average pressure values from the first, second or third measuring position) and the distance between the measuring positions ($L_1 - L_2 = L_2 - L_3$ = 400 mm = 40 cm; and $L_1 - L_3$ = 800mm = 80 cm).
    (Use Figure 1 for the conversion of different pressure units)
    Achten Sie unbedingt auf die richtigen Einheiten!
15. Calculate the friction factor for the tube λ_o and make the percentage relative deviation $F = (\lambda_{ik} - \lambda_o) / \lambda_o \cdot 100$ from the experimentally measured values λ_{ik}.

Protocol-3

Date: Matr.-No.:

Time. Name:

Experiment 3: Determination of friction factor in tube

Time t(s) for V = 20 Liter			**Average velocity $\bar{v}$ (m/s)**			**Reynolds number Re**		
1.Meas.	2.Meas.	3.Meas.	1.Meas.	2.Meas.	3.Meas.	1.Meas.	2.Meas.	3.Meas.

	1st Measurement			**2nd Measurement**			**3rd Measurement**		
	Tube 1	Tube 2	Tube 3	Tube 1	Tube 2	Tube 3	Tube 1	Tube 2	Tube 3
	h_1	h_2	h_3	h_1	h_2	h_3	h_1	h_2	h_3
Reading									
Δp (N/m^2)	Δp_{12}	Δp_{13}		Δp_{12}	Δp_{13}		Δp_{12}	Δp_{13}	

$\rho_{H_2O} = 10^3$ kg/m^3; $\Delta L = 40$ cm; $d_H = d_{Rohr} = 0.,0101$ m;
v from Diagram 3.3; Temperatur H_2O ~ 22 °C

Friction factor in tube λ								
(Diagram) λ_0			λ_{12} (calculated)			λ_{13} (calculated)		
1.Meas.	2.Meas.	3.Meas.	1.Meas.	2.Meas.	3.Meas.	1.Meas.	2.Meas.	3.Meas.
% Relative deviation = $\frac{\lambda_{ik} - \lambda_0}{\lambda_0} *$ 100								

GASE	$10^5\eta_0\ \left[\frac{kg}{m\ s}\right]$
Luft	1,716
Stickstoff	1,651
Wasserstoff	0,835
Ammoniak	0,899
Kohlendioxid	1,370

FLÜSSIGKEITEN	$10^3\eta_0\ \left[\frac{kg}{m\ s}\right]$
Wasser	1,791
Toluol	0,770
Methylalkohol	0,816
Äthylalkohol	1,769
Quecksilber	1,698

Figure 3.1 Viscosity (dynamic) of some substances at 0 °C

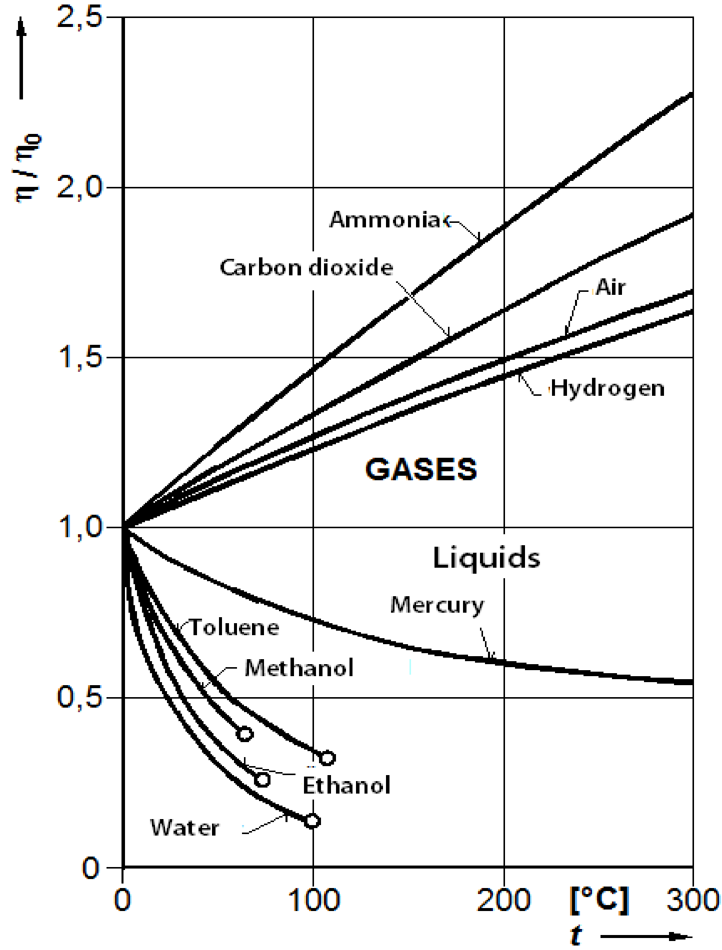

Figure 3.2 Viscosity (dynamic) of some substances (liquids and gases) as a function of temperature

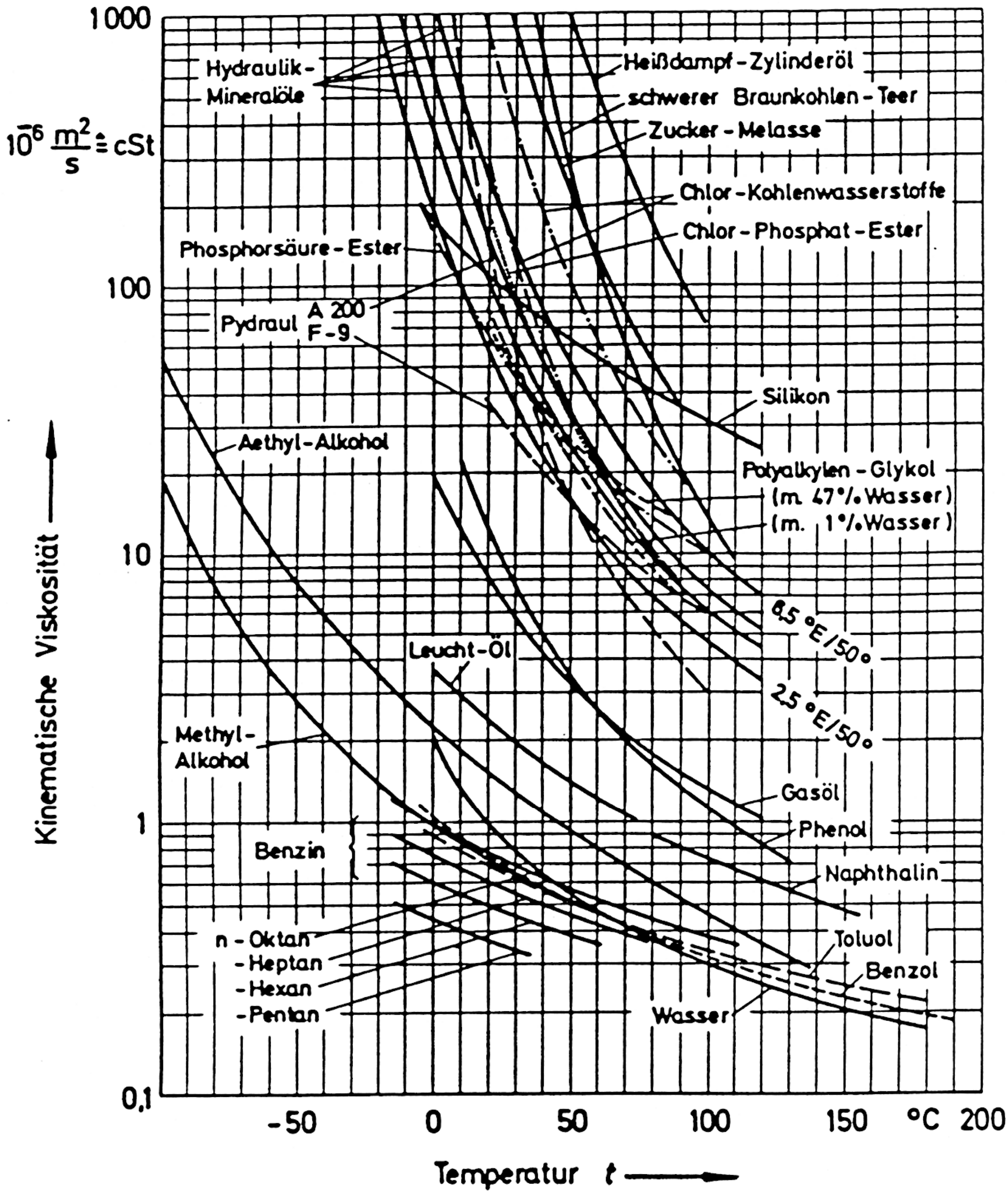

Figure 3.3 Kinematic viscosity as a function of temperature

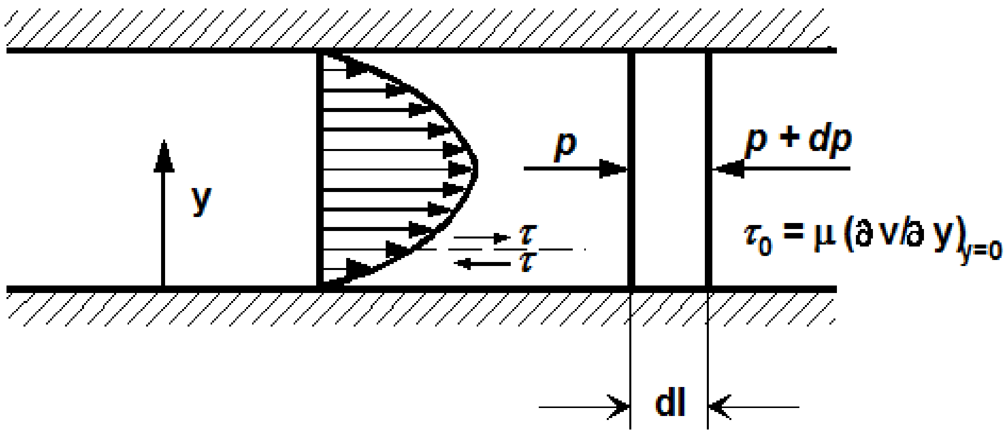

Figure 3.4 Force balance in flow with friction

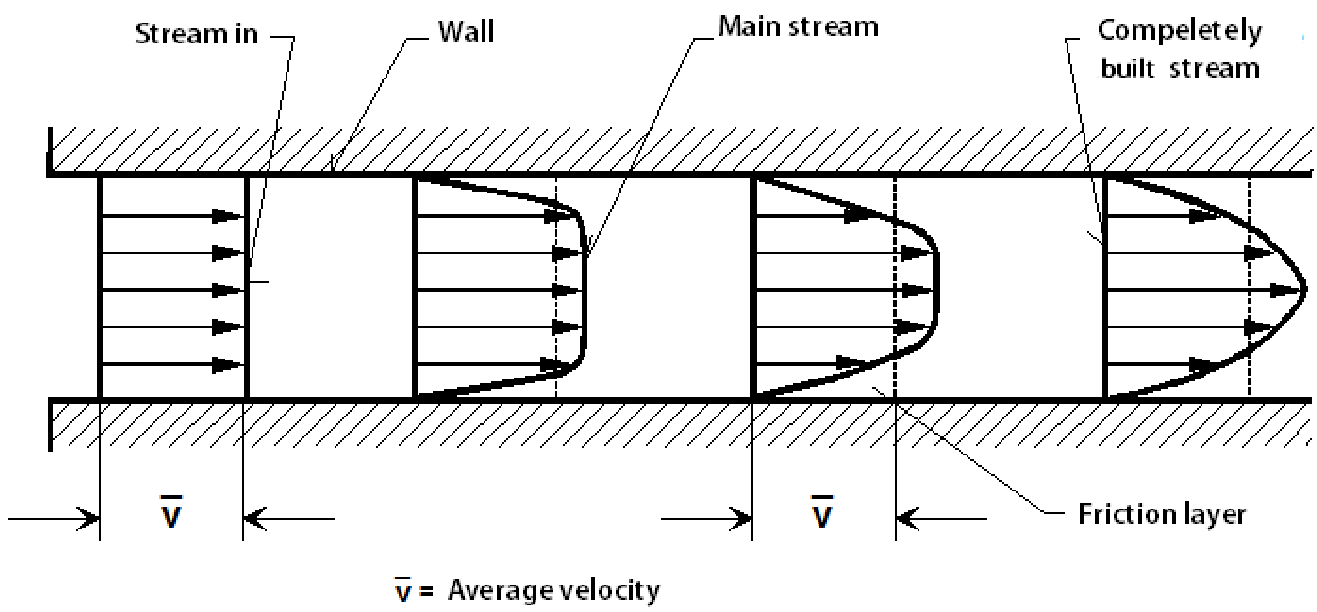

Figure 3.5 Development of velocity profile

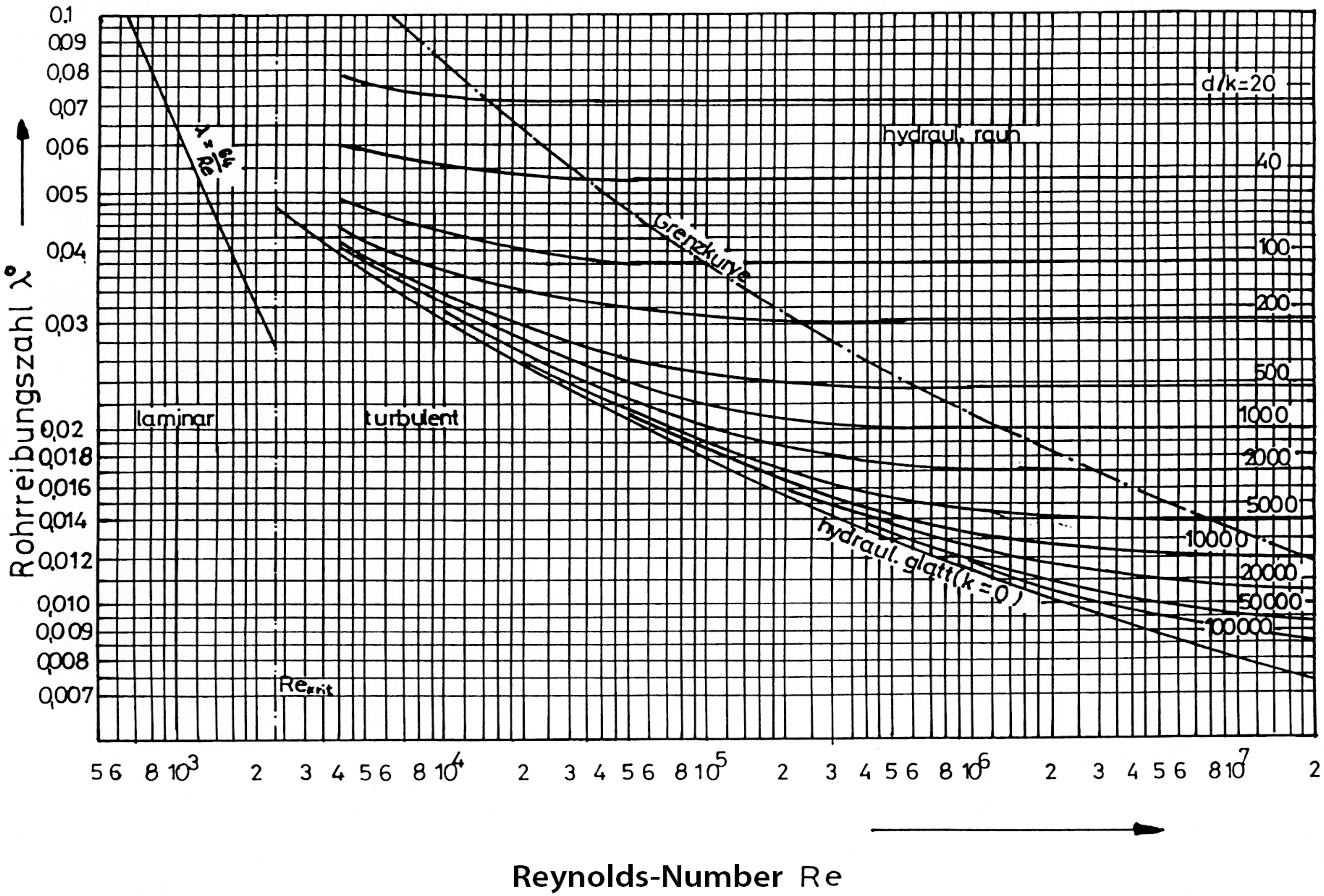

Figure 3.6 Friction factor in tube as a function of Reynolds number

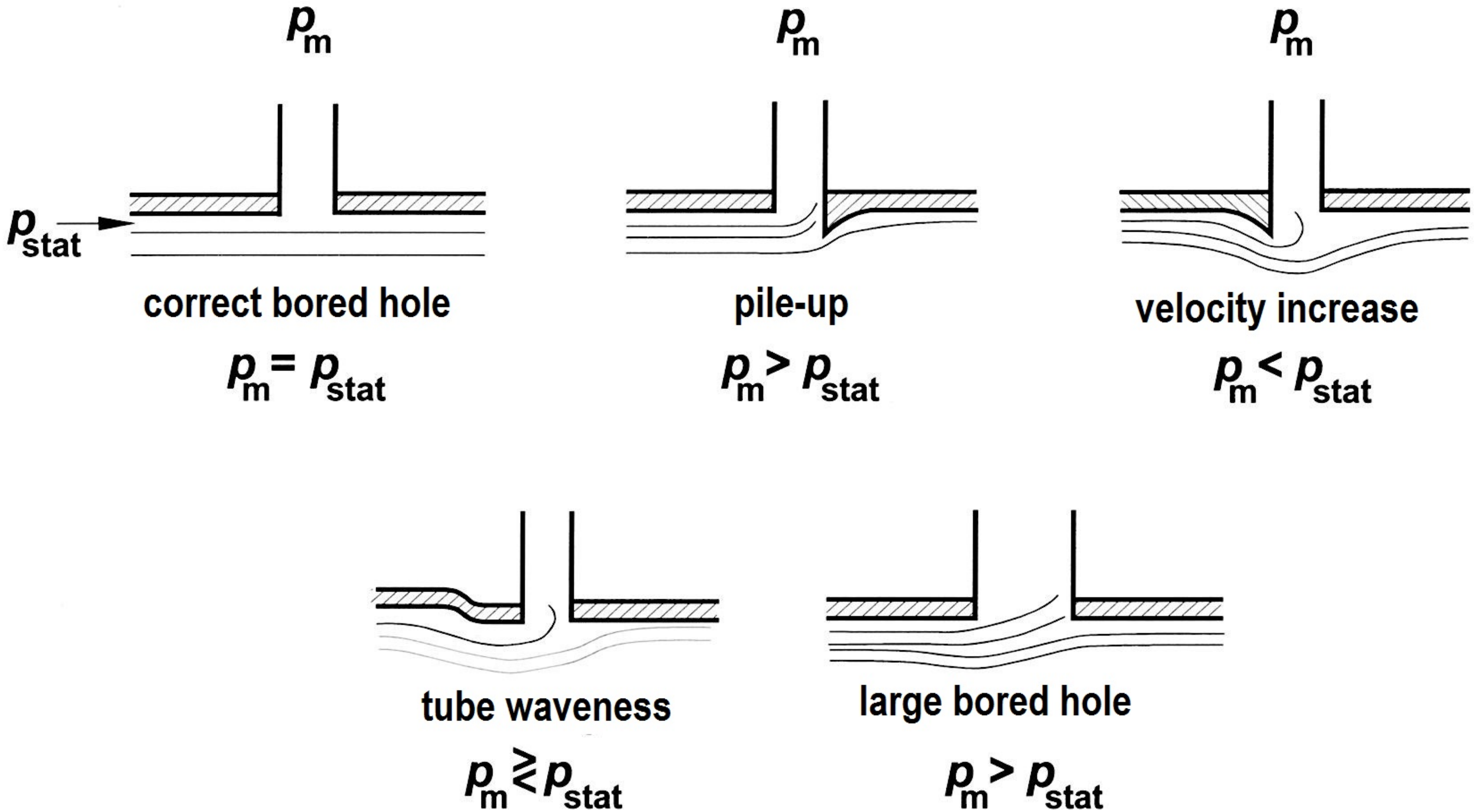

Figure 3.7 Influence of wrong bored hole on the measured pressure

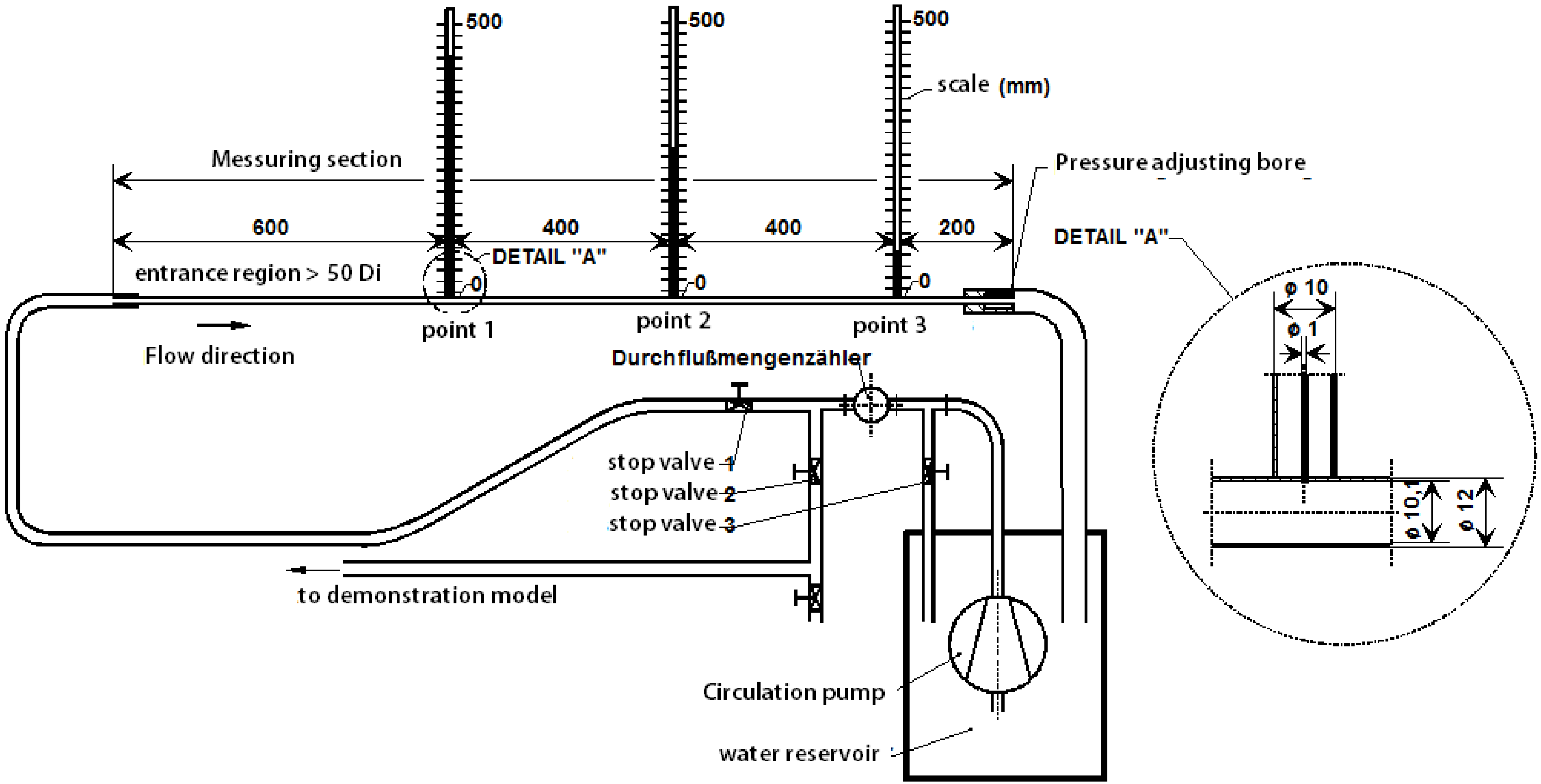

Figure 3.8 Schematic set up for determining the friction factor in tube