5

Pressure measurement

5.1 INTRODUCTION

Pressure measurement in a volume to be evacuated is an essential need. It allows us firstly to check whether the applied pump system works properly during pump-down , and secondly, to determine whether the desired pressure is attained and the system is free of leaks and undesired desorption. In addition, it is often useful to have some kind of vacuum control that verifies the pressure in the vacuum system and, if necessary, switches off the vacuum equipment to avoid possible damage. Various pressure gauges can effectively act as a monitoring system and are applied as such in laboratory and industry.

As already indicated in chapter 1, the pressure of a gas is defined as the average force exerted on a unit surface area by incident and rebounding gas molecules. Historically, pressure has always been measured by means of a mercury column and expressed in terms of its height in ‘mm mercury’. This pressure is referred to as the unit ‘Torr’, after Torricelli. From a mathematically point of view however, this is an impractical unit and the normalized pressure unit 'Pascal' (Pa) is preferred. Alternatively, one often uses the unit 'mbar': 1 Torr = 1.33 mbar = 133 Pa (see also § 1.7). Although standards organizations propagate the monopoly of the unit Pa, the other units are also still frequently used. Of course, in all mercury systems the unit Torr is standard.

Currently, a broad variety of pressure gauge systems is in the market. Depending on the gauge type, pressures can be measured from 1 atmosphere (10^5 Pa) down to about 10^{-10} Pa. These extreme values form the boundaries of the complete 'vacuum spectrum', divided into a number of distinct pressure ranges as schematically depicted in figure 5.1.

Table 5.1 summarizes the pressure gauges to be treated in this chapter with their measuring range. We note that no single pressure measurement principle covers the entire pressure range from 1 atmosphere to 10^{-10} Pa. However, in recent years, gauge heads consisting of a combination of two or more measuring principles, accommodated on a common connection flange, have increasingly appeared on the market. For example,

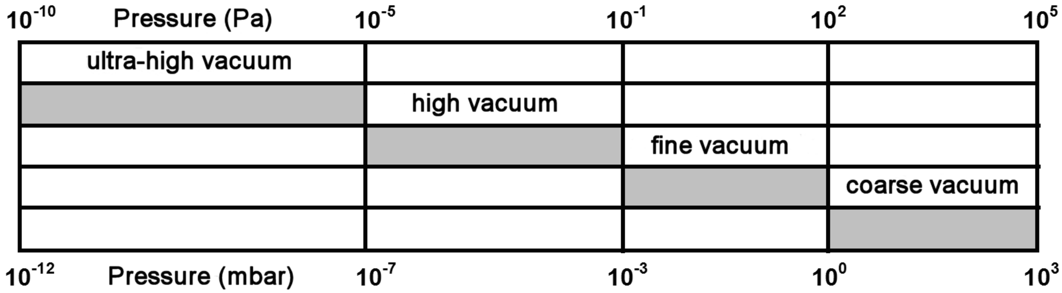

Figure 5.1
Classification of vacuum pressure ranges and their names.

combinations of Pirani/inverted magnetron, Pirani/Bayard-Alpert, quartz crystal friction-/Bayard-Alpert, piezo/Pirani, Pirani/capacitance and Pirani/capacitance/Bayard-Alpert are currently available. Various combinations, also referred to as compound pressure gauges, cover in this way the pressure range from 1 atm to 10^{-8} Pa. The corresponding supplies automatically switch from one measuring principle to another, so the optimal measuring method for a certain pressure range is always deployed.
Most of the pressure gauge systems shown in Table 5.1 are not absolute, i.e. can only be used after prior calibration. Obviously therefore, accurate pressure measurement with a non-absolute gauge system stands or falls with the availability of a so-called *primary standard*, against which the gauge can be calibrated. An additional problem is that the reading of several types of pressure gauges is gas type dependent. Finally, in the practice of pressure measurement a number of general problems arise, which can be summarized as follows:

1. The gauge head can not always be mounted at the position where the pressure is to be measured,
2. The temperature in the gauge head is not equal to the temperature in the vacuum chamber and the pressure reading is temperature dependent,
3. The gauge head itself may influence the local pressure by pumping action and/or adsorption/desorption processes,
4. The reading depends on the type of gas, and the gas composition in the vacuum system is unknown.

As a result of these effects, with decreasing pressure we have to take account of an increasing inaccuracy in pressure measurement. Table 5.2 gives guide numbers for this inaccuracy as a function of the pressure level.
The column 'p/n' in table 5.1 indicates whether pressure reading is based on measurement of the *pressure force* (p) or the *particle density* (n). Direct measurement of the pressure

Table 5.1 Survey of pressure gauges, classification in main groups, pressure ranges and details (i = gas independent, d = gas type dependent, p = measurement of pressure force, n = measurement of density)

Pressure range (Pa) 10^{5} 10^{2} 10^{-1} 10^{-4} 10^{-7} 10^{-10} 10^{-13}

Type	i/d	p/n	**Main group**
U-tube manometer	i	p	Absolute gauges
McLeod manometer	i	p	
Knudsen gauge	i	p	
Bourdon gauge	i	p	Mechanical gauges
Capsule dial gauge	i	p	
Diaphragm vacuum gauge	i	p	
Piezoresistive pressure gauge	i	p	
Capacitance gauge	i	p	
Spinning rotor gauge	d	n	Viscosity gauges
Quartz crystal friction gauge	d	n	
Pirani gauge	d	n	Heat conductivity gauges
Convection gauge	d	n	
Thermocouple gauge	d	n	
Conventional ion gauge	d	n	Hot cathode ionization gauges
High pressure ion gauge	d	n	
Bayard-Alpert gauge	d	n	
Modulated Bayard-Alpert gauge	d	n	
Extractor gauge	d	n	
Lafferty gauge	d	n	
Penning gauge	d	n	Cold cathode ionization gauges
Inverted magnetron gauge	d	n	
Magnetron gauge	d	n	

Pressure range (mbar) 10^{3} 10^{0} 10^{-3} 10^{-6} 10^{-9} 10^{-12} 10^{-15}

Table 5.2 Guide numbers for the relative inaccuracy in pressure reading as a function of pressure level

Pressure level (Pa)	Relative inaccuracy	Pressure level (Pa)	Relative inaccuracy
100	5×10^{-4}	10^{-3}	2×10^{-2}
10	3×10^{-3}	10^{-4}	5×10^{-2}
1	6×10^{-3}	10^{-5}	8×10^{-2}
10^{-1}	8×10^{-3}	10^{-6}	1×10^{-1}
10^{-2}	1×10^{-2}	$< 10^{-7}$	$> 2 \times 10^{-1}$

force is only possible at not too low pressures (coarse and fine vacuum in figure 5.1). In the high or ultra-high vacuum ranges, therefore, the pressure reading of most gauges is a measure of the particle density. Via $p = nkT$ a pressure scale can be derived. However, this pressure scale is only valid at the calibration temperature of the considered gauge. Usually, calibration is carried out by the manufacturer at room temperature (T_k = 300 K). If the pressure gauge is located in an environment of different temperature T, the reading must be corrected by a factor T/T_k.

5.2 ABSOLUTE GAUGES

By an *absolute pressure gauge* we understand a gauge for which the meter constant (= factor between pressure and meter reading), is known or can be easily calculated, i.e. pressure measurement is possible without any prior calibration. Instruments with this characteristic are labeled as a primary standard by definition. In the strict sense, this category includes only three pressure measurement systems, namely:

1. the U-tube manometer,
2. the McLeod manometer,
3. the Knudsen gauge (or: radiometer gauge).

5.2.1 U-tube manometer

A U-tube manometer is nothing else than a U-shaped tube filled with a liquid, usually mercury. The pressure is directly measured as a difference between the mercury levels in the left and right column, which in fact act as interconnected vessels. Figure 5.2 shows an outline of such a U-tube. At the lowest mercury level we apply an imaginary horizontal plane X-X. According to the laws of hydrostatics, the pressure at the level of the plane X-X is equal in both columns. Consequently, the pressure p in the vacuum system is given by