

VACUUM TECHNOLOGY

KNOW HOW

PFEIFFER  *VACUUM*



Vacuum Technology



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1 Introduction to Vacuum Technology

1.1 General

1.1.1 What is vacuum?

A vacuum is defined as a diluted gas, or the corresponding state at which its pressure or density is lower than that of the ambient surrounding atmosphere. Because atmospheric pressure fluctuates locally over the Earth's surface and lessens as altitude above sea level increases, it is not possible to specify a general upper limit for the vacuum range.

1.1.2 Overview of vacuum

Consequently, in order to achieve a vacuum it is necessary to generate a pressure in a vessel that is lower than the ambient pressure. Due to the Earth's gravity, atmospheric pressure varies with altitude in accordance with the barometric altitude formula:

Formula 1-1
Barometer formula

$$p = p_0 \cdot \exp\left(-\frac{g \cdot \rho_0 \cdot h}{p_0}\right)$$

Where:

Atmospheric pressure at sea level $p_0 = 1,013$ mbar

Earth acceleration $g = 9.81$ m/s²

Density of air at sea level at 0 °C $\rho_0 = 1.293$ kg/m³.

Combining the constants yields::

Formula 1-2
Barometer formula
number

$$p = p_0 \cdot \exp\left(-\frac{h}{8,005 \text{ m}}\right)$$

If $p = p_0/2$ and the formula is solved for h , the result is the half altitude value $h_{1/2} = 5,548$ m. In other words: Atmospheric pressure declines by one half every 5.548 km.

At the cruising altitude of a passenger jet, i.e. at approximately 10 km above the surface of the Earth, atmospheric pressure has already decreased to 290 mbar. Weather balloon data are measured at an altitude of approximately 30 km at a pressure of 24 mbar. The pressure levels prevailing at these altitudes can still be categorized as being in the low vacuum range, which will be discussed in greater detail below. An even greater distance from the Earth's surface, finally, brings us to satellite orbits at an altitude of 250 km, where the pressure has now decreased to $10^{-5} - 10^{-6}$. What prevails farther out in space is an ultra high vacuum of less than 10^{-14} .

Practical utilization of pressure differentials to exert a force is meaningful in the 1,000 to 1 mbar range. In this application range, vacuum is indicated in % of atmospheric pressure.

Various aids are required in order to achieve pressures on Earth that are similar to the natural vacuum that prevails in space. These differing pressure ranges can be achieved through the use of vacuum pumps.

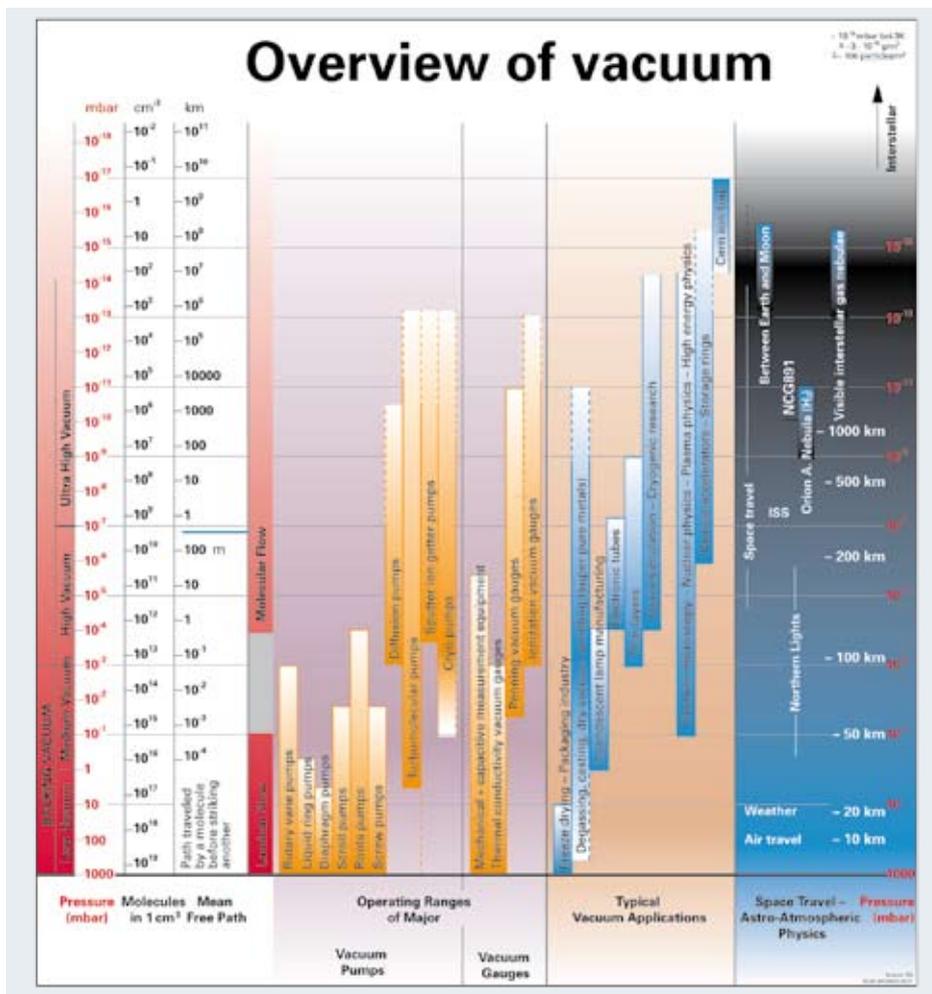


Figure 1.1: Overview of vacuum

Source: Paul Scherer Institut, CH

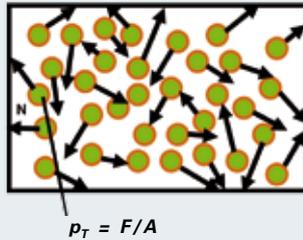
1.2 Fundamentals

1.2.1 Pressure

Any gas enclosed within a volume is always uniformly distributed. The individual gas particles are constantly moving back and forth at high-speed within the volume; upon striking the vessel wall, they exert a force F on surface A due to pulse transmission. The pressure p that is exerted on the wall is defined as

Formula 1-3
Definition of pressure

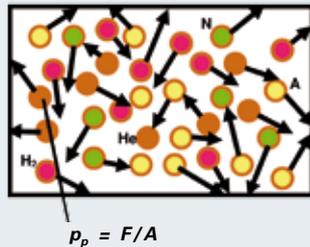
$$p = \frac{F}{A}$$



- ▶ Pressure in vessel
- ▶ One gas, e.g. nitrogen N_2
- ▶ Various gases, e.g. air

Figure 1.2: Definition of total pressure

If the gas is made up of different types of gases, each of these gases will exert a pressure that corresponds to its concentration; this is called partial pressure. The sum of all partial pressures equals the total pressure. Air is a good example of this: In addition to its main constituents of nitrogen, oxygen and water vapor, air also contains many trace gases.



- ▶ Partial pressure
- ▶ Sum of partial pressures of all gases present equals total pressure
- ▶ All gases present evidenced through mass spectrometry

Figure 1.3: Definition of partial pressure

Table 1.1: Total pressure and composition of air at 20 °C and 50 % relative humidity

Gas	Partial Pressure / mbar
Nitrogen	781.8
Oxygen	209.7
Water vapor	12
Argon	9.34
Carbon dioxide	$3.3 \cdot 10^{-1}$
Neon	$1.82 \cdot 10^{-2}$
Helium	$5.23 \cdot 10^{-3}$
Krypton	$1.15 \cdot 10^{-3}$
Hydrogen	$4.94 \cdot 10^{-3}$
Xenon	$8.7 \cdot 10^{-5}$
Total pressure	1,013

The pressure range of vacuum comprises the interval of 0 – 1 bar. A distinction is made between the following pressure ranges:

Table 1.2: Pressure ranges/Molecular number density

Pressure Range	Pressure / mbar	Molecular Number Density / cm ⁻³
Low vacuum	10 ³ – 10 ⁰	2.65 · 10 ¹⁹ – 2.65 · 10 ¹⁶
Medium vacuum	10 ⁰ – 10 ⁻³	2.65 · 10 ¹⁶ – 2.65 · 10 ¹³
High vacuum	10 ⁻³ – 10 ⁻⁷	2.65 · 10 ¹³ – 2.65 · 10 ⁹
Ultra high vacuum	10 ⁻⁷ – 10 ⁻¹²	2.65 · 10 ⁹ – 2.65 · 10 ⁴

In accordance with Formula 1-3 for pressure definition, the SI unit Pa = N/m² will be used for this purpose. Also customary in actual practice are the units of pressure shown in the conversion table below. It is very customary to use mbar as a unit of pressure.

Table 1.3: Conversion table for units of pressure

	Pa = N / m ²	bar	mbar	μbar = dyn / cm ²	Torr = mm Hg	micron μ = mTorr	atm	at	mm WS	psi = lbf / inch ²	psf = lbf / ft ²
Pa	1	1 · 10 ⁻⁵	1 · 10 ⁻²	10	7.5 · 10 ⁻³	7.5	9.87 · 10 ⁻⁶	1.02 · 10 ⁻⁵	0.102	1.45 · 10 ⁻⁴	2.09 · 10 ⁻²
bar	1 · 10 ⁵	1	1 · 10 ³	1 · 10 ⁶	750	7.5 · 10 ⁵	0.987	1.02	1.02 · 10 ⁴	14.5	2.09 · 10 ³
mbar	100	1 · 10 ⁻³	1	1,000	0.75	750	9.87 · 10 ⁻⁴	1.02 · 10 ⁻³	10.2	1.45 · 10 ⁻²	2.09
μbar	0.1	1 · 10 ⁻⁶	1 · 10 ⁻³	1	7.5 · 10 ⁻⁴	0.75	9.87 · 10 ⁻⁷	1.02 · 10 ⁻⁶	1.02 · 10 ⁻²	1.45 · 10 ⁻⁵	2.09 · 10 ⁻³
Torr	1.33 · 10 ²	1.33 · 10 ⁻³	1.33	1,330	1	1,000	1.32 · 10 ⁻³	1.36 · 10 ⁻³	13.6	1.93 · 10 ⁻²	2.78
micron	0.133	1.33 · 10 ⁻⁶	1.33 · 10 ⁻³	1.33	1 · 10 ⁻³	1	1.32 · 10 ⁻⁶	1.36 · 10 ⁻⁶	1.36 · 10 ⁻²	1.93 · 10 ⁻⁵	2.78 · 10 ⁻³
atm	1.01 · 10 ⁵	1.013	1,013	1.01 · 10 ⁶	760	7.6 · 10 ⁵	1	1.03	1.03 · 10 ⁴	14.7	2.12 · 10 ³
at	9.81 · 10 ⁴	0.981	981	9.81 · 10 ⁵	735.6	7.36 · 10 ⁵	0.968	1	1 · 10 ⁻⁴	14.2	2.04 · 10 ³
mm WC	9.81	9.81 · 10 ⁻⁵	9.81 · 10 ⁻²	98.1	7.36 · 10 ⁻²	73.6	9.68 · 10 ⁻⁵	1 · 10 ⁻⁴	1	1.42 · 10 ⁻³	0.204
psi	6.89 · 10 ³	6.89 · 10 ⁻²	68.9	6.89 · 10 ⁴	51.71	5.17 · 10 ⁴	6.8 · 10 ⁻²	7.02 · 10 ⁻²	702	1	144
psf	47.8	4.78 · 10 ⁻⁴	0.478	478	0.359	359	4.72 · 10 ⁻⁴	4.87 · 10 ⁻⁴	4.87	6.94 · 10 ⁻³	1

1.2.2 General gas equation

The following applies for gases: A volume of 22.414 liters (mol volume) at a temperature of 273.15 K (standard temperature = 0 °C) and a pressure of 101,325 pa (standard pressure) contains 6.02 times 10^{23} particles (Avogadro's number). The mass of the gas thus enclosed is its molecular weight in grams.

The general gas equation describes the state of a gas as a function of pressure, temperature and volume.

Formula 1-4

General gas equation

$$p \cdot V = \frac{m}{M} \cdot R \cdot T = n \cdot V \cdot k \cdot T$$

Thus:

Formula 1-5

Gas pressure

$$p = n \cdot k \cdot T$$

Where:

p = pressure [Pa; N/m²]

V = volume [m³]

m = mass [kg]

M = molar mass [kg/kmol]

R = general gas constant $R = 8.314510$ kJ/(kmol K)

T = thermodynamic temperature [K]

n = molecular number density [1/m³]

k = Boltzmann's constant $k = 1.380 \cdot 10^{-23}$ J/K

1.2.3 Molecular number density

As can be seen from Formula 1-4 and Formula 1-5 pressure is proportional to molecular number density. Due to the high number of molecules per unit of volume at standard conditions, it follows that at a pressure of 10^{-12} mbar, for example, 26,500 molecules per cm³ will still be present. This is why it is not possible to speak of a void, or nothingness, even under ultra high vacuum.

1.2.4 Thermal molecular velocity

Gas molecules in a vessel move back and forth in different directions and at different speeds. Their velocity distribution corresponds to a bell curve having its peak at the most probable velocity

Formula 1-6

Probable velocity

$$c_w = \sqrt{\frac{2 \cdot R \cdot T}{M}}$$

The mean thermal velocity is

Formula 1-7

Mean velocity

$$\bar{c} = \sqrt{\frac{8 \cdot R \cdot T}{\pi \cdot M}}$$

The following table shows values for selected gases.

Table 1.4: Molar masses and mean thermal velocities of various gases

Gas	Molar Mass / (g / mol)	Mean Velocity / (m / s)	Mach Number
H ₂	2	1,762	5.3
He	4	1,246	3.7
H ₂ O	18	587	1.8
N ₂	28	471	1.4
Air	29	463	1.4
Ar	40	394	1.2
CO ₂	44	376	1.1

1.2.5 Mean free path

The mean free path is the mean path length that a molecule traverses between two successive impacts with other molecules. It depends upon molecular diameter d_m and temperature T in accordance with the following equation

Formula 1-8
Mean free path

$$\bar{l} \cdot p = \frac{k \cdot T}{\pi \cdot \sqrt{2} \cdot d_m^2}$$

and is of significance for the various flow types of a gas in a vacuum.

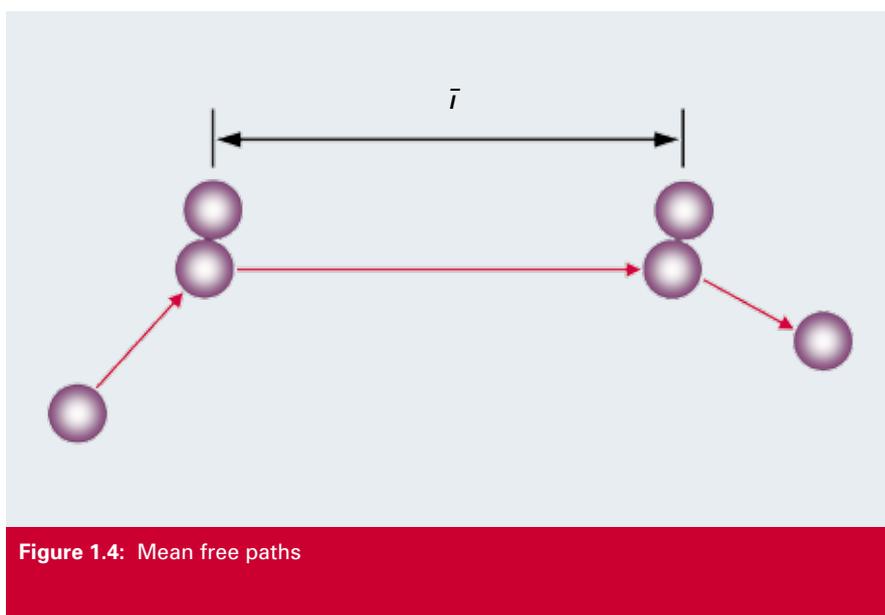


Figure 1.4: Mean free paths

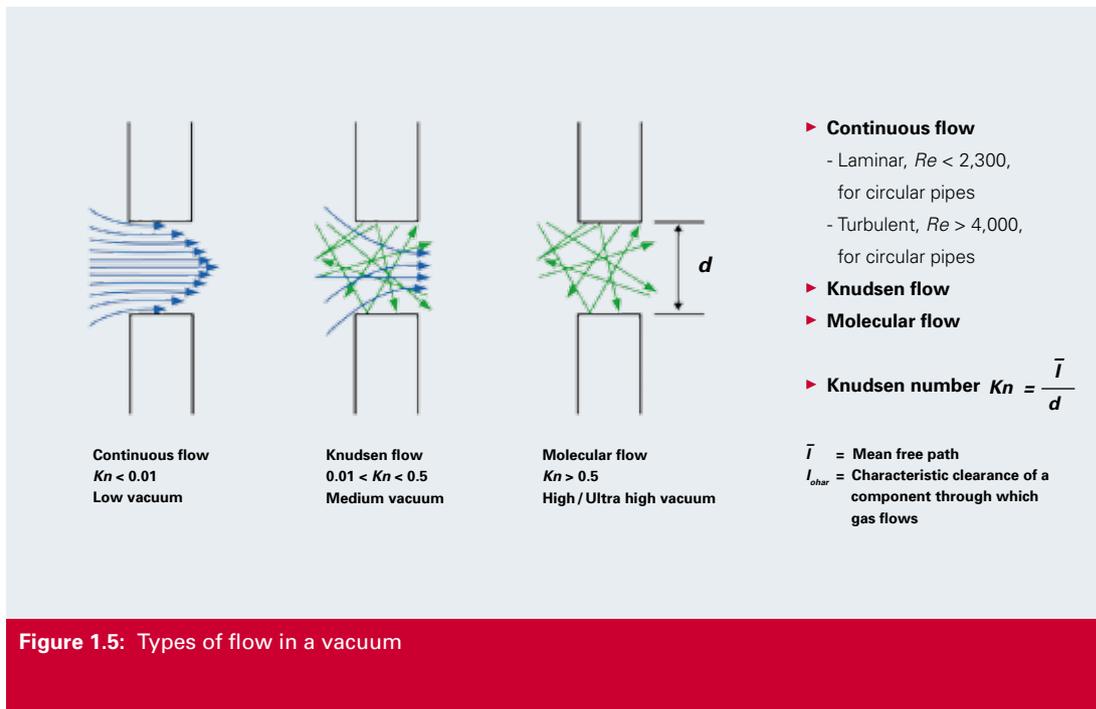
The table [1] below shows the product $\bar{l} \cdot p$ for various gases at 0 °C.

Table 1.5: Mean free paths of various gases at 0 °C

Gas	$\bar{l}_p / (m \cdot Pa)$	Gas	$\bar{l}_p / (m \cdot Pa)$
H ₂	$11.5 \cdot 10^{-3}$	Xe	$3.6 \cdot 10^{-3}$
N ₂	$5.9 \cdot 10^{-3}$	Hg	$3.1 \cdot 10^{-3}$
He	$17.5 \cdot 10^{-3}$	CO	$6.0 \cdot 10^{-3}$
Ne	$12.7 \cdot 10^{-3}$	CO ₂	$4.0 \cdot 10^{-3}$
Ar	$6.4 \cdot 10^{-3}$	HCl	$4.4 \cdot 10^{-3}$
Air	$6.65 \cdot 10^{-3}$	NH ₃	$4.3 \cdot 10^{-3}$
Kr	$4.9 \cdot 10^{-3}$	Cl ₂	$2.8 \cdot 10^{-3}$

1.2.6 Types of flow

A distinction is made between three types of flow in a vacuum. The types of flows described below will occur as a function of pressure, mean free path and component dimensions *d*.



Source: Jousten (publisher) Wutz, Handbuch Vakuumtechnik, Vieweg Verlag

Continuous flow in low vacuum, $p = 10^3 - 10^0$ mbar, where $\bar{l} \ll d$

What characterizes continuous flow, as well as viscous flow, is frequent contact between gas molecules, yet less frequent contact with the walls of the vessel. In this case, the mean free path of the gas molecules is significantly shorter than the dimensions *d* of the vacuum equipment.

The dimensionless Knudsen number Kn is defined as the ratio between mean free path and component diameter

Formula 1-9
Knudsen number

$$Kn = \frac{\bar{l}}{d}$$

In this case, Kn is < 0.01 . In addition, the term viscous flow is used if the product of pressure p and diameter d of the components through which gas is flowing is $p \cdot d \geq 6 \cdot 10^{-1}$ mbar · cm for air.

In the case of viscous flow, a distinction is made between laminar and turbulent flow. Laminar flow prevails at low flow speeds. At higher flow speeds, this changes to a turbulent flow [2]. The occurrence of turbulent flow is contingent upon the Reynolds number

Formula 1-10
Reynolds number

$$Re = \frac{\rho}{\eta} \cdot v \cdot d$$

Where is:

ρ = density [kg/m³]

η = viscosity [Pas]

v = flow velocity [m/s]

d = tube diameter [m]

Up to values of $Re < 2,300$ the flow will be laminar, and where $Re > 4,000$ the flow will be turbulent. In vacuum systems, the lines are dimensioned in such a manner that turbulent flow occurs only briefly at relatively high pressures, as the high flow resistance that occurs in this process necessitates that the pumps produce higher volume flow rates.

Knudsen flow in medium vacuum, $p = 10^0 - 10^{-3}$ mbar, mit $\bar{l} \leq d$

If the Knudsen number is between 0.01 and 0.5, this is termed Knudsen flow. Because many process pressures are in the medium vacuum range, this type of flow occurs with corresponding frequency. Since this is a transitional flow, this range is transited relatively quickly when pumping down vacuum chambers. This means that the influence of this conductivity on pump-down times is correspondingly low. It is a complicated endeavor to perform a precise calculation of conductivity where the flow range is still laminar and yet already molecular, and this will not be discussed here. A simple approximation for the Knudsen range can be obtained by adding the laminar and molecular conductivities. Figure 1.7 shows the conductivities of round, one meter long tubes of differing diameters in all three flow ranges.

Molecular flow in high vacuum, ($p = 10^{-3} - 10^{-7}$ mbar), where $\bar{l} > d$ and in ultra high vacuum ($p < 10^{-7}$ mbar), mit $\bar{l} \gg d$

At Knudsen numbers of $Kn > 0.5$ molecular interaction virtually no longer occurs. What prevails is molecular flow. In this case, the product of pressure p and component diameter d is $p \cdot d \leq 1.3 \cdot 10^{-2}$ mbar · cm.

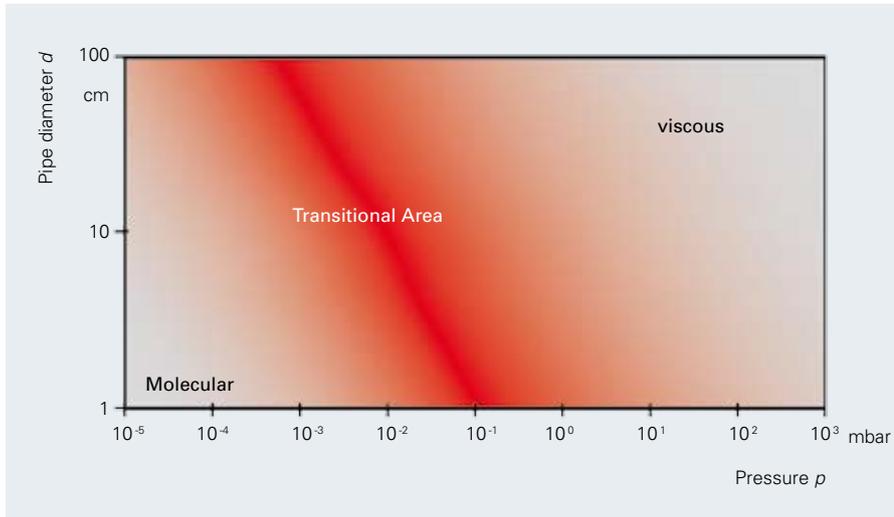


Figure 1.6: Flow ranges in vacuum

1.2.7 pV flow

Dividing the general gas equation by time t yields the gas flow

Formula 1-11
pV flow

$$q_{pV} = \frac{p \cdot V}{t} = \frac{m \cdot R \cdot T}{t \cdot M}$$

This is also referred to as pV flow. As can be seen from the right-hand side of the equation, a constant mass flow is displaced at constant temperature T .

Vacuum pumps, particularly positive displacement pumps, have a constant volume flow rate of

Formula 1-12
Definition of volume flow rate, or pumping speed

$$S = \frac{dV}{dt}$$

over a given inlet pressure range; i.e. they displace a constant volume flow. Multiplying the volume flow rate by the inlet pressure yields the throughput of a pump

Formula 1-13
Vacuum pump throughput

$$q_{pV} = S \cdot p = \frac{dV}{dt} \cdot p$$

Throughput is the gas flow transported by a vacuum pump.

Table 1.6: Conversion table for units of flow, length and temperature

	Pa m³/s = W	mbar l/s	Torr l/s	atm cm³/s	lusec	sccm	slm	Mol/s
Pa m³/s	1	10	7.5	9.87	$7.5 \cdot 10^3$	592	0.592	$4.41 \cdot 10^{-4}$
mbar l/s	0.1	1	0.75	0.987	750	59.2	$5.92 \cdot 10^{-2}$	$4.41 \cdot 10^{-5}$
Torr l/s	0.133	1.33	1	1.32	1,000	78.9	$7.89 \cdot 10^{-2}$	$5.85 \cdot 10^{-5}$
atm cm³/s	0.101	1.01	0.76	1	760	59.8	$5.98 \cdot 10^{-2}$	$4.45 \cdot 10^{-5}$
lusec	$1.33 \cdot 10^{-4}$	$1.33 \cdot 10^{-3}$	10^{-3}	$1.32 \cdot 10^{-3}$	1	$7.89 \cdot 10^{-2}$	$7.89 \cdot 10^{-5}$	$5.86 \cdot 10^{-8}$
sccm	$1.69 \cdot 10^{-3}$	$1.69 \cdot 10^{-2}$	$1.27 \cdot 10^{-2}$	$1.67 \cdot 10^{-2}$	12.7	1	10^{-3}	$7.45 \cdot 10^{-7}$
slm	1.69	16.9	12.7	16.7	$1.27 \cdot 10^4$	1,000	1	$7.45 \cdot 10^{-4}$
Mol/s	$2.27 \cdot 10^3$	$2.27 \cdot 10^4$	$1.7 \cdot 10^4$	$2.24 \cdot 10^4$	$1.7 \cdot 10^7$	$1.34 \cdot 10^6$	$1.34 \cdot 10^3$	1

	cm	inch	ft
cm	1	0.394	0.033
inch	2.54	1	0.083
ft	30.48	12	1

	K	°C	F
K	1	K - 273.15	$9/5 K - 459.67$
°C	$°C + 273.15$	1	$9/5 °C + 32$
F	$5/9 (F + 459.67)$	$5/9 (F - 32)$	1

°C	100	80	60	40	20	0	-20	-40
F	212	176	140	104	68	32	-4	-40

1.2.8 Conductivities

Generally speaking, vacuum chambers are connected to a vacuum pump via piping. Flow resistance occurs as a result of external friction (gas molecules/wall surface) and internal friction (gas molecules/gas molecule "viscosity"). This flow resistance manifests itself in the form of the volume flow rate, or pumping speed. In vacuum technology, it is customary to use the reciprocal, the conductivity of piping L , instead of flow resistance W . This is expressed in [l/s] or [m³/h].

Gas flowing through piping produces a pressure differential Δp at the ends of the piping. The following equation applies:

Formula 1-14
Definition of conductivity

$$q_{pV} = L \cdot \Delta p$$

The conductivity of a line is $L = 1/W$.

Analogously to Ohm's Law $I = \frac{1}{R} \cdot U$ q_{pV} represents flow I , L represents the reciprocal of resistance $1/R$ and Δp represents voltage U . If the components are connected in parallel, the individual conductivities are added:

Formula 1-15
Parallel connection conductivities

$$L_1 + L_2 + \dots L_n = L_{ges}$$

and if connected in series, the reciprocals are added:

Formula 1-16
Series connection conductivities

$$\frac{1}{L_1} + \frac{1}{L_2} + \dots + \frac{1}{L_n} = \frac{1}{L_{ges}}$$

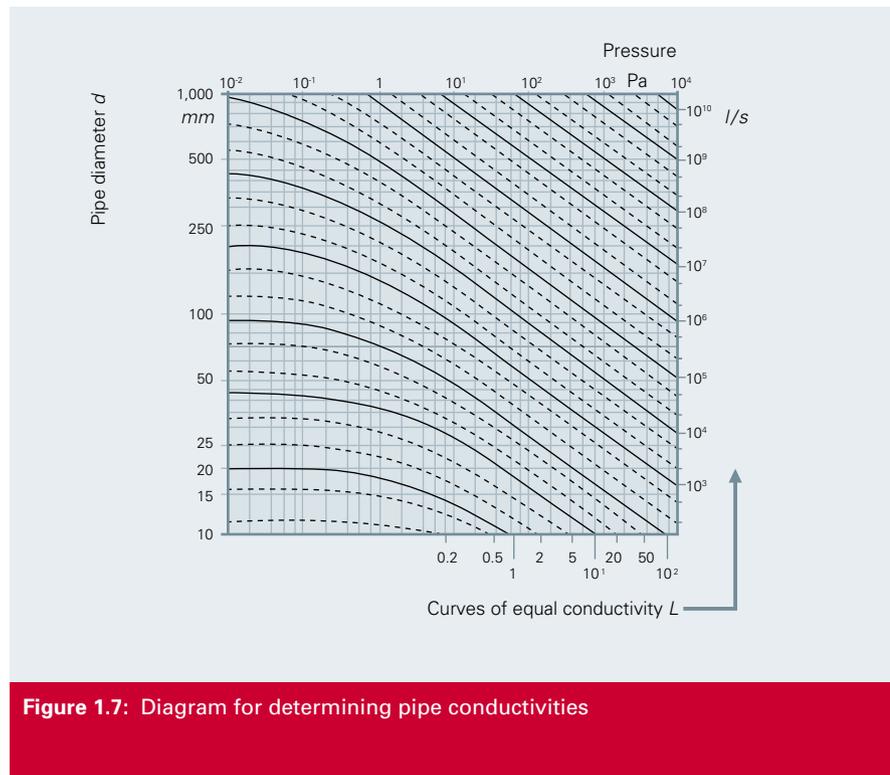


Figure 1.7: Diagram for determining pipe conductivities

Source: Pupp / Hartmann, *Vakuumtechnik, Grundlagen und Anwendungen*, Hanser Verlag

The conductivities of pipes and pipe bends will differ in the various flow ranges. In the case of continuous flow, they are proportional to the mean pressure \bar{p} and in the case of molecular flow they are not a function of pressure. Knudsen flow represents a transition between the two types of flow, and the conductivities vary with the Knudsen number. Since this range is passed through relatively quickly when generating a vacuum, reference is made to the applicable literature [2].

The conductivities of orifices and long round pipes for the laminar and molecular flow ranges are presented briefly below.

The following Formula 1-14 fundamentally applies for conductivity $L = \frac{q_{pV}}{\Delta p} = \frac{q_{pV}}{p_1 - p_2}$

Orifices are frequently encountered in vacuum systems. Examples include constriction of cross sections in valves, ventilation systems or orifices in measuring domes that are used to measure volume flow rate. Similarly, orifice resistance must also be taken into consideration in connection with pipe openings in vessel walls.

Blocked flow

Let us consider venting of a vacuum chamber. When the venting valve is opened, ambient air flows into the vessel at high velocity at a pressure of p_1 . It reaches maximum sonic velocity, and the volume flowing through it q_{pV} is not a function of the vessel's interior pressure p_2 . The following applies for air:

Formula 1-17
Blocking

$$q_{pV} = 15.6 \cdot d^2 \cdot p_1 = 15.6 \frac{l}{s} \cdot \left(\frac{d}{cm} \right)^2 \cdot p_1$$

Gas dynamic flow

If the pressure in the vessel now rises beyond the critical pressure [2], gas flow is reduced and we obtain:

Formula 1-18
Gas dynamic flow

$$q_{pV} = A \cdot \sqrt{\frac{\pi}{4}} \cdot \bar{c} \cdot p_1 \cdot \psi \left(\frac{p_2}{p_1} \right)$$

$\psi(p_2/p_1)$ [3] is termed the outflow function and is shown in the following diagram (figure 1.8).

Molecular flow

If an orifice connects two vessels in which molecular flow conditions exist ($\bar{l} \gg d$), the following will apply for orifice conductivity:

Formula 1-19
Orifice conductivity

$$L_{Bm} = \frac{\bar{c}}{4} \cdot A$$

Accordingly, the following applies for flow:

Formula 1-20
Orifice flow

$$q_{pV} = A \cdot \frac{\bar{c}}{4} \cdot (p_1 - p_2)$$

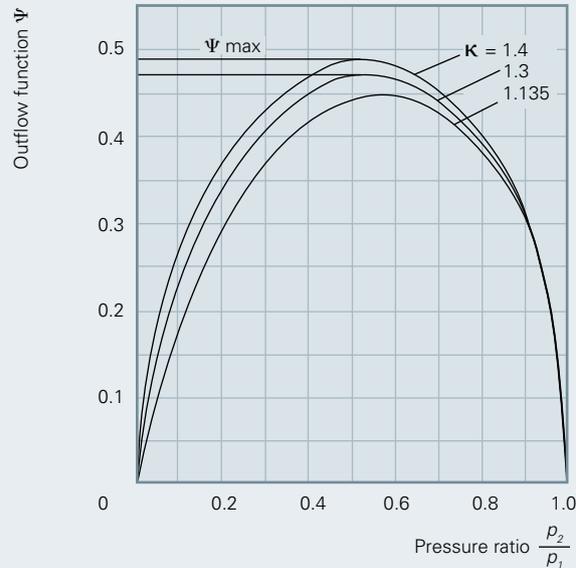


Figure 1.8: Outflow function for gas dynamic flow

Source: Jousten (publisher) Wutz, Handbuch Vakuumentchnik, Vieweg Verlag

Let us now consider specific pipe conductivities. On the one hand, this would be laminar flow in a long pipe having a round cross section:

In the case of laminar flow, the conductivity of a pipe is proportional to the mean pressure \bar{p} :

Formula 1-21
Laminar pipe flow

$$L_{Rl} = \frac{\pi \cdot d^4}{256 \cdot \eta \cdot l} \cdot (p_1 + p_2) = \frac{\pi \cdot d^4}{128 \cdot \eta \cdot l} \cdot \bar{p}$$

On the other, there would be molecular flow in a long pipe having a round cross section: In the molecular flow range, conductivity is constant and is not a function of pressure. It can be considered to be the product of the orifice conductivity of the pipe opening L_{Rm} and passage probability P_{Rm} through a component:

Formula 1-22
Molecular pipe flow

$$L_{Rm} = L_{Bm} \cdot P_{Rm}$$

Passage probability P_{Rm} can be calculated for different pipe shapes, bends or valves using Monte Carlo computer simulation. In this connection, the trajectories of individual gas molecules through the component can be tracked on the basis of wall collisions.

The following applies for long round pipes $P_{Rm} = \frac{4}{3} \cdot \frac{d}{l}$.

Multiplying this value by Orifice Conductivity Formula 1-19 yields

Formula 1-23
Molecular pipe
conductivity

$$L_{Rm} = \frac{\bar{c} \cdot \pi \cdot d^3}{12 \cdot l}$$

L_{Rm} = pipe conductivity [m³/s]
 d = pipe diameter [m]
 l = pipe length [m]
 \bar{p} = $(p_1 + p_2)/2$ pressure [Pa]
 p_1 = pressure at piping inlet [Pa]
 p_2 = pressure at piping outlet [Pa]
 η = viscosity of the gas [Pa · s]
 \bar{c} = thermodynamic gas temperature [m/s]

Figure 1.7 [5] shows curves of identical conductivities L as a function of mean pressure \bar{p} and piping diameter d of one meter long pipes. At lower pressures, the conductivities are constant, and at high pressures they increase proportionately with mean pressure \bar{p} . The bends in the curves represent the Knudsen flow range.

1.3 Disturbing side effects

1.3.1 Contamination

Vacuum chambers must be clean in order to reach the desired pressure as quickly as possible when they are pumped down. Typical contaminants include oil and grease on screws and seals, process reaction products or condensed vapors, particularly water that is adsorbed on the walls of the vessel. Consequently, it is necessary to ensure that the components are clean when installing vacuum equipment. All components attached in the vacuum chamber must be clean and grease-free. All seals must also be installed dry. If high or ultra high vacuum is to be generated, clean gloves must be worn during the assembly process.

1.3.2 Condensation and vaporization

All substances can occur in a liquid, solid or gaseous state. Their aggregate status is a function of pressure and temperature. Liquids are transformed into their gaseous state through vaporization, solids through sublimation. The separation of liquids or solids out of the gaseous phase is termed condensation. Since normal room air contains approximately 10 g of water vapor per m³, condensed water vapor is always present on all surfaces.

Adsorption on surfaces is especially pronounced due to the strong polarity of the water molecules. Natural fibers, in particular, such as paper, contain large quantities of water that escape during drying processes under vacuum. Cooled condensers are used to separate the water vapor in this connection. Even some metals (Cd, Zn, Mg) can vaporize in noticeable quantity at temperatures of several 100 °C. Consequently, use of these metals is avoided in plant construction.

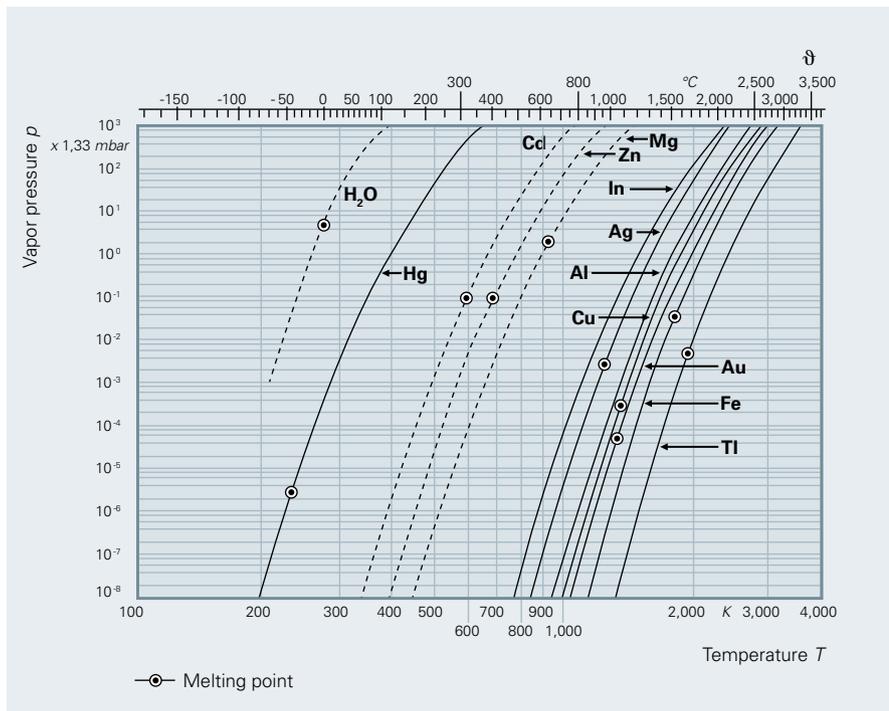


Figure 1.9: Vapor pressure curves of various substances

Source: Josten (publisher) Wutz, Handbuch Vakuumtechnik, Vieweg Verlag

1.3.3 Desorption, diffusion, permeation and leaks

In addition to water, other substances (oil) can be adsorbed on surfaces. Substances can also diffuse out of the metal walls, which can be evidenced in the residual gas. In the case of particularly rigorous requirements, stainless steel vessels can be baked out under vacuum, thus driving the majority of the volatile components out of the metal walls.

Desorption

Gas molecules, (primarily water) are bound to the interior surfaces of the vacuum chamber through adsorption and absorption, and gradually desorb again under vacuum. The desorption rate of the metal and glass surfaces in the vacuum system produces a gas yield that is a function of time, however. A good approximation can be obtained by assuming that after a given point in time $t > t_0$ the reduction will occur on a linear basis over time. t_0 is typically assumed to be one hour.

The gas yield can thus be described as:

Formula 1-24
Desorption

$$Q_{des} = q_{des} \cdot A \cdot \frac{t_0}{t}$$

In this formula, q_{des} is the surface-based desorption rate of the material, A the interior surface area of the vacuum chamber, t_0 the start time and t the duration.

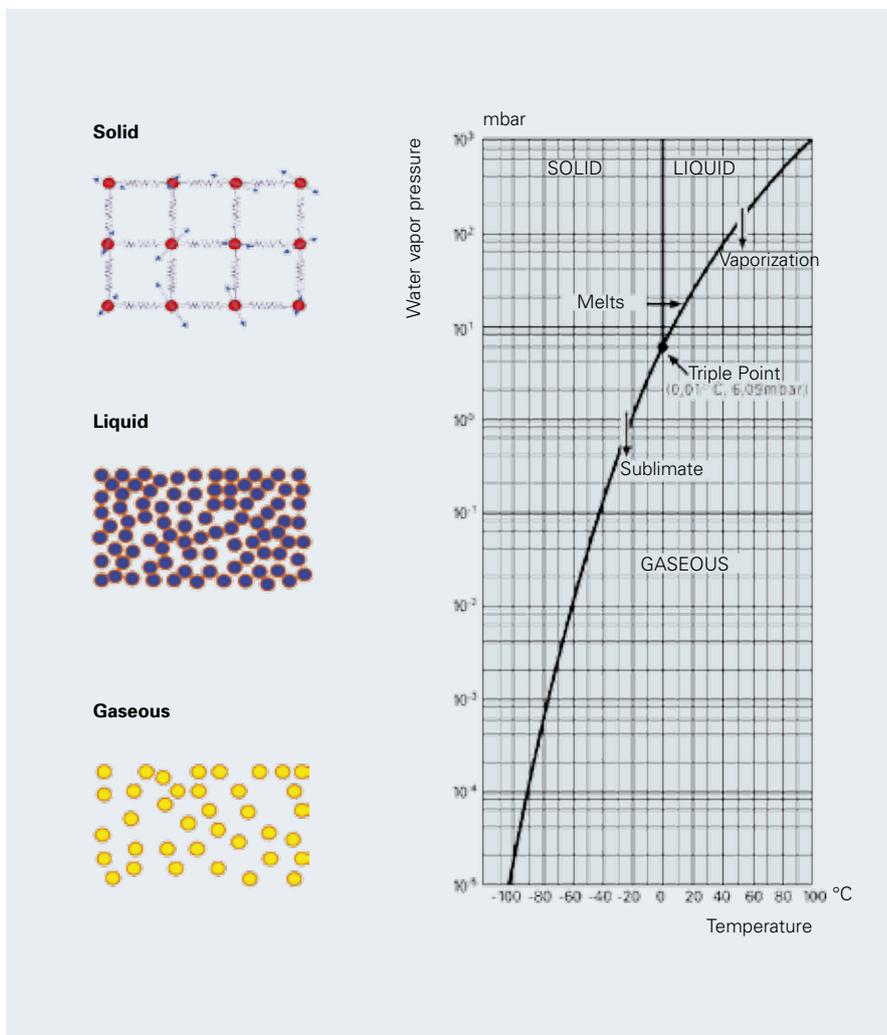


Figure 1.10: Saturation vapor pressure of water

Source: Jousten (publisher) Wutz, Handbuch Vakuumtechnik, Vieweg Verlag

Diffusion with desorption

At operation below 10^{-6} mbar, desorption of plastic surfaces, particularly the seals, assumes greater significance. Plastics mainly give off the gases that are dissolved in these plastics, which first must diffuse on the surface.

Following extended pump downtimes, desorption from plastics can therefore dominate the metal surfaces. Although the surface areas of the seals are relatively small; the decrease in the desorption rate over time occurs more slowly in the case of metal surfaces. As an approximation it can be assumed that the reduction over time will occur at the square root of the time.

The gas produced from plastic surfaces can thus be described as:

Formula 1-25
Desorption from
plastic material

$$Q_{diff} = q_{diff} \cdot A_d \sqrt{\frac{t_0}{t}}$$

where A_d denotes the surface area of the plastics in the vacuum chamber and q_{diff} denotes the surface area-specific desorption rate for the respective plastic. At even lower pressures, similar effects also occur with metals, from which hydrogen and carbon escape in the form of CO and CO₂ and can be seen in the residual gas spectrum. Formula 1-25 also applies in this regard.

Permeation and leaks

Seals, and even metal walls, can be penetrated by small gas molecules, such as helium, through diffusion. Since this process is not a function of time, it results in a sustained increase in the desired ultimate pressure. The permeation gas flow is proportional to the pressure gradient p_0/d (d = wall thickness, p_0 = atmospheric pressure = ambient pressure) and to the permeation constants for the various materials k_{perm} .

Formula 1-26
Permeation

$$k_{perm} \cdot Q_{perm} = k_{perm} \cdot A \cdot \frac{p_0}{d}$$

Permeation first manifests itself at pressures below 10⁻⁸ mbar.

Q_l denotes the leakage rate, i.e. a gas flow that enters the vacuum system through leaks at a volume of V . The leakage rate is defined as the pressure rise Δp over time Δt :

Formula 1-27
Leakage rate

$$Q_l = \frac{\Delta p \cdot V}{\Delta t}$$

If a vessel is continuously pumped out at a volume flow rate S , an equilibrium pressure p_{gr} will be produced. Throughput Formula 1-13 is equal to the leakage rate $Q_l = S \cdot p_{gr}$. A system is considered to be adequately tight if the equilibrium pressure p_{gr} is approximately 10 % of the working pressure. If, for example, a working pressure of 10⁻⁶ mbar is attained and the vacuum pump that is being used has a pumping speed of 100 l/s, the leakage rate should not be more than 10⁻⁵ mbar l/s. This corresponds to a leak of approximately 20·20 μm² in size. Leakage rates Q_l of less than 10⁻⁸ mbar l/s can usually be easily attained in clean stainless steel vessels. The ultimate pressure achievable after a given period of time t primarily depends upon all of the effects described above and upon the pumping speed of the vacuum pump. The prerequisite is naturally that the ultimate pressure will be high relative to the base pressure of the vacuum pump.

The specific pressure components for a given pumping time t can be calculated by using

Formula 1-28
Ultimate pressure (t)

$$Q_{des}(t) + Q_{diff}(t) + Q_{perm} + Q_l = p(t) \cdot S$$

and by solving the equations for t . The achievable ultimate pressure is the sum of these pressures.

1.3.4 Bake-out

The following prerequisites must be satisfied in order to achieve lower pressures ($< 10^{-8}$ mbar):

- ▶ The base pressure of the vacuum pump should be a factor of 10 lower than the required ultimate pressure
- ▶ Stainless steel vacuum recipients and components must be used
- ▶ Metallic seals (CF flange connections) are required
- ▶ Pump and equipment must be baked out
- ▶ Leaks must be avoided and eliminated prior to activating the heater (use helium leak detectors!)
- ▶ Clean work is a must, i.e. all parts must be thoroughly cleaned and must be installed with grease-free gloves

Bake-out significantly increases desorption and diffusion rates, and this produces significantly shorter pumping times. Bake-out temperatures of up to 300 °C are used. The instructions of the pump manufacturers relating to maximum bake-out temperatures and maximum permissible radiation levels in the pump flange must be observed.

Following installation the equipment is switched on, and after reaching a pressure of $p < 10^{-5}$ mbar the heater is then switched on. During the heating process, all gauge heads must be operated and degassed at intervals of 10 hours. In the case of stainless steel vessels and the use of metallic seals, bake-out temperatures of 120 °C and heating times of approximately 48 hours are sufficient for advancing into the pressure range of 10^{-10} mbar. Bake-out should be continued until 100 times the expected ultimate pressure is attained. The heaters for the pump and vacuum chamber are then switched off. After cool-down, the desired ultimate pressure will probably be achieved. In connection with pressures $p < 5 \cdot 10^{-10}$ mbar and large interior surface areas, it will be advantageous to use a titanium sublimation pump that pumps the hydrogen escaping from the metals at a high volume flow rate.

1.3.5 Residual gas spectrum

When working in ultra high vacuum, it can be important to know the composition of the residual gas. The percentages of water ($M = 18$) and its fragment HO ($M = 17$) will be large in the case of vacuum chambers that are not clean or well heated. Leaks can be identified by the peaks of nitrogen ($M = 28$) and oxygen ($M = 32$) in the ratio of $N_2/O_2 = 4/1$.

Hydrogen ($M = 2$), water ($M = 17$ and 18), carbon monoxide ($M = 28$) and carbon dioxide ($M = 44$) will be found in well-heated chambers. No hydrocarbons will be found when using turbomolecular pumps. They are very effectively kept out of the chamber due to the high molecular masses and the resulting high compression ratios. A typical residual gas spectrum for a clean vessel evacuated by a turbomolecular pump is shown in Figure 2.23.

1.3.6 Venting

To avoid undesired contamination, vacuum chambers should be vented with dry nitrogen instead of air. This prevents water vapor from depositing on the vessel walls, which would be difficult to desorb in connection with the subsequent evacuation.

2 Vacuum Generation

2.1 Pump principles and vacuum pump performance data

2.1.1 Classification of vacuum pumps

In connection with vacuum pumps, a distinction is made between gas-displacement vacuum pumps and gas-binding vacuum pumps. While gas-displacement vacuum pumps can be used without limitation, gas-binding vacuum pumps have a limited gas absorption capacity and must be regenerated at certain process-dependent intervals.

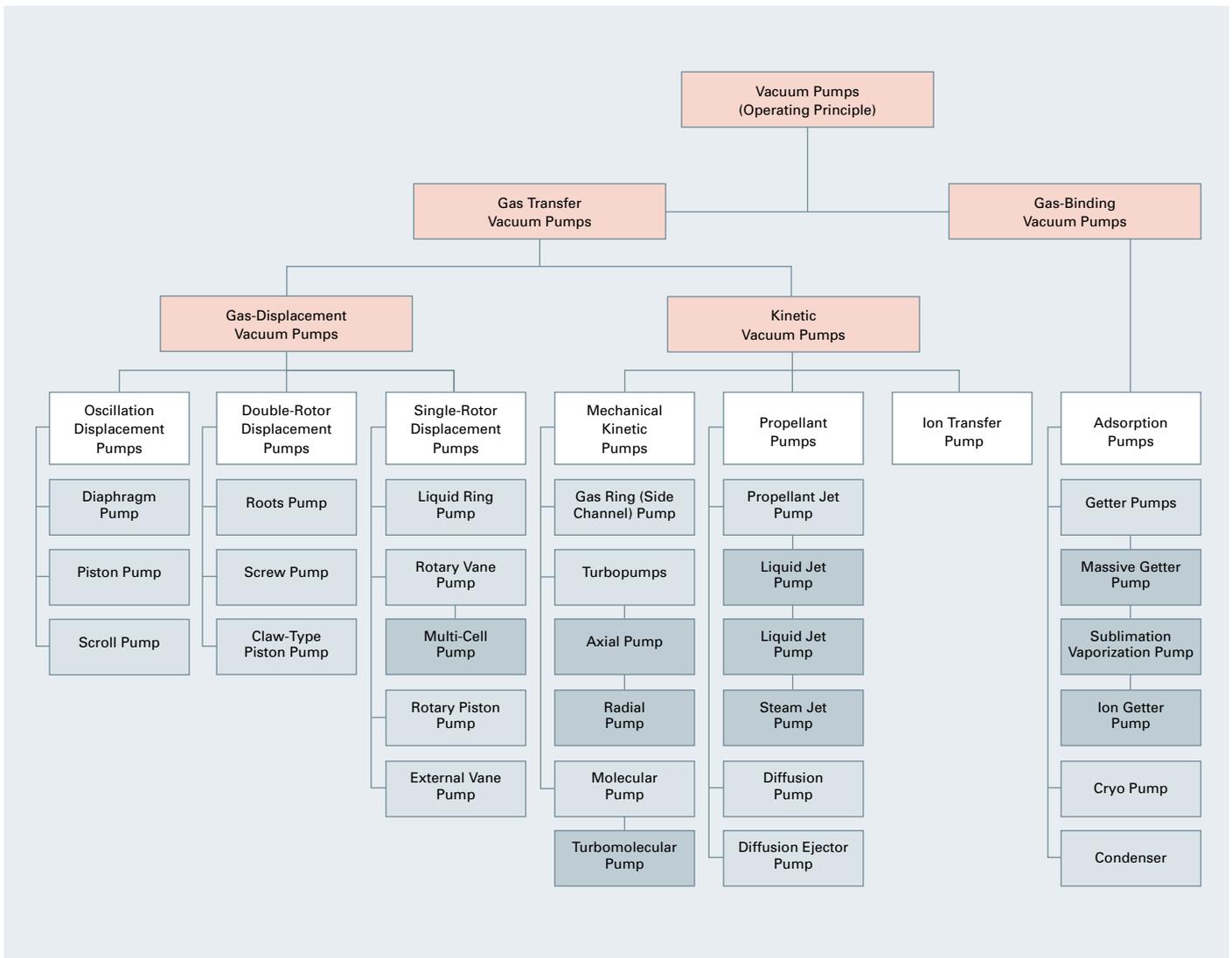


Figure 2.1: Overview of vacuum pumps

Gas-displacement pumps, which are also referred to as gas transfer pumps, are classified either as positive displacement pumps or kinetic vacuum pumps. Positive displacement pumps displace gas from sealed areas to the atmosphere or to a downstream pump stage. Kinetic pumps displace gas by accelerating it in the pumping direction, either via a mechanical drive system or through an aligned vapor stream that is condensed at the end of the pumping section. Gas-binding vacuum pumps either bind the gas to an especially active substrate through gettering or condense the gas at a suitable temperature.

2.1.2 Pumping speed and throughput

Pumping speed $S = \frac{dV}{dt}$ (Formula 1-12) is the mean volume flow through the cross section of the inlet port of a vacuum pump. In the volume flow rate diagram, it is applied as a factor of the inlet pressure of the pump. The pump's maximum achievable pumping speed is always referred to as its rated pumping speed. Determination of the pumping speed is described in base standard ISO 21360-1. Pumping speed is indicated in m^3/s . The units of m^3/h , l/s and l/min are also customary.

Throughput $q_{pV} = S \cdot p = \frac{dV}{dt} \cdot p$ (Formula 1-13) denotes the gas throughput in a vacuum pump as a function of inlet pressure. It is indicated in $\text{Pa} \cdot \text{l}/\text{s}$ or $\text{mbar} \cdot \text{l}/\text{s}$. In the case of pumping stations that consist of gas-displacement pumps, the throughput of all pumps will be the same.

2.1.3 Ultimate pressure and base pressure

Ultimate pressure p_e is the lowest pressure that is asymptotically approached by the pressure of a blank-flanged vacuum pump under defined basic conditions without gas inlet. If a pump is operated at ultimate pressure, the usable pumping speed will be zero, as only its own backflow losses will be displaced. Ultimate pressure is a theoretical value. Today, base pressure is specified instead of ultimate pressure. The conditions for achieving base pressure are specified in standard ISO 21360-1. As the base pressure must be attained within a specified period of time, it is usually higher than the ultimate pressure.

2.1.4 Compression ratio

The maximum pressure ratio between discharge pressure p_2 and intake pressure p_1 is referred to as the compression ratio:

Formula 2-1
Compression ratio

$$K_0 = \frac{p_2}{p_1}$$

In the case of blank-flanged inlet ports, the compression ratio is measured through gas inlet on the discharge side.

2.1.5 Pumping speed of pumping stages connected in series

Let us consider a vacuum pump having a pumping speed S_0 and a compression ratio K_0 . The pump has backflow losses through gaps having conductivity L_R . Let inlet pressure be p_1 and discharge pressure p_2 . An additional pump having a pumping speed S_v is connected on the outlet side.

The pumping station will displace the following volume of gas:

Formula 2-2
Pump combination
gas flow

$$q_{pV} = p_1 \cdot S = p_2 \cdot S_v = S_0 \cdot p_1 - L_R \cdot (p_2 - p_1)$$

Where $L_R \ll S_0$, backflow conductivity L_R is:

Formula 2-3
Backflow conductivity

$$L_R = \frac{S_0}{K_0}$$

and the real compression ratio is:

Formula 2-4
Real compression ratio

$$K = \frac{p_2}{p_1} = \frac{S}{S_v}$$

Using the above formulas, it therefore follows that the pumping speed S of a two-stage pumping station will be:

Formula 2-5
Recursion pumping speed

$$S = \frac{S_0}{1 - \frac{1}{K_0} + \frac{S_0}{K_0 \cdot S_v}}$$

This formula can also be used as the recursion formula for multiple pumping stages that are connected in series by starting with the pumping speed S_v of the last stage and inserting the K_0 and S_0 of the preceding stage.

2.1.6 Gas ballast

Means through which air or another non-condensing gas is admitted into a vacuum pump are referred to as gas ballast. If the pump is displacing vapor that would condense in the pump at the corresponding temperatures without gas ballast, the gas ballast enables the outlet valve to open before the vapor condenses, and the vapor is discharged together with the ballast gas. Both atmospheric air as well as selected inert or process gases are used as ballast gas. The use of the gas ballast increases the attainable base pressure of a vacuum pump slightly. Consequently, for gas ballast vacuum pumps the base pressure is specified both with and without gas ballast.

2.1.7 Water vapor tolerance / water vapor capacity

Water vapor tolerance p_{w0} is the highest water vapor pressure with which a vacuum pump can continuously intake and displace pure water vapor under standard ambient conditions (20 °C, $p_0 = 1,013$ mbar). It can be calculated from pumping speed, gas ballast volume, relative humidity and saturation vapor temperature and is indicated in mbar [7].

Formula 2-6
Water vapor tolerance

$$p_{w0} = \frac{q_{pB} \cdot (p_s - p_l)}{S \cdot (\alpha \cdot p_0 - p_s)}$$

DIN 28426 describes the use of an indirect process to determine water vapor tolerance. Water vapor tolerance increases at higher pump outlet temperature and greater gas ballast volume q_{pB} . It declines at higher ambient pressure.

Without gas ballast, a vacuum pump having an outlet temperature of less than 100 °C would not be capable of displacing even small amounts of pure water vapor. If water vapor is nevertheless pumped without gas ballast, the condensate will dissolve in the pump oil. As a result, the base pressure will rise and the condensate could cause corrosion damage.

Water vapor capacity

Formula 2-7
Water vapor capacity

$$c_{w0} = p_{w0} \cdot S$$

is the maximum volume of water that a vacuum pump can continuously intake and displace in the form of water vapor under the ambient conditions of 20 °C and 1,013 mbar.

2.1.8 Sealing gas

When pumping corrosive process gas, there is a risk that the gas might attack parts of the pump. To counter this danger, sensitive parts, e.g. bearings, must be protected by a continuous flow of inert gas. A special gas inlet system is installed in the pumps for this purpose, through which gas flows into the pumping system via the bearings. In this connection, it is necessary to ensure that the base pressure does not increase excessively.

2.2 Rotary vane vacuum pump

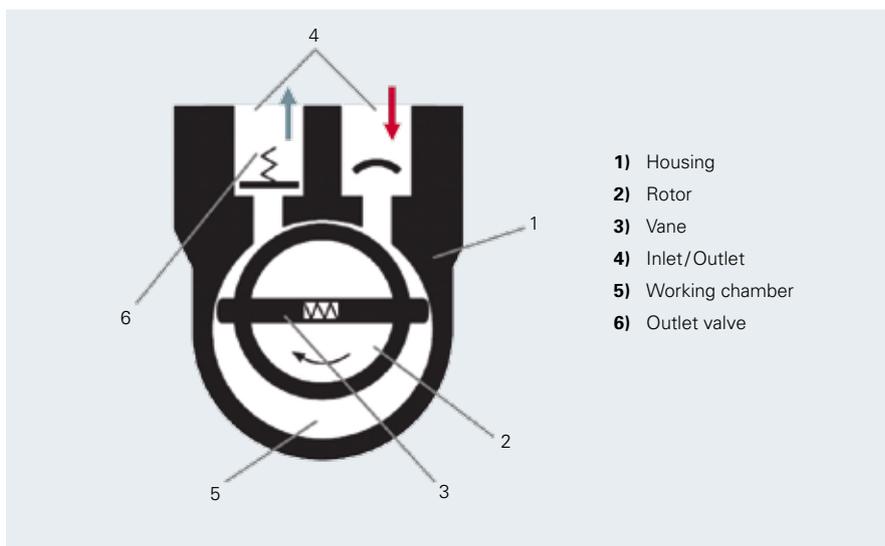


Figure 2.2: Operating principle of a rotary vane pump

2.2.1 Design / Operating principle

A rotary vane vacuum pump is an oil-sealed rotary displacement pump. The pumping system consists of a housing (1), an eccentrically installed rotor (2), vanes that move radially under spring force (3) and the inlet and outlet (4). The outlet valve is oil-sealed. The inlet valve is designed as a vacuum safety valve that is always open during operation. The working chamber (5) is located inside the housing. Rotor and vanes divide the working chamber into two separate spaces having variable volumes. As the rotor turns, gas flows into the enlarging suction chamber until it is sealed off by the second vane. The enclosed gas is compressed until the outlet valve opens against atmospheric pressure. In the case of gas ballast operation, a hole to the outside is opened, which empties into the sealed suction chamber on the front side.

Operating fluid, oil

Pump oil, which is also called as operating fluid, has multiple tasks to perform in a rotary vane pump. It lubricates all moving parts, fills both the harmful space under the outlet valve as well as the narrow gap between inlet and outlet. It compresses the gap between the vanes and the working chamber and additionally ensures an optimal temperature balance through heat transfer.

Multi-stage pumps

Rotary vane vacuum pumps are built in single- and two-stage versions. Two-stage pumps achieve lower ultimate pressures than single-stage pumps. Moreover, the effects of the gas ballast on the ultimate pressure are lower, as the ballast gas is only admitted in the second stage.

Vacuum safety valve

Depending upon the type of pump in question, rotary vane vacuum pumps can be equipped with a vacuum safety valve. The vacuum safety valve disconnects the pump from the vacuum recipient in the event of intentional or unintentional standstill, and uses the displaced gas to vent the pumping system in order to prevent oil from rising into the recipient. After switching on the pump, it opens after a delay once the pressure in the pump has reached the approximate pressure in the recipient.

2.2.2 Application notes

Rotary vane vacuum pumps can be employed universally throughout the entire low and medium vacuum ranges. Either a single- or double-stage pump can be used, depending upon the pressure range in question. Ideal operating conditions always exist if the medium to be pumped down will not condense at pump operating pressure and atmospheric pressure.

Vapors

Vapors that can condense entirely or partially in the pump during the compression phase must also be displaced for distillation and drying processes. Here, opening the gas ballast valve helps to displace the vapor through the pump without condensation. However vapor compatibility is not always sufficient to prevent condensation. Condensates mix with the oil and cause ultimate pressure to increase and diminish the lubricating capacity of the operating fluid. These factors can cause corrosion inside the pump.

Filters

Within certain limits, filters and separators can protect the vacuum pump against wear and corrosion. Separators that are filled with paper filter inserts (STP), Raschig rings (STR) or additionally with cyclone (STZ) bind dust. Activated carbon filters (FAK) bind inorganic vapors, and Fuller's earth filters (FBL) can be connected upstream for absorption of organic vapors. The fillings are replaceable. Inflowing hydrocarbons (oil vapor) can be catalytically incinerated in the heated catalytic trap (URB), and zeolite traps adsorb various vapors. When saturated, they can be regenerated by baking them out. Condensates can be collected in the condensate separator (KAS) and drained manually. Chemical oil filters (OFC) clean the pump oil with the aid of the oil pump that is integrated in the rotary vane pump.

At high gas throughputs and in connection with gas ballast operation, oil mist is entrained out of the pump. 4 ml of oil loss at a throughput of 1 bar · m³ gas can be assumed. The oil vapor can be separated in an oil mist separator (ONF) and returned to the pump's oil circulation system by means of an additional return line.

However if substances are also displaced that chemically attack the pump oil or that have such low vapor pressure that condensation in the pump cannot be avoided, in spite of gas ballast and the above-mentioned accessories, a different type of backing pump should be selected.

2.2.3 Portfolio overview

Pfeiffer Vacuum rotary vane pumps are available as single- and two-stage versions.

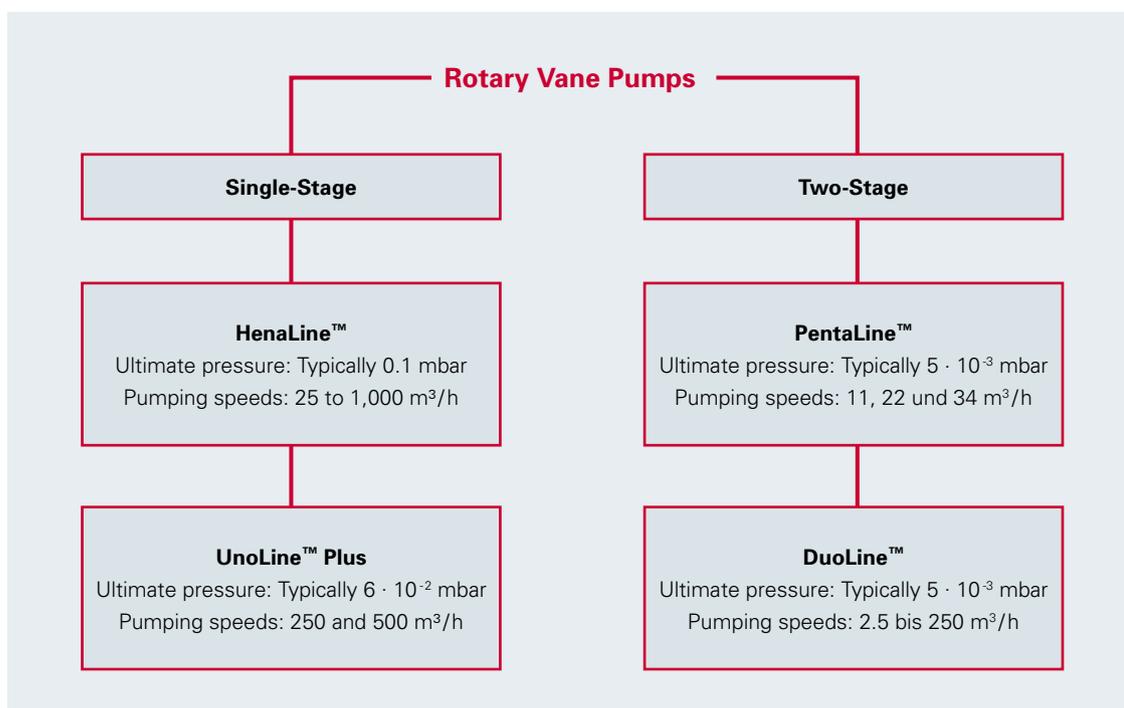


Figure 2.3: Pfeiffer Vacuum rotary vane pumps

2.2.3.1 Single-stage rotary vane vacuum pumps

HenaLine™

HenaLine single-stage, oil-sealed rotary vane vacuum pumps generate a vacuum having volume flow rates of 25 to 1,000 m³/h at ultimate pressures of up to 0.1 mbar. They can be universally employed in many industrial and research environments. They can either be operated as a stand-alone pump or integrated into pumping stations.

With appropriate accessories, these pumps are also suitable for use under the harshest operating conditions, i.e. at high inlet pressures as well as in cycle-mode operation. Oil mist filters, oil return systems and vacuum safety valves are all integrated as standard equipment. In addition to preventing pollution of the ambient air, they also protect the pump and the system. A gas ballast valve enables pump-down of water vapor and other process vapors.

Table 2.1: HenaLine™ performance data

Model	Pumping Speed	Ultimate Pressure	Applications
Hena 25	25 m ³ /h	0.1 mbar	Suitable for electron beam welding, incandescent light bulb manufacturing, surface coating, vacuum drying, leak detection, metallurgy, gas recovery, load lock applications, simulation chambers
Hena 60	60 m ³ /h	0.1 mbar	
Hena 100	100 m ³ /h	0.1 mbar	
Hena 200	200 m ³ /h	0.1 mbar	
Hena 300	300 m ³ /h	0.1 mbar	
Hena 400	600 m ³ /h	0.1 mbar	
Hena 630	630 m ³ /h	0.1 mbar	
Hena 1000	1,000 m ³ /h	0.4 mbar	

UnoLine™ Plus

UnoLine Plus pumps can be optimally employed for industrial applications, first and foremost. These rotary vane vacuum pumps have proven track records as both stand-alone and backing pumps for Pfeiffer Vacuum Roots pumps. An ultimate pressure of approximately $6 \cdot 10^{-2}$ mbar can be attained. These pumps are water-cooled and extremely insensitive to dust and dirt.

They are equipped with an oil regeneration system. Condensates, contaminants and dust particles can be separated from the operating medium, collected in the vapor separator and drained. The adjustable cooling water controller enables the UnoLine Plus pumps to maintain the required operating temperature. These pumps are equipped with gas ballast in order to pump down vapors.

Table 2.2: UnoLine™ Plus performance data

Model	Pumping Speed	Ultimate pressure	Applications
BA 251	250 m ³ /h	$6 \cdot 10^{-2}$ mbar	Suitable for all industrial applications, e. g. metallurgy, transformer drying, coating, chemistry
BA 501	500 m ³ /h	$6 \cdot 10^{-2}$ mbar	

2.2.3.2 Two-stage rotary vane vacuum pumps

Two-stage rotary vane pumps are suitable for applications in the low and medium vacuum ranges to a pressure of 10^{-3} mbar. They are equipped with a vacuum safety valve that prevents oil contamination in the recipient. Integrated gas ballast means allow condensable vapors to be pumped down.

PentaLine™

The pumps in the PentaLine series are characterized by their innovative drive concept. These pumps are powered by an electronically controlled brushless DC motor whose rotor sits directly on the rotor shaft of the pumping system. The pumps are supplied with alternating current via an electronic inverter. Voltage ranges of 100 – 120 volts and 200 – 240 volts can be selected by means of a selector switch. Their advantages include high energy efficiency with approximately 25 % lower energy consumption than conventional rotary vane pumps, and the pump's hermetic seal without shaft feedthrough.

If maximum pump performance is temporarily not required, the RPM of the pump can be reduced to the standby mode for additional energy savings of 50 %. Thanks to this new drive concept, it is possible to avoid the high startup currents that typically occur when the pump is cold, even with asynchronous motors. In addition to the above-mentioned gas ballast, the PentaLine pumps can be operated with temperature control to increase water vapor tolerance. The functions of Pump ON, Standby ON and Enhanced Water Vapor Tolerance ON can be selected by means of a PLC-compatible interface or a remote connection.

Table 2.3: PentaLine™ performance data

Model	Pumping Speed	Ultimate Pressure	Applications
Penta 10	11 m ³ /h	$5 \cdot 10^{-3}$ mbar	Ideally suited for turbopump pumping stations, analysis, industrial applications, research and development, coating
Penta 20	22 m ³ /h	$5 \cdot 10^{-3}$ mbar	
Penta 35	34 m ³ /h	$5 \cdot 10^{-3}$ mbar	

DuoLine™

DuoLine rotary vane vacuum pumps are powered by AC or DC motors, depending upon the size of the pump. In addition to the standard models, the following designs are also available: Magnetically coupled pumps (Duo M series) and corrosive gas pumps, both with and without magnetic coupling (Duo MC series).

Table 2.4: DuoLine™ performance data

Model	Pumping Speed	Ultimate Pressure	Applications
Duo 2.5	2.5 m ³ /h	$6 \cdot 10^{-3}$ mbar	Suited for Turbopump pumping stations, analysis, research and development, coating
Duo 35	35.0 m ³ /h	$3 \cdot 10^{-3}$ mbar	
Duo 120	120.0 m ³ /h	$6 \cdot 10^{-3}$ mbar	
Duo 255	250.0 m ³ /h	$5 \cdot 10^{-3}$ mbar	

Duo M series

M series pumps are equipped with a magnetic coupling with can. This wear-free sealing concept hermetically seals the pumps, making them clean and environmentally friendly. The magnetic coupling minimizes maintenance and thus results in significant savings.

Table 2.5: Duo M series performance data

Model	Pumping Speed	Ultimate Pressure	Applications
Duo 5 M	5 m ³ /h	5 · 10 ⁻³ mbar	Ideally suited for turbopump pumping stations, analysis, research & development, coating, non-explosive toxic gases
Duo 10 M	10 m ³ /h	5 · 10 ⁻³ mbar	
Duo 20 M	20 m ³ /h	5 · 10 ⁻³ mbar	
Duo 35 M	35 m ³ /h	3 · 10 ⁻³ mbar	
Duo 65 M	65 m ³ /h	3 · 10 ⁻³ mbar	

Duo C series and MC series

The C series pumps are suitable for corrosive gas applications. In contrast to standard pumps, they have a special gas ballast valve, through which inert gas can be admitted into the pump. In addition, the pumps are equipped with special vanes that are especially resistant to chemicals. All corrosive gas pumps are ready for operation with chemical-resistant F4 or F5 (perfluoropolyether) operating fluids. The Duo MC pumps are especially suitable for pumping toxic gases, because the hermetically sealed magnetic coupling prevents gas from reaching the outside.

Table 2.6: Duo C series and Duo MC series performance data

Model	Pumping Speed	Ultimate Pressure	Applications
Duo 5 MC	5.0 m ³ /h	5 · 10 ⁻³ mbar	Suitable for corrosive gas applications, chemical labs, toxic non-explosive gases
Duo 10 MC	10.0 m ³ /h	5 · 10 ⁻³ mbar	
Duo 20 MC	20.0 m ³ /h	5 · 10 ⁻³ mbar	
Duo 2.5 C	2.5 m ³ /h	6 · 10 ⁻³ mbar	Suitable for corrosive gas applications, chemical laboratories
Duo 35 C	35.0 m ³ /h	3 · 10 ⁻³ mbar	
Duo 65 C	65.0 m ³ /h	3 · 10 ⁻³ mbar	
Duo 120 C	120.0 m ³ /h	3 · 10 ⁻³ mbar	

2.2.3.3 Operating fluid selection

Because operating fluid comes into contact with the medium to be pumped, it is exposed to the influences of the medium in question. Consequently, operating fluid should be selected on an individual basis in accordance with the respective application. Pfeiffer Vacuum offers four different types of operating fluids that are suitable for all major applications. The pumps are factory-set for the respective operating fluid.

The ultimate pressures of the rotary vane vacuum pumps that are specified in the catalog can only be ensured when using the operating fluid recommended by Pfeiffer Vacuum. The manufacturer cannot accept any liability for damage attributable to the use of other operating fluids. Different types of oil should never be mixed. Some oils do not mix and can thus cause damage to the pumping system.

Table 2.7: Oil types for backing pumps and Roots pumps

<p>P3</p>	<p>High quality mineral oil for standard applications Extremely low vapor pressure Achievable ultimate pressure: $< 1 \cdot 10^{-3}$ mbar Max. operating temperature: 95 °C</p> <p>For pumping down: Air, inert gases, noble gases</p>
<p>D1</p>	<p>Diesteröl für Standard- und Sonderapplikationen Achievable ultimate pressure: $< 5 \cdot 10^{-2}$ mbar Max. operating temperature: 120 °C</p> <p>For pumping down: Air, inert gases, noble gases, oxygen, weakly aggressive and organic solvents</p>
<p>F4 (for pumps < 20 m³/h)</p> <p>F5 (for pumps > 20 m³/h)</p>	<p>Perfluorpolyether for special applications Achievable ultimate pressure: $< 1 \cdot 10^{-3}$ mbar Max. operating temperature: 120 °C</p> <p>For pumping down: Oxygen, ozone, halogens, organic and inorganic solvents, HCl, BF₃, HF, fluorine</p>

2.2.3.4 Accessories

Dust separators (STP, STR, STZ)

If the process produces dust, the pump must be installed downstream from a dust separator. Different versions are available, depending upon the degree of contamination of the pumped-down gases and molecule size.

Condensate separator (KAS)

Condensates can form in the inlet and outlet lines of a vacuum system when pumping down vapors. To protect the pump against these condensates, we recommend providing a condensate separator in both the inlet and outlet lines.

Oil mist separator (ONF)

Oil mist separators are mounted on the outlet port of rotary vane vacuum pumps. They prevent the air from being contaminated by the oil mist that the pump discharges in greater or lesser quantities, depending upon operating pressure. The filter consists of cylindrical filter elements and an aluminum housing with oil collection chamber.

Oil return system (ORF)

The ORF oil return system was developed for collecting and returning pump oil mist. It helps to reduce operating costs, particularly when special oils are being used for fluorine and nuclear technology applications. In this process, the oil accumulating in the ONF is collected in a container and returned into the vacuum pump by a feed pump.

Zeolite trap (ZFO)

A zeolite trap uses adsorption to prevent the backflow of hydrocarbons from rotary vane vacuum pumps to downstream high vacuum components. The adsorption agent can be regenerated by baking it out at 300 °C. The regeneration intervals will depend upon the process in question.

Catalytic trap (URB)

A catalytic trap prevents the backflow of hydrocarbons from single- or two-stage rotary vane vacuum pumps. This is accomplished through catalytic incineration of hydrocarbons at an operating temperature of 250 °C to form CO₂ and water vapor. The oxygen that is admitted into the process chamber through periodic venting suffices for self-regeneration. This means that the regeneration intervals are independent of the process in question. Water cooling is required for direct installation of the traps on the inlet ports and/or for use on single-stage rotary vane pumps.

Activated carbon filters (FAK)

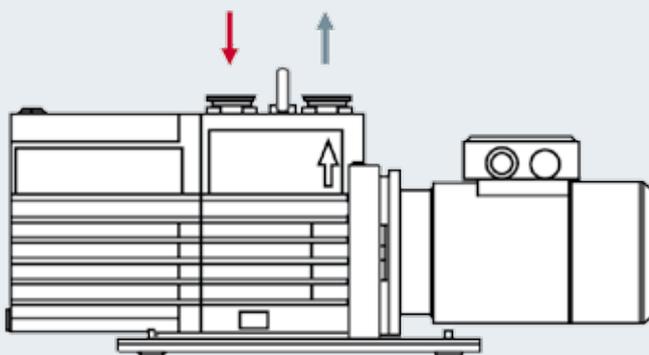
Activated carbon filters are used if there are accumulations of H₂S, HCN, Hg, NH₃ or SO₂ vapors, nitrous gases, as well as vaporous solvents, acids and alkaline solutions. The activated carbon filters come supplied with a filling. This filling is replaceable. The service life of the filling is dependent upon the process in question.

Bleaching earth filter (FBL)

A bleaching earth filter protects both the rotary vane vacuum pump and the operating fluid by adsorbing organic vapors. The bleaching earth filling is replaceable. The service life of the filling is dependent upon the process in question. This filter is used in petrochemical, plastics and resin chemistry applications if there are accumulations of peroxides, hydroperoxides and polycondensation.

Chemical oil filter (OFC)

Chemical oil filters are interposed in the oil circulation systems of rotary vane pumps. These oil filters filter out dust or particulate matter reaching the operating fluid from the process. In addition, chemical oil filters adsorb corrosive substances from the operating fluid. This reduces pump wear.



Inlet

Application: Protects pump and operating fluid

Dust separators (STP, STR, STZ)

- ▶ Prevents dusts from entering the pump
- ▶ STP single-stage filter with cyclone and paper element
- ▶ STR two-stage filter with cyclone and oil-wetted fillers
- ▶ STZ two-stage filter with cyclone and paper element

URB catalytic trap

- ▶ Prevents pump oil backflow to vacuum recipient
- ▶ Operates through catalytic incineration

ZFO zeolite trap

- ▶ Prevents oil backflow
- ▶ Zeolites bind backflowing pump oil
- ▶ Can be regenerated by means of optional heating rod

Outlet

Application: Prevents pump oil mist from escaping to the environment

ONF oil mist separator

- ▶ Prevents oil mist from reaching the atmosphere
- ▶ Degree of filtration with clean filter > 99.98 %

ORF oil return system

- ▶ Returns oil to pump from ONF oil mist separator

KAS condensate separator

- ▶ At inlet and outlet: Prevents condensates from entering the pump
- ▶ Separator for condensed vapors
- ▶ Sight glass for monitoring condensate level
- ▶ Drain plug for draining condensate

Figure 2.4: Operating principle of a diaphragm vacuum pump

2.3 Diaphragm vacuum pumps

2.3.1 Design / Operating principle

Diaphragm vacuum pumps are dry positive-displacement pumps. Their operating principle is explained in Figure 2.5. A crankshaft-driven connecting rod (4) moves the diaphragm (1) that is tensioned between head cover (2) and housing (3). The space between the head cover and the diaphragm forms the suction chamber (5). Diaphragm pumps require inlet valves and outlet valves (6) to achieve aligned gas displacement. Pressure-controlled shutter valves made of elastomer materials are used as valves. Because the suction chamber is hermetically sealed off from the drive by the diaphragm, the pump medium can neither be contaminated by oil nor can aggressive media corrode the mechanics. The harmful space between the outlet valve and the suction chamber results in only a limited compression ratio. This means that an ultimate pressure of only approximately 70 mbar can be attained with a single pump stage. Connecting multiple pumping stages in series can reduce ultimate pressure to 0.5 mbar. Lower pressures cannot be achieved, as in this case there is no longer sufficient force to open the inlet valve. The principle of the diaphragm pump is particularly well suited for low pumping speeds of up to approximately 10 m³/h.

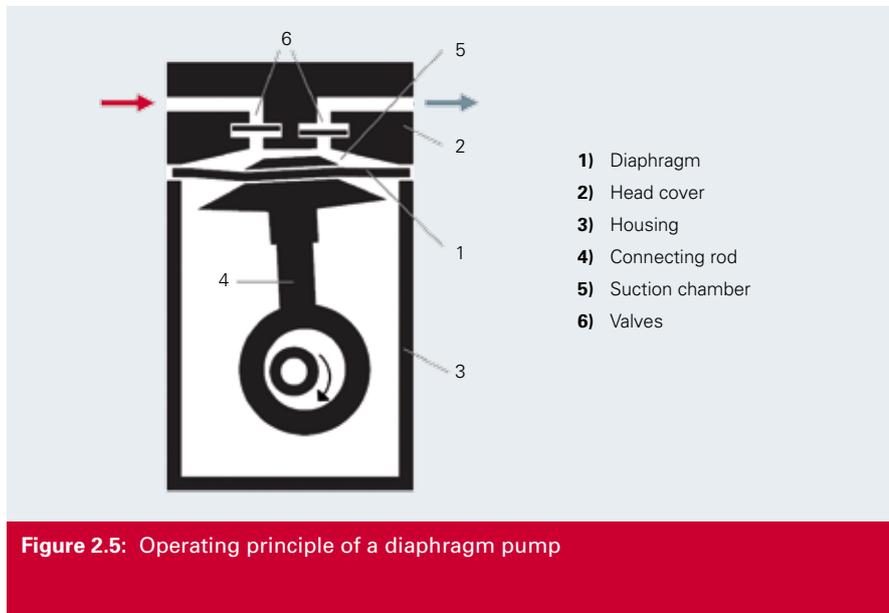


Figure 2.5: Operating principle of a diaphragm pump

2.3.2 Application notes

Their hydrocarbon-free suction chambers make diaphragm pumps particularly well suited as dry backing pumps for turbomolecular pumps with Holweck stage. Even two-stage diaphragm pumps that can reach an ultimate pressure of approximately 5 mbar can be used as backing pumps for Holweck turbopumps. Their clean vacuum is particularly valued for analytical applications. Diaphragm pumps, too, do not displace water vapor without gas ballast. Even the low volumes of water vapor that desorb from the walls of high vacuum equipment can allow the ultimate pressure of a diaphragm pump to increase dramatically. However some diaphragm pumps are equipped with a gas ballast valve that operates in accordance with a patented process.

For this purpose, gas is admitted into the connection channel between the first and second stages of two-stage diaphragm pumps, and communicates with the suction chamber of the first stage via a small hole. If greater volumes of moisture accumulate and diaphragm pumps without gas ballast are being used, suitable separators or cooling traps must be connected upstream to prevent significant condensate formation in the pump. However the ultimate pressure will nevertheless increase.

2.3.3 Portfolio overview

Diaphragm pumps from Pfeiffer Vacuum are available in a variety of versions. They differ in terms of their ultimate pressures and pumping speeds. The pumping speeds of the pumps are between 6 and 160 l/min (0.36 – 9.6 m³/h). Ultimate pressures of less than 4 mbar for two-stage pumps and less than 0.5 mbar for four-stage pumps can be attained. Pumps that feature corrosive gas design with coated diaphragms and corrosion-resistant housings are available for pumping corrosive gases.

Table 2.8: Diaphragm pump performance data

Model	Pumping Speed	Ultimate Pressure	Applications
MVP 006-4	0.28 m ³ /h	≤ 2.0 mbar	Small turbopump pumping stations (ideal with HiPace 10 and HiPace 80), mobile analysis devices
MVP 015-2	0.9 m ³ /h	≤ 3.5 mbar	Turbopump pumping stations, leak detectors, research laboratories, analytical applications, chemistry
MVP 015-4	0.9 m ³ /h	≤ 0.5 mbar	
MVP 040-2	2.3 m ³ /h	≤ 4.0 mbar	
MVP 070-3	3.8 m ³ /h	≤ 1.0 mbar	
MVP 070-3 C	3.4 m ³ /h	≤ 1.5 mbar	Corrosive gas applications requiring a hydrocarbon-free vacuum
MVP 160-3	9.6 m ³ /h	≤ 2.0 mbar	Turbopump pumping stations, leak detectors, research laboratories, analysis, chemistry
MVP 160-3 C	8.3 m ³ /h	≤ 2.0 mbar	Corrosive gas applications requiring a hydrocarbon-free vacuum

The designations for the pumps are selected in such a manner as to indicate the number of pumping stages and the pumping speed. Corrosive gas pumps have the letter C as a suffix to the model designation.

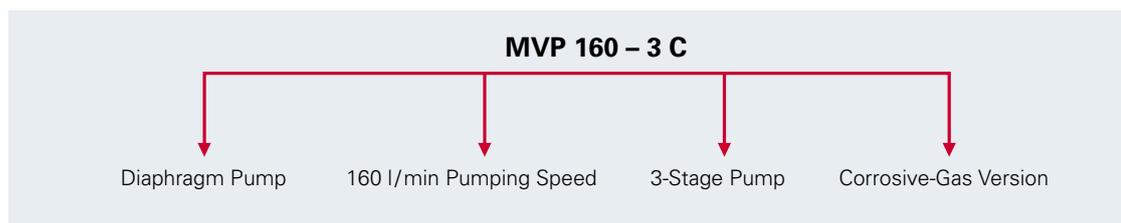


Figure 2.6: Diaphragm pump model designations

2.4 Piston vacuum pumps

2.4.1 Design / Operating principle

The operating principle of piston vacuum pumps is one of the oldest in the history of vacuum generation. Its principle is that of the classical positive-displacement pump. Otto von Guericke, the father of vacuum technology, used a pump incorporating this design for his experiments.

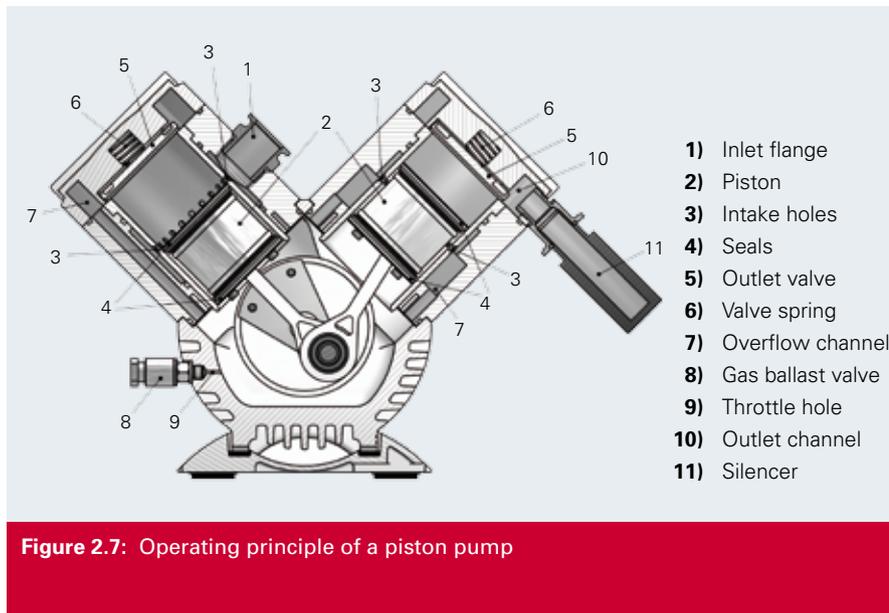


Figure 2.7: Operating principle of a piston pump

Like diaphragm pumps, classical piston vacuum pumps are equipped with an inlet valve and an outlet valve. The arrangement of these valves produces a dead volume above the piston in the cylinder head, which limits the maximum compression ratio. Moreover, ultimate pressure is limited by the force that must be applied to open the inlet valve. These two disadvantages are avoided through the special design of the piston pump described below.

New material pairings enable operation without oil between the piston seals (4) and the cylinder wall. Since the entire cross section of the cylinder is formed as an outlet valve plate (5), the harmful space (dead volume) between the piston (2) and the cylinder head tends toward zero.

A crankshaft-driven connecting rod moves a piston up and down in a cylinder. The inlet flange (1) communicates with the swept volume via the intake holes (3) when the piston (2) is in its bottom-most position. As the piston moves upward, the inlet holes (3) close off again, and the incoming gas is compressed. After reaching the opening pressure, the valve plate (5) lifts and the gas flows to the inlet holes (3) of the second stage via the overflow channel (7) and the crankcase housing. The second seal (4) prevents the inlet channel from communicating with the crankcase during the compression stroke. The second stage operates in the same manner as the first, and discharges the gas to the atmosphere via the outlet channel (10) and the silencer (11).

Gas ballast air can be admitted to the crankcase via the gas ballast valve and the throttling port behind it in order to displace water vapor through the pump without condensation (see also 2.1.6, Gas ballast).

In the case of dry piston pumps, wear occurs on the piston seals during operation, particularly at high average piston speeds. Once the required inlet pressure is reached, seal wear can be significantly reduced by lowering the RPM.

2.4.2 Applications

Dry piston pumps have higher pumping speeds than those offered by diaphragm pumps, and are used where a clean, hydrocarbon-free vacuum is required when operating near ultimate pressure. Eliminating the inlet valve enables lower base pressures to be reached than with diaphragm pumps. Like all true positive-displacement pumps, piston pumps have the same pumping speed for all gases.

Piston pumps are suitable for use as dry backing pumps for turbomolecular pumps. However to prevent enrichment of hydrogen and water vapor in the backing vacuum area of the turbo-pump, they must be operated with gas ballast if necessary. Piston pumps are particularly well suited for analytical applications and for leak detectors (see also 5.2, Design of a helium leak detector). If the test specimens are directly evacuated by the backing pump for leak detection, they cannot be contaminated with oil vapor when a dry backing pump is used.

Piston pumps are not suitable for pumping corrosive or abrasive media.

2.4.3 Portfolio overview

Pfeiffer Vacuum offers two piston vacuum pumps, the single-stage XtraDry 250-1 and the two-stage XtraDry 150-2. These pumps differ in terms of their pumping speeds and ultimate pressures. In particular, the two-stage XtraDry is characterized by:

- ▶ Low base pressure: $p_b = 0.1$ mbar
- ▶ Gas ballast
- ▶ Automatic speed reduction near base pressure

Table 2.9: XtraDry™ piston pump performance data

Model	Pumping Speed	Ultimate Pressure	Applications
XtraDry™ 150-2	7.5 m ³ /h	0.1 mbar	Dry backing vacuum without condensate and dust accumulation
XtraDry™ 250-1	13.0 m ³ /h	7.0 mbar	

2.5 Screw vacuum pumps

2.5.1 Design/Operating principle

Two parallel bearing-supported, intermeshing screw rotors (3) having opposite threads synchronously and contactlessly counter-rotate in a cylindrical housing (2) that tightly encloses them, and together form a multi-stage pump.

Because of the counter-mesh of the two rotors, the volumes sealed in each thread are advanced along the rotors to the outlet (4). The pump has no valves at either inlet (1) or outlet. When a displacement volume reaches the outlet opening, the pressure is equalized with the atmosphere. This means that atmospheric air flows into the displacement volume and is then discharged again as the rotor turns. This pulsing gas flow generates a high level of dissipated energy and heats the pump. The dissipated energy can be minimized by means of internal compression. This internal compression is achieved by reducing the thread pitch in the direction of the outlet. The gaps between housing and rotors, as well as between the rotors relative to one another, determine the achievable ultimate pressure of a screw pump. The geometry and the resulting configuration of the gap in connection with the mesh between the rotors also significantly influence ultimate pressure.

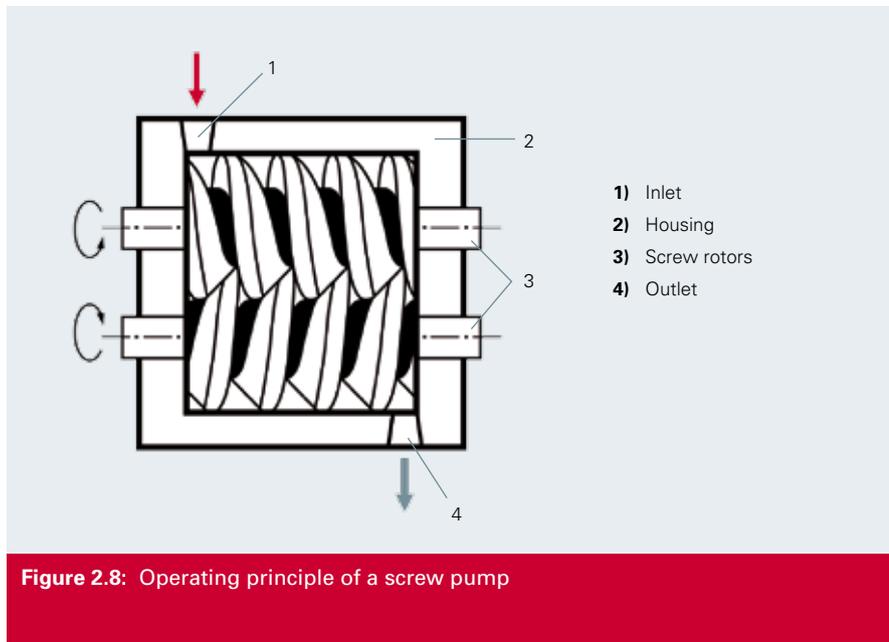


Figure 2.8: Operating principle of a screw pump

Because the dissipated energy that is generated by the pulsing gas flow heats the pump on the outlet side, cooling is required at precisely this location. The gap between housing and rotors is a function of the temperature differential between the warmer rotors and the cooled housing. The amount of heat produced and the temperature are a function of the inlet pressure range. Temperatures are lowest at high inlet pressures (nearly atmospheric), as virtually no compression work is performed here and the displaced air transports sufficient heat out of the pump. In addition, the high gas flow also prevents oscillation of the gas in the last stage. During operation at ultimate pressure ($p < 1$ mbar), the oscillation of the atmospheric air produces higher temperatures at the outlet area, since no gas is passing through the pump, and no heat is thus being transported out of the pump.

HeptaDry pumps are dry screw pumps with internal compression. The screw rotors have a symmetrical geometry with variable pitch. These pumps do not have an end plate with control openings; instead, the gas is discharged axially against atmospheric pressure. Because of the internal compression, the volume of pulsing gas is low.

This results in lower power consumption, quiet operating, uniform temperature distribution within the pump and low cooling water consumption. This makes these pumps extremely cost-effective, in spite of their robust design.



Figure 2.9: HeptaDry™ rotors

2.5.2 Application notes

In recent years, screw pumps have been replacing oil-lubricated rotary vane pumps in the high pumping speed segment (100 – 600 m³/h)

Their advantages include:

- ▶ No lubricant in the gas displacement area
- ▶ No contamination of the medium to be pumped
- ▶ Higher efficiency thanks to internal compression
- ▶ Lower ultimate pressure $p_g < 10^{-1}$ mbar
- ▶ Virtually constant pumping speed between 1 and 1,000 mbar
- ▶ Good liquid and particulate matter tolerance
- ▶ Bearings and seals are protected through low gas pulsation as a result of internal compression
- ▶ High-quality axial face seals
- ▶ Low noise level thanks to standard-feature silencers and outlet valve
- ▶ Temperature-regulated cooling
- ▶ Low energy consumption
- ▶ Extensive use of standard components
- ▶ Mounted ready for connection on a frame with vibration dampers
- ▶ Ideal backing pump for Roots pumps

This makes HeptaDry screw pumps very well suited for chemical applications or processes that generate dust, e.g. for semiconductor production, or if significant volumes of condensate are produced.

In connection with thermostatic cooling, the water flow volume will depend upon the following parameters: Inlet pressure, gas type, rotary speed and pump size. Because of the water-flow cooling, virtually no heat is dissipated to the atmosphere. This can ease the heat load on any existing air conditioning systems and reduce their energy consumption.

Overview of primary applications:

- ▶ Drying, freeze-drying
- ▶ Coating
- ▶ Electron beam welding
- ▶ Metallurgy
- ▶ Load locks
- ▶ Chemistry

2.5.3 Portfolio overview

HeptaDry pumps are dry screw pumps for applications in the low and medium vacuum ranges where high volume flow rates are required. The pumping speeds of this product line range from 100 to 600 m³/h. Ultimate pressures of under 0.1 mbar are attained.

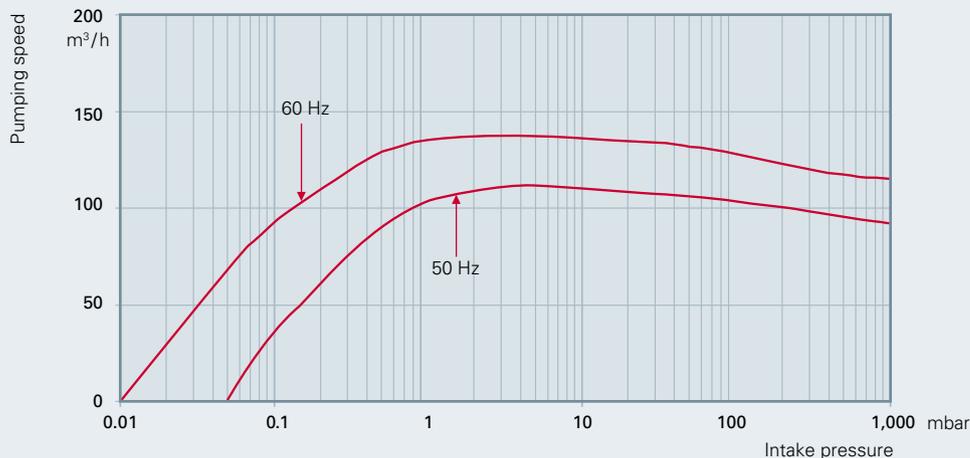


Figure 2.10: HeptaDry™ operating range

Regardless of the model in question, HeptaDry pumps can be continuously operated in the operating range shown in Figure 2.10. Their effective pumping speed declines in the $p < 1$ mbar pressure range due to the ever-stronger backflow between the individual sealed volumes within the pump. See also Formula 2-5. There is a similar reason for the decrease in pumping speed toward high pressure, as in this case the gas is compressed to pressures in excess of atmospheric pressure through internal compression, and consequently backflow increases significantly due to the high differential pressure.

The standard equipment that comes with the pumps includes: Inlet sieve, water-flow cooling with thermostatic valve and thermometer, silencer with non-return valve and frame-mounted design with vibration dampers.

The pumps are driven by a three-phase, temperature-monitored asynchronous motor that is suitable for 50 and 60 Hz (3,000 or 3,600 rpm). Coupling, bearings and flanges are standard components.

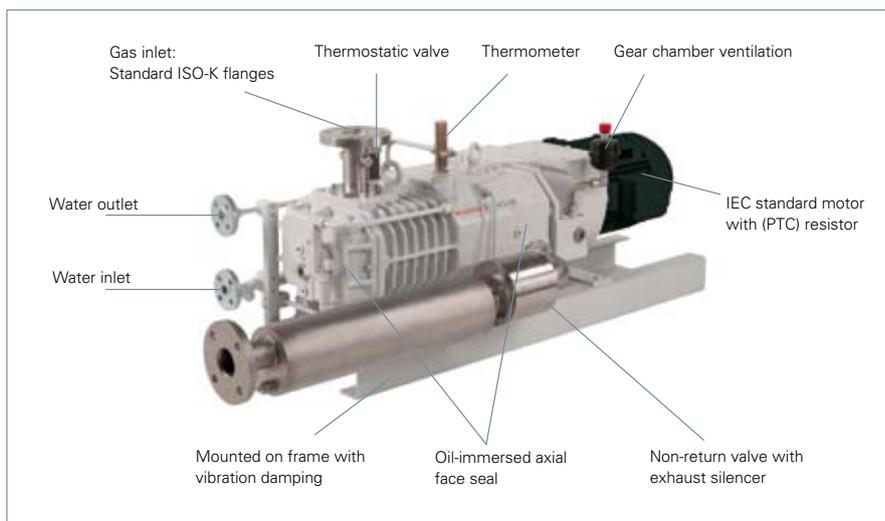


Figure 2.11: HeptaDry™ with connections and accessories

Table 2.10: HeptaDry™ series connections

Model	Intake Connection DN	Exhaust connection DN	Water DN
Hepta 100	63 ISO-K	40 PN 16	15 PN 10
Hepta 200	63 ISO-K	50 PN 16	15 PN 10
Hepta 300	63 ISO-K	50 PN 16	15 PN 10
Hepta 400	100 ISO-K	80 PN 16	15 PN 10
Hepta 600	100 ISO-K	80 PN 16	15 PN 10

Table 2.11: HeptaDry™ performance data

Model	Pumping Speed / (m ³ / h)	Ultimate Pressure / mbar	Motor rating / kW
Hepta 100, 50 Hz	110	< 0.05	3.0
Hepta 100, 60 Hz	130	< 0.01	4.0
Hepta 200, 50 Hz	220	< 0.05	5.5
Hepta 200, 60 Hz	265	< 0.01	7.5
Hepta 300, 50 Hz	320	< 0.05	7.5
Hepta 300, 60 Hz	410	< 0.01	9.2
Hepta 400, 50 Hz	350	< 0.05	7.5
Hepta 400, 60 Hz	420	< 0.01	9.2
Hepta 600, 50 Hz	525	< 0.05	11.0
Hepta 600, 60 Hz	630	< 0.01	15.0

The HeptaDry line is rounded out by the UniDry 50. The UniDry 50 is available either as an S version or a P version with a variety of accessories. It, too, is a dry pump with a pumping speed of 50 m³/h.

Please note the following in connection with pumps that are supplied in the standard scope of delivery:

- ▶ They are not suitable for pumping toxic, flammable and/or explosive gases
- ▶ They are not suitable for corrosive gases
- ▶ No foreign matter
- ▶ No deposit-forming media
- ▶ Limited entrainment of fluid (surge fluid)
- ▶ Permissible inlet temperature between 70 and 200 °C as a function of inlet pressure
- ▶ Coolant limits must be observed: Temperature 10 – 25 °C, pressure 3 – 6 bar
- ▶ Not gas tight

2.6 Roots vacuum pumps

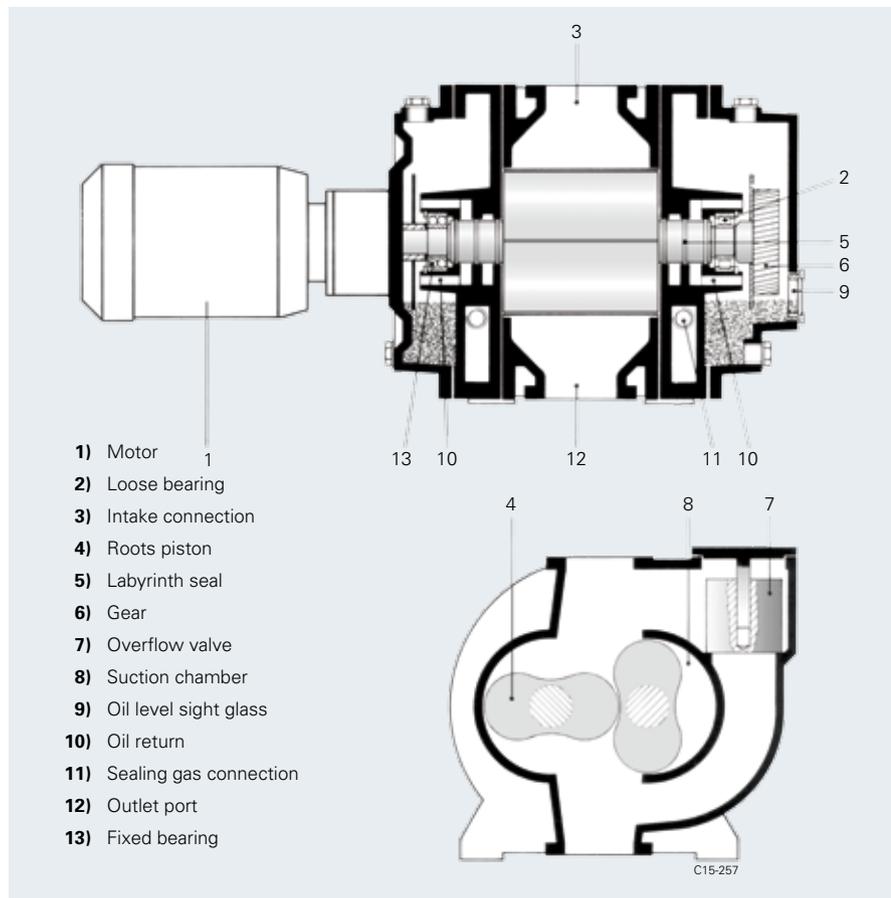


Figure 2.12: Operating principle of a Roots pump

2.6.1 Design / Operating principle

Roots vacuum pumps belong to the category of technically dry-running rotary displacement vacuum pumps. They are also termed Roots pumps or Roots blowers.

Operating principle

In a Roots pump, two synchronously counter-rotating rotors (4) rotate contactlessly in a single housing (Figure 2.12). The rotors have a figure-eight configuration and are separated from one another by a narrow gap. Their operating principle is analogous to that of a gear pump having one two-tooth gear each that pumps the gas from the inlet port (3) to the outlet port (12). One shaft is driven by a motor (1). The other shaft is synchronized by means of a pair of gears (6) in the gear chamber. Lubrication is limited to the two bearing and gear chambers, which are sealed off from the suction chamber (8) by labyrinth seals (5). Because there is no friction in the suction chamber, a Roots vacuum pump can be operated at high rotary speeds (1,500 - 3,000 rpm). The absence of reciprocating masses also affords trouble-free dynamic balancing, which means that Roots vacuum pumps operate extremely quietly in spite of their high speeds.

Design

The rotor shaft bearings are arranged in the two side pieces. They are designed as fixed bearings on one side and as sliding internal rings on the other in order to enable unequal thermal expansion between housing and piston. The bearings are lubricated with oil that is displaced to the bearings and gears by splash disks. The driveshaft feedthrough to the outside is sealed with radial shaft seal rings made of FPM that are immersed in sealing oil. To protect the shaft, the sealing rings run on a protective sleeve that can be replaced when worn. If a hermetic seal to the outside is required, the pump can also be driven by means of a permanent-magnet coupling with can. This design affords leakage rates Q_l of less than 10^{-5} mbar · l/s.

Pump properties, heat-up

Since Roots pumps do not have internal compression or an outlet valve, when the suction chamber is opened its gas volume surges back into the suction chamber and must then be re-discharged against the outlet pressure. As a result of this effect, particularly in the presence of a high pressure differential between inlet and outlet, a high level of energy dissipation is generated, which results in significant heat-up of the pump at low gas flows, which in and of itself transports low quantities of heat.

The rotating Roots pistons can only be provided with relatively weak cooling by comparison with the housing, as there are no contacting surfaces other than the front side. Consequently, they expand more than the housing. To prevent contact or seizing, the maximum possible pressure differential, and thus dissipated energy, is limited by an overflow valve (7). It is connected to the inlet side and the pressure side of the pump-through channels. A weight-loaded valve plate opens when the maximum pressure differential is exceeded and allows a greater or lesser portion of the intake gas to flow back from the pressure side to the inlet side, depending upon the volume of gas encountered. Due to the limited pressure differential, simple Roots pumps cannot discharge against atmosphere and require a backing pump. However Roots vacuum pumps with overflow valves can be switched on together with the backing pump, even at atmospheric pressure, thus increasing their pumping speed right from the beginning. This shortens evacuation times.

Backing pumps

Rotary vane pumps, rotary piston pumps or screw pumps can be used as backing pumps: These kinds of pump combinations can be employed for all applications in the low and medium vacuum ranges involving high pumping speeds. Liquid ring pumps can also be used as backing pumps.

Gas-cooled Roots pumps

To allow Roots vacuum pumps to work against atmospheric pressure, some models do not have overflow valves with gas cooling (Figure 2.13). In this case, the gas that flows from the outlet flange (6) is re-admitted into the middle of the suction chamber (4) through a cooler (7). This artificially generated gas flow cools the pump, enabling it to compress against atmospheric pressure. Gas entry is controlled by the Roots pistons, thus eliminating the need for any additional valves. There is no possibility of thermal overload, even when operating at ultimate pressure.

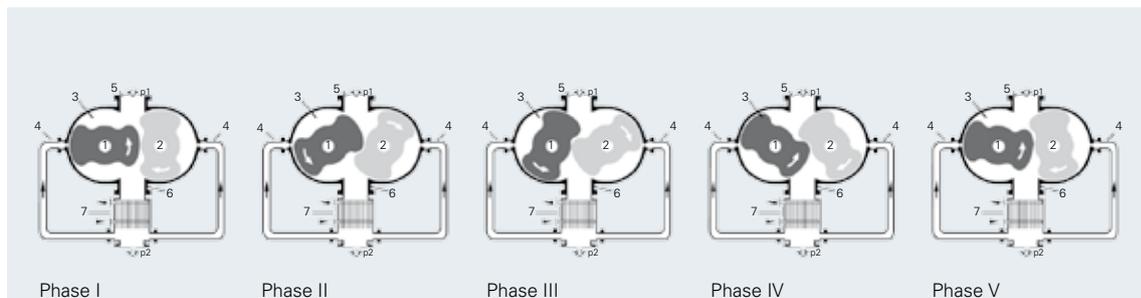


Figure 2.13: Operating principle of a gas-cooled Roots pump

Figure 2.13 shows a cross section of a Roots vacuum pump. The direction of gas flow is vertical from top to bottom, enabling the liquid or solid particles entrained in the inlet flow to flow off downward. In phase I, the chamber (3) is opened by the rotation of the pistons (1) and (2). Gas flows into the chamber through the inlet flange at pressure p_1 . In phase II, the chamber (3) is sealed off against both the inlet flange and the pressure flange. The inlet opening (4) for the cooling gas is opened by the rotation of the pistons. In Phase III, the chamber (3) is filled at the outlet pressure p_2 , and the gas is advanced toward the pressure flange. Initially, the suction volume does not change with the rotary movement of the Roots pistons. The gas is compressed by the inflowing cooling gas. The Roots piston now continues to rotate (phase IV), and this movement pushes the now compressed gas over the cooler (7) to the discharge side (Phase V) at pressure p_2 .

Gas-cooled Roots pumps can be used in the inlet pressure range of 130 to 1,013 mbar. Because there is no lubricant in the suction chamber, they do not discharge any mist or contaminate the medium that is being pumped. Connecting two of these pumps in series enables the ultimate pressure to be reduced to 20 to 30 mbar. In combination with additional Roots vacuum pumps, the ultimate pressure can be reduced to the medium vacuum range.

Pumping speed and compression ratio

The characteristic performance data of Roots pumps are: The pumping speed $S_m = S_o$, which is the volume flow rate the pump displaces without counter-pressure, and the (no-load) compression ratio $K_m = K_o$ without gas displacement, which is a function of the exhaust pressure p_2 . Pumping speeds range from 200 m³/h to several thousand m³/h. Typical K_o values are between 10 and 75.

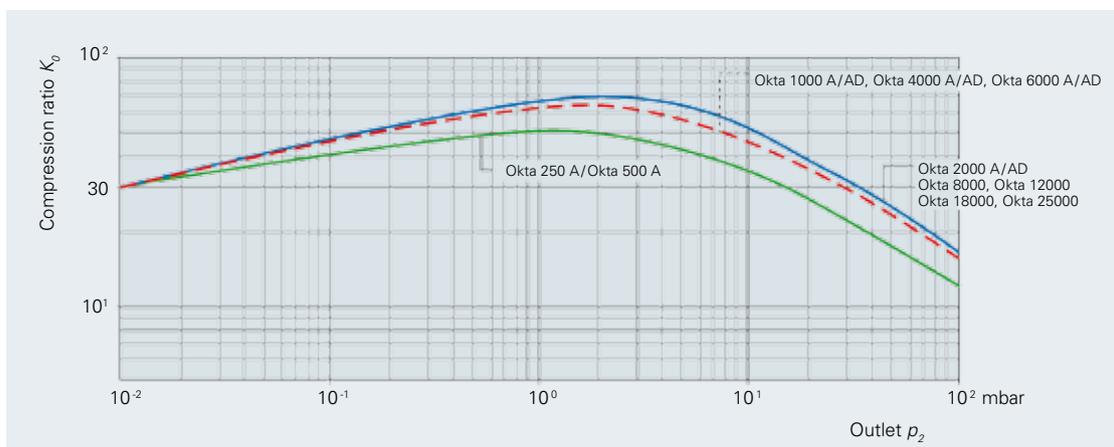


Figure 2.14: No-load compression ratio for air with Roots pumps

The compression ratio is negatively impacted by two effects:

- ▶ By the backflow into the gaps between piston and housing
- ▶ By the gas that is deposited on the surfaces of the piston on the outlet side and is re-desorbed after rotating toward the suction side

In the case of outlet pressures of 10⁻² to 1 mbar, molecular flow prevails in the seal gaps, which results in less backflow due to their lower conductivities. However the volume of gas that is pumped back through adsorption, which is relatively high by comparison with the pumped gas volume, reduces the compression ratio.

K_o is highest in the 1 to 10 mbar range, since molecular flow still prevails due to the low inlet pressure in the pump's sealing gaps, and backflow is therefore low. Because gas transport through adsorption is a function of pressure, it is less important than the pressure-proportional gas flow that is transported by the volume flow.

At pressures in excess of 10 mbar, laminar flow occurs in the gaps and the conductivities of the gaps increase significantly, which results in declining compression ratios. This effect is particularly noticeable in gas-cooled Roots pumps that achieve a compression ratio of only approximately $K_o = 10$.

The gap widths naturally have a major influence on the compression ratio. However to avoid piston scraping they should not be smaller than certain minimum values due to the thermal expansion of the pistons and the housing.

2.6.2 Calculations

Power requirements of a Roots vacuum pump

A Roots vacuum pump is a pure positive-displacement pump without internal pre-compression. Consequently, its power input P , as well as the pressure differential Δp between inlet side connection and pressure side connection S_p , are proportional.

Formula 2-8

Roots pump power input

$$P = \frac{S_0 \cdot \Delta p}{\eta_{mech}}$$

S_0 = pumping speed of a Roots vacuum pump without counter-pressure, in m^3/s

Δp = pressure differential between inlet-side connection and pressure-side connection, in Pa

η_{mech} = mechanical efficiency of the pump (approximately 0.85 for Roots vacuum pumps)

P = power requirement or motor rating, in W

Although the mechanical losses are low, it is advisable to use contactors in the control cabinet for heavy-duty start-up. After power-up, the power requirement in the medium vacuum range is low.

All further calculations relating to the pumping speeds of pumping stations and pump-down times are provided in Chapter 7: Configuration.

2.6.3 Application notes

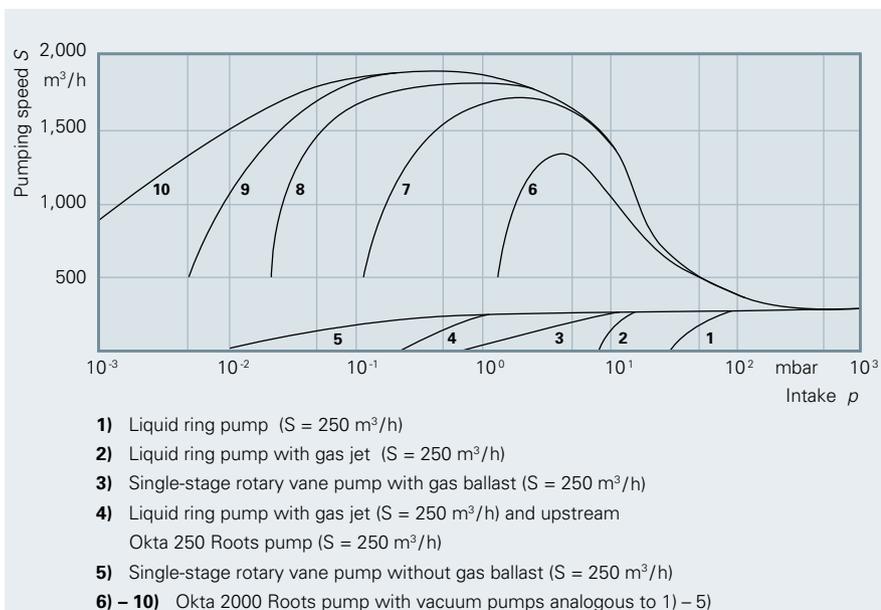


Figure 2.15: Pumping speeds of pumping stations with Okta 2000 and various backing pumps

Due to their low compression ratios, Roots pumps must always be operated as pump combinations for vacuum generation. Their achievable final pressures will be a function of the ultimate pressures of the selected backing pumps. Due to gas transport through adsorption, it is no longer practical to use Roots pumps in the range below 10^{-4} mbar. The behavior of the pumping speed and ultimate pressure of pumping stations with various backing pumps is shown in Figure 2.15. The curves clearly show that the pumping speed of this kind of pump combination rises by a factor of 8 and its ultimate pressure reduces by a factor of 15 relative to the backing pump.

2.6.3.1 Backing pump selection

Rotary vane pumps

If there will be no negative impact on function due to the process, a rotary vane vacuum pump is the most cost-effective backing pump for a Roots vacuum pumping station. Rotary vane vacuum pumps have ultimate pressures of around $p < 1$ mbar over a broad pressure range at constant pumping speed. A Roots vacuum pumping station achieves ultimate pressures of approximately 10^{-2} mbar with the gas ballast valve open.

Water vapor can be extracted with these kinds of pumping stations, as well as many solvent vapors and other vapors that have sufficiently high vapor pressures and do not chemically decompose the pump oil (alcohols, halogenated hydrocarbons, light normal paraffins, etc.).

Liquid ring vacuum pumps

Liquid ring vacuum pumps are a suitable solution for extracting vapors that chemically attack and decompose the backing pump oil or that have such low pressure that condensation in the backing pump cannot be avoided, in spite of gas ballast. However they will only achieve an ultimate pressure that is determined by the vapor pressure of the operating fluid. If 15 °C water is used, an ultimate pressure of approximately 20 mbar can be expected at the liquid ring vacuum pump, and it is then already working in the cavitation area.

A cavitation-free liquid ring vacuum pump working through the addition of air achieves an ultimate pressure of approximately 25 to 30 mbar, and a combination of Roots pump and liquid ring pump reaches approximately 1 mbar. A liquid ring pump should not be used with fresh water when evacuating environmentally harmful substances. In this case, a closed circulation system must be provided to advance a suitable operating fluid over a cooled heat exchanger in order to extract the heat of compression.

Liquid ring vacuum pump with gas jet device

The combination of Roots vacuum pump, gas jet device and liquid ring vacuum pump achieves an ultimate pressure of 0.2 mbar. If lower pressures need to be achieved, an additional Roots vacuum pump must be connected upstream.

Gas-cooled Roots vacuum pumps

Since Roots vacuum pumps are technically dry pumps, their employment is advisable when pumps with liquid-tight suction chambers cannot be used.

Their applications include:

- ▶ Extracting and compressing helium on cryostats
- ▶ Extracting and compressing SF₆
- ▶ Clean recovery of a wide variety of gases and vapors in a wide variety of processes, e.g. distillation
- ▶ Evacuating molecular sieves, etc.
- ▶ Pumping down and displacing toxic substances in closed circulation systems
- ▶ Evacuating extremely large-volume vessels

Roots pumping stations with gas-cooled Roots pumps can be configured with a wide variety of inlet characteristics. In extreme cases, it is possible to achieve a virtually constant pumping speed throughout the entire pressure range of 1 bar to 10⁻³ mbar, and the individual pump stages can be selected in the ratio of 2:01 to 3:01.

To do this, however, the Roots vacuum pumps must be equipped with correspondingly powerful motors, and outlet valves to the atmosphere must be provided instead of overflow valves.

Screw pumps

With the HeptaDry screw pumps, a complete line of technically dry pumps is available that offer pumping speeds of 100 to 600 m³/h. As stand-alone pumps (see also Figure 2.10), they cover an extensive pressure range in the low and medium vacuum segments. Due to their internal compression, they can work continuously with relatively low drive power throughout the entire inlet range of 0.1 to 1,000 mbar. In combination with OktaLine Roots pumps, it is even possible to achieve ultimate pressures of 5 · 10⁻³ mbar.

2.6.4 Portfolio overview

Roots pumps are offered in four versions:

- ▶ Standard pumps with shaft seal rings and cast iron housing (A series)
- ▶ Hermetically sealed standard pumps with magnetic coupling and cast-iron housing (AM series)
- ▶ Roots pumps for potentially explosive environments (ADx series)
- ▶ Roots pumps for potentially explosive environments and for displacement of explosive gases (ATEx series)

Table 2.12: OktaLine™ performance data

Model	Pumping Speed S ₀	Maximum Differential Pressure	Maximum Compression Ratio K ₀	Applications
Okta 250	270 m ³ /h	75	50	Suitable for industrial/chemical applications: E.g. oil regeneration, transformer drying, steel degassing, freeze-drying, leak detection systems, metallurgy, packaging industry, electron beam welding
Okta 500	490 m ³ /h	75 (ADEx: 53)	50	
Okta 1000	1,070 m ³ /h	45 (ADEx: 30)	63	
Okta 2000	2,065 m ³ /h	35 (ADEx: 20)	70	Suitable for large-area coating: E.g. photovoltaics, wear protection, glass coating
Okta 4000	4,050 m ³ /h	25 (ADEx: 20)	63	
Okta 6000	6,075 m ³ /h	20	63	Suitable for research & development: E.g. accelerators, simulation chambers
Okta 8000	8,000 m ³ /h	27	70	
Okta 18000	17,850 m ³ /h	10	70	

2.6.4.1 Standard pumps

The performance data of the standard pumps (A series) are shown in Table 2.12. These performance data also apply to all other series. The maximum differential pressures are a function of the overflow valves. In the ADEx series, these maximum differential pressures are smaller than for the other series in order to satisfy the temperature requirements specified by the ADEx guidelines and are shown in parentheses in the table. The housings for these pumps are manufactured of cast iron and are tested at 1 bar overpressure. The seal to the atmosphere consists of radial shaft seal rings. The standard pumps are characterized by their robust, compact design as well as by their high compression ratios, which result in high pumping speeds for the pump combination, even with small backing pumps, and thus afford short pump-down times. The vertical direction of flow renders this pump largely insensitive to dusts and liquids.

2.6.4.2 Standard pumps with magnetic coupling

The AM series can be used for processes that place the most rigorous requirements on sealing and require the longest service intervals. For the most part, this series is identical to the A series, however it is additionally characterized by a hermetically sealed magnetic coupling instead of radial shaft seal rings. This means that it is virtually wear-free in operation. The integral leakage rate of the pump is $Q_l < 1 \cdot 10^{-6}$ mbar l/s.

This precludes the possibility of oil leaks, nor is there any exchange between process gas and the environment. AM series standard pumps are suitable for all applications shown in Table 2.12. In addition, however, these pumps can also be employed in industrial / chemical applications for pumping toxic gases, as well as for superclean gas applications: e.g. for CVD and PVD processes in the semiconductor industry or for evacuating load locks / transfer chambers and for the production of flat screens. The AM series is available in sizes that range from 250 m³/h to 6,000 m³/h.

2.6.4.3 Explosion-protected pumps

The ADx and ADEx series are available for processes in potentially explosive environments, or for evacuating explosive gases..

PTFE-sealed ADx series pumps with pumping speeds from 500 to 4,000 m³/h are made of nodular graphite cast iron 40.3 and are supplied either with or without ATEX motor. Although they are not suitable for pumping explosive gases, they can be operated in potentially explosive environments. They satisfy the explosion protection requirements specified in Directive 94/9/EG –(ii)/II 3G II BT3 (o).

ADEx series pumps are identical to the ADx series pumps. They are equipped with an ATEX coupling, an integrated ATEX temperature sensor and can be supplied either with or without ATEX motor (EEx de IIC T4). From 800 mbar onward, they can be switched on without bypass line, which eliminates valves. They satisfy the explosion protection requirements specified in Directive 94/9/EG (II 2G IIB T3 (i) (o)).

Generally speaking, additional measures and/or components are required for safe pump operation, such as start-up and shut-down procedures, special backing pumps, flashback arrestors and pressure sensors. The entire plant must naturally be designed and operated in accordance with the respective explosion-protection regulations. Both series of pumps are available in pumping speeds that range from 500 to 4,000 m³/h.

Gas-cooled Roots pumps

Upon request, the gas-cooled Roots pumps described in Section 2.6.1 can also be supplied in sizes ranging from 500 m³/h (18.5 kW drive power) to 12,000 m³ (200 kW drive power).

2.6.4.4 Pumping stations

Pfeiffer Vacuum offers its CombiLine standard pumping stations with single- and two-stage backing pumps:

Roots pumping stations WU ... with single-stage HenaLine/UnoLine Plus rotary vane pumps with an ultimate pressure of $p < 5 \cdot 10^{-2}$ mbar. They are cost-effective and suitable for the following applications:

- ▶ Evacuating load lock chambers (e.g. electron beam welding, coating)
- ▶ Helium leak detection
- ▶ Vacuum drying and degassing, metallurgy, (e.g. hardening, sintering, soldering, casting, smelting)

Roots pumping stations WD ... with two-stage DuoLine rotary vane pumps with an ultimate pressure of $p < 5 \cdot 10^{-4}$ mbar for the following applications:

- ▶ Backing pump station for high vacuum pumps
- ▶ Coating (e.g. wear protection, decorative coatings, thermal protection coatings, optical coatings)
- ▶ Metallurgy (e.g. hardening, sintering, soldering, casting, smelting, degassing)

Roots pumping stations WH ... with UniDry 50 or HeptaDry dry screw pumps with an ultimate pressure of $p < 1 \cdot 10^{-2}$ mbar for the following applications:

- ▶ Coating (solar industry, metalizing, surface treatment)
- ▶ Degassing steel and plastics
- ▶ Vacuum drying, workpiece cleaning
- ▶ Leak test systems
- ▶ Freeze drying

2.6.5 Accessories

Splinter shield inserts are offered as accessories for all OktaLine series Roots pumps.

The following oils for lubricating the gearing and the bearings are available as lubricants (Table 2.7):

- ▶ Mineral oil P3 (in 0.5 l to 200 l containers)
- ▶ Perflourpolyether F5 (in 0.5 l to 50 l containers)
- ▶ Diester oil D1 (in 0.5 l to 200 l containers)

Caution: Different kinds of oil should not be mixed. The pumps are prepared for one of these types of oil at delivery.

Since many Roots pumps are installed in pump combinations, it is possible to integrate the following accessories on an as-needed basis:

- ▶ Electrical controllers
- ▶ Measuring instrumentation for temperature and pressure
- ▶ Pressure regulation means
- ▶ Heat exchangers and condensers

- ▶ Soundproofing encapsulation for indoor and outdoor installation
- ▶ Silencers
- ▶ Dust separators
- ▶ Flushing devices
- ▶ Vibration isolation
- ▶ Liquid separators
- ▶ Gear chamber extraction
- ▶ Sealing gas supply

Measurement connections

In the case of many Roots pumps, it is possible to use the measurement connections on the inlet and pressure sides of the pump. To do this, the existing locking screws can be replaced with small ISO-KF flange unions. This enables connection of appropriate temperature sensors and pressure sensors for monitoring the pump.

Sealing gas connection

When pumping solvents or reactive gases, the risk exists that the lubricant will be significantly diluted as a result of condensation. Reactive gases or vapors can also attack parts of the gear chamber. For the most part, this risk can be avoided by admitting a sealing gas in the area of the shaft feedthrough between working space and gear chamber. Inert gases, mostly nitrogen (N₂), are used as the sealing gas.

Gear chamber extraction

In the case of all processes in which large Roots vacuum pumping stations must reach certain pressures in short cycle times (fast evacuation), it is practical to pump down the gear chambers of a Roots pump via an oil separator, by means of a separate vacuum pump in each case. This prevents gas from flowing out of the gear chamber and into the suction chamber, thus enabling the desired working pressure to be reached faster. The desired working pressure will determine whether it is possible to connect the gear chamber toward the backing-vacuum side of the Roots pump.

Flushing devices

A flushing device can be used for processes in which deposits form in the suction chambers. The design of this device will be coordinated individually with the customer on the basis of the specific requirements. The flushing device for standard pumps requires the use of sealing gas to prevent the flushing liquid from reaching the bearings or gear chambers.

Surface protection

If the media to be pumped down are corrosive, components that come into contact with the product can be provided with durable surface protection. The plasma-polymer thin-layer system consists of a bonding agent layer, a corrosion-protection layer and a non-stick coating. The thickness of the layer is less than 1 µm. Upon request, the pump chamber can be phosphated, vented with nitrogen and vacuum sealed in order to provide short-term surface protection, e.g. for warehousing and shipment.

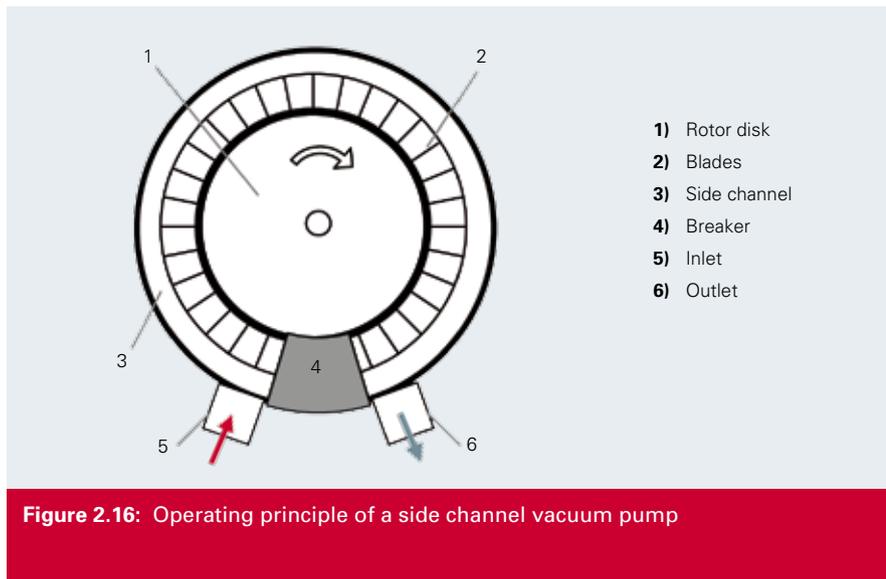
Seals

Roots vacuum pumps come factory-equipped with O-rings made of FPM. For special applications, all pumps can be equipped with the specific O-rings or seals that are required for the respective application.

2.7 Side channel high vacuum pumps

2.7.1 Design / Operating principle

The side channel high vacuum pump is a vacuum pump that works from atmosphere to the high vacuum range. The pump uses two operating principles to do this. In the upper pressure range (laminar flow range), the pump primarily works in accordance with the principle of a side channel vacuum pump, while working as a Holweck vacuum pump in the lower pressure range.



The pumping system in a side channel vacuum pump (Figure 2.16) consists of a rotor disk (1) having blades (2) that are arranged on the outer perimeter and a ring-shaped working chamber, the side channel (3). The side channel is narrowed to the disk profile at one point by a breaker (4).

The pumping effect occurs through a helical flow from the inlet to the outlet that is produced by the blades of the rotating rotor. This results in a pressure differential between inlet (5) and outlet (6). Lower ultimate pressures can be attained by connecting multiple pumping stages in series. At pressures of between 1 and 20 mbar, the pump leaves the laminar flow range, and a Holweck stage (Figure 2.21) takes over displacement of the gas. To adapt to the pressure of the side channel pump stages, which is still quite high, the Holweck channels are small on the vacuum side and the gap is narrow. Larger channel cross sections are used toward the suction side in order to increase the pumping speed.

2.7.2 Application notes

This kind of pump is particularly well suited for generating clean high vacuum. It works completely dry, as it only has one oil-lubricated bearing on the atmosphere side. It is ideally suited for fast evacuation of load locks or transfer chambers, since no backing pumps or bypass lines are required. The pump can be used either as a stand-alone pump or as a backing pump for turbopumps. Corrosive gases, condensates and particulate matter cannot be pumped due to the narrow gaps.

2.7.3 Portfolio overview

Pfeiffer Vacuum offers a dry side channel high vacuum pump in the form of the OnTool Booster 150:

Table 2.13: OnTool™ Booster performance data

Model	Pumping Speed in m ³ /h	Base Pressure in mbar	Compression Ratio	Applications
OnTool™ Booster 150	130	1 · 10 ⁻⁵	10 ⁸	Load locks, backing pumps for turbopumps

2.8 Turbomolecular pumps

2.8.1 Design / Operating principle

The turbomolecular pump was developed and patented at Pfeiffer Vacuum in 1957 by Dr. W. Becker. Turbomolecular pumps belong to the category of kinetic vacuum pumps. Their design is similar to that of a turbine. A multi-stage, turbine-like rotor with bladed disks rotates in a housing. Interposed invertedly between the rotor disks are bladed stator disks having similar geometries.

Bearings

Mounting the rotors by means of two ball bearings would be problematic, since the lubricants require that both bearings be arranged on the backing-vacuum side, and the rotor, with its high mass, can only be supported by bearings on one side (floating).

Hybrid bearing support offers advantages in this regard with respect to rotor dynamics. In this case, an oil-lubricated ball bearing sits on the end of the shaft on the backing-vacuum side, and the high vacuum side is equipped with a maintenance- and wear-free permanent magnetic bearing that centers the rotor radially. A small dry safety bearing is arranged within the magnetic bearing stator. During normal operation, a journal rotates freely within this bearing. In the event of strong radial shocks, it stabilizes the rotor and rotates only briefly. If the rotor is out of balance, the bearings on both ends of the shaft will generate significantly lower bearing-stressing vibration forces than in the case of a floating bearing. Moreover, this enables the larger of the two bearings on the drive shaft, whose size allows only limited rotor speeds, to be eliminated.

So-called 5-axis magnetic bearings are used in large pumps. The rotor is levitated axially through digital electronic control via distance sensors and electromagnets, and in two radial directions each at both shaft ends. Electronic balance compensation and the absence of mechanical contact between rotor and housing keep the vibration generated by the pump low. In addition to the absence of oil on the backing-vacuum side, as well, freedom from wear and maintenance is another advantage. In the event of a power failure, the magnetic bearings are supplied with electricity through the rotational energy of the pump.

This enables power failures to be easily bridged for several minutes. Should the power failure be of longer duration, the rotor will safely come to a stop at only very low speed through the use of an integrated safety bearing. If the electronics are defective or if there is significant ingress of air, the rotor will be braked without damage with the aid of safety bearings.

Motors / Drives

Brushless DC motors that afford rotational frequencies of up to 1,500 Hz (90,000 rpm) are used to drive the rotors. This enables the blade velocities that are necessary for pumping the gases to be achieved.

Today, the drives are typically attached directly to the pumps. Power that is generated by external power supply units is supplied at 24 VDC or 48 VDC. In the case of large pumps, the drives are supplied directly from the rectified mains voltage.

2.8.1.1 Turbomolecular pump operating principle

The pumping effect of an arrangement consisting of rotor and stator blades is based upon the transfer of impulses from the rapidly rotating blades to the gas molecules being pumped. Molecules that collide with the blades are adsorbed there and leave the blades again after a certain length of time. In this process, blade speed is added to the thermal molecular speed. To ensure that the speed component that is transferred by the blades is not lost due to collisions with other molecules, molecular flow must prevail in the pump, i.e. the mean free path length must be greater than the blade spacing.

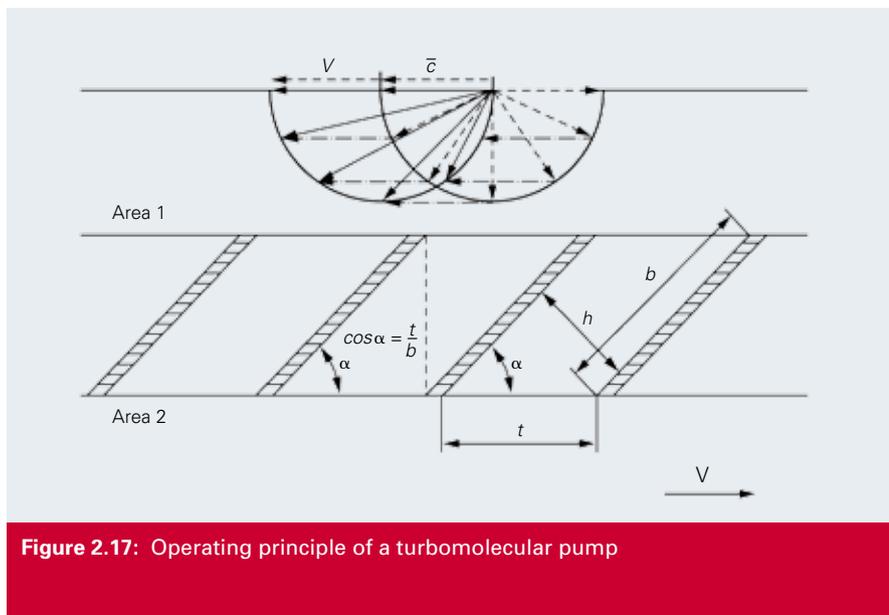


Figure 2.17: Operating principle of a turbomolecular pump

Source: Jousten (publisher) Wutz, Handbuch Vakuumentchnik, Vieweg Verlag

In the case of kinetic pumps, a counter-pressure occurs when pumping gas; this causes a backflow. The pumping speed is denoted by S_0 . The volume flow rate decreases as pressure increases and reaches a value of 0 at the maximum compression ratio K_0 .

Compression ratio

The compression ratio, which is denoted K_0 , can be estimated according to Gaede's considerations [9]. The following applies for visually dense blade structure (Figure 2.17).

Formula 2-9
Turbopump K_0

$$K_0 = \exp\left(\frac{v}{\bar{c} \cdot g \cdot t \cdot \sin\alpha}\right)$$

The geometric ratios are taken from Figure 2.17. The factor g is between 1 and 3 [10]. From the equation, it is evident that K_0 increases exponentially with blade velocity v as well as with \sqrt{M} because

$$\bar{c} = \sqrt{\frac{8 \cdot R \cdot T}{\pi \cdot M}} \quad (\text{Formula 1-7}).$$

Consequently, the compression ratio for nitrogen, for example, is significantly higher than for hydrogen.

Pumping speed

Pumping speed S_0 is proportional to the inlet area A and the mean circumferential velocity of the blades v , i.e. rotational speed [9]. Taking the blade angle α into account produces:

Formula 2-10
Turbopump
pumping speed

$$S_0 = \frac{1}{2} \cdot A \cdot v \cdot \sin\alpha \cdot \cos\alpha$$

Taking the entry conductivity of the flange into account, $L_{Bm} = \frac{\bar{c}}{4} \cdot A$ (Formula 1-19) as well as the optimal blade angle of 45° , produces the approximate effective pumping speed S_{eff} of a turbopump for heavy gases (molecular weight > 20) in accordance with the following formula:

Formula 2-11
Turbopump S_{eff}

$$S_{eff} = \frac{S_0 + L_{Bm}}{S_0 \cdot L_{Bm}} = \frac{A \cdot v}{4 \cdot \left(\frac{v}{\bar{c}} + 1\right)}$$

Dividing the effective pumping speed by the bladed entry surface of the uppermost disk and taking the area blocked by the blade thickness into consideration with factor $d_f \sim 0.9$ provides the specific pumping speed of a turbopump for nitrogen, for example (curve in Figure 2.18):

Formula 2-12
Specific pumping speed

$$S_A = \frac{S_{eff}}{A} = \frac{d_f \cdot v}{4 \cdot \left(\frac{v}{\bar{c}} + 1\right)}$$

In Figure 2.18, the specific pumping speed $d_f = 1$ in $l/(s \cdot \text{cm}^2)$ is plotted on the ordinate and the mean blade speed on the abscissa $v = \pi \cdot f \cdot (R_a + R_i)$. Moving up vertically from this point, the point of intersection with the curve shows the pump's maximum specific pumping speed S_A . Multiplying this value by the bladed surface area of the inlet disk: $A = (R_a^2 - R_i^2) \cdot \pi$, yields the pumping speed of the pumps and enables it to be compared with the catalog information.

The points plotted in Figure 2.18 are determined by Pfeiffer Vacuum on the basis of the measured values of the indicated pumps. Points that are far above the curve are not realistic.

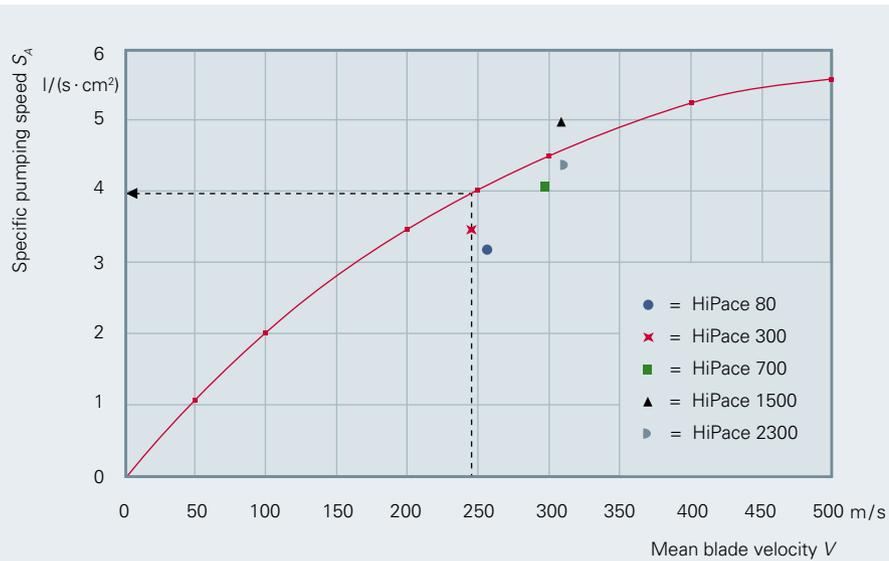


Figure 2.18: Specific turbopump pumping speeds

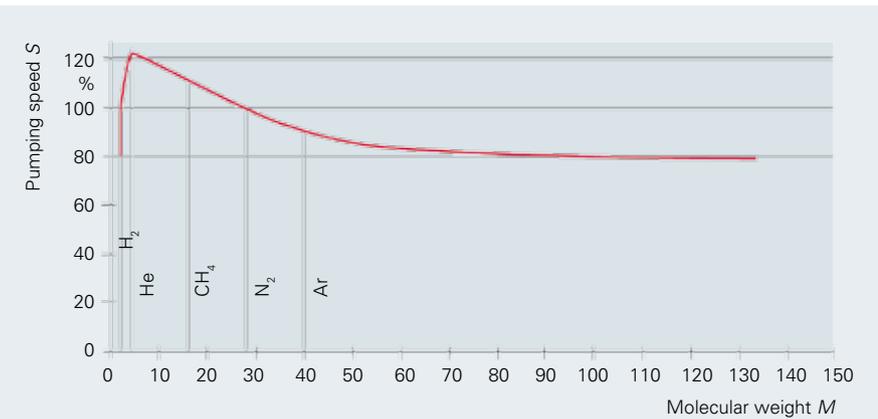


Figure 2.19: Pumping speed as a function of molecular weight

The pumping speeds (l/s) thus determined still tell nothing about the values for light gases, e.g. for hydrogen. Pump stages having differing blade angles are normally used in a turbopump to optimize the maximum pumping speed for hydrogen. This produces pumps with sufficient compression ratios for both hydrogen (approximately 1,000) and nitrogen, which should be 10^9 due to the high partial pressure in the air. In the case of pure turbomolecular pumps, backing-vacuum pressures of approximately 10^{-2} mbar are required due to their molecular flow.

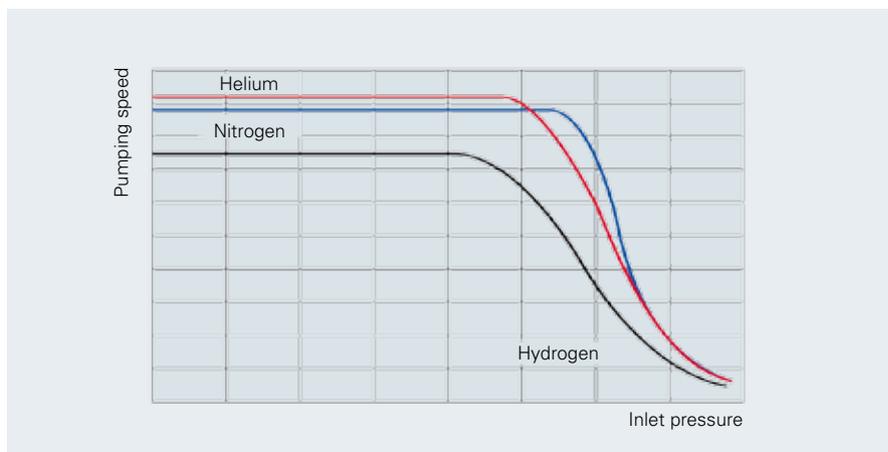


Figure 2.20: Pumping speed as a function of inlet pressure

2.8.1.2 Holweck stage operating principle

A Holweck stage is a multi-stage Gaede's type molecular pump [10] having a helical pump channel. Due to the rotation of the rotor, gas molecules entering the pump channel receive a stimulus velocity in the direction of the channel. Backflow losses occur through gaps between the webs that separate the Holweck channels from one another and the rotor. The gap widths must be kept small to minimize backflow. Cylindrical sleeves (1) that rotate about helical channels in the stator (2) are used as Holweck stages. Arranging stators both outside as well as inside the rotor enables two Holweck stages to be easily integrated within one and the same pump.

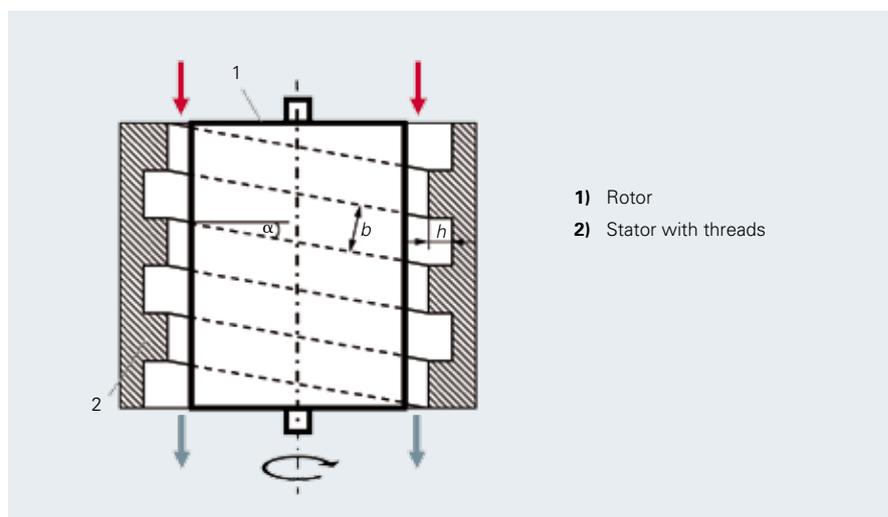


Figure 2.21: Operating principle of a Holweck stage

The pumping speed S_0 of the Holweck stages is equal to:

Formula 2-13
Holweck stage
pumping speed

$$S_0 = \frac{1}{2} \cdot b \cdot h \cdot v \cdot \cos\alpha$$

Where $b \cdot h$ is the channel cross section and $v \cdot \cos\alpha$ the velocity component in the channel direction.

The compression ratio increases exponentially as a function of channel length L and velocity $v \cdot \cos\alpha$ [4]:

Formula 2-14
Holweck stage
compression ratio

$$K_0 = \frac{v \cdot \cos\alpha \cdot L}{\bar{c} \cdot g \cdot h} \text{ mit } 1 < g < 3$$

The values yielded by this formula are much too large, because backflow over the web from the neighboring channel dramatically reduces the compression ratio, and this influence is not taken into account in Formula 2-14.

In order to use small dry backing pumps, e.g. diaphragm pumps having ultimate pressures of less than 5 mbar, turbopumps are today equipped with Holweck stages. These kinds of pumps are termed turbo drag pumps. Since the Holweck stages require only low pumping speeds due to the high pre-compression of the turbopump, the displacement channels and, in particular, both the channel height as well as the clearances to the rotors can be kept extremely small, thus still providing a molecular flow in the range of 1 mbar. At the same time, this increases the compression ratios for nitrogen by the required factor of 10^3 . The shift of the compression ratio curves to higher pressure by approximately two powers of ten can be seen from Figure 2.22.

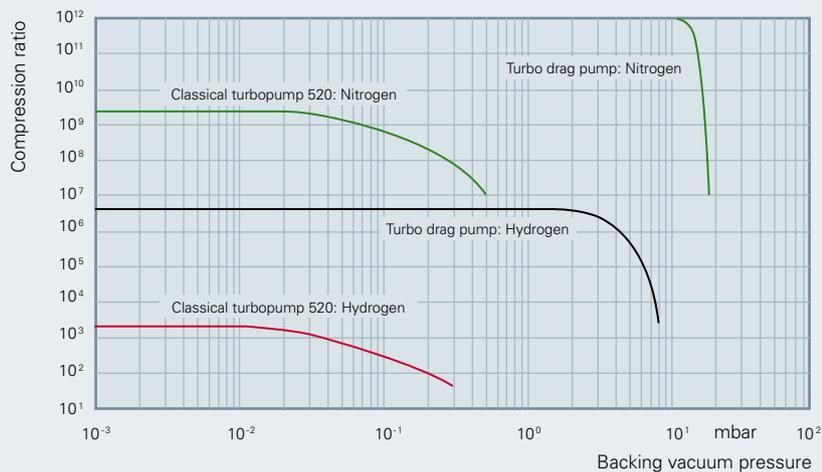


Figure 2.22: Compression ratios of pure turbopumps and turbo drag pumps

2.8.1.3 Turbopump performance data

Gas loads

The gas loads $q_{pV} = S \cdot p = \frac{dV}{dt} \cdot p$ (Formula 1-13), that can be displaced with a turbomolecular pump increase proportionally to pressure in the range of constant volume flow rate, and in the declining range reach a maximum that also is a function of the size of the backing pump. The maximum permissible gas loads depend upon the type of cooling and gas in question.

Displacing heavy noble gases is problematic, because they generate a great deal of dissipated energy when they strike the rotor; and due to their low specific heat, only little of it can be dissipated to the housing. Measuring the rotor temperature and reducing the RPM enables the pump to be operated in the safe range. The technical data for the turbopumps specify the maximum permissible gas loads at nominal RPMs for hydrogen, helium, nitrogen and argon.

Critical backing pressure

Critical backing pressure is taken to mean the maximum pressure on the backing-vacuum side of the turbomolecular pump at which the pump's compression decreases. This value is determined as part of the measurements for determining the compression ratio in accordance with ISO 21360-1 by increasing the backing-vacuum pressure without gas inlet on the intake side. In the technical data for turbomolecular pumps, the maximum critical backing pressure is always specified for nitrogen.

Base pressure, ultimate pressure, residual gas

In the case of vacuum pumps, a distinction is made between ultimate pressure and base pressure (see also 2.1.3). While the pump must reach base pressure p_b within the prescribed time under the conditions specified in the measurement guidelines, ultimate pressure p_e can be significantly lower. In the HV range, base pressure is reached after 48 hours of bake-out under clean conditions and with a metallic seal. What is specified as the base pressure for pumps with aluminum housings is the pressure that is achieved without bake-out and with clean FPM seals. Corrosive gas-version pumps have a higher desorption rate, which can temporarily result in higher base pressures due to the coating on the rotor surface.

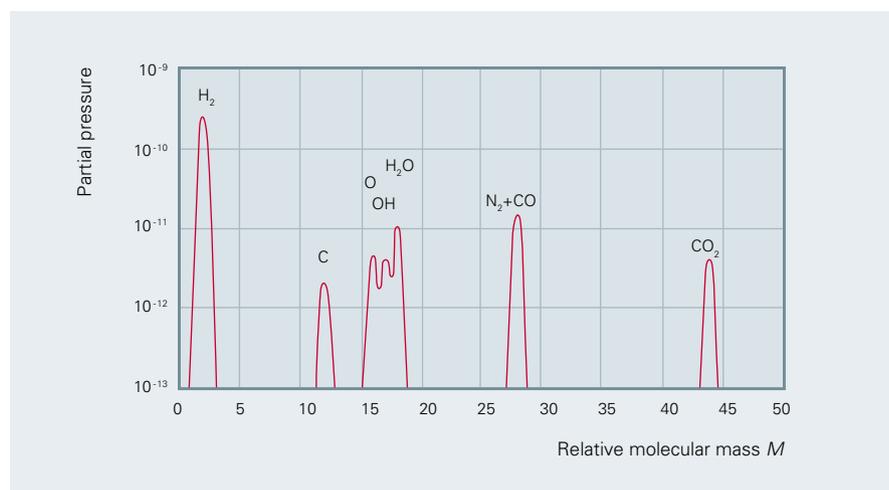


Figure 2.23: Typical residual gas spectrum of a turbomolecular pump

Dividing the backing pressure by the compression ratio yields the ultimate pressure.

Formula 2-15
Ultimate pressure

$$p_e = \frac{p_v}{K_0}$$

Whether ultimate pressure will be achieved will hinge upon the size and cleanliness of both the equipment and the pump, as well as upon the bake-out conditions. After extreme bake-out (to 300 °C) only H₂, CO and CO₂ will be found in the residual gas. These are gases that are dissolved in the metal of the recipient and continuously escape.

The gas ballast in the backing pump that is being used should be activated occasionally to prevent hydrogen from accumulating in the backing-vacuum area. In many cases, the actual ultimate pressure will be a factor of the desorption conditions on the high vacuum side of the turbopump and its pumping speed, and not the compression ratios of the pumps.

2.8.2 Application notes

Generating clean vacuum

Turbopumps are suitable for generating clean vacuums in the range of 10⁻³ to 10⁻¹⁰ mbar. Thanks to their high compression ratio, they reliably keep oil from the inlet area of rotary vane pumps away from the recipient. Models with stainless steel housings and CF flanges can be baked out. This makes these pumps ideally suited for research and development applications where contamination of the residual gas is undesirable. Turbopumps can be used for evacuating large vessels, with rotary vane pumps being employed as backing pumps. In the case of turbo drag pumps, even two-stage diaphragm pumps will suffice as backing pumps; however due to their lower pumping speed, it will take them a great deal of time to pump down larger vessels. The gas throughput of the combination will also be highly restricted by the diaphragm pump.

However this combination is an extremely cost-effective solution for a dry pumping station. It is often used in connection with differentially pumped mass spectrometers. Pumping stations consisting of a backing pump and a turbopump do not require valves. Both pumps are switched on at the same time. As soon as the backing pump has reached the necessary backing-vacuum, the turbopump quickly accelerates to its nominal speed and quickly evacuates the vessel to a pressure of $p < 10^{-4}$ mbar with its high pumping speed. Brief power failures can be bridged by the high rotational speed of the rotor. In the case of longer power failures, both the pump and the recipient can be vented automatically if the RPMs decline below a minimum speed.

The effects that play a role in evacuating vessels are described in Chapter 7. Dimensioning issues as well as calculation of pump-down times are also presented in that chapter.

Evacuating load lock chambers

Evacuating load-lock chambers definitely requires clean handling when transferring the workpieces to be treated in a vacuum process. If these items are channeled in from atmospheric pressure, the chamber should first be pre-evacuated via a bypass line. The running turbopump is then connected between the backing pump and the chamber via valves.

Analytical applications

In many cases, mass spectrometers are used in analysis devices today. Fluids are often injected and evaporated in the inlet chamber of the vacuum system. Pressure is reduced in several stages, and the individual chambers are isolated from one another by orifices. Since each chamber must be pumped, the objective is to combine the gas flows via taps on the turbopump through skillful combination of backing pumps and turbopumps. Specially modified turbopumps with taps are used for series applications.

Helium leak detectors, too, are equipped with turbopumps. In this case, the counter-flow principle is often used; i.e. a mass spectrometer is arranged on the high vacuum side of the pump. Due to the lower compression ratios of turbopumps for helium than for nitrogen or oxygen, the pump acts as a selective amplifier for the helium partial pressure.

Pumps with high gas loads in vacuum processes

The turbopump offers two advantages when pumping high gas loads for vacuum processes: It generates clean vacuum at the beginning of each process step, and can then pump down process gas without any harmful backflow. In the second step, the primary objective is to maintain the given pressure at which the desired vacuum process should run. In this process, gas throughputs and working pressure will be determined by the application in question; i.e. a given volume flow rate will be pumped at a given gas throughput. Moreover, it should be possible to quickly achieve clean intermediate vacuum when changing workpieces. Since these are conflicting requirements, a turbopump of sufficient size for the required gas throughput and the required intermediate vacuum will be selected. The process pressure will be regulated via an inlet (butterfly) valve. An example of how to dimension this kind of pumping station is shown in Chapter 7. The maximum permissible gas loads specified in the technical data should be taken to mean permissible continuous loads. This applies subject to the assurance of sufficient cooling in accordance with the specification and a backing pressure that is less than 50 % of the critical backing pressure.

Pumping corrosive and abrasive substances

When pumping corrosive gases, measures must be taken to protect the motor/bearing areas and the rotor, in particular, against corrosion. To do this, all surfaces that come into contact with corrosive gas are either provided with a coating or made from materials that can withstand attacks by these gases. A defined inert gas flow is admitted into the motor/bearing area in the backing-vacuum via a special sealing gas valve. From there, the gas flows through labyrinth seals to the backing-vacuum area, mixes with the corrosive gas and is pumped down together with the corrosive gas.

The blades can wear mechanically should dust accumulate; this could necessitate repairs and replacement of the rotor. It should also be noted that deposits can be expected to form in the pump, which will necessitate shorter service intervals. In particular, it is necessary to ensure that deposits in the pump do not react with the moisture in the air to become aggressive substances. Consequently, the pumps should be vented with dry inert gases only, and should be fitted with sealed backing-vacuum and high vacuum flanges. Turbopumps for these applications are always classical turbopumps without a Holweck stage, as the narrow gaps and pump channels in the Holweck stage would quickly clog with dust deposits and the rotor would seize.

2.8.3 Portfolio overview

Als führender Hersteller von Turbomolekularpumpen bietet Pfeiffer Vacuum mechanisch gelagerte und magnetisch gelagerte Baureihen an.

2.8.3.1 Mechanical-bearing turbopumps

In the case of HiPace turbopumps with oil-lubricated ball bearings on the backing-vacuum side and permanent magnet-bearings on the high vacuum side, a distinction is made between the following turbopump series:

- ▶ HiPace turbo drag pumps with Holweck stages offering pumping speeds of less than 1,000 l/s with ISO-K flanges to generate high vacuum for standard applications, or
- ▶ with bakeable CF flanges to generate ultra high vacuum
- ▶ Classical HiPace turbopumps offering pumping speeds of over 1,000 l/s with ISO-K flanges to generate high vacuum for standard applications, or with bakeable CF flanges to generate ultra high vacuum
- ▶ Classical HiPace C turbopumps with coating and sealing gas system for corrosive gas applications

Classical HiPace C turbopumps offering pumping speeds of less than 1,000 l/s but with coating and sealing gas system for corrosive gas applications are available upon request.



Figure 2.24: Standard HiPace™ turbopumps

The advantages and disadvantages of classical turbopumps and turbo drag pumps are shown in the table 2.14.

Table 2.14: Comparison between turbopumps and turbo drag pumps

Characteristic	Advantages	Disadvantages
Pure turbo stages	<ul style="list-style-type: none"> ▶ Insensitive to particulate matter, dust and condensates ▶ High gas loads possible ▶ Robust/High flood rates possible 	<ul style="list-style-type: none"> ▶ Lower compressions ▶ Lower backing vacuum tolerance ▶ Larger backing pump with base pressure < 0.1 mbar required
Turbo stages and drag stages (Holweck)	<ul style="list-style-type: none"> ▶ Higher compressions ▶ Higher backing vacuum tolerance ▶ Smaller backing pump with base pressure > 1 mbar can be used 	<ul style="list-style-type: none"> ▶ Sensitive to particulate matter, dust and condensates ▶ Lower gas loads (narrow gap)

2.8.3.2 Magnetic-levitation turbopumps

With their high pumping speeds of over 1,500 l/s, magnetic-levitation turbopumps require large backing pumps. Since diaphragm pumps with base pressures of over 1 mbar are out of the question, these turbopumps are not equipped with Holweck stages. These pumps, too, are available as:

- ▶ Classical HiPace turbopumps offering pumping speeds of over 2,000 l/s with ISO-K flanges to generate high vacuum for standard applications, or
- ▶ with bakeable CF flanges to generate ultra high vacuum
- ▶ Classical HiPace C turbopumps with coating and sealing gas system for corrosive gas applications



Figure 2.25: HiPace™ MC magnetic-levitation turbopump

Table 2.15 below contains the performance data for the standard pumps. All other series are modifications of these standard models and essentially offer the same performance data.

Table 2.15: HiPace™ performance data

Model	Pumping Speed for N ₂	Compression Ratio N ₂	Applications
HiPace™ 10	11.5 l/s	$3.0 \cdot 10^7$	Analytical applications, leak detectors, gas flow control systems, incandescent and fluorescent lamp manufacturing
HiPace™ 80 (DN 40)	35.0 l/s	$> 1.0 \cdot 10^{11}$	Analytical applications, research & development, coating, semiconductor manufacturing
HiPace™ 80 (DN 63)	67.0 l/s	$> 1.0 \cdot 10^{11}$	
HiPace™ 300	260.0 l/s	$> 1.0 \cdot 10^{11}$	
HiPace™ 400	355.0 l/s	$> 1.0 \cdot 10^{11}$	
HiPace™ 700	685.0 l/s	$> 1.0 \cdot 10^{11}$	
HiPace™ 1200	1,250.0 l/s	$> 1.0 \cdot 10^8$	Glass coating, solar cell manufacturing, surface finishing, CVD, PVD/sputtering, ion implantation, plasma physics, space simulation
HiPace™ 1500	1,450.0 l/s	$> 1.0 \cdot 10^8$	
HiPace™ 1800	1,450.0 l/s	$> 1.0 \cdot 10^8$	
HiPace™ 2300	1,900.0 l/s	$> 1.0 \cdot 10^8$	
HiPace™ 2400 MC	2,100.0 l/s	$> 1.0 \cdot 10^9$	Coating industry, semiconductor manufacturing, research & development
HiPace™ 3400 MC	2,950.0 l/s	$> 1.0 \cdot 10^9$	

The base pressures of standard pumps with ISO-K flanges are: $p_b < 1 \cdot 10^{-7}$ mbar. Equipped with CF flanges, these pumps can attain base pressures of $p_b < 5 \cdot 10^{-10}$ mbar after bake-out.

2.8.3.3 Controls, displays and drives

A variety of controls, displays and drives are available for operating turbopumps in different applications; they are shown in the table 2.16.

The numbering used below is based upon Figure 2.26 (Accessories for turbopumps).

HiPace Models 10 to 300 (1a) are equipped with attached drive TC 400 (1b). They require a supply voltage of 24 VDC. Integrated power supplies TPS 110/111 or 180/181 (2c) or power supply modules DCU 110 or DCU 180 (2a) with DCU 002 display control unit are available for off-line operation. HiPace Models 400 and 700 are equipped with the TC 400 drive.

The TC 400 can be operated either with 24 VDC or 48 VDC, depending upon the pump that is connected. The supply voltage of 48 V can be provided by the TPS 400 integrated power supply or the DCU 400 power supply module. The large HiPace 1200 to 2300 pumps are powered by the attached TC 1200, which is supplied directly from the mains.

All HiPace 10 to 700 pumps can also be supplied without attached drive (e.g. for radioactive environments). The TCP 350 drive with integrated power supply and with DCU 002 (2b) for control is used for operation.

The magnetic-levitation HiPace 2400 MC and 3400 MC are controlled by the TM 3000 operating unit. The 140 V supply voltage can be provided by the TPS 1400 power supply module. Alternatively available is the attached OPS 900 (Onboard Power Supply) power supply that mounts beneath the base plate of the pump.

The DCU 002 (2b) can be connected to the RS-485 interface for operation and for setting various parameters. The HPU 001 handheld programming unit can also be connected; this unit can also be used to store parameter records and enter them in multiple pumps. A USB converter (5b) can also be used to connect a PC (5a) to the RS-485 interface in order to execute programming and switching functions or to transfer status displays.

In addition, Profibus DP and DeviceNet converters are available for integrating the pumps into appropriate plant control systems.

The major switching functions can also be executed via a remote control plug with the aid of switches. Moreover, some status displays can be taken from relay outputs.

A selector switch can be used to select pump operation either by means of this approach or via the serial interface.

Table 2.16: Drives and power supplies

	Drives					Power Supplies			Display Units	
	TC 110 24 V	TC 400 24/48 V	TC 1200 90–240 V	TM 3000 140 V	TCP 350 with DCU 90–240 V	Integrated TPS power supply	Power supply module with DCU	Attached OPS power supply	HPU 001 handheld programming unit	DCU Power supply module
HiPace™										
HiPace™ 10	●					●	●		●	●
HiPace™ 80	●				●	●	●		●	●
HiPace™ 300	●	●			●	●	●		●	●
HiPace™ 400		●			●	●	●		●	●
HiPace™ 700		●			●	●	●		●	●
HiPace™ 1200			●					+	●	●
HiPace™ 1500			●					+	●	●
HiPace™ 1800			●					+	●	●
HiPace™ 2300			●					+	●	●
HiPace™ 2400 MC				●		●		●	●	
HiPace™ 3400 MC				●		●		●	●	

- Recommended
- + Always with OPS (Onboard Power Supply)

2.8.3.4 Accessories



- | | | |
|-----------------------------|------------------------------------|----------------------------------|
| 1a) Turbopump | 4) Fan | 7a) Sealing gas throttles |
| 1b) TC 400 | 5a) PC | 7b) Sealing gas valve |
| 2a) DCU power supply | 5b) USB converter | 8) Electric vent valve |
| 2b) DCU 002 | 6) „Backing pump“ relay box | 9) Heater |
| 3) Water cooling | | |

Figure 2.26: Accessories for turbopumps

In addition to the electrical operating devices described above, various accessories are also available for special applications. Some DCU power supplies enable a TPR 280 vacuum gauge to be connected in order to measure pressures in a vacuum system.

With the aid of the “backing pump” relay box (6) the DCU power supply (2a) can be converted to a pumping station controller that can switch on both turbopump (1a) and backing pump simultaneously.

Either a fan (4), or water cooling (3) for high gas loads, can be attached to cool the pumps.

An electric vent valve (8) vents the turbopumps if the RPM declines below a given speed. In the event of a brief power failure, the vent valve will remain closed to maintain the vacuum. The pumping station will then re-start immediately when mains voltage is restored. However this necessitates a backing pump with a safety valve that will close automatically in the event of a power failure.

For UHV applications, a heater (9) can be connected to the pump that switches on automatically after a preselected RPM is attained, and switches off when RPM decreases.

Electromagnetic sealing gas valves (7b) with matching throughputs, as well as sealing gas throttles (7a) for pumps of various sizes, are available for corrosive gas pumps.

3 Vacuum Measuring Equipment

Pressure is defined as force per unit of area: $p = F/A$ (Formula 1-3), where F is force and A the area to which the force is applied. The SI unit of pressure is $1 \text{ N/m}^2 = 1 \text{ Pa}$. Other frequently-used units of pressure are: $1 \text{ mbar} = 100 \text{ Pa}$ and $1 \text{ torr} = 133,322 \text{ Pa}$. If pressure is measured via the force that is exerted on an area, it is termed a pressure measurement that is independent of the type of gas in question.

Pressure measurement on the basis of force reaches its limits at pressures of less than 1 mbar , because the exerted forces become too small. Consequently other processes must be used. The thermal conductivity of the enclosed gas can be used, for example, or the gas molecules can be ionized, the ion streams flowing between electrodes measured.

A spinning rotor gauge (SRG), a so-called gas friction gauge, is used for calibration purposes [11]. A sphere is magnetically suspended in the vacuum and caused to rotate rapidly, at which point the drive is then de-energized. The pressure of the type of gas that is present can be calculated from the decrease in rotational frequency due to gas friction. These devices measure pressures p of more than 10^{-7} mbar . Calibrated spheres can be used as a transfer standard.

3.1 Fundamentals of total pressure measurement

In vacuum technology, no one measurement method covers the entire pressure range. It is therefore necessary to use different sensors. The criteria for selecting a pressure sensor are based upon various conditions:

- ▶ The pressure range to be detected
- ▶ Gas composition: Inert or corrosive
- ▶ Required accuracy and repeatability
- ▶ Environmental conditions, such as radioactivity

3.1.1 Direct, gas-independent pressure measurement

Diaphragm vacuum gauges

In the case of a diaphragm vacuum gauge, pressure is measured in accordance with the definition. A pressure p is exerted on a diaphragm having a defined area A and deflects the diaphragm proportionally to the pressure. A sensor measures the deflection. Piezo-resistive or capacitive sensors receive the pressure signal and convert it into an electrical signal.

Piezo-diaphragm vacuum gauges

A simple and extremely robust method involves the use of a piezo-resistive pick-up. The design is shown in Figure 3.1. A diaphragm is arranged over a well-evacuated volume having a reference pressure p_0 , into which the expansion measurement resistances are diffused. The measured change in resistance as a result of diaphragm deflection serves as a parameter for the pressure. This pick-up is characterized by its insensitivity to gas inrush and its high accuracy.

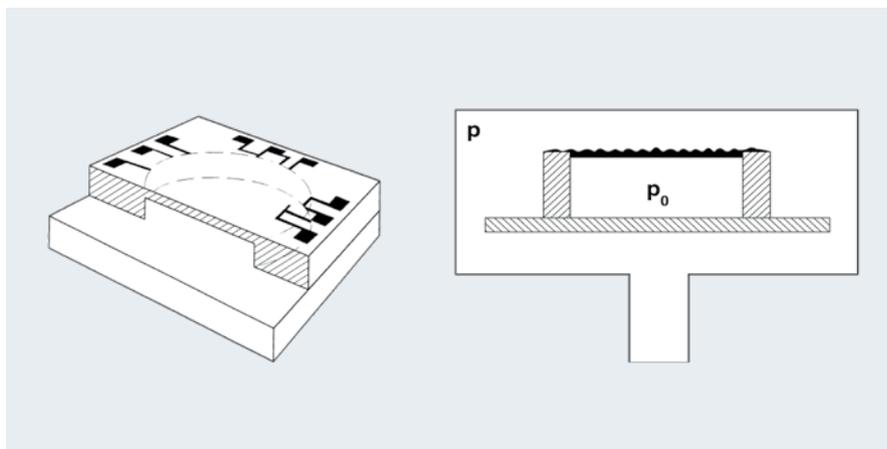


Figure 3.1: Design of a diaphragm vacuum gauge

Source: Wutz, *Handbuch der Vakuumtechnik*, Wiesbaden 2006, p. 453

Capacitive diaphragm vacuum gauges

In a capacitive vacuum gauge (Figure 3.2), deflection of the diaphragm is measured as the change in capacity of a plate capacitor that is formed by the diaphragm and a fixed counter-plate in a well-evacuated space having a pressure p_0 . The diaphragm is comprised either of ceramic with a vacuum-metalized coating or of stainless steel. This method and diaphragms of varying sensitivity can be used to perform measurements of four decades each. The lower measurement limit is 10^{-5} mbar.

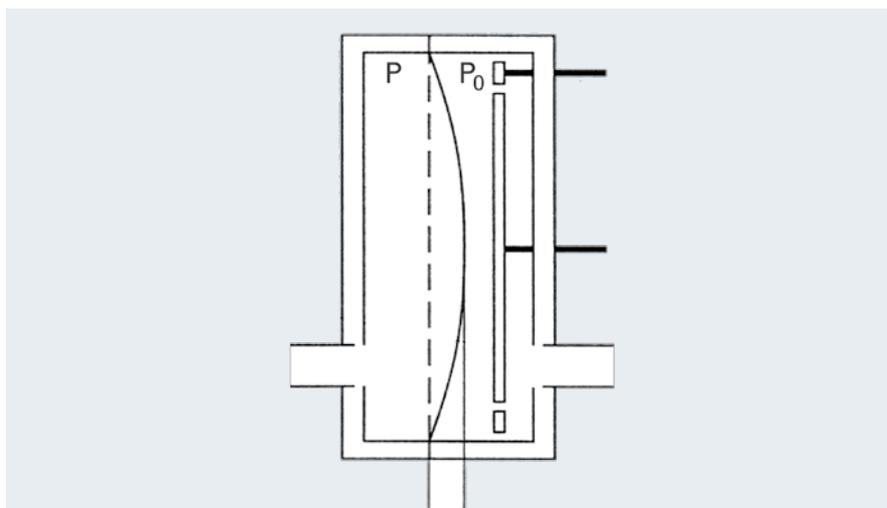


Figure 3.2: Design of a capacitive diaphragm vacuum gauge

Source: Wurz, *Handbuch der Vakuumtechnik*, Wiesbaden 2006, p. 459

The limiting effects are:

- ▶ Change in clearance within the pressure transducer due to the influence of temperature
- ▶ Decreasing forces acting on the diaphragm at low pressures

The influence of temperature can be eliminated through electronic compensation of a known temperature drift or by means of an installed heater that maintains the sensor at a constant temperature. The influence of temperature can be further minimized through the use of ceramic diaphragm material.

3.1.2 Indirect, gas-dependent pressure measurement

At extremely low pressures, the influence of the force on a diaphragm becoming negligible. This is why pressure is determined by means of the molecular number density, which is proportional to pressure. The status equation that applies for an ideal gas is: $p = n \cdot k \cdot T$ (Formula 1-5). Thus, pressure is proportional to molecular number density where temperature T is identical. This formula is satisfied for the pressures that prevail in vacuum technology. Various physical effects, such as thermal transfer, ionization capacity or electrical conductivity, are measured for this purpose. These values are a function of both pressure as well as molecular weight. This results in a pressure measurement that produces differing results for different heavy gases.

Pirani (thermal transfer) vacuum gauges

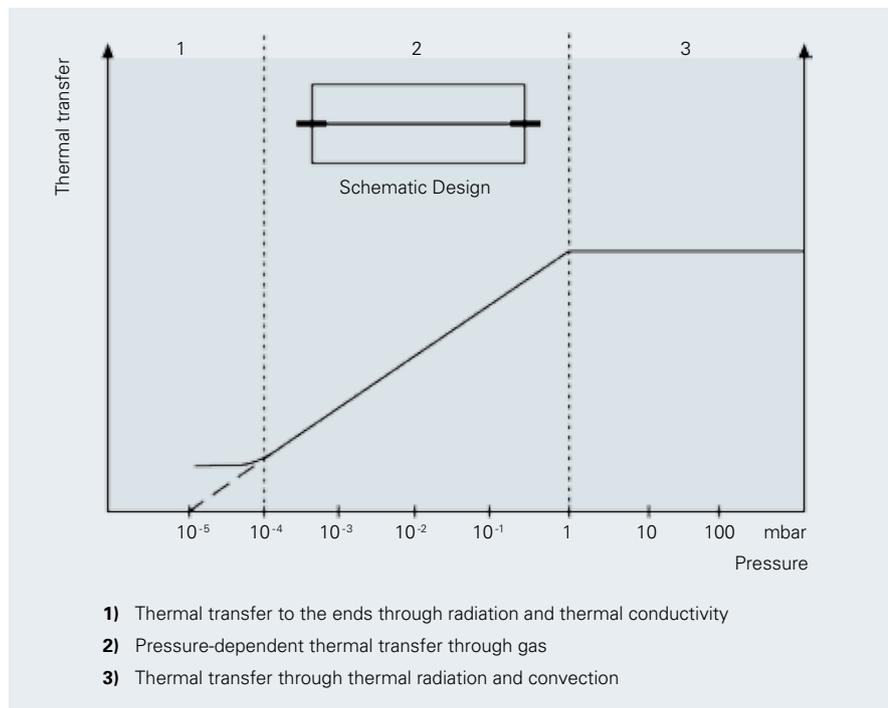


Figure 3.3: Operating principle of a Pirani vacuum gauge

Source: Inficon 2000-2001 Catalog, p. 82

A Pirani vacuum gauge utilizes the thermal conductivity of gases at pressures p of less than 1 mbar. Wire (usually tungsten) that is tensioned concentrically within a tube is electrically heated to a constant temperature between 110 °C und 130 °C by passing a current through the wire. The surrounding gas dissipates the heat to the wall of the tube. In the molecular flow range, the thermal transfer is the molecular number density and is thus proportional to pressure. If the temperature of the wire is kept constant, its heat output will be a function of pressure. However it will not be a linear function of pressure, as thermal conductivity via the suspension of the wire and thermal radiation will also influence the heat output.

The limiting effects are:

- ▶ Thermal conductivity will not be a function of pressure in the range of 1 mbar to atmospheric pressure (laminar flow range)
- ▶ The thermal conductivity of the gas will be low relative to the thermal transfer over the wire ends at pressures below 10^{-4} mbar, and will thus no longer influence the heat output of the wire. Consequently, the measurement limit is approximately at 10^{-4} mbar
- ▶ Thermal radiation will also transfer a portion of the heat output to the wall of the tube

Figure 3.4 shows the different curves for various gases between 1 mbar and atmospheric pressure. While good linearity can still be seen for nitrogen and air, significant deviations are indicated for light (He) and heavy gases (Ar).

In the case of gas-dependent measuring methods, it is also common to speak of the nitrogen equivalent that is displayed.

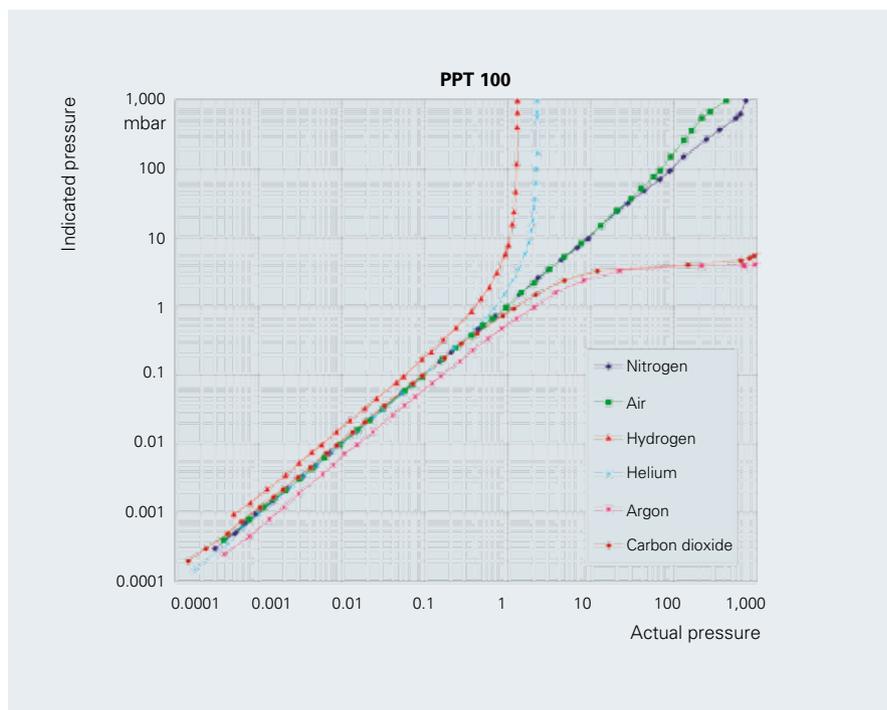


Figure 3.4: Pirani vacuum gauge curves

Cold cathode ionization vacuum gauges

Cold cathode ionization vacuum gauges essentially consist of only two electrodes, a cathode and an anode, between which a high voltage is applied via a series resistor. Negatively charged electrons leave the cathode because of the high voltage, moving at high velocity from the cathode toward the anode. As they travel this path, they ionize neutral gas molecules, which ignites a gas discharge. The measured gas discharge current (Figure 3.5) is a parameter for pressure. However only few molecules are ionized with straight electron trajectories, which results in lower sensitivity and interruption of the gas discharge at approximately 1 mbar. A design that avoids this disadvantage is the inverted magnetron after Hobsen and Redhead. A metal pin (anode) is surrounded by a rotationally symmetrical measurement chamber (cathode) (Figure 3.5). An axially magnetized, cylindrical, permanent-magnet ring is placed on the exterior of the measurement chamber to generate a magnetic field within the chamber.

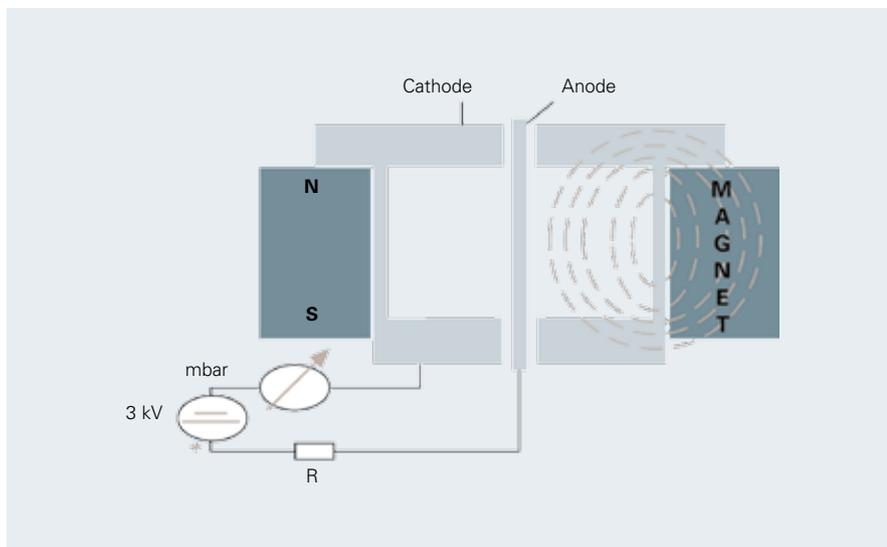


Figure 3.5: Design of an inverted magnetron

The electrons travel through the magnetic field on spiral trajectories (Figure 3.6). The electron paths extended in this manner increase the probability of collisions with the gas molecules and ensure that sufficient ions are generated to maintain the gas discharge, even at pressures of less than 1 mbar. The pressure reading will depend upon the type of gas in question due to the different ionization probabilities of the various gases. For example, a lower pressure will be indicated for helium than for air.

Cold cathode vacuum gauges can be easily contaminated under the following conditions:

- ▶ If the device is activated at pressures p of more than 10^{-1} mbar
- ▶ Argon is often used for applications in sputtering systems. This results in sputtering of the cathode, as well, which can cause short circuits and thus failures of the gauges
- ▶ Gases are also gettered on the surfaces of the cathode. This produces a pumping effect that will falsify the measurement signal.

When installing the gauge in a vacuum system, it is necessary to take the magnetic field into consideration, as it can interfere with sensitive equipment.

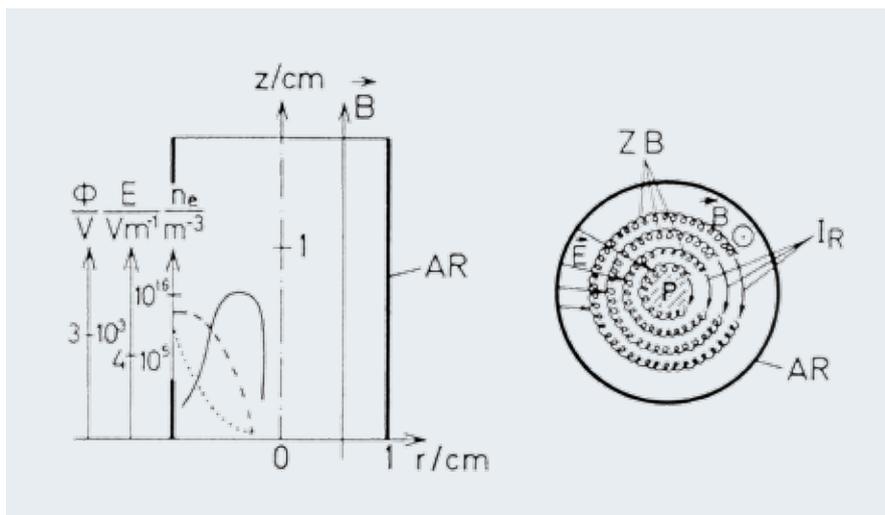


Figure 3.6: Operating principle of an inverted magnetron

Source: Jousten (publisher) Wutz, *Handbuch Vakuumtechnik*, Vieweg Verlag

Hot cathode ionization vacuum gauges

In this case, as opposed to cold cathode ionization vacuum gauges, electrons are generated with the aid of a heated cathode. Figure 3.7 shows the design of a gauge after Bayard–Alpert. A thin wire is arranged in the middle of the cylindrical, lattice-shaped anode; this wire serves as the ion collector. A voltage of approximately 100 V is applied between anode and cathode. This accelerates all emitted electrons toward the anode. The emission current is measured in the anode circuit, which can be set by means of the heat output of the cathode. As they travel toward the anode, gas molecules that strike the collector, which has the potential of the cathode, are ionized by electron collisions. The measured collector current is a parameter for pressure. Since the emission current is proportional to the ion current, it can be used to set the sensitivity of the gauges.

Pressures can be accurately measured to $1 \cdot 10^{-10}$ mbar with Bayard-Alpert sensors.

Measuring errors result from the pumping effect of the sensor, as well as from the following two limiting effects:

- ▶ **X-ray braking radiation** Electrons that strike the anode cage cause x-rays to be emitted, some of which strike the collector. This x-ray effect causes the collector to emit photoelectrons that flow off toward the anode. The resulting photoelectron current increases and falsifies the pressure-dependent collector current. Consequently the collector wire should be selected as thin as possible so that it collects only little x-ray radiation.
- ▶ **ESD ions** ESD (electron stimulated desorption) means that gas molecules deposited on the anode cage are desorbed and ionized by electrons. These ions also increase the pressure-proportional ion current.

A hot cathode vacuum gauge also measures independently of the type of gas in question. However the measurement results are significantly more accurate than those obtained with a cold cathode ionization vacuum gauge.

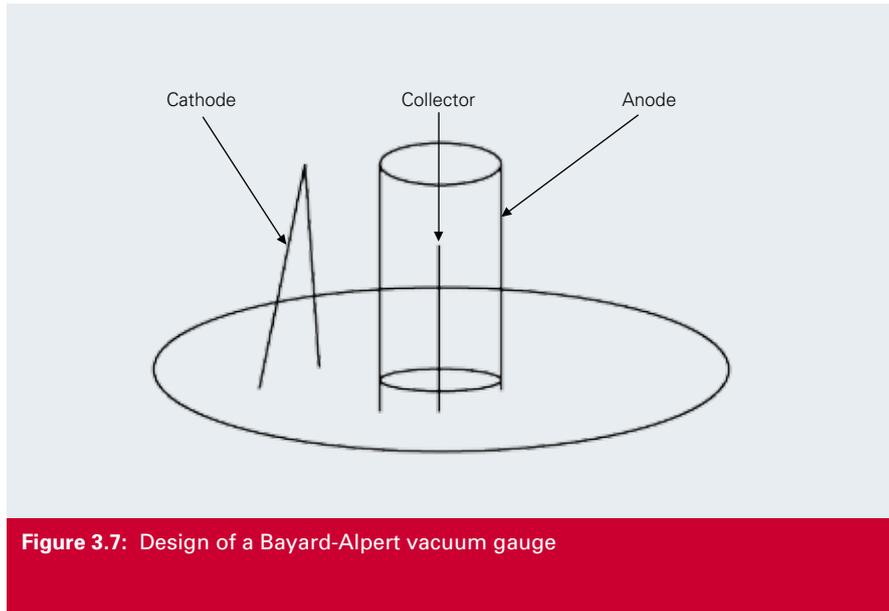


Figure 3.7: Design of a Bayard-Alpert vacuum gauge

3.2 Application notes

The following conditions must be observed in selecting and installing the measurement devices:

- ▶ Appropriate selection of the installation location due to potential pressure gradients in the recipient
- ▶ Potential pumping effect of the sensors
- ▶ Sputter effect of cold cathode gauges
- ▶ Strong magnetic and electrical fields
- ▶ Bake-out of the equipment and the gauges when generating ultra high vacuum
- ▶ Selection of switching points for ionization gauges in such a manner as to avoid contamination

Cold cathode gauges can be easily removed and cleaned in the event of contamination. Bayard-Alpert immersion measurement systems can also be cleaned, with any defective components, such as heating filaments, anode gates or collectors, being replaced. Contaminated anode gates and collectors can cause significant measurement errors due to the charging effects.

3.2.1 Measurement ranges

Pointer-type vacuum gauges are used in the pressure range from 1,000 - 1 mbar; however these gauges offer only limited accuracy and can only be read directly at the point of installation. Diaphragm vacuum gauges are used to obtain more accurate measurements.

Pirani thermal conductivity vacuum gauges are used between 1 and 10^{-4} mbar. It is also possible to use special „high-pressure“ hot cathode ionization vacuum gauges at pressures p of less than 10^{-2} mbar.

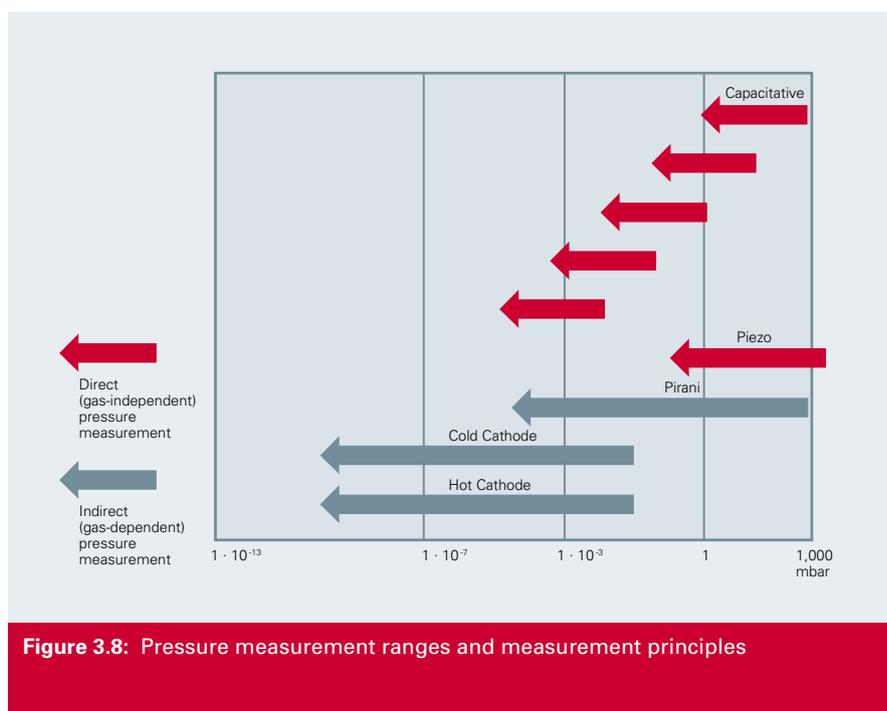


Figure 3.8: Pressure measurement ranges and measurement principles

Either cold cathode ionization vacuum gauges, or ionization vacuum gauges after Bayard-Alpert in the case of clean conditions and rigorous accuracy requirements, are used for pressures of less than 10^{-3} mbar. It is always meaningful to use a combination of measuring sensors that covers the entire pressure range in use.

In the case of diaphragm vacuum gauges and Pirani vacuum gauges, pressure switch points are generated in order to not activate ionization vacuum gauges until sufficiently low pressure prevails, thus protecting them against contamination or burn-out of the heated cathode. Consequently, combination sensors are also offered, which are described below.

3.2.2 Transmitters

Transmitters are measuring sensors that output the measured pressure either in the form of an analog measurement signal (0 - 10 V) or a digital signal to a standardized interface. They must be supplied with a direct-current voltage (e.g. 24 V). Power supplies that display the measured values are also offered for the transmitters.

3.2.3 Vacuum gauges

Vacuum gauges are connected to control units via cables; the control units afford power supply, analysis and display of the measured data. These devices usually also have analog voltage outputs.

Table 3.1: Transmitters and vacuum gauges

Sensor Design	Designation
Vacuum sensor with adapted electronics Input: Feed voltage (e.g. 24 V) Output: Analog signal (e.g. 0-10 V) or Digital signal (RS-232, 485, Profibus, DeviceNet)	Transmitter
Vacuum sensor connected to required feed and analysis electronics via cable	Measurement gauge

3.2.4 Combination sensors

Combination sensors combine two sensors in one and the same measurement cell and offer the following advantages:

- ▶ Broader measurement range
- ▶ Only one measured value output
- ▶ Sensitive high vacuum sensors are protected against being activated at excessive pressure
- ▶ Only one connection flange is required

The various combinations are described in connection with the individual series.

3.3 Portfolio overview

3.3.1 Product lines

Pfeiffer Vacuum offers transmitters in the form of single or combination sensors, as well as conventional gauges.

3.3.1.1 DigiLine™

DigiLine sensors are supplied with 24 VDC. The measured values are output via an RS-232 or RS-485 digital interface. The various application options are described in Figure 3.9.

Individual transmitters can be operated and their measured values displayed by means of the DPG 101 controller. The DPG 109 can supply up to nine transmitters. Transmitter signals can also be directly displayed and processed on a PC or PLC by means of the DokuStar Plus software. With the aid of converters, the RS-485 signal can be converted to a fieldbus signal (Profibus-DP or DeviceNet), thus enabling it to be used in plant control systems with a fieldbus controller that enables especially simple and cost-effective cabling.

Table 3.2: Pressure sensor selection table

	Measurement Range			Application					
		max. (mbar)	min. (mbar)	Vacuum furnaces	Sputtering	Vaporization chambers	Reactive processes	Load locks	Accelerators
● Recommended ▲ Possible									
Transmitters / Measurement Gauges									
DigiLine™									
Digital piezo transmitter	CPT 100	2,000	1	▲	▲	▲	▲	▲	
Digital Pirani transmitter	PPT 100	1,000	$1 \cdot 10^{-4}$	●	▲	●	▲	●	
Digital piezo/Pirani transmitter	RPT 100	1,200	$1 \cdot 10^{-4}$	●	▲	●	▲	●	
Digital Pirani/cold cathode transmitter	MPT 100	1,000	$5 \cdot 10^{-9}$	●	●	●	●	▲	▲
Digital Pirani/Bayard-Alpert transmitter	HPT 100	1,000	$1 \cdot 10^{-9}$	▲	●				
ActiveLine									
Active piezo transmitter	APR 250	1,100	$1 \cdot 10^{-1}$	▲	▲	▲	▲	▲	
	APR 260	1,100	$1 \cdot 10^{-1}$	▲	▲	▲	▲	▲	
	APR 262	2,200	$2 \cdot 10^{-1}$	▲	▲	▲	▲	▲	
	APR 265	5,500	0.5	▲	▲	▲	▲	▲	
	APR 266	11,000	1	▲	▲	▲	▲	▲	
	APR 267	55,000	5	▲	▲	▲	▲	▲	
Active capacitive transmitter	CMR 361	1,100	$1 \cdot 10^{-1}$	▲	●	●	●		
Temperature compensated	CMR 362	110	$1 \cdot 10^{-2}$	▲	●	●	●		
	CMR 363	11	$1 \cdot 10^{-3}$	▲	●	●	●		
	CMR 364	1.1	$1 \cdot 10^{-4}$	▲	●	●	●		
	CMR 365	0.11	$1 \cdot 10^{-5}$	▲	●	●	●		
Temperature regulated	CMR 271	1,100	$1 \cdot 10^{-1}$	▲	●	●	●		
	CMR 272	110	$1 \cdot 10^{-2}$	▲	●	●	●		
	CMR 273	11	$1 \cdot 10^{-3}$	▲	●	●	●		
	CMR 274	1.1	$1 \cdot 10^{-4}$	▲	●	●	●		
	CMR 275	0.11	$1 \cdot 10^{-5}$	▲	●	●	●		
Active Pirani transmitter	TPR 280	1,000	$5 \cdot 10^{-4}$	●	▲	▲		▲	
	TPR 281	1,000	$5 \cdot 10^{-4}$	●	▲	▲	▲	▲	
Active Pirani/capacitive transmitter	PCR 260	1,500	$5 \cdot 10^{-4}$	●	▲	▲		●	
Active cold cathode transmitter	IKR 251	0.01	$2 \cdot 10^{-9}$	▲	▲	●	▲		
	IKR 261	0.01	$2 \cdot 10^{-9}$	▲	▲	●	▲		
	IKR 270	0.01	$5 \cdot 10^{-11}$	▲	▲	●	▲		
Active Pirani/cold cathode transmitter	PKR 251	1,000	$5 \cdot 10^{-9}$	▲	▲	▲	▲		
	PKR 261	1,000	$5 \cdot 10^{-9}$	▲	▲	▲	▲		
Active hot cathode transmitter	IMR 265	1,000	$2 \cdot 10^{-6}$	▲	●	▲			
Active Pirani/Bayard-Alpert transmitter	PBR 260	1,000	$5 \cdot 10^{-10}$	▲	▲	▲	▲		
ModulLine									
Pirani pressure gauge	TPR 010	1,000	$8 \cdot 10^{-4}$	▲	▲	▲	▲	▲	▲
	TPR 017	1,000	$8 \cdot 10^{-4}$	▲	▲	▲	▲	▲	●
	TPR 018	1,000	$8 \cdot 10^{-4}$	▲	▲	▲	●	▲	●
Cold cathode pressure gauge	IKR 050	$5 \cdot 10^{-3}$	$2 \cdot 10^{-9}$	▲	▲	●	▲		●
	IKR 060	$5 \cdot 10^{-3}$	$1 \cdot 10^{-10}$	▲	▲	●	▲		●
	IKR 070	$5 \cdot 10^{-3}$	$1 \cdot 10^{-11}$	▲	▲	●	▲		●

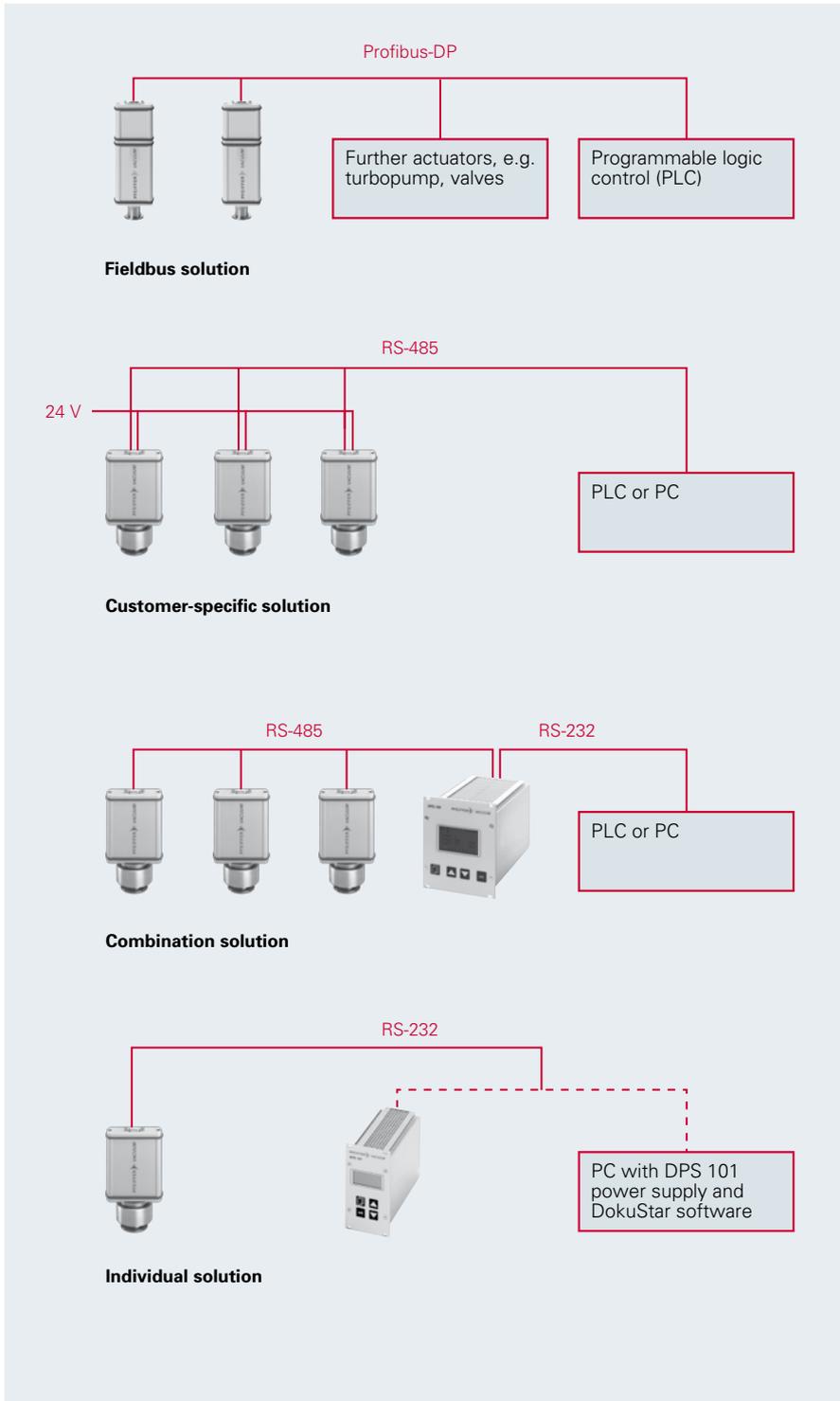


Figure 3.9: DigiLine™ application concepts

DigiLine sensors offer the following advantages:

- ▶ Freely combinable components
- ▶ Measured values are transmitted directly; no curve correction is required
- ▶ Secure data transmission thanks to digital signals
- ▶ Reversible RS-232/RS-485 serial interface
- ▶ Data can be analyzed directly on a PC with DokuStar Plus software
- ▶ Can be integrated into a plant control system by means of a fieldbus converter
- ▶ Simple calibration
- ▶ Suitable for industrial use

Single-sensor transmitters are available in the form of a **CPT 100 piezo-diaphragm system** (2,000 – 1 mbar) and a **PPT 100 Pirani system** (1,000 – 10^{-4} mbar).

The following combination sensors are available in the DigiLine series:

- ▶ **RPT 100 piezo-Pirani combination.** Since the thermal conductivity effect for the Pirani vacuum gauge is not a function of pressure, a diaphragm vacuum gauge is used for pressures p of over 1 mbar. This affords good accuracy throughout the entire measurement range from 1,200 to $1 \cdot 10^{-4}$ mbar, enabling processes to be controlled by means of this gauge
- ▶ **MPT 100 Pirani-cold cathode combination.** This combination covers the pressure from 1,000 to $5 \cdot 10^{-9}$ mbar. The gas discharge of the cold cathode measuring sensor is range initiated by the pressure that is measured with the Pirani sensor. Using this process prevents inadvertent activation of the cold cathode at excessive pressure, thus avoiding contamination.
- ▶ **HPT 100 Pirani/Bayard-Alpert combination.** This covers a pressure range from 1,000 to $5 \cdot 10^{-10}$ mbar. Pressure monitoring by the Pirani sensor protects the hot cathode gauges against operating at excessively high temperatures and prevents burn-out of the hot cathode. This enables extremely long cathode service life to be achieved.

3.3.1.2 ActiveLine

The ActiveLine family includes three control units and eight transmitters.

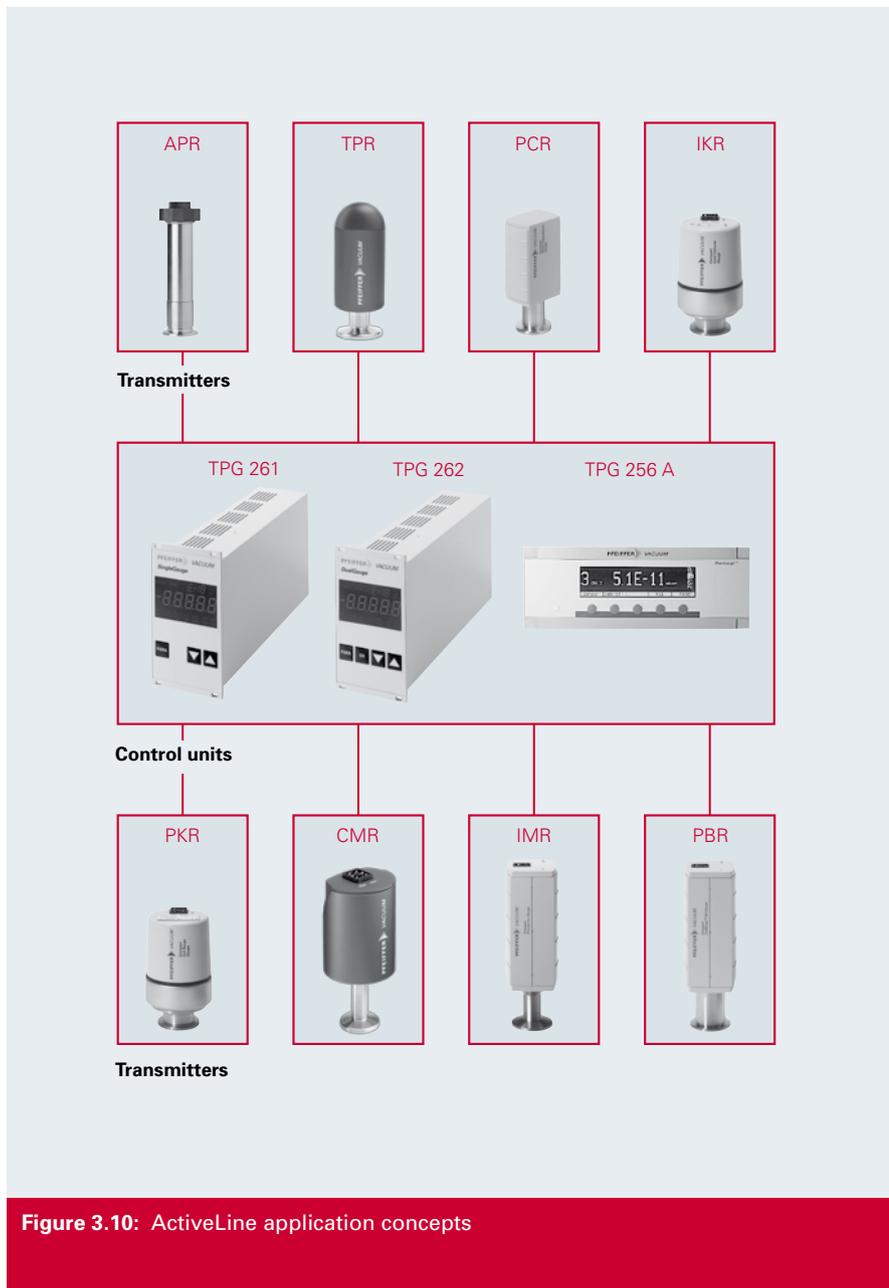
The APR piezo transmitters cover five measurement ranges from 55 bar to 0.1 mbar with six transmitter models.

Capacitive CMR diaphragm-type transmitters are available in the form of both temperature-compensated and temperature-regulated versions, in four or five measurement ranges each from 1,100 – 10^{-5} mbar. The use of diaphragms of differing thicknesses results in the following categories:

- ▶ 1,100 to 10^{-1} mbar
- ▶ 110 to 10^{-2} mbar
- ▶ 11 to 10^{-3} mbar
- ▶ 1.1 to 10^{-4} mbar
- ▶ 0.11 to 10^{-5} mbar

These ceramic-technology capacitive diaphragm vacuum gauges from Pfeiffer Vacuum have a proven track record in many, even corrosive applications.

The electrodes (anode, cathode, collector) in the sensor of the IMR 265 hot cathode transmitters are designed with extremely small clearances between one another.



Molecular flow therefore prevails, even at pressures p of less than 10^{-2} mbar, enabling ion currents there to be measured. An additional advantage is its lower sensitivity to contamination than the Bayard-Alpert design. Moreover, there are two TPR Pirani transmitters and three IKR cold cathode transmitters with measuring ranges from 0.01 bis $5 \cdot 10^{-11}$ mbar.

The TPR 280 Pirani vacuum gauges can also be connected to DCU pumping station display control units, thus providing a pressure reading at no additional expense.

The following combination sensors are available:

- ▶ **PCR 260 capacitive diaphragm-Pirani combination transmitter** with a measurement range from 1,500 to $5 \cdot 10^{-4}$ mbar
- ▶ **PKR 251 and 261 Pirani-cold cathode combination transmitters** with measurement ranges from 1,000 to $5 \cdot 10^{-9}$ mbar
- ▶ **PBR 260 Pirani/Bayard-Alpert combination transmitter** with a measurement range from 1,000 to $5 \cdot 10^{-10}$ mbar.

ActiveLine transmitters offer the following advantages:

- ▶ There are three control units for one, two or six transmitters
- ▶ Any transmitter can be operated with any control unit
- ▶ Uniform connection cable

3.3.1.3 ModulLine

The ModulLine series includes three TPR Pirani vacuum gauges with a measurement range from 1,000 to $8 \cdot 10^{-4}$ mbar and three IKR cold cathode measuring tubes with measurement ranges from $5 \cdot 10^{-3}$ to 10^{-11} mbar. Because these vacuum gauges do not contain any electronics, they are suitable for use in high-radiation environments.

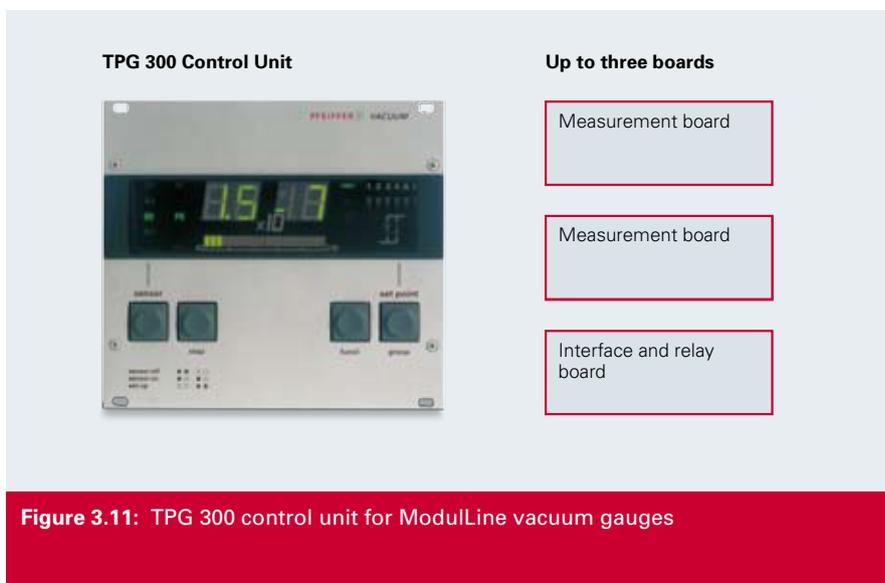


Figure 3.11: TPG 300 control unit for ModulLine vacuum gauges

A TPG 300 with the following features serves as the control unit:

- ▶ Two measurement boards can be inserted, as well as
- ▶ An RS-232/RS-485 interface board with relay outputs
- ▶ Connection of up to four vacuum gauges
- ▶ Fieldbus connection is possible

4 Mass Spectrometers and Residual Gas Analysis

4.1 Introduction, operating principle

Mass spectrometry is one of the most popular analysis methods today. A mass spectrometer analyzes the composition of chemical substances by means of partial pressure measurement.

Mass and Charge

- ▶ Total pressure is the sum of all partial pressures in a given gas mixture
- ▶ In order to determine the partial pressure of a given component of a gas, it must be measured in isolation from the mixture
- ▶ This necessitates prior separation of the mixture
- ▶ This is accomplished on the basis of the ratio between mass and charge m/e

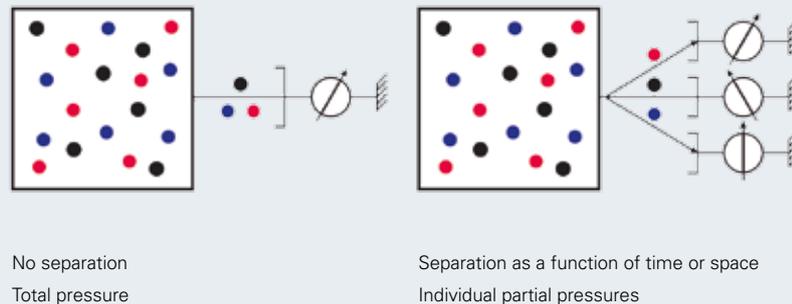


Figure 4.1: Total and partial pressure measurement

Source: Pupp / Hartmann, *Vakuumtechnik, Grundlagen und Anwendungen*, Hanser Verlag

Analyses are typically performed in the field of research & development and in the production of products that are used in daily life:

- ▶ Analysis of products from the chemical industry
- ▶ Drug development
- ▶ Doping tests
- ▶ Quality assurance of food products
- ▶ Monitoring semiconductor production processes
- ▶ Isotope analysis

Gaseous or liquid substances that vaporize under vacuum are admitted to a mass spectrometer. The gas is diluted by being partially pumped down to a low pressure (molecular flow range) in a vacuum chamber and ionized through electron bombardment. The ions thus generated are introduced to a mass filter and separated on the basis of their charge-to-mass ratio.

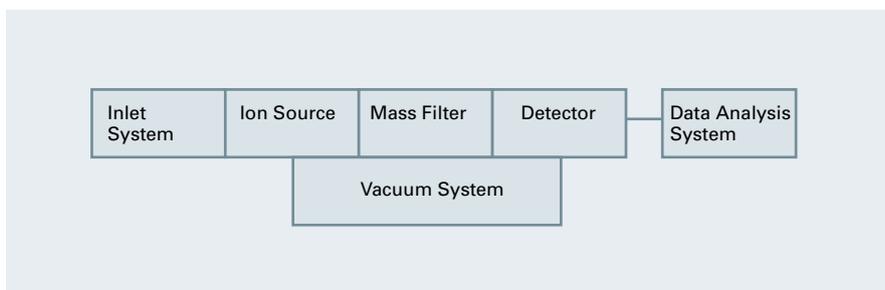


Figure 4.2: Components of a mass spectrometer

Figure 4.2 shows the typical structure of a mass spectrometer system:

- ▶ The substances to be analyzed are admitted into a vacuum chamber through the **inlet system** via a capillary or metering valve, for example, and then
- ▶ Partially pumped down to the system's working pressure

The actual analyzer is located in the vacuum and consists of the following components:

- ▶ The **ion source** ionizes neutral gas particles, which are then
- ▶ Sorted in the **mass filter** on the basis of their mass-to-charge ratio m/e
- ▶ The ion current is measured using a Faraday **detector** or a secondary electron multiplier (SEM) after the ions have left the separating system. The measured current is a parameter of the partial pressure of the respective gas molecules or a parameter of fractals that may possibly have been generated in the ion source
- ▶ A **data analysis system** processes the ion currents measured with the aid of the detector and presents these currents in various forms. Today, data analysis software programs are capable of supporting the user in interpreting mass spectra.

Mass spectrometers differ as a result of the wide variety of available versions. The main difference consists of the separating systems. The following four types of mass filters are in widespread use today:

- ▶ **Sector field devices** use the deflection effect of a magnetic field on moving charge carriers
- ▶ Time-of-flight mass (TOF) spectrometers utilize the differing velocities of molecules of equal energy for separation
- ▶ In ion traps, the trajectories of the ions are influenced by a high-frequency field
- ▶ Quadrupole mass spectrometers utilize the resonance of moving ions in a high-frequency field (similar to ion traps)

Our discussion will be confined to sector field mass spectrometers and quadrupole mass spectrometers, as these are the mass spectrometers that are most widely used in the field of vacuum technology.

4.1.1 Sector field mass spectrometers

Because of their simple, robust design, sector field mass spectrometers are used for helium leak detectors, where only little demands are placed on resolution.

The operating principle of sector field mass spectrometers is shown in Figure 4.3.

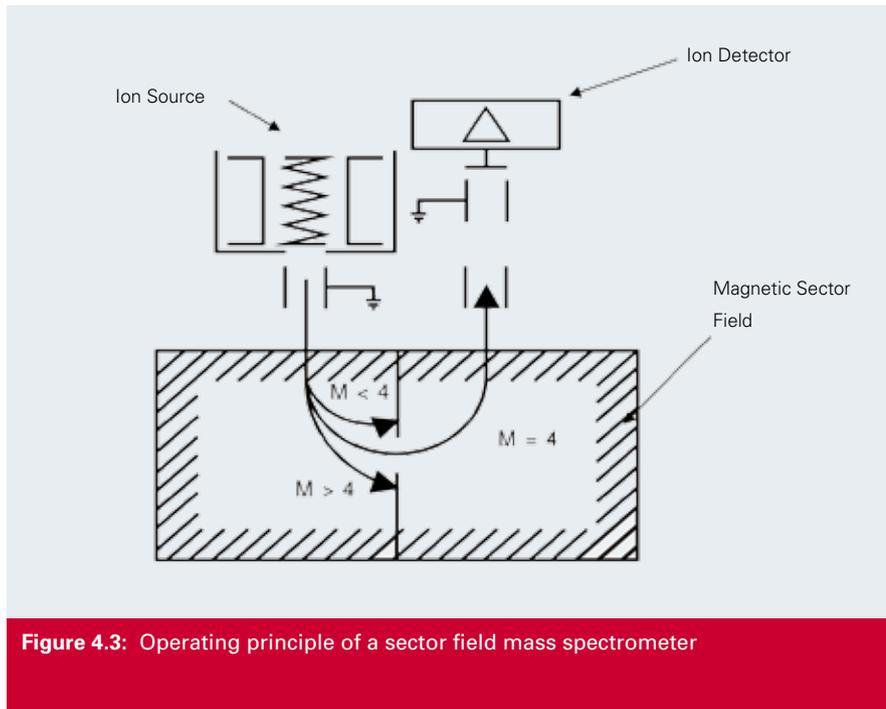


Figure 4.3: Operating principle of a sector field mass spectrometer

Neutral gas molecules are ionized in an ion source through electron bombardment. The electrons thus generated are accelerated into the magnetic sector field with the aid of an electrical voltage. The magnetic field is homogeneous in the area of the trajectories of the ions and is positioned perpendicular to the image plane. Helium ions having a mass of 4 amu are able to pass through a slot to reach the detector. All other molecules are unable to pass through the slot and are re-neutralized. The ion current measured for helium is proportional to the helium partial pressure.

4.1.2 Quadrupole mass spectrometers (QMS)

4.1.2.1 Quadrupole mass filter

The filter system of a quadrupole mass spectrometer consists of four parallel rods arranged in the form of a square. Each pair of opposite rods in Figure 4.4, designated (+) or (-), is connected with the other. Voltage

Formula 4-1

Quadrupole
deflection voltage

$$U_1 = U + V \cdot \cos \omega t$$

is applied between the two pairs of rods.

At this point, only a brief phenomenological description of the operating principle will be provided. Reference is made to the literature for a detailed presentation [14, 15, 16].

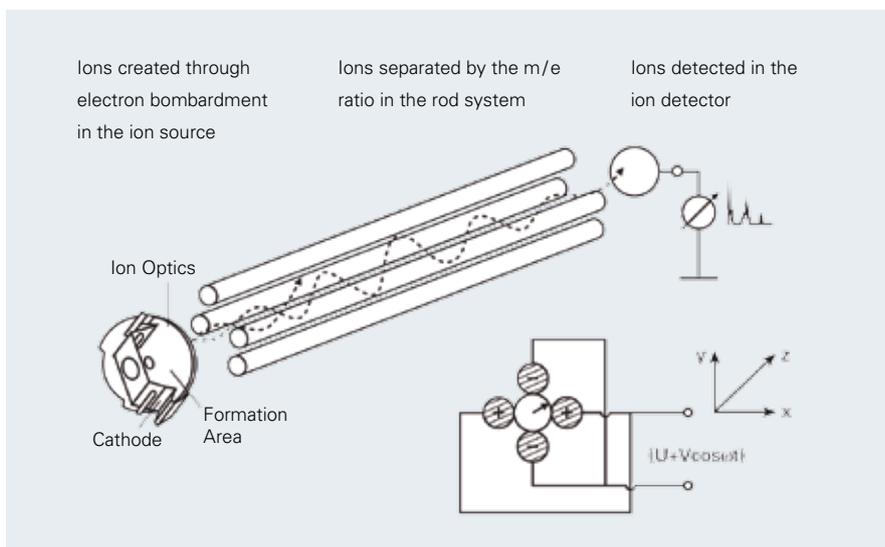


Figure 4.4: Operating principle of a quadrupole mass spectrometer

Ideal quadrupole fields require rods that have a hyperbolic profile. In actual practice, however, round rods are used, with the rod radius being equal to 1.144 times the field radius r_0 . An electrical quadrupole field is formed between the rods. Ions of varying mass are shot axially into the rod system at approximately equal energy and move through the rod system at uniform velocity. The applied quadrupole field deflects the ions in the X and Y directions, causing them to describe helical trajectories through the mass filter. To solve the movement equations, the dimensionless variables

Formula 4-2
Stability parameter a

$$a = \frac{8 \cdot e \cdot U}{m \cdot r_0^2 \cdot \omega^2}$$

and

Formula 4-3
Stability parameter q

$$q = \frac{4 \cdot e \cdot V}{m \cdot r_0^2 \cdot \omega^2}$$

are introduced to obtain Mathieu's differential equations. Their solutions yield the stable area with oscillation amplitudes of less than r_0 beneath the triangle formed by the two solubility curves in Figure 4.5. The values $a_p = 0.23699$ and $q_p = 0.706$ apply for the apex of the triangle. All solutions outside result in increasing oscillation amplitudes and thus in neutralization of the ions on the rods of the quadrupole filter.

Dividing the two equations by one another yields: $\frac{a}{q} = 2 \cdot \frac{U}{V}$.

This is the pitch of the so-called load line of the mass filter.

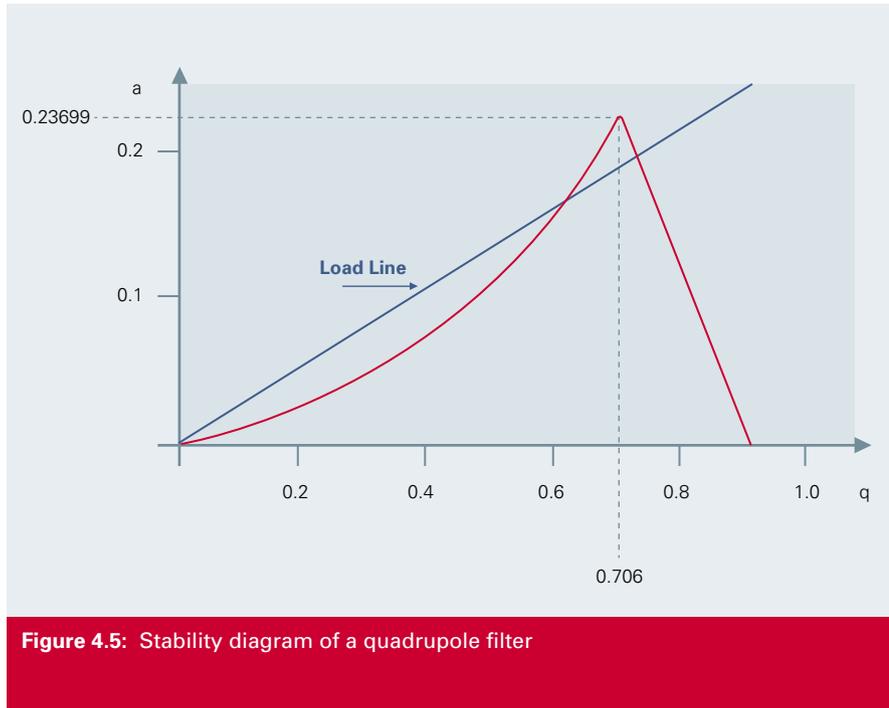


Figure 4.5: Stability diagram of a quadrupole filter

From Figure 4.5, it can be seen that:

- ▶ All ions whose parameters a and q are located in the triangle above the load lines will reach the detector
- ▶ The ions will only reach the detector under voltage conditions $\frac{U}{V} = \frac{a_p}{2 \cdot q_p} < 0.1678$.

Introducing the ratio between the atomic mass unit $1 \text{ amu} = 1.66055 \cdot 10^{-27} \text{ kg}$ and the elementary charge $e = 1.602 \cdot 10^{-19} \text{ A} \cdot \text{s} \cdot \frac{m_{\text{amu}}}{e} = 1.0365 \cdot 10^{-8} \frac{\text{kg}}{\text{A} \cdot \text{s}}$ and multiplying it by the dimensionless mass number M of the corresponding ion yields the following conditions for U and V for the apex of the stability triangle:

Formula 4-4
Stability condition U

$$U = 1.2122 \cdot 10^{-8} \frac{\text{kg}}{\text{A} \cdot \text{s}} \cdot M \cdot r_0^2 \cdot f^2$$

and

Formula 4-5
Stability condition V

$$V = 7.2226 \cdot 10^{-8} \frac{\text{kg}}{\text{A} \cdot \text{s}} \cdot M \cdot r_0^2 \cdot f^2$$

With the DC voltage de-energized, $U = 0$, all trajectories of the ions where $q < 0.905$ will be stable; according to Formula 4-5, these will all be masses where

Formula 4-6
High-pass condition

$$M > \frac{1.0801 \cdot 10^7 \cdot V}{r_0^2 \cdot f^2} \cdot \frac{\text{A} \cdot \text{s}}{\text{kg}}$$

The filter thus acts as a high pass. As HF amplitude (V) increases, ever-heavier types of ions become unstable, starting with the light masses, and are thus sorted out. This operating mode produces an integral spectrum.

The shot conditions are crucial for transmission of ions through the filter. Ions parallel to the rod system must be shot in within the following diameter:

Formula 4-7
Shot orifice

$$D = \frac{1}{2} \cdot r_0 \cdot \frac{M}{\Delta M}$$

The maximum shot angle must satisfy the condition:

Formula 4-8
Shot angle

$$\text{tg} \psi < 11.85 \cdot \frac{r_0^2}{L^2}$$

and the energy must be as uniform as possible. The advantages of the Pfeiffer Vacuum ion sources described in 4.1.4.1 translate into high transparency and thus high sensitivity.

In order for the amplitudes of the unstable ions to become large enough to strike the rods, where they are neutralized, these ions must perform a minimum number of oscillations in the separating field. The following equation applies for the maximum acceleration voltage in the Z direction:

Formula 4-9
Maximum acceleration
voltage U_{zmax}

$$U_{zmax} \approx 4.2 \cdot 10^{-6} \frac{\text{kg}}{\text{A} \cdot \text{s}} \cdot L^2 \cdot f^2 \cdot M \cdot \frac{\Delta M}{M}$$

In practical operation, the ratio U/V is activated as a function of the mass number in such a manner that the actual resolution $\Delta M/M$, does not remain constant, but that instead the line width ΔM remains constant. This means that resolution increases proportionally to the mass number. Due to Formula 4-5 (V is proportional to M), the quadrupole (as opposed to the sector field mass spectrometer) produces a linear mass scale.

One point of major significance for a QMS is the required HF power. If C is used to designate the entire capacity of the system and Q to designate the factor quality of the power circuit, the required HF power

Formula 4-10
HF power

$$N_{HF} \approx \frac{C}{Q} \cdot M^2 \cdot f^5 \cdot r_0^4$$

will increase with high powers of f and r_0 . An enlargement of field radius r_0 will lessen the occurring relative mechanical tolerances, thus resulting in improved behavior. Essentially, it is advantageous to select f_0 and r_0 as large as possible. However there are limits in this regard due to the associated increase in HF power (Formula 4-10). While extending the rod system permits a lower operating frequency, the size of a production unit should not exceed certain dimensions.

The required mass range and desired resolution are governed by the dimensions of the filter and the selection of the operating frequency. Devices with 6, 8 and 16 mm rod diameters and appropriately matched electronics are available to satisfy the respective requirements.

What follows is a brief digression on the relationship between resolution and mechanical precision. Let us consider a quadrupole mass filter that works at the apex of the stability diagram; i.e. that works at high resolution.

$$U = 1.2122 \cdot 10^{-8} \frac{\text{kg}}{\text{A} \cdot \text{s}} \cdot M \cdot r_0^2 \cdot f^2 \quad \text{Formula 4-4 applies for the DC amplitude}$$

$$\text{and Formula 4-5 } V = 7.2226 \cdot 10^{-8} \frac{\text{kg}}{\text{A} \cdot \text{s}} \cdot M \cdot r_0^2 \cdot f^2 \quad \text{for the AC amplitude.}$$

Here, M designates the mass of the ion, r_0 the field radius and f the frequency at which the filter is operated. We are making the idealized assumption that both voltages U and V , as well as frequency f , can be set and maintained "as precisely as desired."

What follows from this is: $M = c_k \cdot \frac{1}{r_0^2}$ (c_k is a constant), and following differentiation and division by M , the filter scatter caused by r_0 is:

Formula 4-11
Scatter

$$\frac{dM}{M} = \frac{-2 \cdot dr_0}{r_0}$$

Let us assume that the field radius r_0 changes by $\Delta r_0 = 0.03$ mm over the length of the mass filter. Now let us consider the effect of this change on scatter $\Delta M/M$ for two mass filters of different sizes. For optimal transmission, the resolution set on the spectrometer (we select: $\Delta M/M = 1/100$) must be greater than the scatter generated by the fluctuation of r_0 :

$$\frac{\Delta M}{M} > \frac{-2 \cdot \Delta r_0}{r_0} .$$

For a filter (a) having a field radius of 3 mm, this results in $\Delta M/M = 0.02$, i.e. a contradiction; and for a filter (b) having a field radius of 12 mm, this results in $\Delta M/M = 0.005$, i.e. coincidence with the above condition. In other words: If a resolution of $\Delta M/M = 0.01$ has been set for both filters, most of the ions will not be able to pass through the filter in case (a). In the case of the larger filter (b), all ions will be able to pass through the filter, since the set resolution is greater than the scatter.

Although this simplified error calculation does not nearly take into account all of the effects that can contribute to transmission, it does teach several fundamental relationships:

- ▶ The field radius must be maintained significantly better than 1% over the entire length of the filter, depending on the selected mass range. Fluctuations in the field radius will lead to transmission losses
- ▶ The larger the dimensions of the rod system are selected, the lower the influence of the absolute mechanical tolerances will be

- The higher the mass range, and if differentiation between adjacent masses is still to be made, the stricter will be the requirements relating to the relative accuracy of the mass filter. In this simple picture, the required relative accuracy is scaled linearly with the mass range

Summary

A quadrupole mass filter is a dynamic mass filter for positive and negative ions. The mass scale is linear to the applied amplitude of the HF voltage. Mass resolution can be conveniently and electrically set by means of the ratio between the DC voltage U and the high-frequency voltage amplitude V . Due to their small dimensions and light weight, quadrupole mass spectrometers are suitable both as pure residual gas analyzers and, in higher-quality design, as sensors for gas analysis.

4.1.2.2 Ion sources

Before gases can be analyzed in a mass filter, they must first be ionized in an ion source by means of electron bombardment.

Electrons are emitted from an electrically heated cathode (filament). A voltage is applied between anode and cathode, which accelerates the electrons. Neutral gas molecules that are present in the formation space between anode and cathode are ionized by collisions between electrons, forming single and multiple positive ions. The energy of the colliding ions exerts a significant influence on both the number and type of ions that will be formed.

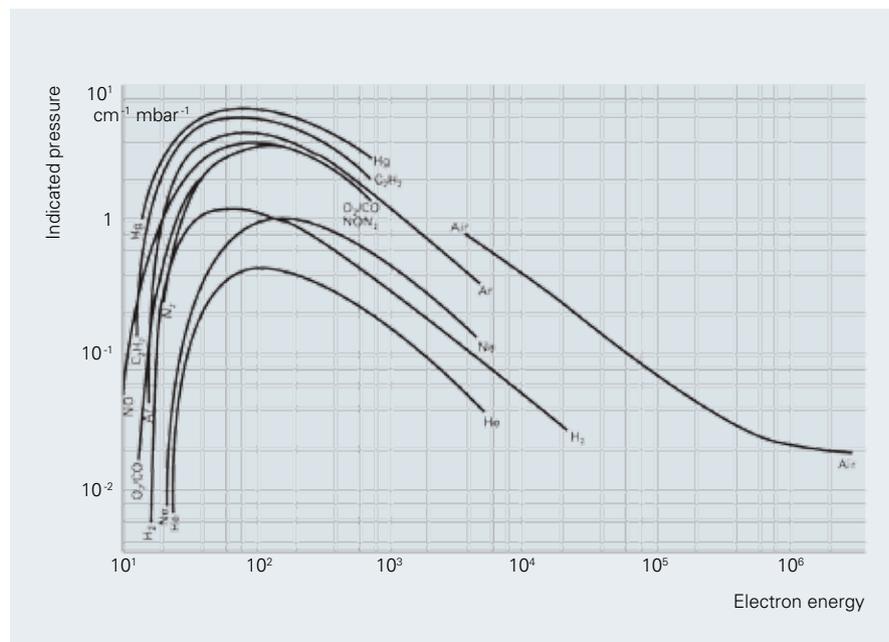


Figure 4.6: Ion density as a function of electron energy

Source: Pupp / Hartmann, *Vakuumtechnik, Grundlagen und Anwendungen*, Hanser Verlag

Ionization of the neutral particles commences at a minimum electron energy of between 10 and 30 eV (appearance potential). The number of formed ions quickly increases as electron energy rises (acceleration voltage), reaches a maximum at 50 to 150 eV depending upon the type of gas in question, and slowly declines again as energy continues to rise. Since the yield in ions, and thus the sensitivity of the mass spectrometer, should be as large as possible, electron energies between 70 and 100 eV are typically used.

The ion current I_{K^+} of a gas component K can be calculated from the following relationship:

Formula 4-12
Ion current

$$I_{K^+} = \dot{i}_- \cdot l_e \cdot s \cdot p_K$$

Where:

\dot{i}_- = electron current (emission current), in A

l_e = mean path length of the electrons, in cm

s = differential ionization effect cross section K, in $1/(\text{cm} \cdot \text{mbar})$

p_K = partial pressure of the gas component K, in mbar

Many types of ions are formed when ionizing complex molecules. In addition to single- and multiple-charge molecule ions (ABC_x^+ , ABC_{x+}^+) fractal ions also occur:

- ▶ $\text{ABC}^+ + 2e^-$
- ▶ $\text{ABC}^{++} + 3e^-$
- ▶ $\text{AB}^+ + \text{C} + 2e^-$
- ▶ $\text{BC}^+ + \text{A} + 2e^-$
- ▶ $\text{A}^+ + \text{BC} + 2e^-$
- ▶ $\text{C}^+ + \text{AB} + 2e^-$
- ▶ $\text{B}^+ + \text{A} + \text{C} + 2e^-$

In addition to these types, it is also possible for recombination ions, such as AC^+ , to form.

The occurrence and relative frequency of individual types of ions are characteristic of a certain type of molecule and serve as an important aid in identifying the molecule, and thus as an aid in qualitative gas analysis. Figure 4.7 shows the fragment ion distribution (cracking pattern or fractal pattern) of the simple molecule CO_2 , recorded at 70 eV of electron energy.

Selection of the ion source and the optimal filament material is based upon the requirements imposed by the measurement task. Applications often impose contradictory requirements on the ion source. In order to achieve optimal results, the ion source must be matched to the task at hand. This has resulted in the development of different types of ion sources that can almost all be equipped with cathodes made of rhenium (Re), tungsten or yttriated iridium ($\text{Y}_2\text{O}_3/\text{Ir}$).

T-cathodes are preferred in the UHV range or where the vapor pressure of Re could have a disturbing effect. However the brittleness of tungsten cathodes due to the tungsten/carbon/oxygen cycle must be taken into account; i.e. due to the formation of W_2C . Yttriated iridium is increasingly being used today instead of the pure metal cathodes that were used in the past. The advantages offered by these cathodes are significantly lower operating temperature and relative insensitivity to air inrush. Consequently, the preferred fields of implementation for these cathodes are analysis of temperature-sensitive substances, e.g. metal-organic compounds, or analysis of contaminants in gas mixtures containing a high concentration of oxygen.

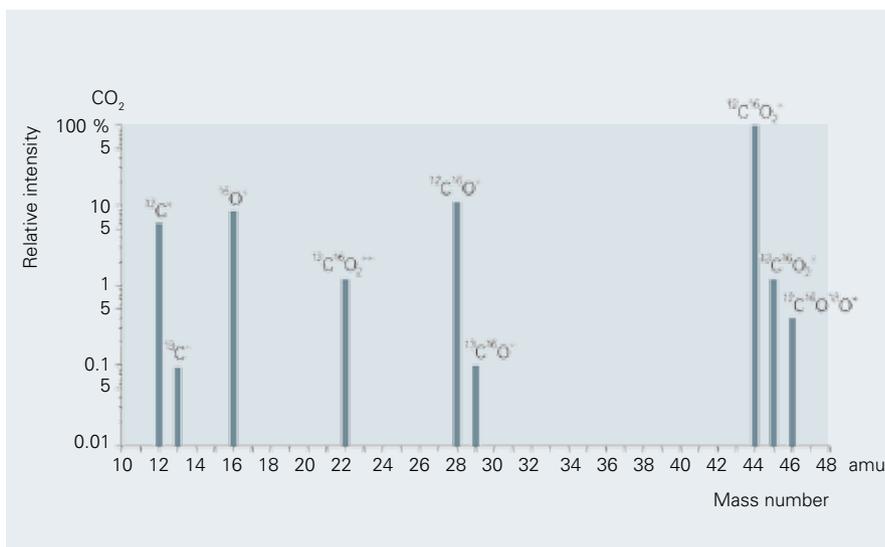


Figure 4.7: Fractal ion distribution of CO₂

Table 4.1: Filament materials and their employment

Material	Temperature	Applicable Gases	Remarks
Y ₂ O ₃ /Ir	1,300 °C	Inert gases, Air/O ₂ , NO _x , SO _x	Short service life with halogens, insensitive to high O ₂ concentrations, generates some CO/CO ₂ from O ₂ or H ₂ O background
W	1,800 °C	Inert gases, H ₂ , halogens, freons	Short service life with O ₂ applications, generates some CO/CO ₂ from O ₂ or H ₂ O background, C causes brittleness
Re	1,800 °C	Inert gases, hydrocarbons, H ₂ , halogens, freons	Service life around three months due to vaporization of the material, used in connection with hydrocarbons

The various ion sources are described below on the basis of their attributes and fields of application. What all ions have in common is that they can be electrically biased up to 150 V. This avoids signal background due to ESD ions. This technology will be explained in detail later.

Axial ion source

This ion source is characterized by its extremely robust mechanical design and high sensitivity. It is primarily employed for residual gas analysis in high vacuum systems due to its open construction. Figure 4.8 shows a schematic diagram of an axial ion source.

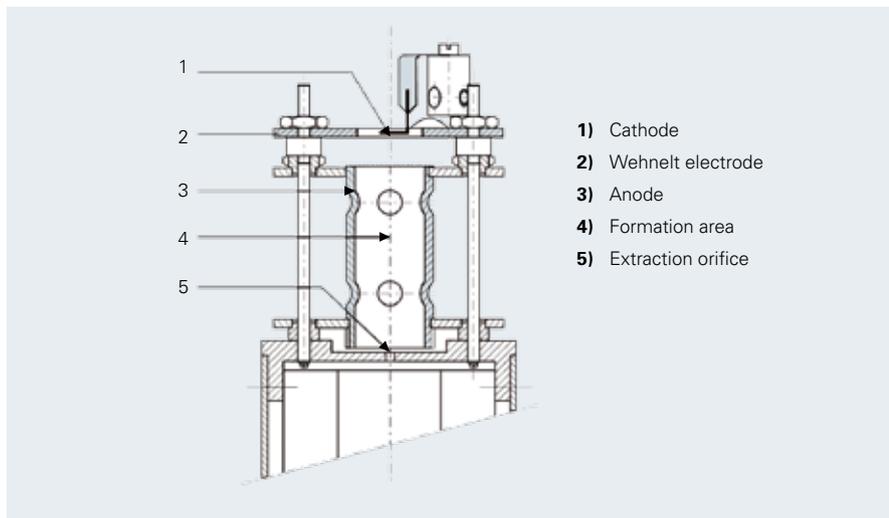


Figure 4.8: Section through an axial ion source

The cathode (1) is arranged within a hole in the Wehnelt electrode (2) and is connected with this electrode on one side. The electrons accelerated toward the anode (3) ionize gas molecules in the formation area (4). The positive ions reach the mass filter through the extraction orifice (5). Due to its relatively open construction, only minor falsification occurs through desorption and surface reactions.

Lattice ion source

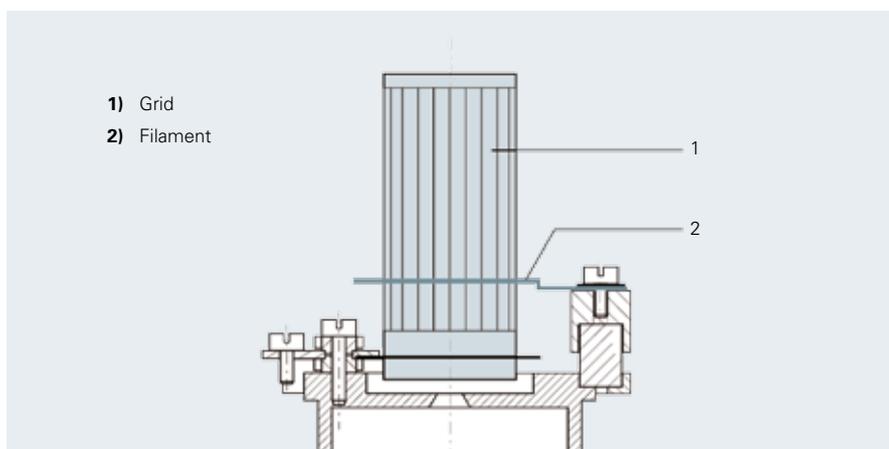
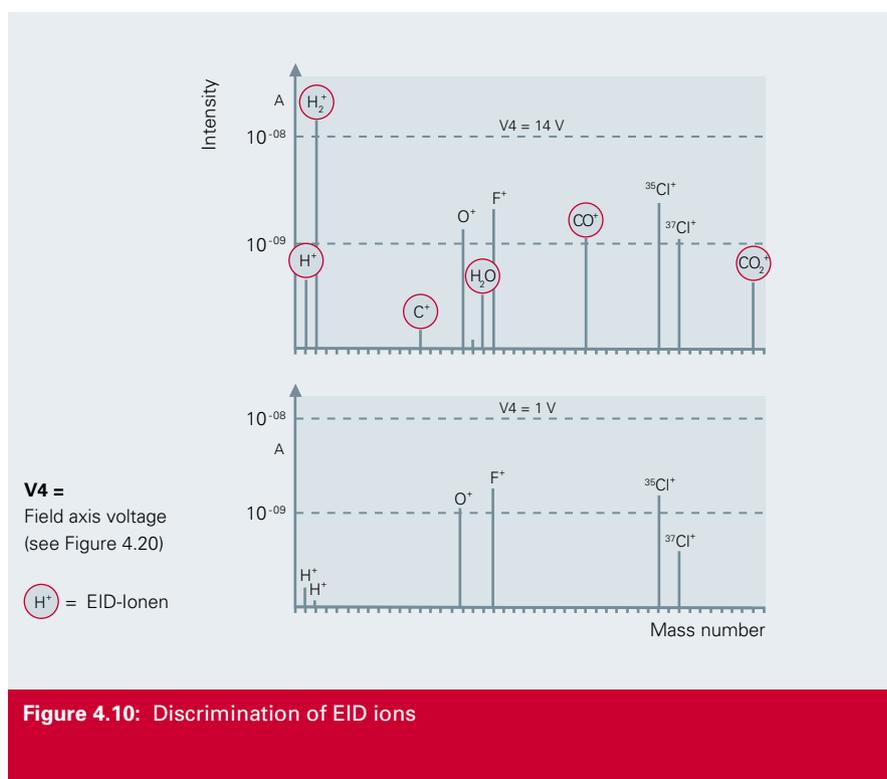


Figure 4.9: Lattice ion source

A lattice ion source is used to examine residual gas in UHV or even XHV applications. Its extremely open construction and the selection of materials ensure extremely low internal gas emission. This ion source is equipped with two tungsten filaments that can be heated simultaneously for degassing. If work is to be performed at temperatures below 10^{-11} mbar, rod systems that have been highly degassed especially for this purpose would be used. Measurements in the pressure range below 10^{-10} mbar can be falsified by so-called EID (electron impact desorption) ions. These (H^+ , O^+ , F^+ , Cl^+) ions are directly desorbed by electron bombardment of surfaces, often with a high yield. EID ions come from adsorbed coatings that originate earlier in the history of the UHV equipment or the ion source, and usually have an initial energy of several eV. This attribute is utilized by skilled selection of the field axis voltage to suppress the EID ions relative to ions from the gas phase having energy of approximately eV, (Figure 4.10).



Crossbeam ion source

A crossbeam ion source (Figure 4.11) allows direct passage of molecular beams perpendicular and parallel to the system axis. The system emits electrons with pre-selectable energy (90 – 120 eV) into the formation area (3), from either the left or the right filament (1). The Wehnelt cylinder (4) at filament potential prevents the electrons from scattering to the environment. Because the electron energy can be set within broad limits, this ion source can be used to determine the appearance potential. The crossbeam ion source very precisely maintains the shot conditions of the ions into the mass filter.

Crossbeam ion sources are used for diagnosing bundled molecular beams. In this process, the molecular beam is shot into the formation area perpendicular to the axis of the plane of projection (Figure 4.11). After passing through the ion source (7), un-ionized neutral gas molecules are either channeled into a pump or into a cold trap for condensation. Mass spectrometers with this type of ion source are also used as „rate meters“ for molecular beam epitaxy.

- 1) Cathode
- 2) Anode
- 3) Formation area
- 4) Wehnelt electrode
- 5) Lens
- 6) Extraction orifice
- 7) Opening for molecular beam

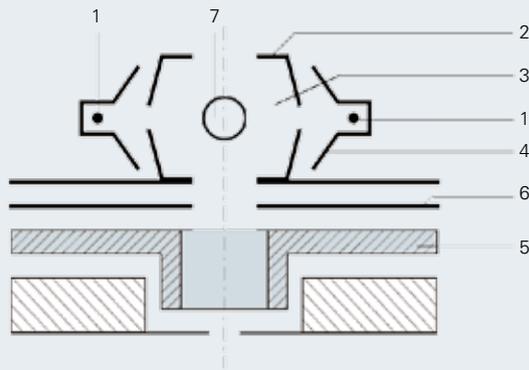


Figure 4.11: Crossbeam ion source

Gas-tight ion sources

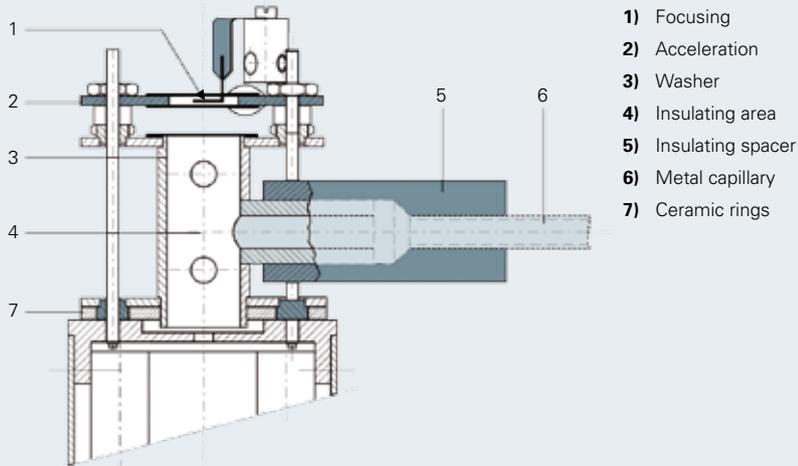


Figure 4.12: Gas-tight axial ion source

Some of the above-described ion sources are also available in gas-tight versions. Gas-tight ion sources are used if only small quantities of gas samples are available, or if the signal background generated by residual gas needs to be effectively suppressed. In this connection, the gas inlet system (e.g. a heated capillary) and the ion source must be matched to one another. The inflowing gas volume will determine the pressure in the formation area, which can be a multiple of the pressure in the surrounding vacuum chamber, by means of the conductivity of the ion source. The operating principle will now be presented using an axial ion source by way of example (Figure 4.12).

The gas to be analyzed is introduced directly into the formation area via a metal capillary (6) that is at ground potential and an insulating spacer (5). The conductivity to the vacuum chamber is approximately 1 l/s.

Sputter process monitor (SPM) ion source

In this ion source, the formation area (7) communicates directly with the process chamber. The analyzer is equipped with a small turbopumping station (1), which also evacuates the cathode space (5) to approximately 10^{-5} mbar. Electrons are shot into the formation area (7) from the low pressure side through small holes in order to ionize them.

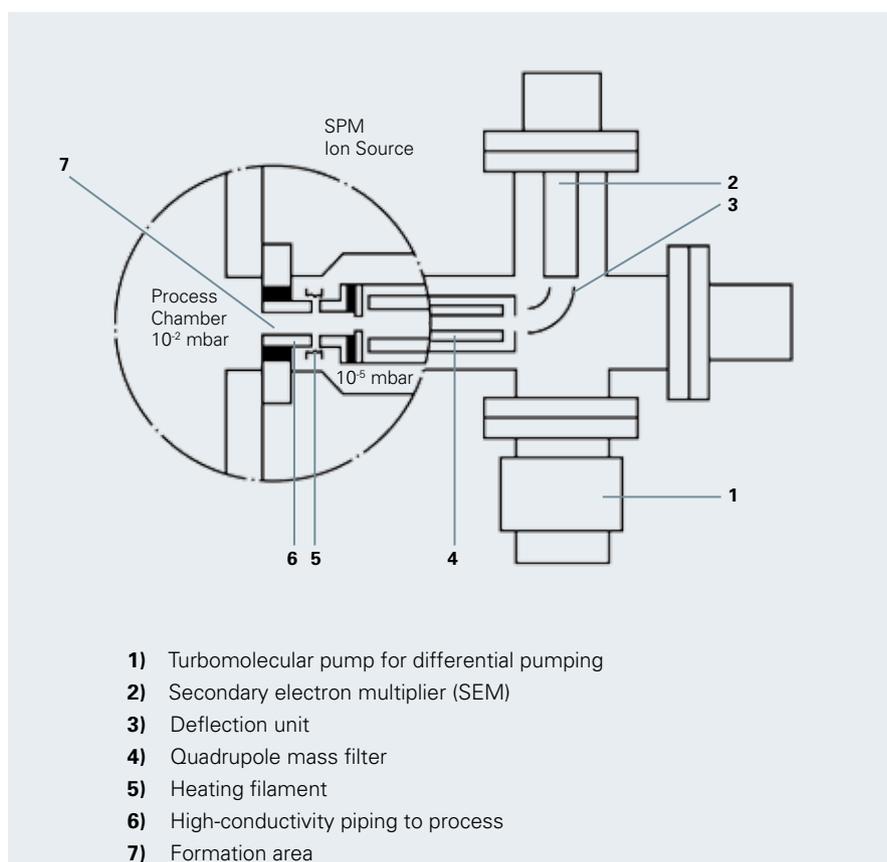
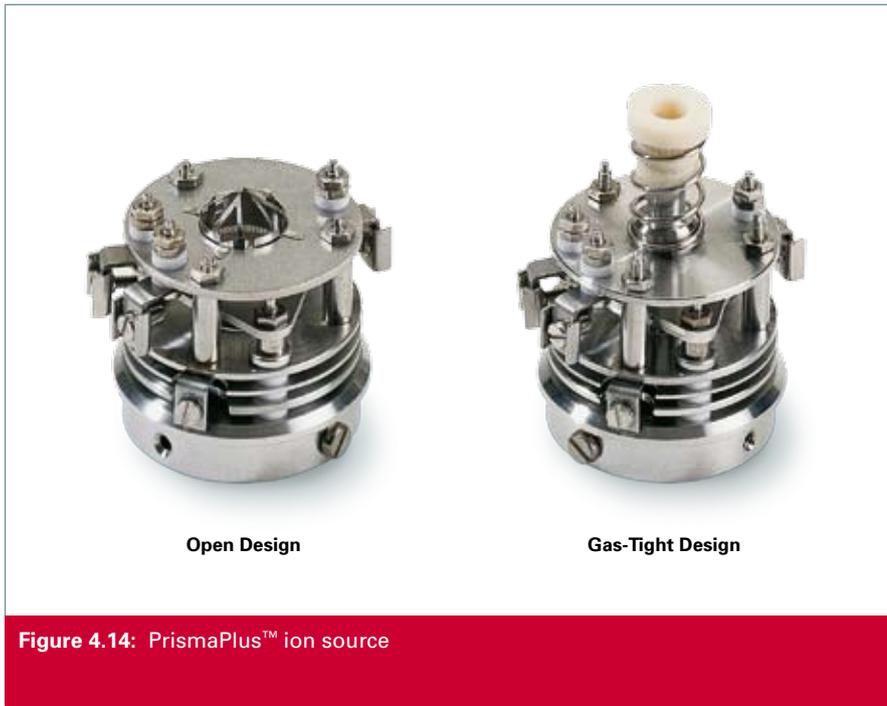


Figure 4.13: Sputter process monitor (SPM) ion source

The ions thus formed are also extracted to the mass filter through a small opening to the low-pressure side. This ion source offers two crucial advantages for examining the composition of the gas in sputtering processes. On one hand, the analysis is performed at an ion source pressure that is up to three orders of magnitude higher; i.e. a higher concentration of residual gas can be tolerated in the vacuum chamber. On the other hand, the hot filament is not in direct contact with the sputtering process. This avoids contamination by the hot cathode for sensitive processes.

Standard PrismaPlus™ ion source

The PrismaPlus mass spectrometer from Pfeiffer Vacuum is equipped with this robust and highly sensitive ion source. It is an ion source that is especially suitable for residual gas analysis. Its design is comparable to that of a lattice source; like the lattice ion source, it has two cathodes, thus affording particularly secure operation. Both an open version as well as a gas-tight version with gas inlet in the axial direction are available.



All ion sources described here ionize by means of electron collision. The ion sources can be categorized into two groups:

- ▶ Open ion sources are used if the process gas is to be analyzed and additional pressure reduction is not required
- ▶ Closed ion sources are used in analytical applications, for example, in order to require only small volumes of gas or to increase sensitivity relative to the substrate of the vacuum system

Closed ion sources are used in combination with a differentially pumped system (Figure 4.13) in order to analyze higher-pressure gases.

4.1.2.3 Detectors

The ions that are separated in the rod system on the basis of their mass-to-charge ratio can be electrically detected by means of various types of detectors:

- ▶ By means of a Faraday cup for direct measurement of the ion current using an electrometer amplifier
- ▶ Using a secondary electron multiplier (SEM) of discrete design with individual dynodes
- ▶ By means of a continuous secondary electron multiplier (C-SEM)

Detector selection will primarily be based upon requirements that relate to detection sensitivity, detection speed and signal-to-noise ratio. However it will also be governed by other application-specific requirements that relate to stability, thermal and chemical resistance, as well as space requirements.

Faraday cup

In the simplest case, the ions strike a Faraday collector (Faraday cup), where they emit their electrical charge.

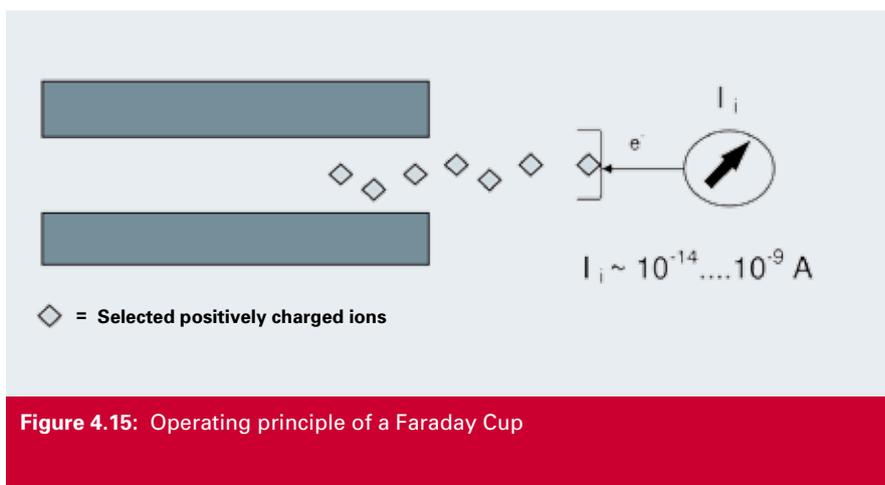


Figure 4.15: Operating principle of a Faraday Cup

The resulting current is converted to a voltage that is proportional to the ion current by means of a sensitive current/voltage inverter (electrometer amplifier). Because it is necessary for the input resistance R of the current amplifier to be extremely high, time constants $\tau = R \cdot C$ where $0.1 \text{ s} < \tau < 100 \text{ s}$ occur together with the capacities C of the measurement lead. Depending upon the time constant, the measurement limit is between $1 \cdot 10^{-16}$ and $1 \cdot 10^{-14} \text{ A}$.

In addition to its simple, robust design, a Faraday detector is characterized by its long-term stability and its ability to withstand high temperatures. To keep the time constants small and to avoid other interfering effects, the electrometer amplifier is connected directly to the analyzer and its output signal is supplied directly to the data analysis system. This is why the Faraday Cup is also present in all Pfeiffer Vacuum mass spectrometers. It is only suitable for detecting positive ions.

If extremely small ion currents are to be measured or if an extremely high measuring speed is required, physical pre-amplifiers, so-called secondary electron multipliers, are used.

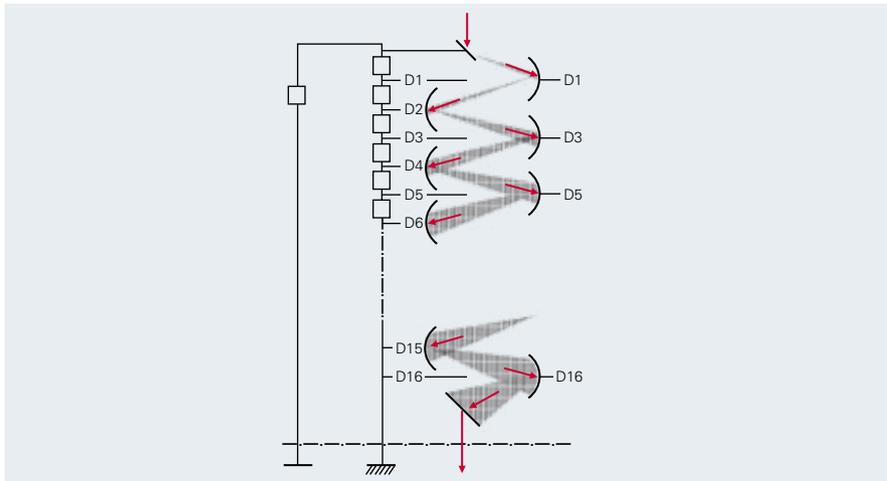


Figure 4.16: Secondary electron multiplier (SEM)

Figure 4.16 shows the design of such an amplifier. Cylindrically shaped pieces of sheet metal (dynodes) are coated with a layer that affords a low level of electron work function. Depending upon its kinetic energy, an ion or an electron generates multiple secondary electrons upon striking this layer. Connecting multiple stages in series produces an avalanche of electrons from a single ion. Positive voltages of approximately 100 V are applied between the dynodes to accelerate the electrons. Technical implementation of this arrangement is produced by supplying a high voltage (approximately 3,000 V) to it by means of a resistance chain, with the individual dynodes being connected to the taps of this voltage. The positive high-voltage pole is grounded to keep the escaping electrons at approximately ground potential. These types of arrangements produce current amplification factors of 10^7 .

A secondary electron multiplier offers the following advantages over a Faraday cup:

- ▶ It dramatically increases the sensitivity of the instrument, affording sensitivity increases of up to 10 A/mbar
- ▶ This means that lower partial pressures can be scanned at shorter intervals of time with the downstream electrometer amplifier
- ▶ The signal-to-noise ratio is significantly higher than that of an electrometer amplifier, which means that the detection limit can be lowered by several orders of magnitude. This applies only if a lower dark current (noise portion) is also flowing in the SEM at high amplification. An increase in sensitivity in its own right is of little value

However an SEM also has disadvantages:

- ▶ Its amplification can change due to contamination or a chemical change in the active layer
- ▶ The number of electrons (conversion factor) that generate a colliding ion (approximately 1 to 5 electrons) will be a factor of the ion energy (mass discrimination)

Amplification changes as a result of this effect. Consequently, it must be calibrated from time to time. Changes in amplification can easily be adjusted by modifying the high voltage. The conversion factor can be kept constant by supplying the first dynode with a separate high voltage that seeks to equal the energy of the various ions.

Table 4.2: Detectors and their attributes

	PrismaPlus™	HiQuad™ with SEM 217	HiQuad™ with SEM 218
Detectors	Faraday / C-SEM	Faraday / SEM	Faraday / SEM with conversion dynode
Maximum possible pressure, Faraday	10 ⁻³ mbar	10 ⁻⁴ mbar	10 ⁻⁴ mbar
Maximum possible pressure, SEM/C-SEM	10 ⁻⁵ mbar	10 ⁻⁵ mbar	10 ⁻⁵ mbar
Maximum measuring speed/amu	2 ms	125 μs	125 μs
Bake-out temperature (max)	300	400	400
Counting operation	No	Yes	Yes
Detection of positive ions	Yes	Yes	Yes
Detection of negative ions	No	Yes	No
Counter option	No	Yes	Yes

Extremely fast measurements are possible with the aid of secondary electron multipliers. As can be seen from Table 4.2, the measuring speeds are significantly higher than with a Faraday cup.

In addition to operation as current amplifiers, discretely designed SEMs are also suitable as ion counters. Extremely low count rates of 1 ion per 10 s can be attained with this configuration. High count rates are also possible, producing an extremely broad dynamic range by comparison with operation as a current amplifier.

In the counting mode, the speed of the SEM serves as the upper limit of the dynamic range. With a pulse width of 20 ns, non-linearity begins at a count rate of 10⁶ events per second. Given its pulse width, the SEM must be suitable as a counter.

What all secondary electron multipliers have in common is that they are restricted to operating at pressures of less than 10⁻⁵ mbar. At pressures of more than 10⁻⁵ mbar, the layer of water on the dynodes can lead to pyrolysis in operation, and thus to premature aging. Due to the high voltages involved, gas discharges that could destroy the SEM can occur at high pressures.

A C-SEM (Figure 4.17) is a continuous secondary electron multiplier, in which ions trigger an electron avalanche through secondary electron emissions. It consists of a glass tube whose interior is coated with a conductive layer that has high resistance and a low work function. High voltage is applied to the layer in order to obtain a uniform voltage gradient throughout the length of the tube. Ions from the quadrupole system are routed to the conversion dynode and generate secondary electrons that trigger an electron avalanche in the tube. Current amplification factors of 10⁶ are attained at an amplification current of 2.5 kV.

Here, too, amplification and dark current govern the signal-to-noise ratio, and the maximum current/dark current ratio of 10⁶ the current amplification factor. Thanks to a C-SEM arrangement that is slightly offset relative to the axis of the quadrupole, both a Faraday cup as well as a C-SEM can be used next to one another in the analyzer, with changeover from one detector to the other even being possible when necessary.

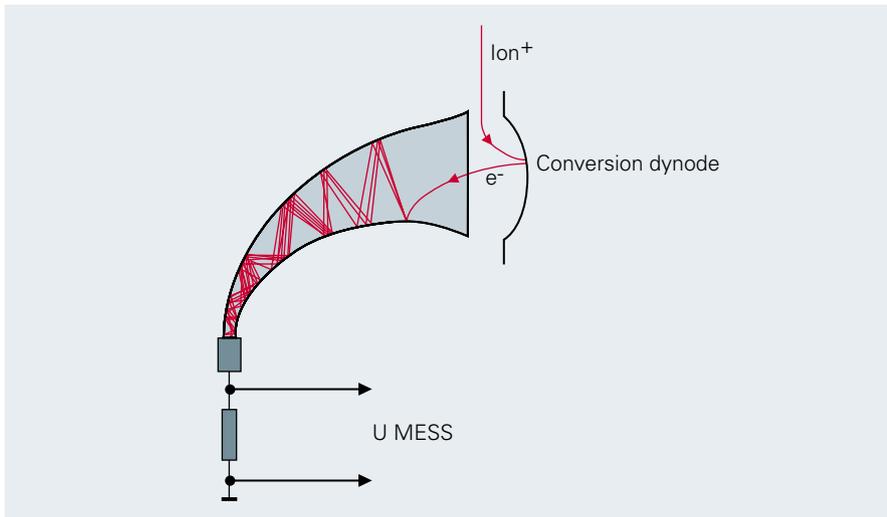


Figure 4.17: Operating principle of a C-SEM

4.1.2.4 Vacuum system

Pressures of less than 10^{-4} mbar are required for operation of quadrupole mass spectrometers. This necessitates an appropriate pumping station with pressure monitoring. In order to perform gas analysis with optimal sensitivity, only a low a base pressure is necessary and the residual gas should only contain unavoidable partial pressures stemming from desorption from the walls of the equipment. Residual gas spectra of this type and low base pressures are best attained with turbo drag pumping stations (Figure 2.22). An additional total pressure gauge protects the mass spectrometer against being energized at excessively high pressures.

When setting up such a system, attention must be paid to meaningful arrangement of gas inlet, valves, pumps and measurement instruments in order to avoid falsification stemming from unfavorable flow conditions. A separate pumping station that evacuates the measurement system is often required during the course of vacuum processes that run at high pressure. Small pumping stations with turbo drag pumps and diaphragm pumps are used for this purpose.

4.1.2.5 Inlet system

Many vacuum technology processes that are monitored by mass spectrometers occur in pressure ranges of more than 10^{-4} mbar. Gases to be analyzed must also be relieved from atmospheric pressure to pressures of less than 10^{-4} mbar. Differing pressure reducing procedures are used, depending on the pressure gradient in question.

Gas mixtures should be admitted to the mass spectrometer without de-mixing if possible:

- ▶ At pressures p of more than 10 mbar, pressure is reduced by means of a (heatable) capillary, in which laminar flow prevails, with a downstream gas inlet valve. Under some circumstances, pressure reduction by means of an additional pump will be necessary upstream of the valve

- ▶ At pressures p of less than 10 mbar, pressure is reduced by means of an orifice and with a mass spectrometer that is differentially pumped by means of a turbomolecular pump
- ▶ At pressures p of less than 10^{-4} mbar, the mass spectrometer can be installed directly in the process chamber with an open ion source

Table 4.3: Various gas inlet systems and their attributes

Inlet System	Pressure Range	Product Example	Characteristics
No pressure reduction	10^{-12} to 10^{-4} mbar	PrismaPlus QMG 220, HiQuad QMG 700	A further pressure range can be covered with various ion sources
SPM ion source	10^{-9} to 10 mbar	PrismaPlus SPM 220, HiQuad SPM 700	Special ion source for analyzing sputter processes. This system analyzes the unfalsified state of the plant by means of pressure reduction
Capillary inlet	700 to 1,100 mbar, as a function of capillary length and upstream orifice	OmniStar, ThermoStar, GES 020 and GES 010 inlet system	Differentially pumped inlet system, low mass discrimination, not suitable for changing inlet pressures
Orifice inlet	0.1 to 10 mbar, as a function of orifice diameter	PrismaPlus HPA 220	Orifices with diameters of 0.01 to 0.5 mm, simple, robust design, mass discrimination, changing inlet pressure possible with various orifice diameters, not suitable for fast-changing gas compositions
Metering valve	0.1 to 1,000 mbar	HPA 220 PrismaPlus, UDV 040 to 146 metering valves	Metering valves are suitable for gas inlet throughout a very broad measurement range, differentially pumped valves also enable analysis of rapidly changing gas compositions
Pressure-regulated gas inlet	10^{-3} to 1,000 mbar	EVR 016 with RVC 300, OmniStar with pressure-regulated inlet	Differentially pumped inlet system, comprising a control loop with regulating valve and pressure measurement, relatively large dead volume, long gas changing times

4.1.3 Application notes

Mass spectrometer analysis is every bit as varied as vacuum applications. The above-described gas inlet systems with heated capillaries are used for gas analysis in the pressure range of up to 1 bar. Gas flows can be channeled directly to gas-tight ion sources in order to reduce the background noise of the vacuum environment. Gas beams are passed through crossbeam ion sources, with the beam either falling directly into a vacuum pump or condensing in a cooling trap.

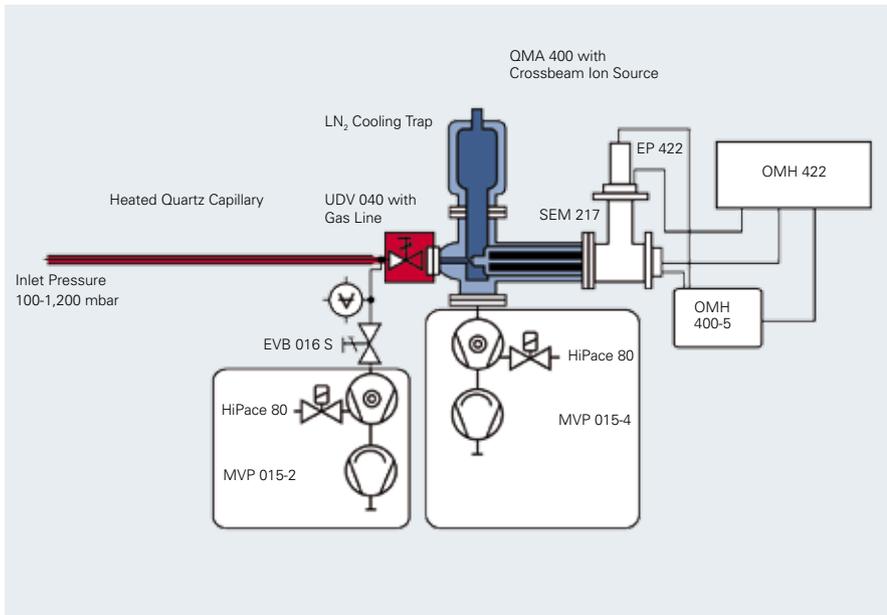


Figure 4.18: Quadrupole mass spectrometer with gas inlet system, crossbeam ion source and cooling trap

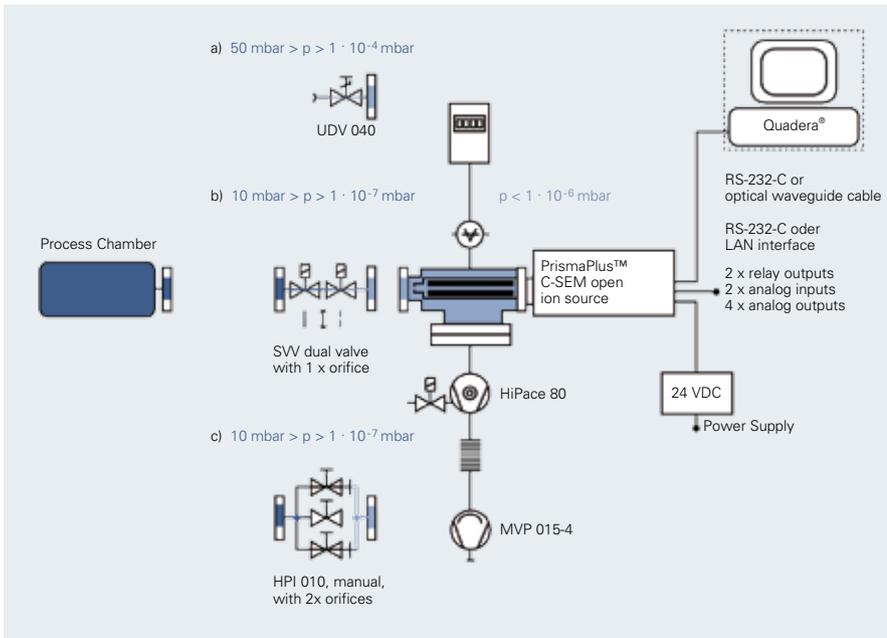


Figure 4.19: Differentially pumped quadrupole mass spectrometer with various gas inlets

In the pressure range of less than 10 mbar (etching, sputtering or other coating processes), the gas is admitted into the mass spectrometer via an orifice or a valve. A turbopump is attached to the measuring system for pressure reduction. There are special versions for corrosive gases.

Open ion sources are used at extremely low pressures, particularly in the UHV range. Due to the low gas densities, secondary electron multipliers (SEM) that are arranged perpendicular to the axis of the quadrupole must be used as detectors. To improve the signal-to-noise ratio, a turbopump that pumps down the inflowing neutral particles is attached opposite the SEM.

Secondary ion mass spectrometry (SIMS) represents a special case. In this process, ions are shot onto surfaces that generate positively or negatively charged secondary ions, which are detected directly by a QMS without an ion source. The measuring arrangement described in the preceding section is used in this case as well.

4.1.4 Portfolio

Pfeiffer Vacuum offers two basic mass spectrometer models:

- ▶ The compact PrismaPlus with a 6 mm rod system and a length of 100 mm, and
- ▶ The high-resolution HiQuad with mass filter diameters of 8 mm and 16 mm and a length of 300 mm

PrismaPlus™

This is a compact device whose entire electronics are attached to the analyzer and can be removed for bake-out. The PrismaPlus unites the following features:

- ▶ Mass ranges of 100, 200 and 300 amu
- ▶ A Faraday cup and a C-SEM are available as detectors
- ▶ Can be equipped with a variety of ion sources and filaments
- ▶ The analyzer can be baked out at up to 150 °C

The PrismaPlus is used as a standalone device, and can also be integrated into modules and analysis systems.

HiQuad™

These devices offer the utmost in accuracy and unite the following features:

- ▶ The 1–16 amu, 1–128 amu, 1–340 amu, 1–300 amu, 1–512 amu, 1–1,024 amu and 1–2,048 amu mass ranges can be covered by various models
- ▶ There are various mass filters with rod diameters of 6 mm, 8 mm molybdenum, 8 mm stainless steel and 16 mm molybdenum
- ▶ Virtually all of the above-described ion sources can be combined with the analyzers
- ▶ There are ion optics for analyzing neutral particles as well as both positive and negative ions (SIMS)
- ▶ All types of detectors, i.e. Faraday cup, Faraday cup and SEM, Faraday cup and C-SEM, as well as ion counters, are available in various arrangements
- ▶ These mass spectrometers can be integrated into analysis systems with the aid of input/output modules

Modules

Modules are special process monitoring or gas analysis devices that are equipped with various gas inlet systems and attached turbo drag pumps for evacuating the analyzer:

- ▶ The HPA 220 high-pressure analyzer, based upon the PrismaPlus
Process pressure up to 5 mbar
- ▶ The SPM 220 sputter process monitor, based upon the PrismaPlus
Process pressure up to 10^{-2} mbar or 10 mbar
- ▶ The SPM 700 sputter process monitor, based upon the HiQuad
Process pressure same as SPM 220
- ▶ The EPD 700 is used to detect positive ions when etching in the gaseous phase and is based upon the HiQuad, Process pressure up to 10^{-2} mbar

Benchtop mass spectrometers

There are complete systems for process pressures of 1 bar; they are based upon the PrismaPlus:

- ▶ The OmniStar GSD 320 O with one gas inlet is used for quantitative gas analysis at atmospheric pressure with heated and temperature-regulated gas inlet systems
- ▶ The ThermoStar GSD 320 T is designed to be coupled with thermal scales

These devices, or elements of them, are installed in complete devices by OEM customers.

4.1.4.1 Advantages of Pfeiffer Vacuum mass spectrometers

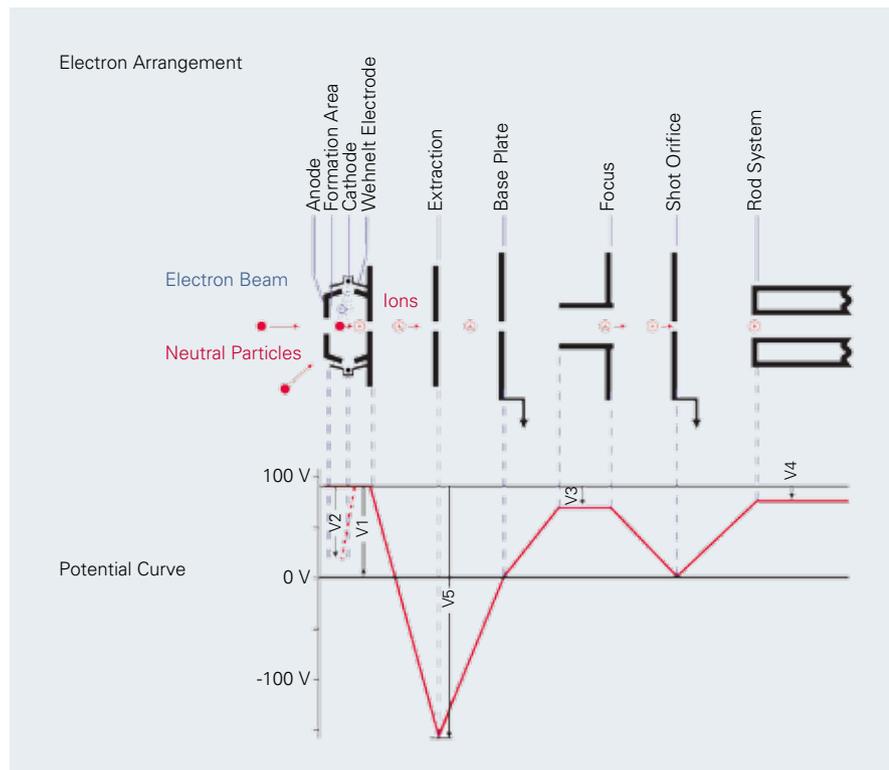


Figure 4.20: Potential curve in an electrically biased ion source

The potential curve in a Pfeiffer Vacuum ion source is shown in Figure 4.20. The heated, electron-emitting cathode has a potential of approximately 20 V. The Wehnelt electrode is typically connected to the positive pole of the cathode and prevents electrons from being scattered in the vicinity of the ion source. An anode voltage V_2 of 80 V accelerates the electrons into the formation area (100 V), where they ionize penetrating neutral gas molecules. The ions are accelerated through an orifice at a potential V_5 of -150 V, and are again decelerated to $V_3 = 80$ V by the focusing electrode. The shot orifice accelerates the ions once more before they then enter the mass filter and are decelerated by the field axis potential $V_4 = 85$ V at an energy of approximately 15 eV (difference between formation area and field axis).

The Pfeiffer Vacuum PrismaPlus and HiQuad mass spectrometers are characterized by their above-described electrically biased ion source and their field axis technology.

Electrically biased ion source

In many quadrupole mass spectrometers, the cathode is grounded or even has a negative potential. The cathode (filament) accelerates the emitted electrons to the formation area (anode), where they ionize neutral gas particles, which are then extracted in the mass filter. Given these field conditions, however, electrons can also strike other surfaces in the vacuum, where they trigger electron stimulated desorption (ESD) ions. This results in undesirable background noise and can cause considerable gas eruptions when the filament is energized if there are highly-populated surfaces in the recipient.

Pfeiffer Vacuum ion sources have a positive potential (approximately 10 – 100 V). Electrons emitted from them are repelled from all surfaces having a negative potential and are thus kept away from these surfaces to avoid triggering interfering ESD ions.

Field axis technology

The ions formed in the ion source are accelerated toward the mass filter at high kinetic energy. As a result, the ions cannot be influenced by the peripheral or interference fields, and initially move toward the mass filter at high energy. This enables optimal shot conditions to be achieved in the quadrupole field, even without the pre-filters that are required with other mass spectrometers. The mass filter, itself, is appropriately biased to the field axis voltage, which decelerates the ions to a kinetic energy of approximately 15 eV again upon entering the filter. This energy – which the industry terms the field axis voltage – together with the mass of the ions determines the velocity of the ions, and thus their time of flight in the mass filter. The favorable shot conditions thus produced result in a high transmission of ions through the mass filter over a broad mass range, thus producing the high sensitivity of the entire system.

SEM: 90 degrees off axis

An additional advantage of Pfeiffer Vacuum mass spectrometers is the arrangement of the secondary electron multiplier (SEM), which is offset by 90° relative to the filter axis (“SEM: 90 degrees off axis”).

If the SEM (4.1.2.3) is arranged in the axial direction behind the mass filter, all colliding particles (neutral particles, ions, electrons, photons) will generate secondary electrons and thus contribute to the background signal.

This is why the ions escaping from the filter are deflected by 90 degrees and then accelerated to the first dynode of the SEM. Neutral particles and photons are not deflected at all by the electrical deflection unit, and electrons are deflected to a much greater extent than ions. This means that almost all of the ions that are allowed through the filter will strike the amplifier, which significantly improves the signal-to-noise ratio. Except for a few special versions, HiQuad analyzers are equipped with “90 degrees off-axis SEMs.”

In the PrismaPlus, an axial C-SEM is offered as a current amplifier. In this case, too, the ions exiting the mass filter are deflected slightly toward the C-SEM, and in a weakened state are thus separated from the undesired particles.

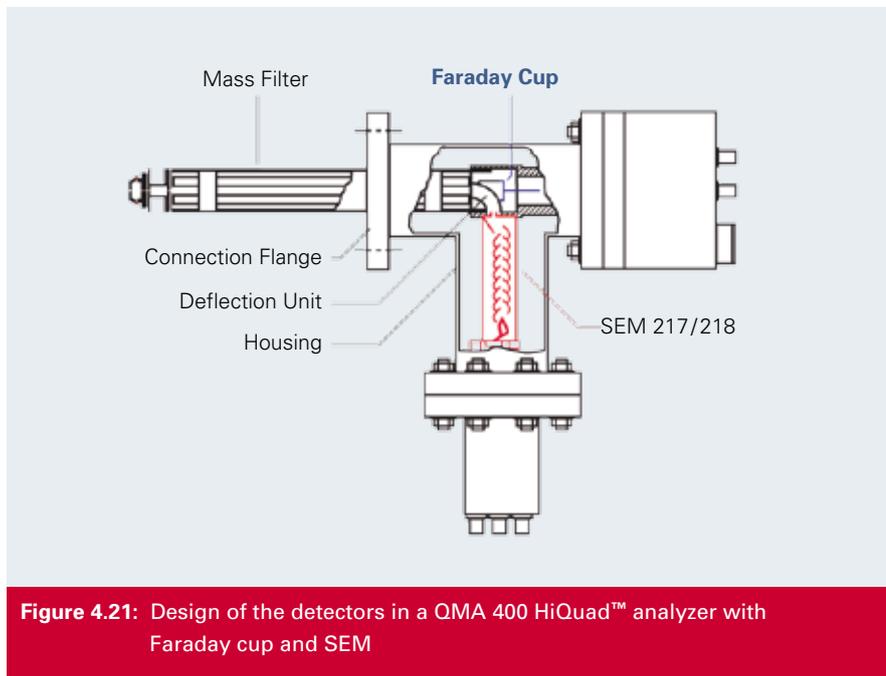


Figure 4.21: Design of the detectors in a QMA 400 HiQuad™ analyzer with Faraday cup and SEM

Mass discrimination

If ions strike the first dynode of the SEM with different pulses, differing quantities of secondary electrons will be generated. The conversion rate at the amplifier is a function of mass. This effect is called mass discrimination, and is less pronounced with an SEM of discrete design than with a C-SEM. Mass discrimination can be reduced by accelerating the ions to a high energy before they strike the conversion dynode.

Summary

Both a stable HF supply as well as a mechanically precise filter are necessary in order to achieve maximum possible transmission over a broad mass range with a pre-selected mass resolution. A biased ion source with suitably selected field axis technology, as well as the “90 degrees off-axis” arrangement of the SEM considerably improve the signal-to-noise ratio.

Mass discrimination in an SEM or a C-SEM can be reduced with the aid of a conversion dynode to which a high voltage is applied.

Quadrupole mass spectrometers differ from other designs through the following attributes:

- ▶ Compact dimensions and light weight
- ▶ Linear relationship between mass and HF voltage amplitude
- ▶ High sensitivity
- ▶ Large signal-to-noise ratio
- ▶ High measuring speed and repeat rate
- ▶ Broad dynamic range (up to 10 decades)
- ▶ Any installation orientation
- ▶ No magnetic field interference

With these advantages, the quadrupole mass spectrometer has become the most widely used mass spectrometer.

4.1.4.2 Data analysis systems

The electrical control units of Pfeiffer Vacuum mass spectrometers do not include any operating or display possibilities. Consequently, operation, data analysis, display and data storage are performed on a PC with the "Quadera" software.

Pfeiffer Vacuum's Quadera mass spectrometer software is a modular system. Quadera can be used with the PrismaPlus and HiQuad devices, which are equipped with newly developed electronics. The PC can be connected to the Prisma or HiQuad mass spectrometers via an Ethernet.

To perform certain measurement tasks, the PC transfers parameter records to the mass spectrometer in order to set the device. The data read out during or after the measurement is transferred back to the computer, where it can be analyzed, displayed or stored.

The following data are typically displayed:

- ▶ Mass spectra with adjustable mass range, and linearly or logarithmically calibrated for concentration
- ▶ Display of the chronological sequence of partial pressures
- ▶ Bar graph measurements to reduce the volume of data

Typical measuring tasks, such as residual gas analysis or leak detection, are pre-programmed and can be launched with a mouse click.

If quantitative analysis is to be performed, the mass spectrometer must be calibrated beforehand. If this involves recurring processes, such as calibration with subsequent quantitative analysis, these processes can be programmed by means of "visual basic for applications". Programming skills are not required, as pre-engineered modules are available for this purpose.

To solve complicated measurement tasks, a library containing fractal ion distributions for several frequently occurring gases and compounds is available in the Quadera software. However these and other distributions obtained from spectra libraries can only be viewed as guideline values, as they are influenced by various parameters, such as ionization energy, temperature or the transmission characteristics of the mass analyzer.

In analyzing mixtures containing multiple gas components, the problem of overlapping ion currents of differing origin on the same mass numbers is one that frequently occurs. There are mass numbers whose intensity is produced exclusively by a single gas component (e.g. argon on mass number 40, oxygen on mass number 32, carbon dioxide on mass number 44 and water on mass number 18).

In the case of other mass numbers, the overall intensity of the detected ion current is governed by the overlapping of different concentrations of fractal ions from diverse gas components. Depending upon the composition and concentration ratios in the gas mixture to be analyzed, suitable algorithms and calibration procedures must also be formulated for the measurement task in question.

Through the admission of suitable calibration mixtures having non-overlapping components, the respective calibration factors must be determined for each individual gas component on all overlapping mass numbers prior to performing quantitative gas analyses. The concentration or the partial pressure can then be determined for these gases within the framework of a matrix calculation. These kinds of matrix calculations and the required gas-specific calibration routines are supported by the Quadera mass spectrometer software.

5 Leak detection

5.1 General

5.1.1 Leaks and leak detection

What is a leak? A leak, also referred to as leakage, enables a substance to flow toward a pressure gradient. Expressed in simpler terms, leaks are small holes through which gases or liquids flow from the side of higher pressure to the side of lower pressure. This can involve simple, harmless leaks, such as a dripping water faucet, or hazardous toxic substances that escape through leaks.

Any number of technical products will not function, or will not function for an adequate period of time, if they have leaks. Examples include: The refrigerant circulation system in refrigerators, air conditioning systems in cars, automobile tires, automotive fuel tanks or home fuel oil tanks, as well as distillation systems in the chemical or pharmaceutical industries. In many cases, the leak-tightness of machines and systems in the production process is an indispensable prerequisite for the quality of the manufactured products.

Returning to the original definition of a leak, we thus find that it is impossible to completely prevent substances from flowing through a wall. The term "tight" therefore refers to the requirements of the respective machine, plant or vessel, and must be quantified accordingly.

5.1.2 Leakage rate

Let us consider a bicycle tube having a volume $V = 4\text{ l}$. It has been inflated to a pressure of three bar, and without any additional inflation should have a maximum pressure loss of $\Delta p = 1,000\text{ mbar}$ after time t (30 days).

The leakage rate has already been defined in 1.3.3: $Q_l = \frac{\Delta p \cdot V}{\Delta t}$ (Formula 1-27).

Or to illustrate: The leakage rate of a vessel having a volume of 1 liter is 1 mbar · l/s if the interior pressure increases or decreases by 1 mbar in 1 second. Please refer to Table 1.6 for conversion to other customary units. Inserting the values for our bicycle tube then yields the permissible leakage rate:

$$Q_l = \frac{1,000\text{ mbar} \cdot 4\text{ l}}{30 \cdot 24 \cdot 3,600\text{ s}} = 1.5 \cdot 10^{-3} \frac{\text{mbar} \cdot \text{l}}{\text{s}}$$

and we find that the bicycle tube with this leakage rate is sufficiently tight.

These kinds of leakage rates can be found by means of the well-known bubble test method (Figure 5.1).

Now let us consider a refrigerator in which a loss of 10 g of refrigerant having a molecular weight of 102 g/mol, i.e. around 2.24 bar · l, is allowable over a ten-year period. This results in a permissible leakage rate of

$$Q_l = \frac{2.24\text{ l} \cdot 1,000\text{ mbar}}{10 \cdot 365 \cdot 24 \cdot 3,600\text{ s}} = 7.1 \cdot 10^{-6} \frac{\text{mbar} \cdot \text{l}}{\text{s}}$$

These kinds of leakage rates can only be localized and quantified by means of extremely sensitive measuring methods, for example with mass spectrometry and test gases that are not present in the atmosphere.

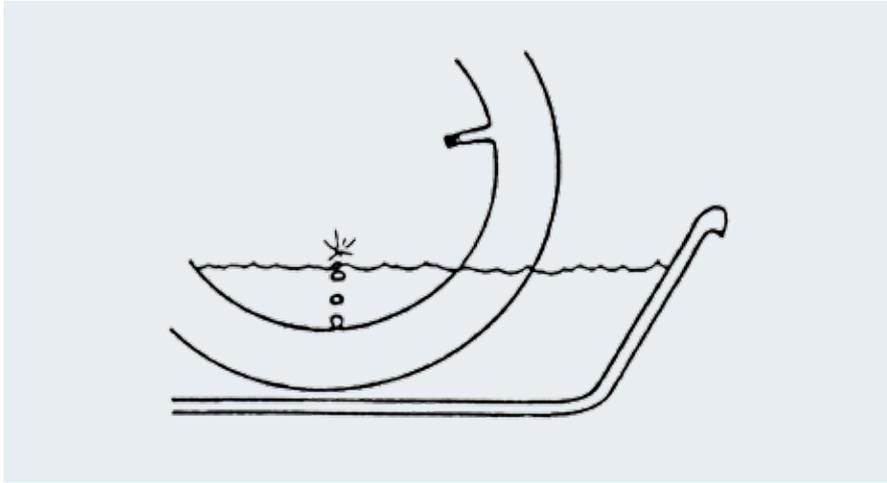


Figure 5.1: Bubble leak test for a bicycle tube

5.1.3 Test gases

The test gases that are used for leak detection (also called tracer gases) should satisfy the following prerequisites:

They should

- ▶ Be non-toxic to humans, animals and the environment
- ▶ Not displace air, as hazardous situations, such as suffocation, could otherwise occur
- ▶ Be inert, i.e. slow to react, and should neither react chemically nor be flammable
- ▶ Not be present in air, if possible. Only with a gas that is present in the smallest possible concentration in the ambient air is it possible to detect even the smallest leaks
- ▶ Cannot be mistaken for other gases

The test gas helium satisfies all of these requirements. As a noble gas, it is not capable of chemically reacting. Only 5 ppm of it is present in atmospheric air, thus enabling even the smallest leakage to be detected. Since it is lighter than air, it thus does not pose a health hazard.

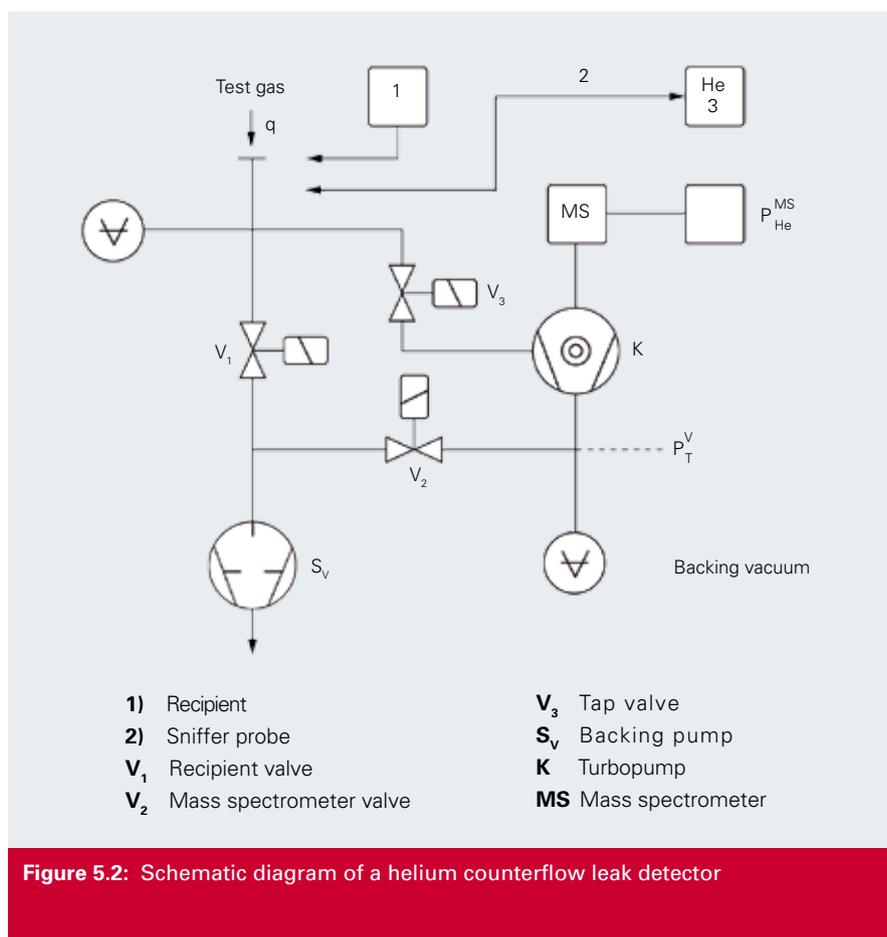
5.2 Leak detection with helium

Mass spectrometers that are set to helium's atomic weight of 4 are used to detect the pre-presence of helium. Mass spectrometers operate only in the molecular flow range, i.e. under vacuum at pressures p of less than 10^{-4} mbar. Sector field devices are used for reasons of cost and because of their robust design.

The operating principle of these devices is described in 4.1.1.

5.2.1 Design of a helium leak detector

Helium counterflow leak detectors are designed in accordance with the schematic diagram in Figure 5.2. A mass spectrometer MS is mounted on the intake flange of a turbomolecular pump. A backing pump S_v evacuates the turbomolecular pump via valve V_2 .



A workpiece 1 is evacuated via the test gas connection with valve V_1 open. Valves V_2 and V_1 are connected in such a manner that the required backing vacuum pressure of the turbopump always takes priority over evacuation of the workpiece. Once the workpiece is evacuated, it can be connected to the backing vacuum, or to a tap on the turbomolecular pump via valve V_3 . Depending upon the pressure range in question, helium is now sprayed onto the workpiece from the outside and together with the ambient air penetrates into the workpiece through leaks. The helium present in the residual gas flows counter to the pumping direction through valves V_1 and V_2 and through the turbopump to mass spectrometer MS, where it is detected. The differing compression ratios of the turbopump for helium and air, which differ by multiple powers of ten, are utilized in this regard. While the high compression ratio of the turbopump keeps air away from the mass spectrometer, the helium arrives there at a relatively high partial pressure. The turbopump thus acts as a selective amplifier for helium.

This is why a mass spectrometer enables helium to be detected in the workpiece even at pressures of less than 1 mbar. Several powers of ten of the helium partial pressure, and thus a leakage rate range of between 10 and 10^{-9} mbar l/s, can be covered by means of various taps on the turbopump (V_3), as well as by operating it at different speeds that exponentially influence the compression ratio. A pressure of 10^{-3} mbar must be attained in the workpiece for the highest sensitivity stage of the leak detector (inlet via V_3).

Because of the upstream turbopump, the mass spectrometer always operates at an extremely low total pressure, and is thus well protected against contamination and failure.

5.2.2 Test methods

A distinction is made between two methods of leak detection:

- ▶ Local leak detection, which is used to find leaks
- ▶ Integral leak detection, where the leakage rate of workpieces is typically determined for quality assurance purposes

Leak detectors are equipped for two operating methods:

- ▶ The pump-down method, in which the workpiece is evacuated and helium exerts its effect from the outside
- ▶ The sniffer method, in which the workpiece is filled with a helium overpressure Δp of more than 100 mbar, and the escaping helium is sucked into the leak detector via a sniffer valve (capillary, metering valve) and detected

5.2.3 Calibrating the leak detector

The leak detector must be calibrated in order to determine leakage rates. This is done by means of a commercial test leak, a small helium-filled vessel with a shut-off valve that emits the defined quantity of gas. This is usually integrated into the leak detector or connected to the intake side of it. For calibration, an appropriate working cycle is often built in that automatically performs the calibration.

To obtain precise measurements, the device should be calibrated before each use. To test large workpieces for which additional vacuum pumps are in use, it is advantageous to use an external test leak. The measurement accuracy can be a function of where the test leak is attached. Consequently, it is necessary to take flow conditions within the vacuum area into consideration.

5.2.4 Local leak detection

Local leak detection is used to identify leakage in a workpiece.

Under the pump-down method, the workpiece (vessel) is connected to the leak detector, and helium is briefly sprayed onto a suspicious area by means of a spray gun. If the pressure in the workpiece is in the molecular flow range, i.e. less than 10^{-3} mbar, there will be an immediate display as a result of the high velocity of the helium atoms. At higher pressures, particularly in the laminar flow range that starts at 1 mbar, the display speed will be much slower and will be governed by the pumping speed of the leak detector's backing pump.

Under the sniffer method (Figure 5.3), the workpiece (3) is filled with a helium overpressure. A sniffer probe (2) is connected to the test gas connection. The helium that escapes through leaks in the workpiece can be detected by sniffing with the probe.

Individual leaks can be identified using local leak detection. However the sum of all leakage cannot be determined. That is why this process offers only limited suitability for providing a GO/NO GO indication for quality assurance purposes.

Sniffer Leak Detection	Vacuum Leak Detection
Sniffing the helium-filled workpiece	Sprayed with helium
Overpressure-proof workpiece	Vacuum-proof workpiece
Detection limit $5 \cdot 10^{-8}$ mbar l/s	Detection limit $5 \cdot 10^{-12}$ mbar l/s

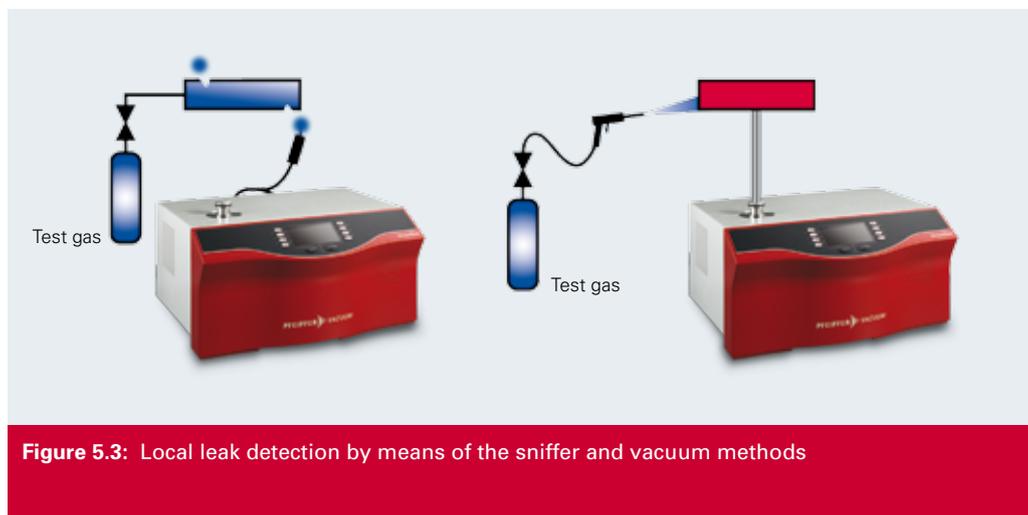


Figure 5.3: Local leak detection by means of the sniffer and vacuum methods

5.2.5 Integral leak detection

Integral leak detection is used to determine the total of all leaks (total leakage) in the workpiece. Here, too, the pump-down method and the sniffer method can be used.

Under the pump-down method, a workpiece is enclosed, filled with helium and the surrounding vessel evacuated. Or the workpiece is evacuated (vacuum system) and the surrounding space is filled with helium. In this connection, the enclosure can be a plastic film, or it can be a rigid vessel for commercial test systems. Under the sniffer method, the workpiece (e.g. an automotive fuel tank) is filled with helium and a given volume of gas is evacuated from the surrounding vessel through the leak detector's sniffer probe (Figure 5.4). The best result that can be obtained using the sniffer method is general confirmation that the workpiece is tight. However this method is not suitable for quantitative integral leakage rate measurement.

A pressure differential $\Delta p = p_1 - p_2 = 100$ mbar is sufficient when testing with an overpressure in the workpiece. Assuming laminar flow at the leak for the leakage rate $Q_{\Delta p}$ thus determined, this can be converted to value Q_l for vacuum measurement at outside atmospheric pressure p_0 in accordance with the following formula:

$$Q_l = \frac{Q_{\Delta p} \cdot p_0^2}{p_1^2 - p_2^2}$$

Formula 5-1
Leakage rate conversion with
differential pressure measurement

This conversion formula is derived from Formula 1-14 and Formula 1-21.

Sniffer Leak Detection	Vacuum Leak Detection
Overpressure-proof workpiece	Vacuum-proof workpiece
Use of a sniffer probe	Workpiece filled with helium
Detection limit $5 \cdot 10^{-8}$ mbar l/s	Detection limit $5 \cdot 10^{-12}$ mbar l/s

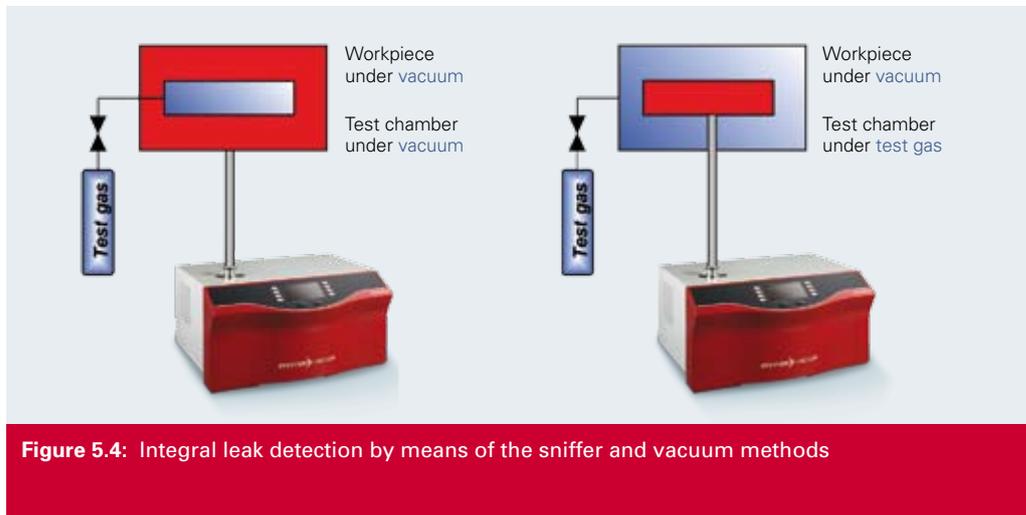


Figure 5.4: Integral leak detection by means of the sniffer and vacuum methods

5.3 Application notes

Prior to beginning any leak detection process with helium, the user must clarify several fundamental questions:

- ▶ Is the workpiece vacuum-proof?
- ▶ Is the workpiece overpressure-proof?
- ▶ Is the total leakage rate of the workpiece to be determined?
- ▶ Is only the location of the leakage to be determined or should it be quantified?

An appropriate test method can be selected from among the methods indicated under 5.2.2 to 5.2.5.

Leak detection with helium

The leak detector must be calibrated prior to beginning. A helium test leak integrated in the Pfeiffer Vacuum SmartTest leak detector is used for this purpose. The calibration routine is started at the touch of a button and runs automatically. Following calibration, the leak detector is ready for use. For leak detection under the vacuum method, the best option is to use an audible indicator, where the frequency of the signal tone rises as the leakage rate increases, thus eliminating the need for a second person to read the display while the workpiece is being sprayed.

The following must always be observed when using helium as the test gas:

- ▶ Helium is lighter than air. So when helium is used in the atmosphere, the leak detection process should always begin at the highest point of the workpiece
- ▶ Excessive amounts of the test gas should not be sprayed, as this can increase the concentration of helium in the ambient air, which would constantly simulate leaks that do not exist

- ▶ Because helium accumulates in the backing pump, in the exhaust space and in the oil, and can return to the backing vacuum area from these points, the gas ballast in the backing pump must be energized if there are high leakage rates. This usually occurs automatically when the higher measuring ranges are selected in the leak detector. The gas ballast must be energized manually if auxiliary pumps are being used

Under the vacuum method, it is necessary to generate sufficiently good vacuum to allow the leak detector to be operated at maximum sensitivity.

Additional vacuum pumps (auxiliary pumps) with high pumping speeds must therefore often be used for large workpieces. In this case, the leak detector should be connected directly to the recipient pump ports for the large vacuum pump, or at least directly adjacent to them.

When the auxiliary pump is running, the measured leakage rate must be increased by the pumping speed ratio between the auxiliary pump and the leak detector in order to determine the leakage rate.

When working with the sniffer valve, the pressure in the vessel must be at least 100 mbar higher than the ambient pressure. Due to strong mixing with the air, the sensitivity of the sniffer method is lower than that of the vacuum method. Moreover, the delayed reaction of the leak detector to the inflowing helium must also be taken into consideration.

5.4 Portfolio

Table 5.1: SmartTest leak detector selection table

Leak Detector	Mode	Workpiece Use		Workpiece Volume		Detectable Leak Rate, in mbar l/s		Remarks
		Vacuum	Overpressure	> 20 l	< 20 l	< $1 \cdot 10^{-7}$	> $1 \cdot 10^{-7}$	
SmartTest HLT 550	Vacuum	●	▲	■	✘	●	●	External vacuum pump required
	Sniffer	●	●	●	●	●	●	
SmartTest HLT 560	Vacuum	●	▲	●	●	●	●	Rotary vane pump S = 5 m ³ /h
	Sniffer	●	●	●	●	●	●	
SmartTest HLT 565	Vacuum	●	▲	●	●	●	●	Rotary vane pump S = 30 m ³ /h
	Sniffer	●	●	●	●	●	●	
SmartTest HLT 570	Vacuum	●	▲	●	●	●	●	Dry backing pump S = 2 m ³ /h
	Sniffer	●	●	●	●	●	●	
SmartTest HLT 572	Vacuum	●	▲	●	●	●	●	Dry backing pump S = 7.5 m ³ /h
	Sniffer	●	●	●	●	●	●	
SmartTest HLT 575	Vacuum	●	▲	●	●	●	●	Dry backing pump S = 26 m ³ /h
	Sniffer	●	●	●	●	●	●	

- Suitable
- ▲ With test chamber
- External backing pump,
S > 10 m³/h
- ✘ External backing pump,
S < 10 m³/h

Pfeiffer Vacuum offers the “SmartTest” leak detector with the following equipment:

- ▶ Counterflow leak detector with turbopump and sector field mass spectrometer
- ▶ Calibration leak with automatic calibration
- ▶ Sniffer probe
- ▶ Digital display with automatic measurement range selection
- ▶ Audible leakage indication via the pitch of a signal tone
- ▶ Various types of backing pumps

The SmartTest HLT 550 permits any suitable backing pump to be connected, making it ideally suited for integration into leak detector systems.

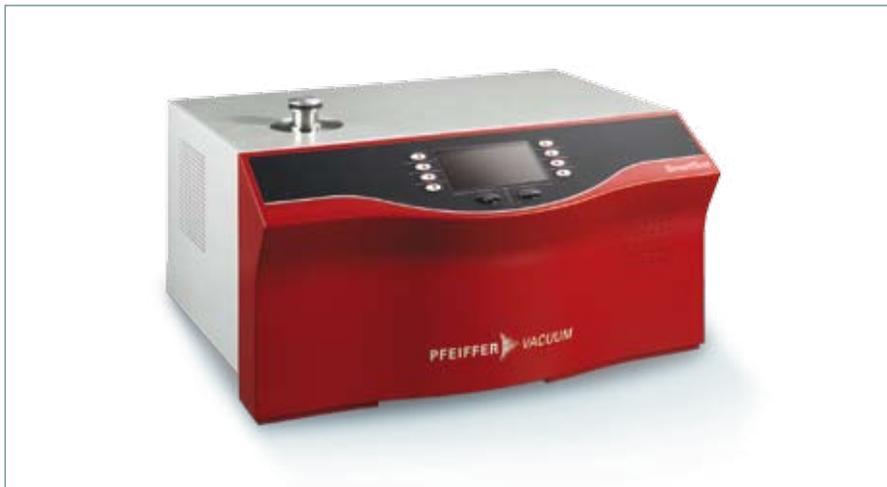


Figure 5.5: SmartTest HLT 560 leak detector

The SmartTest HLT 560 (Figure 5.5) is a helium leak detector with an integrated rotary vane pump offering a pumping speed of 5 m³/h. With this configuration, leak detection in the vacuum mode is also possible within a reasonable period of time for larger workpieces (Table 5.1). The HLT 560 can naturally also be used in the sniffer mode when attached to vessels that are charged with helium.

The SmartTest leak detector is mounted on a trolley together with larger backing pumps. The following versions are available:

- ▶ With a 30 m³/h rotary vane pump
- ▶ With dry backing pumps of various sizes if an oil-free environment is required (Figure 5.6)
- ▶ With a bypass option enabling large vessels to be pre-evacuated by means of an additional backing pump. During this phase, an upstream valve isolates the leak detector from the workpiece, thus preventing contamination of the leak detector
- ▶ With remote control and sniffer probe as accessories

The versions described here are shown in Table 5.1.



Figure 5.6: SmartTest leak detector, HLT 572 with bypass and dry backing pump XtraDry™

6 Valves and Components

6.1 General

A vacuum system includes a variety of different components, such as recipients, vacuum pumps, measurement instruments, shut-off devices, filters, separators, etc., that must be joined together to form a unit. A distinction is made between detachable connections, which are equipped with seals, and non-detachable connections. The various types of connections that have to be taken into consideration in configuring a system and selecting components for it are described and presented in the sections below.

6.2 Seals

When vacuum technology components are detachably joined, seals must be used to prevent ambient air from flowing into the vacuum. There are different designs for this purpose, depending upon the application and pressure range in question.

O-rings / round rubber rings

O-rings are the most frequently used of all seals. O-rings are available in a variety of materials, usually elastomers with hardness ranging from 65 to 80 Shore. Their suitability as good vacuum seals stems from their ability to adapt to the minute unevenness of the mating surfaces. The surface of the o-ring must be free of releasing grease or talcum, smooth and crack- or scratch-free. In the low vacuum range the o-ring can be coated with a thin film of a low vapor pressure grease (silicon grease, Fromblin grease or mineral oil-based grease), depending upon the application in question. In the case of dry installation, particular attention must be paid to surface quality, the cleanliness of the mating surfaces as well as to the sealing material. The cross section diameter (thickness) of the o-rings can be 2 to 12 mm. 5 mm thicknesses are used for many joints, while rings with thicknesses of 8, 10 or even 12 mm are used only for very large seals. The o-rings should be seamlessly pressed. The parting line of the compression molding die is in the plane of the cross section diameter and is usually removed by abrasion.

Generally speaking, o-rings are used as static seals. If dynamic stress is involved, precision o-rings that are manufactured especially for this purpose should be used. A discussion on how to dimension the grooves for this purpose will not be presented here. O-rings can also be used in axial or radial grooves, in addition to being employed in conjunction with centering rings or sealing washers. In most cases, o-rings are placed in grooves and pressed between flanges, with one flat flange and one grooved flange typically being used. The grooves must be carefully dimensioned in accordance with the following criteria:

- ▶ Compression, i.e. the ratio (width/height)-1, should be a maximum of 30 % for o-ring thicknesses (cross sections) of less than 3 mm, and 20–15 % for thicknesses of 5–10 mm
- ▶ The groove fill factor should be between 79 and 91 %
- ▶ The inside diameter of the groove should be equal to or only slightly larger than the inside diameter of the o-ring
- ▶ The outside diameter of the groove may be larger than the outside diameter of the o-ring in its compressed state

If these conditions are maintained, the seals can be reused multiple times without any problem. If the groove is overfilled, the o-rings will be damaged and the flange might even bend, because the ring material is non-compressible. The table below shows groove dimensions, with the inside diameter of the groove and the inside diameter of the o-rings being equal.

Table 6.1: O-ring groove dimensioning table for axial, static seals

Thickness ∅	Tolerance +/-	Groove Width	Tolerance +/-	Groove Depth	Tolerance +/-	Mean Compression	Max. Fill Factor
1.00	0.08	1.45	0.05	0.70	0.05	30.0 %	86.3 %
1.20	0.08	1.65	0.05	0.85	0.05	29.2 %	88.4 %
1.50	0.08	2.00	0.05	1.10	0.05	26.7 %	86.3 %
1.60	0.08	2.10	0.05	1.20	0.05	25.0 %	85.3 %
1.78	0.08	2.30	0.05	1.30	0.05	27.0 %	88.5 %
2.00	0.10	2.50	0.10	1.50	0.05	25.0 %	90.3 %
2.20	0.10	2.80	0.10	1.65	0.05	25.0 %	88.0 %
2.40	0.10	3.00	0.10	1.80	0.05	25.0 %	89.1 %
2.50	0.10	3.10	0.10	1.90	0.05	24.0 %	88.4 %
2.62	0.10	3.20	0.10	2.00	0.05	23.7 %	89.2 %
3.00	0.13	3.70	0.10	2.30	0.05	23.3 %	87.3 %
3.35	0.13	4.10	0.10	2.60	0.05	22.4 %	86.4 %
3.50	0.13	4.30	0.10	2.70	0.05	22.9 %	86.4 %
3.53	0.13	4.30	0.10	2.80	0.05	20.7 %	84.7 %
4.00	0.15	5.00	0.10	3.20	0.05	20.0 %	81.4 %
4.50	0.15	5.50	0.10	3.60	0.05	20.0 %	83.0 %
5.00	0.15	6.00	0.10	4.00	0.05	20.0 %	84.3 %
5.34	0.15	6.50	0.10	4.30	0.05	19.5 %	82.3 %
6.00	0.15	7.20	0.10	4.90	0.10	18.3 %	83.0 %
7.00	0.14	8.50	0.10	5.80	0.10	17.1 %	80.4 %
8.00	0.14	9.50	0.10	6.70	0.10	16.3 %	81.0 %
10.00	0.14	12.00	0.10	8.50	0.15	15.0 %	79.0 %

To facilitate assembly, the diameter of the o-ring groove is usually selected somewhat larger than the diameter of the o-ring. This keeps the o-ring in the groove during assembly. There is no problem in stretching an o-ring by 5 % in length, however not more than 10 %. If the o-ring is used on a centering ring, e.g. in ISO-K and ISO-KF flange connections, the centering ring must be designed in such a manner that it properly positions the o-ring, supports it and limits its compression. There are centering rings that have inner support rings, outer support rings (for overpressure applications), as well as inner and outer rings.

To seal screws, e.g. oil filler screws or oil drain plugs, the o-ring is installed in an angular position. The thread has a 45° chamfer at the upper end, into which the o-ring is inserted. Here, too, the fill factor should be 79–91 %, as in the case of axial installation. The o-ring is then compressed by surface of the screw. The o-ring should be lubricated for this installation method to prevent it from being damaged when the screw is tightened.

- 1) Groove depth ~ See Table 6.1
- 2) Groove width → See Table 6.1

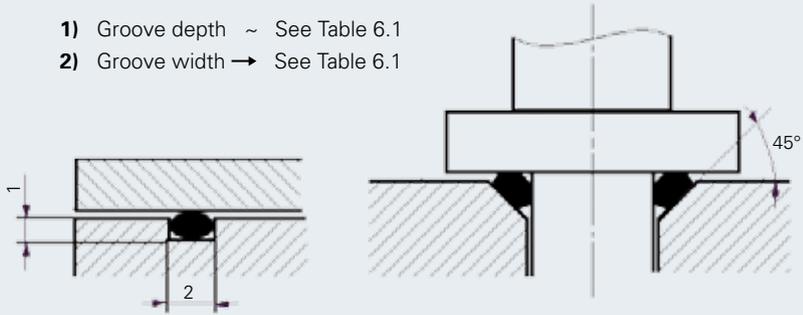


Figure 6.1: O-ring in groove and corner positions



Centering ring with elastomer o-ring (ISO-KF)



Centering ring with elastomer seal and outer ring (ISO-K)

Figure 6.2: Centering rings

Trapezoid seals

Elastomer seals having a trapezoid configuration or a similar cross section are used for valve seats and for the covers and doors of large vacuum chambers, for example, where they are tightly fitted to prevent them from being pulled out when the valve plate lifts or the chamber door is opened. Since enormous surface loads can occur in connection with large chamber dimensions, deformation of the seals is kept within the desired limits by attaching spacers in applications that involve large chamber doors.

Flat seals should be avoided wherever possible in the field of vacuum technology, because it is difficult to achieve the pressure required for the sealing material to fill our all surface unevenness.

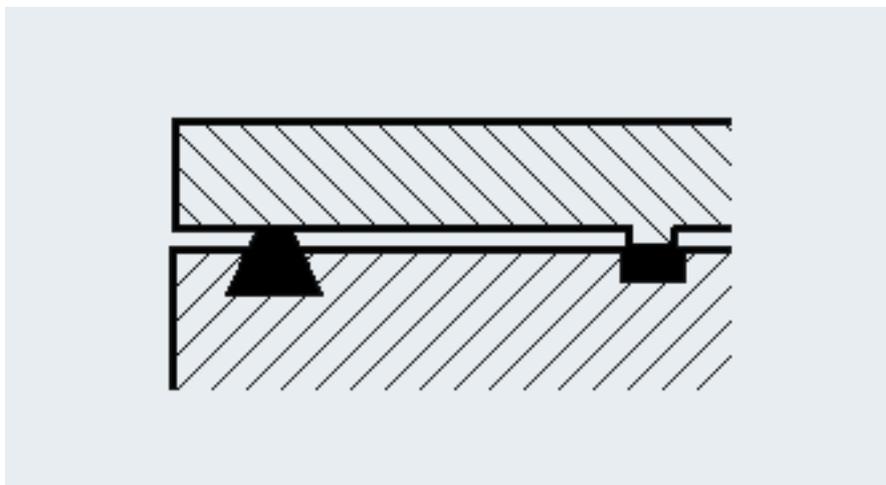


Figure 6.3: Trapezoid seal with spacer

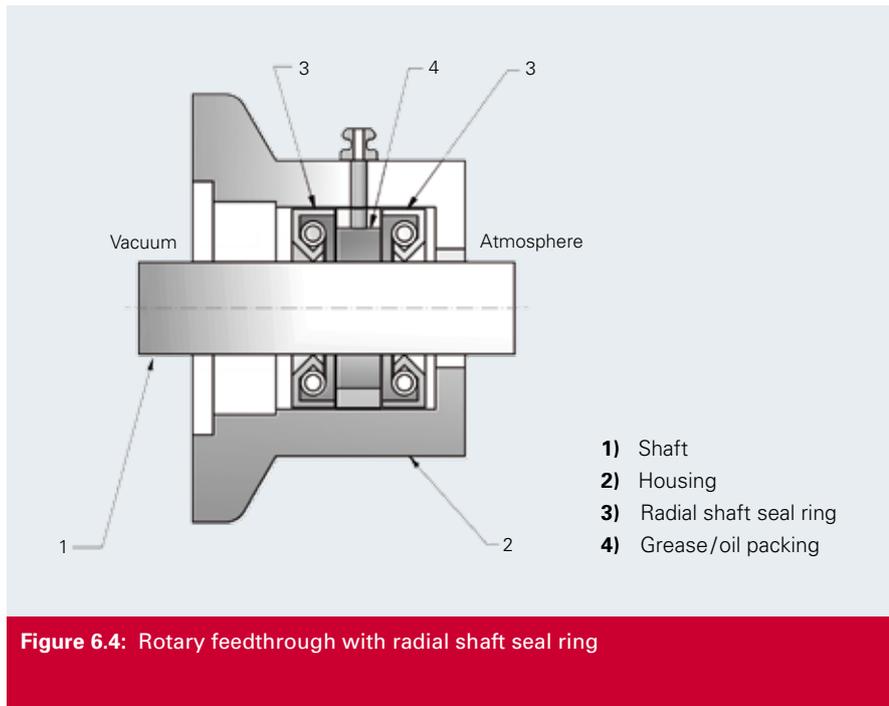
Shaft seal rings / cap seals

Radial shaft ring seals or cap seals are used to seal rotating shafts (Figure 6.4). In this connection, care should be taken to assure that only shaft seal rings with a metal ring that is fully coated in rubber are used. While these seals are quite tight in the static state, the fact must be taken into consideration that their leakage rate will be significantly higher when the shaft is in motion. Cap seals are only suitable for slow-running feedthroughs, e.g. for manually rotated feedthroughs.

Metal seals

Metal seals must be used instead of elastomer seals in high-temperature applications (e.g. baking out vacuum chambers), for high radiation loads and wherever very low permeation rates are the priority. Materials that are frequently used for metal seals are copper, aluminum, indium and in some cases silver and gold. Gold, silver and indium are usually used as wire seals; in addition to wire form, aluminum can also be used as a profile seal. In the case of all metal seals, care must be taken to ensure that the specific contact forces (up to 6000 N per cm of seal length) are maintained.

Cut-edge seals made of copper are used for UHV systems. They are placed between Conflat® flanges. Silver-plated copper gaskets are used for temperatures of over 200 °C. In this case, the silver coating serves as a diffusion barrier against atmospheric oxygen to prevent the copper from oxidizing. Metal seals can be used only once. Indium is also employed as a metal seal, where it is placed between smooth flanges in the form of a wire. Although its ease of welding and its malleability are advantages, its low melting point prevents it from being baked out at high temperatures. In addition to temperature resistance, there can be other reasons for using metal as a seal material, e.g. resistance to radioactivity.



Greases, oils

Greases are still being used as a full-fledged sealing material only in the field of glass technology or as a makeshift solution for slightly damaged seals. In addition to its use as a seal in oil-tight vacuum pumps, oil is being used virtually only as an aid in sealing detachable connections in the low and medium vacuum ranges.

Table 6.2: Comparison of sealing materials

Material	Pressure / Length	Maximum Temperature
CR (Neoprene)	1 N/mm	100 °C
FPM	1 N/mm	150 °C
Indium	7 N/mm	100 °C
Aluminum	30 – 200 N/mm	200 °C
Copper	150 – 600 N/mm	450 °C
Gold	100 – 500 N/mm	800 °C

6.3 Detachable joints

The individual components of a vacuum system, e.g. pumps, valves, measurement instruments, vacuum chambers, etc., are connected with one another either directly or by means of hoses or piping. The joints between these components must be vacuum-tight and detachable. In configuring a vacuum system, however, as few detachable joints as possible should be used, as they represent a significantly more frequent source of potential leakage than non-detachable joints.

Piping and piping components made of aluminum, plain steel and stainless steel are used as connection elements. Metal hoses made of stainless steel are preferable to thick-walled rubber or thermoplastics for flexible joints, and they are a strict necessity from the lower medium vacuum range onward. To reduce the wide variety of existing dimensions and shapes, internationally valid series of nominal diameters have been specified. The series of nominal diameters that originated with the PNEUROP manufacturers' association and which were later adopted by the ISO is:

- ▶ 10 - 16 - 25 - 40 - 63 - 100 - 160 - 250 - 400 - 630 - 1000 and is supplemented by the auxiliary series 20 - 32 - 50 - 80 - 125 - 200 - 320 - 500 - 800

Small flanges

The small flange connection (ISO-KF in accordance with ISO 2861/1/DIN 28403), consisting of two flat flanges having tapered rear sides, a centering ring, a sealing ring and a circlip (clamp), is available in nominal diameters of DN 10, 16, 25, 40 and 50 ISO-KF, whereby DN 50 ISO-KF comes from the auxiliary series and is being used more and more rarely today. An adaptation of components with one of the old nominal widths, 20 and 32, can be adapted by means of a reducing centering ring, or by means of an old DN 25/20 ISO-KF or DN 40/32 ISO-KF outside centering ring. Small flanges can also be held against flat surfaces by means of claws (Figure 6.5).

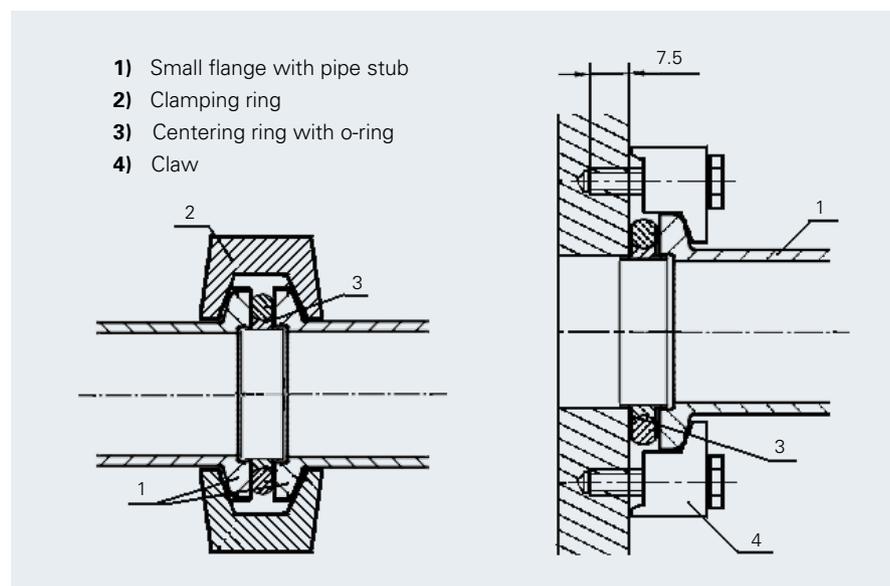


Figure 6.5: Small flange connection

Fixed flanges and clamping flanges

Standard ISO 1609.4/DIN 28404 specifies fixed flanges for nominal diameters of DN 10 – 1000 ISO-F and clamping flanges for nominal diameters of DN 10 – 630 ISO-K. The small flange components are usually preferred for nominal diameters of DN 10 – 50. As in the case of small flanges, fixed and clamping flanges with centering rings have a seal between the flat mating surfaces of the flanges. The flanges are fastened by means of special clamps (clamping flanges) or by means of screws or pins (fixed flanges). By using a collar flange that is held in a groove on the clamping flange by means of a retaining ring or claws, it is also possible to connect clamping flanges to fixed flanges. When installing turbomolecular pumps with clamping flanges, the manufacturer's special instructions in the operating manuals must be observed for reasons of safety.

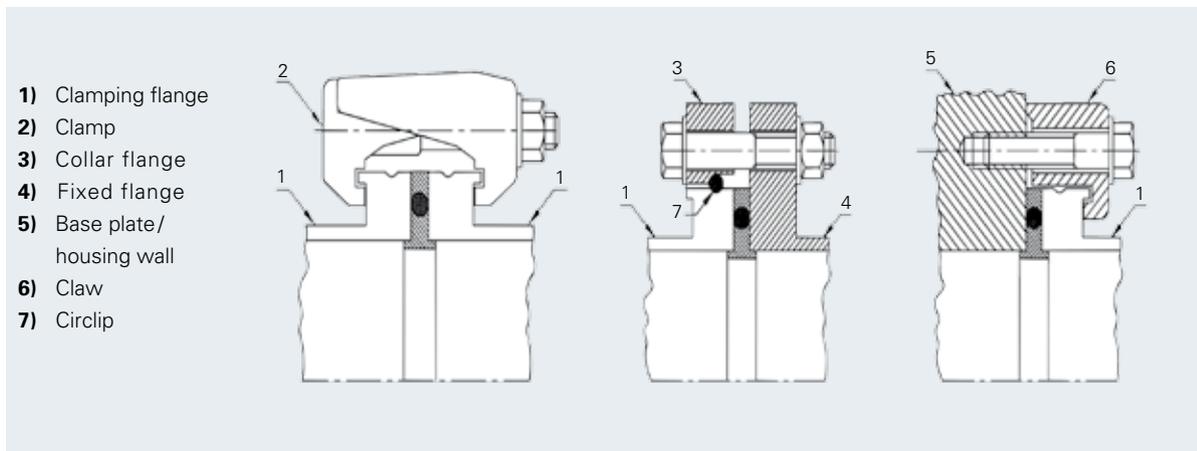


Figure 6.6: Clamping and fixed flange connections

DIN flanges

Since fixed and clamping flange connections are not designed for overpressure applications and because there are process technologies in which the connections are charged with both vacuum as well as overpressure, DIN flanges continue to be used. DIN 2501 (ND 6) and DIN 2502 (ND 10) specify the flange pattern of these flanges. One flange with o-ring groove and one flange with a smooth mating surface must be paired for each connection. Another disadvantage of these flanges relative to the ISO flanges consists of their significantly higher material and space requirements.

UHV flanges

Flanges with cutting edges and copper gaskets, (also referred to as Conflat® or CF flanges) are used for UHV applications. A copper ring is placed between two flanges. The concentric peripheral cutting edges of the flanges penetrate into the copper to form a metallic seal that is characterized by an extremely low leakage and permeation rate, as well as by high temperature resistance. These flanges are standardized in accordance with ISO TS 3669. A sufficient number of screws ensure the necessary high contact pressure. Once used, copper gaskets cannot be reused.

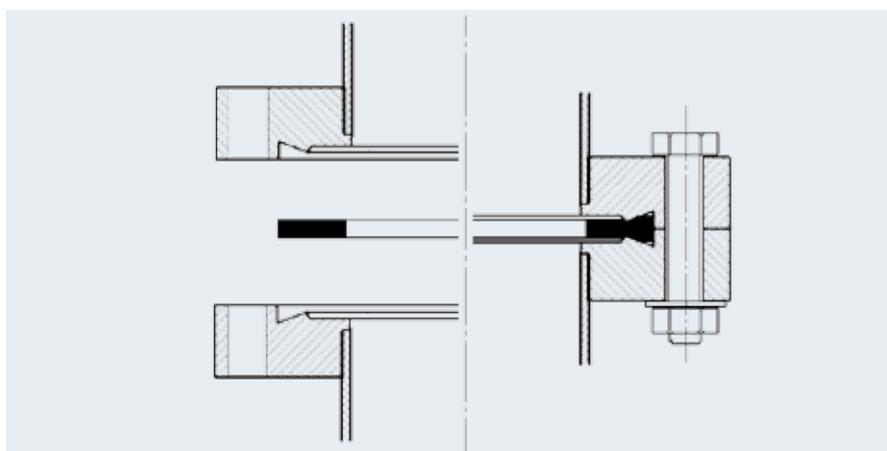


Figure 6.7: Conflat® flange connection

Glass connections

Vacuum systems for glass technology applications employ a glass or ground-in connection, which is used only in connection with small nominal diameters. The connections, consisting of the a tapered male ground joint and the corresponding female ground joint, are held together by the ambient air pressure and are sealed with vacuum grease.

Portfolio

Pfeiffer Vacuum offers all popular standard flanges and other connection elements.

6.4 Non-detachable connections

Non-detachable connections in vacuum technology are achieved by welding, brazing or fusing, or by metalizing or sintering with subsequent brazing. In recent years, vacuum-resistant adhesives have also come into use to join components for applications that do not involve UHV technology. The selected connection technology must be appropriately designed for the major requirements with respect to mechanical strength, temperature and alternating thermal loads, as well as the required gas-tightness. Material pairings such as metal-to-metal, glass-to-glass, glass-to-metal, metal-to-ceramic and glass-to-ceramic are being used more or less frequently in vacuum technology. Metals are most often joined by means of welding and brazing. In glass equipment, the individual glass components are joined through fusion. Non-detachable joints between metal and glass that are produced by fusing or metalizing and fusing are less frequent, and joints between metal and ceramic, which are produced by metalizing or sintering, are also less frequent.

Welded connections

In vacuum equipment, components of plain and stainless steel are usually welded together for vessels and joints. In addition, it is also possible to weld aluminum components together. To ensure that the welds that are produced are vacuum-tight, it is necessary to use proper materials that are free of cracks and voids, and whose surfaces are smooth and free of grease.

In addition, a special geometric design is also required that sometimes differs from the normal welded connections that are employed for non-vacuum applications. Wherever possible in terms of engineering, interior welds must be provided in order to avoid vacuum-side gaps and cracking, so-called latent leaks. If this is not possible, the weld must extend through to the vacuum side. Where necessary, a supplemental atmosphere-side weld can be employed to increase mechanical stability.

In this connection, it is important that this supplemental weld not be continuous in order to allow leak detection, if necessary, and have no air inclusions. In addition to the TIG welding process, microplasma welding also plays a role in vacuum technology, particularly for welding extremely thin-walled components and, to an increasing extent, in electron beam welding, which must be performed under vacuum.

Brazed connections

In addition to welding, the brazing process is also used to join metals. Brazed joints at soldering temperatures of above 600 °C are used almost exclusively in vacuum technology. In order to eliminate the need for highly corrosive flux when soldering, which usually involves high vapor pressure, and in order to obtain oxide-free, high-strength joints, the soldering process is performed under vacuum or in a clean inert gas atmosphere. Soft solder joints are not suitable for vacuum applications. They typically cannot be baked out, have less mechanical strength and in addition to tin frequently contain other alloy components with high vapor pressures.

Fusing

The fusing process is an alternative that is primarily used for joining glass components (in glass equipment) and for glass-to-metal connections. Glass-to-metal fusions are especially important in the production of vacuum-tight current feedthroughs, for bakable sight glasses and in the production of vacuum gauges. To fuse glass-to-metal transitions, the materials must be selected in such a manner that the thermal expansion coefficients of these materials are as similar to one another as possible throughout a broad temperature range. Numerous special alloys have been developed for this purpose that are known under trade names such as Fernico, Kovar, Vacon, Nilo, etc. Fusions with quartz glass are difficult to perform, as this material has an extremely low thermal expansion coefficient; no metal or metal alloy even comes close.

Metalized connections

Ceramic-to-metal connections are used for highly bakable and highly insulating current feedthroughs. They are also employed for manufacturing high-performance transmitting tubes and for configuring ceramic vacuum chambers for particle accelerators at major physics research facilities. In the case of this connection technology, the ceramic, e.g. aluminum oxide (92 % to 98 % Al_2O_3), is pre-metalized at those points to be joined with the metal. In this connection, it is particularly important to ensure that the thin metal layer (molybdenum or titanium) create an intensive connection with the ceramic substrate that is free of voids and pores. Applied to this is a layer of nickel; this enables a metal cap to be brazed on, for example, to which the current conductors of the current feedthrough are subsequently soldered.

6.5 Valves

Depending upon the application in question, shut-off elements (valves) in vacuum systems can also be subject to special requirements, in addition to the general technical requirements for shut-off elements that are typical of vacuum technology and have to be taken into consideration in engineering the products.

The minimum displaced ultimate pressure and the high flow resistance of components in the molecular flow range must be taken into consideration in configuring and selecting vacuum valves. In addition, minimum leakage rates are required for the valve housing and valve seat.

Vacuum-side lubricants for the moving parts in the valves must be suitable for the required pressure and temperature ranges, or avoided entirely, if possible, in high or ultra high vacuum. Minimum dead volumes and high conductivities are important, particularly in the molecular flow range.

The feedthrough for mechanical actuation elements must be designed in such a manner as to satisfy requirements with respect to tightness, as well as the pressure and temperature ranges. Depending upon the quality required, elastomer-sealed feedthroughs (e.g. shaft seal rings) can be used for lower vacuum requirements in the pressure range of over 10^{-4} mbar, while diaphragm or spring bellows are used for pressure ranges of less than 10^{-4} mbar. In addition, valves sealed with a metal bellows can be baked out if appropriately engineered. Valves with elastomer housing, plate and flange seals are used for pressures of up to 10^{-8} mbar.

All-metal valves, in which all seals are made of metal, are suitable for UHV applications and higher bake-out temperatures, however they usually require higher closing forces to seal. Soft metals (gold on a stainless steel substrate, copper or special alloys) are used as sealing materials. In addition to higher closing forces, shorter seal service life must also be expected.

There are a variety of different types of valves for the various applications in the field of vacuum technology; these valves are named on the basis of their design or function. There are also various ways in which valves can be actuated. Valves can be actuated manually, electromagnetically, pneumatically or electropneumatically, and even by means of electric motors. Depending on the requirement and version in question, visual and / or electrical position indicators (limit switches) are available for most valves.

Angle valves

Angle valves consist of a valve housing having an angled configuration. The valve plate is forced onto the valve seat to close the valve. The valve plate is sealed with either a trapezoid or o-ring elastomer seal.

Figure 6.8 shows the design of an angle valve that is sealed with a metal bellows. Since the mechanical activation elements are located outside the vacuum chamber, they can also be lubricated without any problem. These types of valves are available with either manual actuation or with electromagnetic or pneumatic drives.

Rubber plugs or small plates that seal against blade-shaped valve seats (solenoid valves) are also used for extremely small valves.

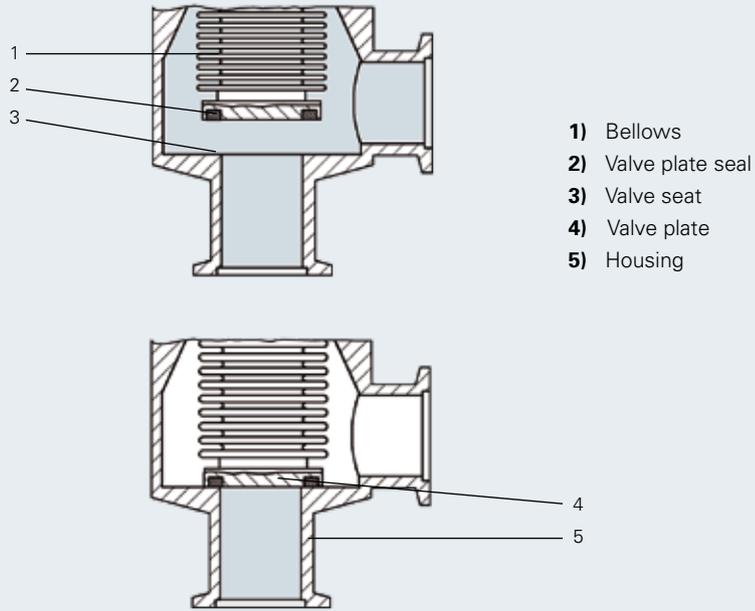


Figure 6.8: High vacuum angle valve

Gate valves

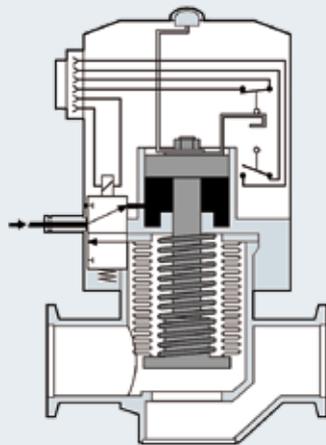


Figure 6.9: Electropneumatically actuated high vacuum inline valve

In principle, inline valves are designed the same as the above-described angle valves, however they differ from them in that the connection flanges are located on one axis. Due to their design, the flow resistance of inline valves is usually higher than that of comparable angle valves.

Gate valves

Gate valves are used for large nominal diameters (> DN 100). They are characterized by their low flow resistance and short physical height. Valve plates, usually of double design, move back and forth to open and close these valves. In the closed position, both elements are forced apart and against the sealing surfaces by means of balls. Depending upon the direction of movement of the valve gate, a distinction is made between rebound valves, shuttle valves and rotary vane valves. While most gate valves can seal against a differential pressure of 1 mbar on the valve plate due to their special design, they can only open in the presence of a low differential pressure on the valve plate.

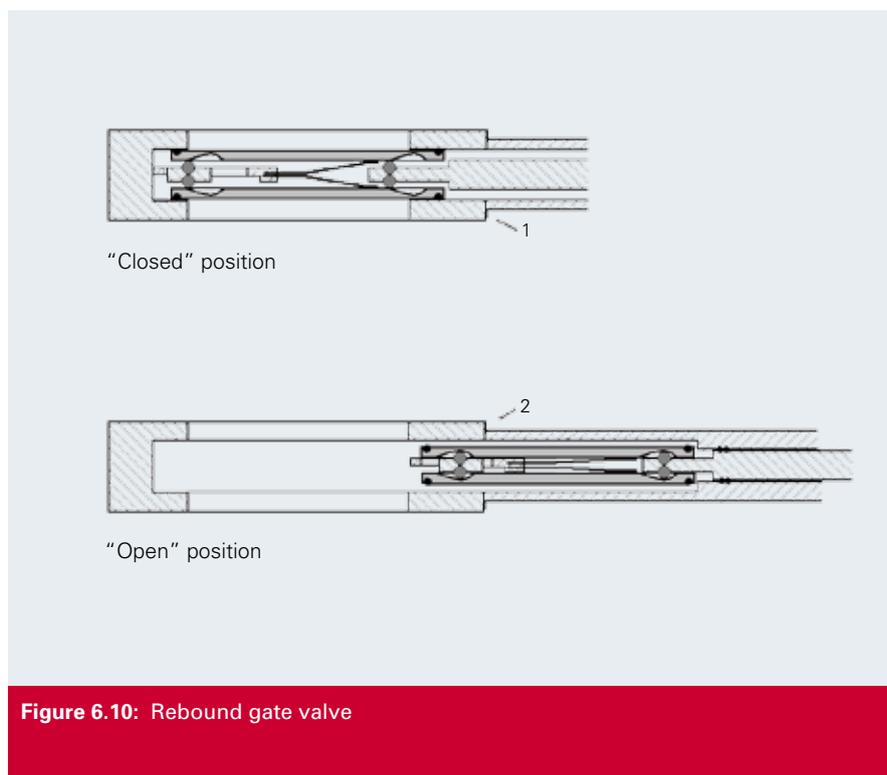


Figure 6.10: Rebound gate valve

Plate and butterfly valves

In valves of this type, the sealing valve plate is swung open by a lever (plate valve) or tilted open by means of a simple rotary motion (butterfly valve), with the valve plate remaining in the valve opening. Plate valves, in particular, are used to close larger nominal diameters.



Figure 6.11: Electromagnetically actuated bellows-sealed rebound gate valve

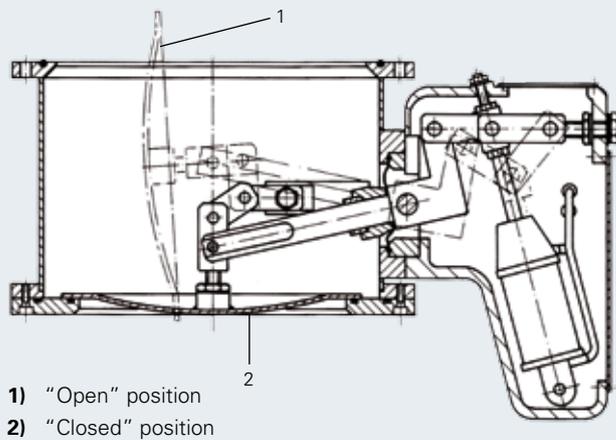


Figure 6.12: Pneumatically actuated plate valve

Source: Pupp / Hartmann, *Vakuumtechnik, Grundlagen und Anwendungen*, Hanser Verlag

Stopcocks

Stopcocks are shut-off elements in which the sealing and shut-off element has a hole through it, and the flow is shut off or released by rotating this element. Ball valves have a proven track record in the fine and medium vacuum ranges. A ball with a hole through it is rotatably supported and sealed on both sides by means of universal ball joints (usually made of Teflon), which also have holes through them. When the hole is in the direction of flow, the entire cross section is released. Ball valves are actuated either manually by means of a rotary feedthrough or by means of pneumatic swivel actuators for larger nominal diameters. It should be noted that ball valves contain an enclosed volume when closed.

Special valves

In addition to the above-described types of valves, there are also numerous special valves in differing configurations for differing applications:

- ▶ Venting valves for slow, dosed venting of a vacuum system
- ▶ Gas-dosing valves, some with a control unit, for manual or automatic pressure or flow regulation
- ▶ Needle valves for admitting minute volumes of gas that can be very precisely and reproducibly set
- ▶ Fast-action valves, e.g. to quickly close a vacuum system in the event of a malfunction
- ▶ Pressure relief and differential pressure valves that open and close automatically under certain pressure conditions
- ▶ Bakeable UHV dosing valves that seal against a metal seat by means of a ceramic plate (Figure 6.13)



Figure 6.13: UHV dosing valve and electromagnetic angle valve

Portfolio

Pfeiffer Vacuum offers all popular types of valves. Please refer to the appropriate sections in the catalog in this connection.

6.6 Feedthroughs

It is often necessary for mechanical movements, electrical current, light or optical signals and liquids to be transferred to the vacuum through vacuum-tight feedthroughs. If they are not integrated in the equipment itself, such as pumps or valves, these feedthroughs are usually installed in vacuum-tight flanges.

Rotary feedthroughs

Although the o-ring is the simplest form of seal, it cannot be used for high speeds and continuous-duty operation due to the high and uncontrolled contact pressures involved.

What are used most frequently are radial shaft seal rings or cap seals, even though they require lubrication. Hydrocarbons in the form of vapors or crack products can penetrate into the vacuum system through the lubricant.

A magnetic coupling consists of a bell-shaped permanent magnet arrangement on the outside that rotates the rotor, which is rotatably mounted in the vacuum and is also equipped with magnets. The two components are separated by a can that forms a hermetic seal. In the case of slow rotation, dry-running ceramic ball bearings can be used in the vacuum. Fast-running shafts in vacuum can be magnetically levitated.

So-called cat's-tail or wobble-tail feedthroughs also afford hermetic separation between vacuum and atmosphere.

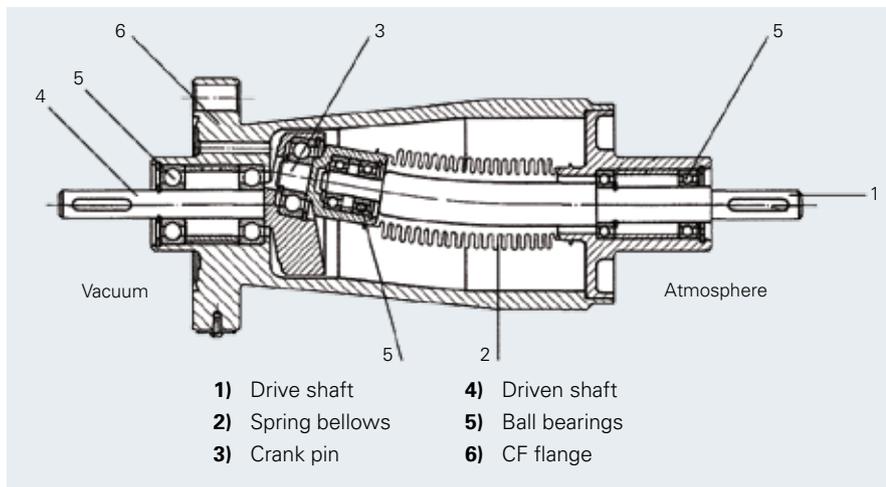


Figure 6.14: UHV cat's-tail feedthrough

Figure 6.14 shows the design of such a feedthrough. The angled drive shaft (1), whose end is supported in a crank pin (3), rotates the driven shaft (4) in the vacuum. The hermetic seal consists of a non-rotating bellows seal (2) that performs a wobbling movement. UHV-suitable dry-lubrication ball bearings are used for mounting the drive shaft in the vacuum.

Electric feedthroughs

A major factor in engineering an electric feedthrough is the type of current and voltage for which it will be used and the requirements it will have to satisfy with respect to vacuum-tightness and temperature resistance. The manufacturing processes for feedthroughs are discussed in Section 6.4. Feedthroughs with organic insulating materials can only be used for lower voltages. Simple cast-resin feedthroughs are frequently used for moderate current loads, e.g. for measurement currents. Epoxy resin is very well suited as an insulator and as a vacuum seal for moderate temperatures.

Multi-pole glass-molded feedthroughs to which the leads can be soldered on both sides are installed in small flanges. There are also versions with tubes through which leads can be inserted and soldered in place.



Figure 6.15: UHV multiple metal-to-ceramic electric feedthrough

This is important when using thermocouples, for example, as solder joints could falsify the measuring voltage. The feedthroughs are cooled with water for high amperages.

With respect to their insulating resistance, feedthroughs with glass-to-metal fusings are suitable for high-voltage and weak-current feedthroughs for electronic devices. Feedthroughs with ceramic insulation offer greater mechanical stability and temperature resistance than glass. In addition, ceramic (e.g. aluminum oxide) can also be produced in an insulating form that is suitable for high voltage. This is why ceramic feedthroughs are superior to glass feedthroughs for high voltages and high performance. Only rigid metal-to-ceramic connections should be considered for the most rigorous electrical, thermal and vacuum technology requirements.

The voltage level must be taken into account for electric feedthroughs, because gas discharges and flashover can occur in the vacuum if there are small clearances between conductors with high voltage differentials. In the vulnerable pressure range between 10^{-3} and 10 mbar, appropriate clearances must be provided between high-voltage conductors. Potting with cast resin can also be useful in this regard.

Feedthroughs for liquids and gases

Problems can occur with these feedthroughs if media at extremely high or low temperatures (liquid air) must be advanced into the vacuum vessel. Feedthroughs can be employed in which the thermal conductivity between flange and tube is reduced far enough by a sufficiently long, thin-walled stainless steel tube that the flange remains at room temperature, with normal elastomer seals being used to seal the flange.

Sight glasses

Sight glasses are primarily used to observe the interior of the vacuum chamber, even during the process. Consequently, normal window glass of an appropriate thickness is usually employed and installed in a sight glass flange by means of elastomer seals (ISO-K and ISO-KF sight glasses). The glass is metalized and soldered into the sight flange (CF sight glasses) for UHV applications and high temperatures.

7

Configuration

7.1 General

This section will discuss simple dimensioning questions:

- ▶ What size pump should I select in order to attain a specific pressure in a vacuum vessel within a given period of time?
- ▶ How large should the backing pump be for a high vacuum pump?
- ▶ What do I need to be aware of when pumping high gas loads?
- ▶ What is the influence of piping on the volume flow rate of a vacuum pump?

All of these questions can naturally not be discussed exhaustively in this chapter. Simple examples will be used and the anticipated results estimated. The technical data of the pumps and components that are used must be taken into consideration for the concrete application in question. And special literature can also be useful for dimensioning.

Units

Every physical technical parameter consists of a numeric value and a unit. The SI system has been adopted worldwide and standards have been defined for the basic values of length (m), mass (kg), time (s), temperature (K), substance volume (mol), electric current (A) and luminous intensity (cd); these values are used for calibration purposes in the individual countries. All other values are derived from these basic values. With few exceptions, the formulas that are used in this discussion contain only the physical technical values and no conversion factors whatever, such as Pa to mbar. This means that after employing the values in SI units, the results will also be in SI units. Examples of SI units are $1 \text{ Pa} = 1 \text{ N/m}^2 = 0.01 \text{ mbar}$ for pressure and $1 \text{ m}^3/\text{s} = 3,600 \text{ m}^3/\text{h}$. Used largely throughout the following sections are popular non-SI units; however SI units will be used wherever it would appear to be appropriate due to the required conversion.

Exclusive use of SI units would avoid many errors and much conversion effort. Unfortunately, this advantage is only very slowly gaining acceptance throughout the world.

7.2 Calculations

7.2.1 Dimensioning a Roots pumping station

Various preliminary considerations are first required in dimensioning a Roots pumping station.

Compression ratio

The compression ratio K_0 of a Roots pump is typically between 5 and 70. To determine this ratio, we first consider the volume of gas pumped and the backflow by means of conductivity L_R , as well as the return flow of gas from the discharge chamber at volume flow rate S_R :

Formula 7-1

Roots pump
gas load

$$p_a \cdot S = p_a \cdot S_0 - L_R (p_v - p_a) - S_R \cdot p_v$$

where p_a = intake pressure and p_v = backing vacuum pressure.

Selecting S as being equal to 0 yields the compression ratio:

Formula 7-2
 K_0 of a Roots
vacuum pump

$$\frac{p_v}{p_a} = K_0 = \frac{S_0 + L_R}{L_R + S_R}$$

The following applies in the laminar flow range: $S_0 \gg L_R \gg S_R$ and thus

Formula 7-3
 K_0 laminar

$$K_{0l} = \frac{S_0}{L_R}$$

and the following applies in the molecular flow range due to

Formula 7-4
 K_0 molecular

$$S_0 \gg S_r \gg L_R : K_{0m} = \frac{S_0}{S_R}$$

At laminar flow (high pressure), the compression ratio is limited by backflow through the gap between piston and housing. Since conductivity is proportional to mean pressure, the compression ratio will decline as pressure rises.

In the molecular flow range, the return gas flow $S_R \cdot p_v$ from the discharge side predominates and limits the compression ratio toward low pressure. Because of this effect, the use of Roots pumps is restricted to pressures p_a of less than 10^{-4} mbar.

Volume flow rate (pumping speed)

Roots pumps are equipped with overflow valves that allow maximum pressure differentials Δp_d of between 30 and 60 mbar at the pumps. If a Roots pump is combined with a backing pump, a distinction must be made between pressure ranges with the overflow valve open (S_1) and closed (S_2).

Since gas throughput is the same in both pumps, the following applies:

Formula 7-5
 S_1 for $\Delta p_d \ll p_v$

$$S_1 = \frac{S_v \cdot p_v}{p_v - \Delta p_d}$$

As long as $\Delta p_d \ll p_v$ the volume flow rate (pumping speed) of the pumping station will be only slightly higher than that of the backing pump. As backing vacuum pressure nears pressure differential Δp_d , the overflow valve will close and $S = \frac{S_0}{1 - \frac{1}{K_0} + \frac{S_0}{K_0 \cdot S_v}}$ will apply (Formula 2-5).

Let us now consider the special case of a Roots pump working against constant pressure (e. g. condenser operation). Formula 7-3 will apply in the range of high pressures. Using value L_R in Formula 7-1 and disregarding S_R against L_R yields:

Formula 7-6
 S against high pressure

$$S = S_0 \cdot \left(1 - \frac{1}{K_0} \left(\frac{p_v}{p_a} - 1 \right) \right)$$

At low pressures, S_a from Formula 7-4 is used and yields:

Formula 7-7
S against low pressure

$$S = S_0 \left(1 - \frac{p_v}{K_0 \cdot p_a} \right)$$

From Formula 2-5, it can be seen that S tends toward S_0 if $K_0 \gg \frac{S_0}{S_v}$.

Using z. B. $K_0 = 40$ und $\frac{S_0}{S_v} = 10$, for example, yields $S = 0.816 S_0$.

Consequently, the following should apply for rating a pumping station: $\frac{S_0}{S_v} \leq 10$.

Because the overflow valves are set to pressure differentials of around 50 mbar, virtually only the volume flow rate of the backing pump is effective for pressures of over 50 mbar. If large vessels are to be evacuated to 100 mbar within a given period of time, for example, an appropriately large backing pump must be selected.

Let us consider the example of a pumping station that should evacuate a vessel of $V = 2 \text{ m}^3$ to $5 \cdot 10^{-3}$ mbar in 10 minutes. To do this, we would select a backing pump that can evacuate the vessel to 50 mbar in $t_1 = 5$ minutes. The following applies at a constant volume flow rate:

Formula 7-8
Pump-down time

$$t_1 = \frac{V}{S} \ln \frac{p_0}{p_1}$$

Formula 7-8 yields the volume flow rate $S_v = \frac{2,000 \text{ l}}{300 \text{ s}} \ln \frac{1,000}{50} = 20 \frac{\text{l}}{\text{s}}$.

We select a Hepta 100 with a pumping speed (volume flow rate) S_v of 100 m³/h as the backing pump. Using the same formula, we estimate that the pumping speed of the Roots pump will be 61 l/s = 220 m³/h, and select an Okta 500 with a pumping speed S_0 of 490 m³/h and an overflow valve pressure differential Δp_d of 53 mbar for the medium vacuum range.

From Table 7.1 below, we select the backing vacuum pressures on the basis of gap p_v , use the corresponding pumping speeds S_v for the Hepta 100 from Figure 2.10 and calculate the throughput: $Q = S_v \cdot p_v$.

The compression ratio $K_d = \frac{p_v + \Delta p_d}{p_v}$ is calculated for an open overflow valve to a backing vacuum pressure of 56 mbar. K_0 can be found in Figure 2.14 for backing vacuum pressures of 153 mbar or less. There are two ways to calculate the pumping speed of the Roots pump:

S_1 can be obtained from Formula 7-5: $S_1 = S_v \cdot K_d$ or an open overflow valve, or S_2 on the

basis of Formula 2-5 for a closed overflow valve $S_2 = \frac{S_0}{1 - \frac{1}{K_0} + \frac{S_0}{K_0 \cdot S_v}}$

As the backing vacuum pressure nears pressure differential Δp_d , S_1 will be greater than S_2 . The lesser of the two pumping speeds will always be the correct one, which we will designate as S .

The inlet pressure is obtained on the basis of: $p_a = \frac{Q}{S}$ Figure 7.1 shows the pumping speed curve of this pumping station.

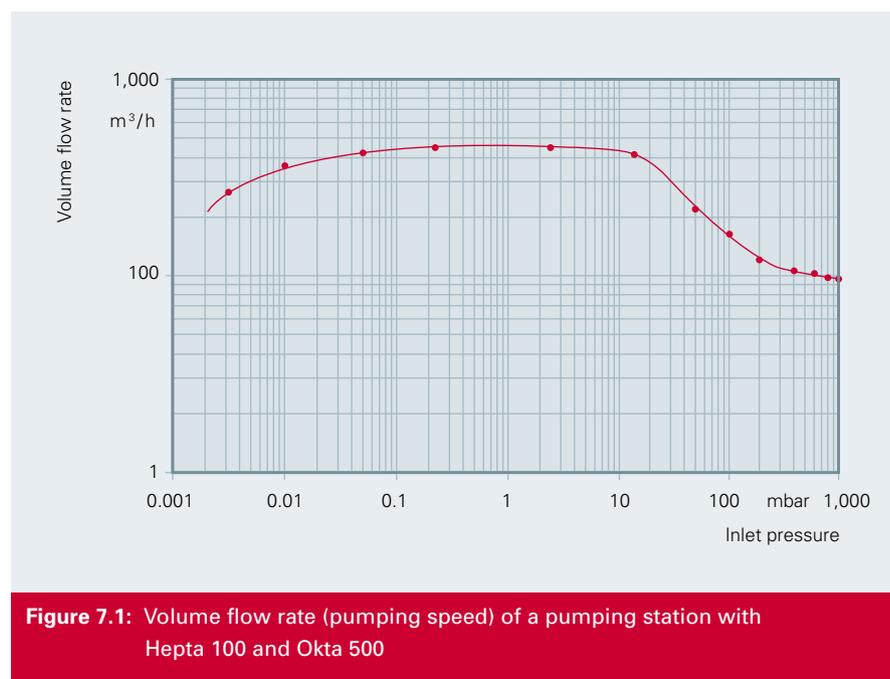
Table 7.1: Volume flow rate (pumping speed) of a Roots pumping station

p_a /mbar	p_v /mbar	S_v /(m ³ /h)	Q /(mbar·m ³ /h)	K_Δ	K_0	S_1 /(m ³ /h)	S_2 /(m ³ /h)	t/h	t/s
1,000.0000	1,053.00	90.00	94,770.00	1.05		94.77		0.00490	17.66
800.0000	853.00	92.00	78,476.00	1.07		98.10		0.00612	22.04
600.0000	653.00	96.00	62,688.00	1.09		104.48		0.00827	29.79
400.0000	453.00	100.00	45,300.00	1.13		113.25		0.01359	48.93
200.0000	253.00	104.00	26,312.00	1.27		131.56		0.00652	23.45
100.0000	153.00	105.00	16,065.00	1.53	7.00	160.65	321.56	0.00394	14.18
50.0000	103.00	105.00	10,815.00	2.06	13.00	216.30	382.20	0.00608	21.87
14.9841	56.00	110.00	6,160.00	18.70	18.00	2,053.33	411.10	0.00822	29.58
2.5595	10.00	115.00	1,150.00		36.00		449.30	0.01064	38.30
0.2300	1.00	105.00	105.00		50.00		456.52	0.00670	24.13
0.0514	0.30	75.00	22.50		46.00		437.39	0.00813	29.27
0.0099	0.10	37.00	3.70		40.00		375.17	0.00673	24.23
0.0033	0.06	15.00	0.90		39.00		270.42	0.00597	21.51
0.0018	0.05	5.00	0.25		37.00		135.29		

Pump-down time: 344.94 s

Pump-down times

The pump-down time for the vessel is calculated in individual steps. In ranges with a strong change in volume flow rate, the backing vacuum pressure intervals must be configured close together. Formula 7-8 is employed to determine the pump-down time during an interval, with S being used as the mean value of the two volume flow rates for the calculated pressure interval. The total pump-down time will be the sum of all times in the last column of Table 7-1.



The pump-down time will additionally be influenced by the leakage rate of the vacuum system, the conductivities of the piping and of vaporizing liquids that are present in the recipient, as well as by degassing of porous materials and contaminated walls. Some of these factors will be discussed in Sections 7.2.3.1 and 7.3. If any of the above-mentioned influences are unknown, it will be necessary to provide appropriate reserves in the pumping station.

7.2.2 Condenser mode

In many vacuum processes (drying, distillation), large volumes of vapor are released that have to be pumped down. Moreover, significant volumes of leakage air will penetrate into large vessels, and those substances that are being vaporized or dried will release additional air that is contained in pores or dissolved in liquids.

In drying processes, the vapor can always be displaced against atmospheric pressure by a vacuum pump having sufficient water vapor capacity and can then be condensed there. However, this process has the following disadvantages:

- ▶ The pump must be very large
- ▶ A large volume of gas ballast air will be entrained which, together with the vapor, will carry a great deal of oil mist out of the pump
- ▶ It will be necessary to dispose of the resulting condensate from the water vapor and oil mist, which is a costly process

Distillation processes operate with condensers, and the object is to lose as little of the condensing distillate as possible through the connected vacuum pump.

Let us consider a vacuum chamber containing material to be dried, to which enough energy will be supplied by heat that 10 kg of water will evaporate per hour. In addition, 0.5 kg of air will be released per hour. The pressure in the chamber should be less than 10 mbar. A pumping station in accordance with Figure 7.2 is used for drying, enabling the steam to be condensed cost-effectively through the employment of a condenser.

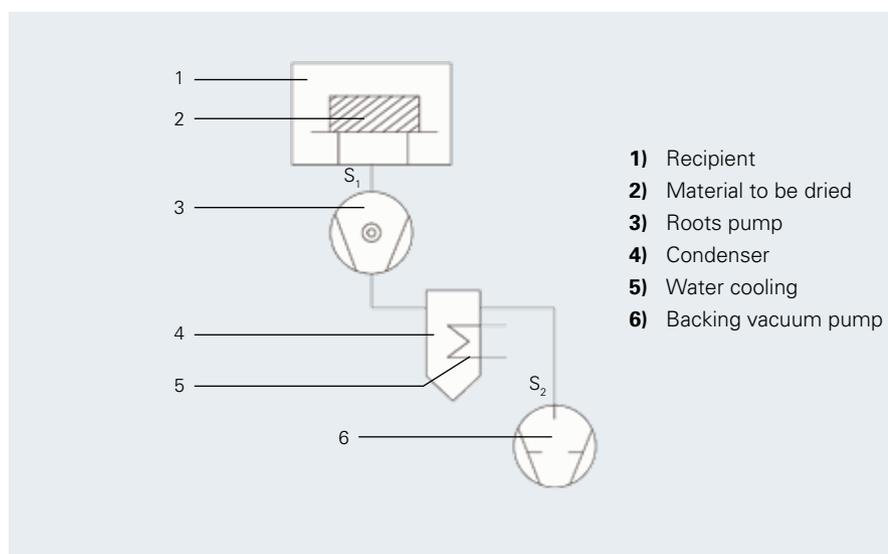


Figure 7.2: Drying system (schematic)

The material to be dried (2) is heated in the vacuum chamber (1). The Roots pump (3) pumps the vapor/air mixture into the condenser (4), where a major portion of the vapor condenses. The condenser is cooled with water. The condensing water at a temperature of 25 °C is in equilibrium with the water vapor pressure of 30 mbar. An additional vacuum pump (6) pumps the percentage of air, along with a small volume of water vapor, and expels the mixture against atmospheric pressure. The first step is to calculate gas throughput

$$Q = P_{ia} \cdot S_i \text{ using Formula 1-11: } Q = S_i \cdot p_{ia} = \frac{R \cdot T}{t} \cdot \left(\frac{m_{wat}}{M_{wat}} + \frac{m_{air}}{M_{air}} \right)$$

where:

$T = 300$ K suction gas temperature

$R = 8,314$ J/(kmol · K)

$t = 3,600$ s time

$p_a = 10$ mbar = 1,000 Pa inlet pressure

$m_{wat} = 10$ kg volume of water vapor

$M_{wat} = 18$ kg/kmol molar mass of water

$m_{air} = 0.5$ kg volume of air

$M_{air} = 28.8$ kg/kmol molar mass of air,

to find the gas throughput: $Q = 397$ Pa · m³/s and after being divided by inlet pressure

$p_a = 1,000$ Pa to obtain the volume flow rate of the Roots pump: $S_i = 0.397$ m³/s = 1,428 m³/h.

Gas throughput Q is comprised of 385 Pa · m³/s of water vapor and 12 Pa · m³/s of air.

When evacuating the condenser, the partial air pressure should not exceed 30%, i.e. a maximum of 12.85 mbar. It follows from this that:

$$S_2 = \frac{Q_{air}}{0.3 \cdot p_{air}} \cdot S_2 = 0.031 \text{ m}^3/\text{s} = 112 \text{ m}^3/\text{h}.$$

We therefore select a Hepta 100 screw pump as the backing vacuum pump. Because its pumping speed is somewhat lower than the calculated volume flow rate, this pump will achieve a slightly higher partial air pressure. And we select an Okta 2000 with the following values as the Roots pump:

$S_0 = 2,065$ m³/h

$\Delta p_a = 35$ mbar differential pressure at the overflow valve

$K_0 = 28$ at $p_v = 43$ mbar.

We estimate the inlet pressure p_a to be 1,000 Pa and calculate S_i in accordance with Formula 7-6:

$$S_i = S_0 \cdot \left[1 - \frac{1}{K_0} \left(\frac{p_v}{p_a} - 1 \right) \right] 1,822 \text{ m}^3/\text{h} = 0.506 \text{ m}^3/\text{s}.$$

Using $p_a = \frac{Q}{S_i}$, $p_a = 785$ Pa yields the inlet pressure in the drying chamber which, when again used in Formula 7-6, provides a more precise volume flow rate S_i of 1,736 m³/h at an inlet pressure p_a of 823 Pa.

We calculate the condenser for a 10 kg/h volume of vapor to be condensed. The following applies for the condensation surface area:

Formula 7-9

Calculation of the condensation surface area

$$A_k = \frac{Q_{wat} \cdot m_{wat}}{t \cdot \Delta T_m \cdot k}$$

where:

$Q_{wat} = 2.257$ 106 WC/kg specific enthalpy of evaporation

$m_{wat} = 10$ kg volume of water vapor

$\Delta T_m = 60 \text{ K}$ temperature differential between vapor and condensation surface area
 $t = 3,600 \text{ s}$
 $k = 400 \text{ W}/(\text{m}^2 \cdot \text{K})$ thermal transmission coefficient,
 which yields $A_k = 0.261 \text{ m}^2$ as the condensation surface area.

The vapor is heated by more than 100 K through the virtually adiabatic compression, however it re-cools on the way to the condenser. So the assumption that $\Delta T_m = 60 \text{ K}$ is quite conservative. The thermal transmission coefficient k [17] declines significantly as the concentration of inert gas increases, which results in a larger condensation surface area. Inversely, with a lower concentration of inert gas, it is possible to work with a larger backing pump and a smaller condensation surface area. Particular attention should be paid to small leakage rates, as they, too, increase the concentration of inert gas.

Further technical details can be seen from the literature [18].

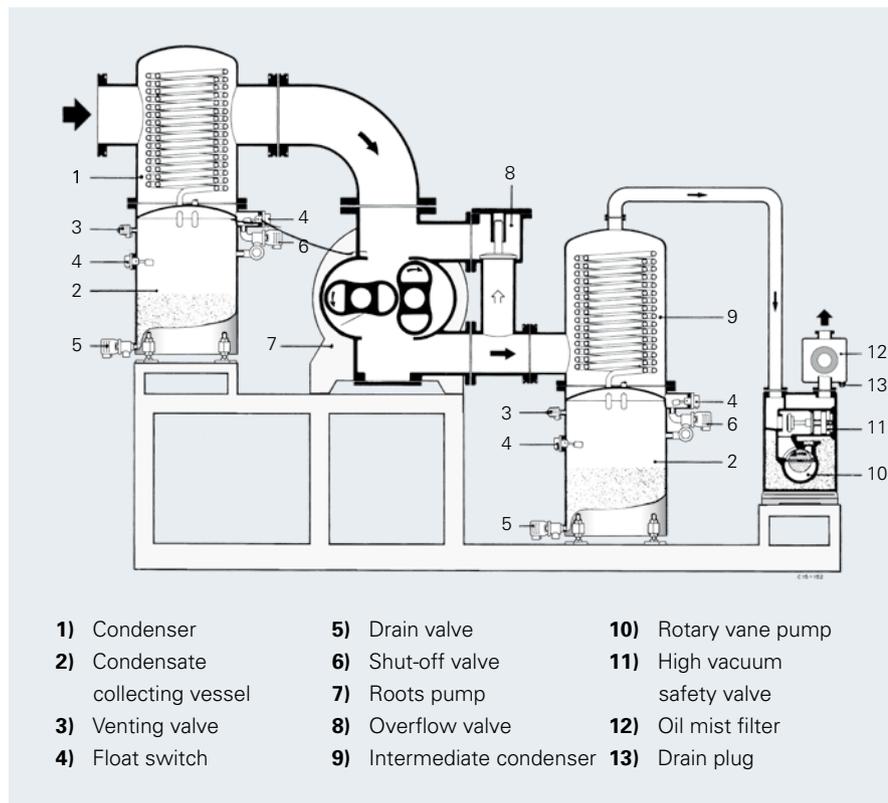


Figure 7.3: Roots pumping station for vapor condensation

In the interest of completeness, let us again consider the entire sequence of the drying process: A pressure equilibrium initially occurs in the drying chamber, which results from the water volume that is being vaporized, which is caused by heat-up of the material to be dried and the volume flow rate of the Roots pump.

The Roots pump advances the water vapor into the condenser, where it condenses. Because laminar flow prevails there, the vapor flow advances the inert gas being released by the material to be dried into the condenser.

Were the backing pump to be shut down, the entire condensation process would quickly come to a stop, as the vapor could only reach the condensation surface area through diffusion. As the drying process progresses, the volume of vapor declines and less condenses in the condenser; however the concentration of vapor being extracted by the backing pump will tend to be larger if the concentration of inert gas decreases. If the vapor pressure in the condenser declines below the condensation threshold, the condensate will begin to re-evaporate. This can be prevented if the condensate drains into a condensate storage vessel via a valve and this valve closes when the vapor pressure declines below the condensation pressure.

In the case of large distillation systems, the pumping speed of the backing pump should be regulated on the basis of the condensation rate. This can be accomplished, for example, with the aid of a dosing pump that uniformly discharges the volume of pumped condensate from the storage vessel. When the concentrate level in the storage vessel declines below a given level, the backing pump's inlet valve opens and the inert gas that has collected in the condenser is pumped down. The condensation rate now increases again, the condensate level increases and the backing pump's inlet valve closes again. This arrangement means that the system pumps only when the condensation rate is too low, and only little condensate is lost.

Summary

When pumping down vapors (drying, distillation), the major pumping effect can be provided by a condenser. Depending upon pressure and temperature conditions, either one or two condensers can be employed (Figure 7.3). The condenser between Roots pump and backing pump is more effective, as the vapor flows into the condenser at a higher temperature and higher pressure, and a small backing pump evacuates only a portion of the vapor. In distillation, condensate loss can be minimized by regulating the pumping speed of the backing pump.

7.2.3 Turbopumping stations

7.2.3.1 Evacuating a vessel to 10^{-8} mbar by means of a turbopumping station

A vessel made of bright stainless steel is to be evacuated to a pressure p_b of 10^{-8} mbar in 12 hours. As can be seen from Section 1.3, there are other effects to consider in addition to the pure pump-down time for air. Both desorption of water vapor and adsorbed gases as well as outgassing from seals will lengthen the pump-down time. The pump-down times required to attain the desired pressure of 10^{-8} mbar are comprised of the following:

- ▶ t_1 = pump-down time of the backing pump to 0.1 mbar
- ▶ t_2 = pump-down time of the turbopump to 10^{-4} mbar
- ▶ t_3 = pumping time for desorption of the stainless steel surface
- ▶ t_4 = pumping time for outgassing the FPM seals

The desired base pressure p_b is comprised of the equilibrium pressure caused by gas flowing into the vessel through leaks and permeation Q_l , as well as by gas released from the metal surface Q_{desM} and the seals Q_{desK} :

$$p_b = \frac{Q_l}{S} + \frac{Q_{desM}(t_3)}{S} + \frac{Q_{desK}(t_4)}{S}$$

The vessel has the following data:

$$V = 0.2 \text{ m}^3 \text{ volume}$$

$$A = 1.88 \text{ m}^2 \text{ surface area}$$

$$q_{desM} = 2.7 \times 10^{-6} \text{ mbar} \cdot \text{m}^3/(\text{s} \cdot \text{m}^2) \text{ desorption rate of stainless steel}$$

$$q_{desK} = 1.2 \times 10^{-5} \text{ mbar} \cdot \text{m}^3/(\text{s} \cdot \text{m}^2) \text{ desorption rate of FPM}$$

$$A_d = 0.0204 \text{ m}^2 \text{ surface area of the FPM seal}$$

$$Q_l < 10^{-8} \text{ mbar} \cdot \text{l/sec leakage rate}$$

The backing pump should evacuate the vessel to 0.1 mbar in $t_1 = 180 \text{ s}$, and should also be able to achieve this pressure with the gas ballast valve open. The volume flow rate can be obtained in accordance with Formula 7-8:

$$S_v = S_v = \frac{V}{t_1} \ln \frac{p_0}{p_1} \quad 10.2 \text{ l/s} = 36.8 \text{ m}^3/\text{h}.$$

We select a Penta 35 with a pumping speed $S_v = 35 \text{ m}^3/\text{h}$.

The turbomolecular pump should have approximately 10 to 100 times the pumping speed of the backing pump in order to pump down the adsorbed vapors and gases from the metal surface. We select a HiPace 700 with a pumping speed S of 685 l/s. Using Formula 7-8 yields

$$t_2 = \frac{V}{S} \ln \frac{p_1}{p_2} = 2.01 \text{ s}$$

Desorption from the surface of the vessel

Gas molecules (primarily water) adsorb on the interior surfaces of the recipient and gradually vaporize again under vacuum. The desorption rates of metal surfaces decline at a rate of $1/t$. Time constant t_0 is approximately 1 h.

Using $Q_{des} = q_{des} \cdot A \cdot \frac{t_0}{t_3}$ (Formula 1-24), we calculate the time needed to attain the working

$$\text{pressure } p_{b3} = 10^{-8} \text{ mbar: } t_3 = \frac{q_{desM} \cdot A \cdot t_0}{S \cdot p_{b3}}; \quad t_3 = 2.67 \cdot 10^6 \text{ s} = 741 \text{ h}.$$

This takes too much time! The process must be shortened by baking out the vessel. Increasing the temperature of the vessel from 293 to 370 K, a temperature that the FPM seals can easily withstand, will theoretically increase the desorption speed by more than a factor of 1,000 [6], and the bake-out time will in effect be shortened to several hours.

High desorption rates can also be lowered by approximately a factor of 100 by annealing the vessel under vacuum or by means of certain surface treatments (polishing, pickling). Bake-out, however, is the most effective method.

Since many pre-treatment influences play a role, precise prediction of the pressure curve over time is not possible. However in the case of bake out temperatures of around 150 °C, it will suffice to turn off the heater after attaining a pressure that is a factor of 100 higher than the desired base pressure. The desired pressure p_{b3} will then be attained after the recipient has cooled down.

Seal desorption

The outgassing rates of plastic are important at operation below 10^{-6} mbar. Although the surface areas of the seals are relatively small, desorption decreases only at $\frac{t_0}{\sqrt{t_4}}$ (Formula 1-25).

The reason for this is that the escaping gases are not only bound on the surface, but must also diffuse out of the interior of the seal. With extended pumping times, desorption from plastics can therefore dominate desorption from the metal surfaces. The outgassing rate of plastics is calculated in accordance with:

$$Q_{desK} = q_{desK} \cdot A_d \sqrt{\frac{t_0}{t}} \quad (\text{Formula 1-25}).$$

We use $Q_{desK} = S \cdot p_{desK}$ and obtain the following for $p_{bd} = 10^{-8}$ mbar: $t_4 = 459 \cdot 10^8 \text{ s} = 1,277 \text{ h}$. In this connection, $t_0 = 3,600 \text{ s}$ and the associated value q_{desK} is read from the diagram for FPM [19]. It can be seen that the contribution to pump-down time made by desorption of the cold-state seal is on a similar order of magnitude as that of the metal surface.

Since the diffusion of the gases released in the interior of the seal will determine the behavior of the desorption gas flow over time, the dependence of diffusion coefficient D upon temperature will have a crucial influence on pumping time:

Formula 7-10
Diffusion coefficient (T)

$$D = D_0 \exp\left(-\frac{E_{diff}}{R \cdot T}\right)$$

As temperature rises, the diffusion coefficient increases, as well; however it will not rise as much as the desorption rate of the metal surface. We thus see that elastomer seals can have a pronouncedly limiting effect on base pressure due to their desorption rates, which is why they are not suitable for generating ultra high vacuum.

Leakage rate and permeation rate

The gas flow that flows into the vacuum system through leaks is constant and results in pressure $p_l = \frac{Q_l}{S}$. A system is considered to be sufficiently tight when this pressure is less than 10 % of working pressure. Leakage rates of 10^{-8} mbar · l/s are usually easy to attain and are also required for this system. This results in a pressure proportion of the leakage rate of $p_l = 1.46 \cdot 10^{-11}$ mbar. This value is not disturbing and can be left out of consideration.

Permeation rates through metal walls do not influence the ultimate pressure that is required in this example; however diffusion through elastomer seals can also have a limiting effect on base pressure in the selected example.

Summary

Pressures of up to 10^{-7} mbar can be attained in approximately one day in clean vessels without the need for any additional measures.

If pressures of up to 10^{-4} mbar are to be attained, the pump-down times of the backing pump and the turbopump must be added together. In the above-mentioned case, this is approximately 200 s. At pressures of less than 10^{-6} mbar, a high turbomolecular pump pumping speed will be required, in particular in order to pump down the water adsorbed on the metal walls.

This will only be possible by additionally baking out the vacuum vessel (90 to 400 °C) if the required base pressure p_0 of 10^{-8} mbar is to be attained within a few hours. The heater is turned off after 100 times the value of the desired pressure has been attained. The base pressure will then be reached after cool-down of the vacuum vessel.

At pressures of less than 10^{-8} mbar, only metal seals should be used in order to avoid the high desorption rates of FPM seals.

Leakage and permeation rates can easily be kept sufficiently low in metal vessels at pressures of up to 10^{-10} mbar.

7.2.3.2 Pumping high gas loads by means of turbomolecular pumps

Turbopumps are subject to high stresses under high gas loads. Gas friction heats up the rotors. The maximum gas loads are limited by the permissible rotor temperature of $120\text{ }^{\circ}\text{C}$. Because the friction loss is proportional to the square of the peripheral speed, it is necessary to reduce the RPM of pumps that operate under high gas loads. This means that higher gas loads are attained at the expense of pumping speed, and in particular, at the expense of the compression ratio; this is not a major disadvantage for these kinds of pumps, as they are not used for generating high vacuum. Pumping heavy noble gases is particularly critical. Due to their high atomic weights, heavy noble gases generate large quantities of heat when they strike the rotor. As a result of their low specific thermal capacity, however, they can transfer only little heat to the stator or to the housing, which results in high rotor temperatures. The maximum gas loads for these gases are therefore relatively low.

When operating with process gases, the turbopump performs two important functions:

- ▶ Fast evacuation of the process chamber to a low pressure (clean initial conditions)
- ▶ Maintaining the desired pressure at a constant level during the vacuum process (coating, etching, etc.)

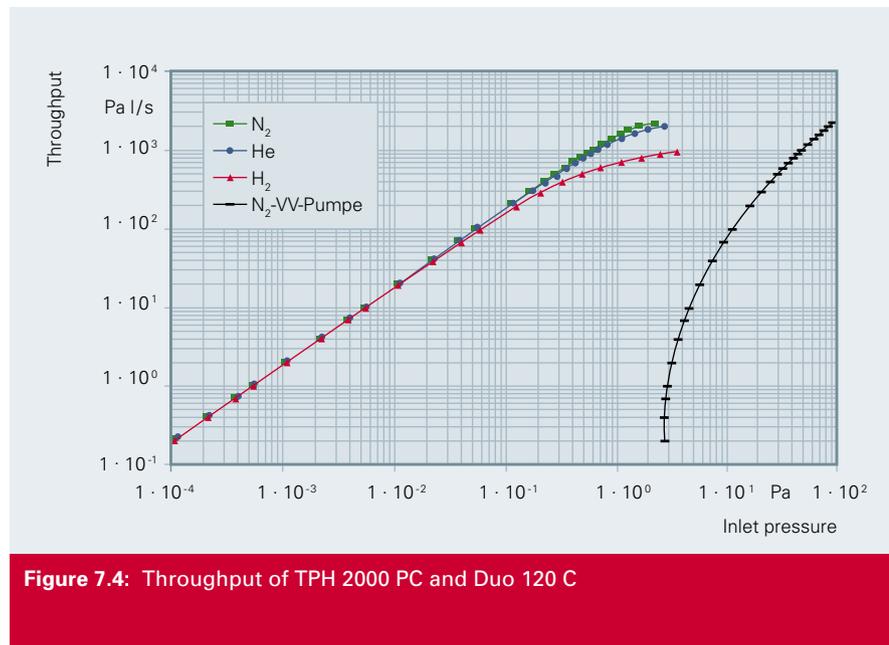


Figure 7.4: Throughput of TPH 2000 PC and Duo 120 C

Gas throughput Q and working pressure p_a during a process are typically specified, and thus the volume flow rate at $S = \frac{Q}{p_a}$ the process chamber, as well.

The turbopump will be selected on the basis of the required gas throughput. The maximum permissible gas throughputs for various gases are specified for the respective pumps in the catalog, with the throughput curves of turbopumps and backing pumps being used in this connection (Figure 7.4). The throughput must be the same for both pumps, because the same gas flow will pass through both pumps successively: $S_v = \frac{Q}{p_v}$.

The following rule of thumb applies for the backing pump: If the maximum gas throughput of the turbopump is attained, the pumping speed of the backing pump must be selected high enough so that only one half of the critical backing pressure will be utilized.

The volume flow rate at the process chamber is throttled to the required level by means of either RPM or a regulating valve. It is frequently not possible to employ regulation as a function of RPM, as it takes too long to set the desired pressure via RPM.

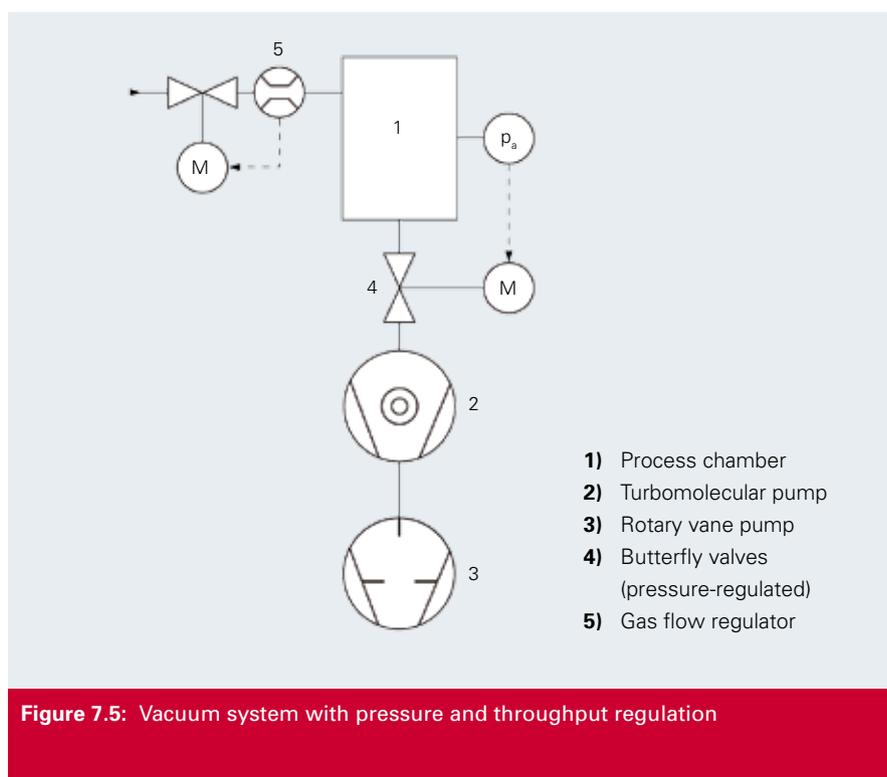


Figure 7.5: Vacuum system with pressure and throughput regulation

Example:

Let us consider a system in accordance with Figure 7.5.

$$Q = 20 \text{ mbar} \cdot \text{l/s gas throughput}$$

$$p_a = 0.05 \text{ mbar process pressure}$$

This results in a volume flow rate S of 400 l/s. We select a HiPace 2300 as the turbopump (2) and a Uno 120 as the backing pump (3). With this backing pump, we can attain a backing vacuum pressure of 0.8 mbar at a gas throughput of 20 mbar · l/s, i.e. a little less than one half of the critical backing pressure of 1.8 bar.

The process gas is admitted to the chamber (1) via a gas flow regulator (5). The butterfly valve (4) that is controlled by pressure p_a throttles the pumping speed of the turbopump (2). After the conclusion of the process step, the gas supply is shut off and the control valve opens completely to cleanly evacuate the chamber again. As this is happening, a new work piece is loaded into the process chamber. Further information relating to pumping high gas loads as well as corrosive and abrasive substances is provided in Section 2.7.3.

7.3 Piping conductivities

In calculating the pump-down times of vessels, we have left piping resistance out of consideration for both Roots pumping stations as well as for turbopumping stations. However the piping between a vessel and a pump will also reduce the volume flow rate.

7.3.1 Laminar conductivity

Let us consider the pumping station for the drying system in Section 7.2.2 (Figure 7.2) and calculate the drop in pressure between condenser and backing pump. In this case, a gas throughput of $Q = 4,285 \cdot 2.9722 \cdot 10^{-2} = 127 \text{ Pa} \cdot \text{m}^3/\text{s}$ is specified as a result of the pressure of 4,285 Pa and the volume flow rate S_v of the backing pump of $107 \text{ m}^3/\text{h} = 2.9722 \cdot 10^{-2} \text{ m}^3/\text{s}$. The DN 63 piping has an inside diameter of 0.07 m and a length of 2 m. Two 90° pipe bends having an equivalent length of 0.2 m each are also taken into consideration.

From $p_2 = 4,285 \text{ mbar}$ and $\bar{l} \cdot p_2 = 6.65 \cdot 10^{-3} \text{ Pa} \cdot \text{m}$ as well as the pipe diameter $d = 0.07 \text{ m}$ we use the Knudsen number $Kn = \frac{\bar{l}}{d}$ (Formula 1-9) to determine the flow range and obtain $Kn = 2.22 \cdot 10^{-5}$. Since Kn is less than 0.01, this results in viscous flow. This can be either laminar or turbulent, although we prefer laminar flow as the conductivities here are significantly higher than for turbulent flow, which means that significantly lower volume flow losses will occur. The Reynolds number Re must be less than 2,300 for laminar flow.

To calculate the Reynolds number, we first determine the flow velocity v in the piping:

$$v = \frac{4 \cdot S_v}{d^2 \cdot \pi} = 8.66 \frac{\text{m}}{\text{s}}$$

and the density ρ of the air at 42.85 mbar from the air density $\rho_0 = 1.293 \text{ kg/m}^3$ at atmospheric pressure.

$$\rho = \frac{1.293 \cdot 42.85}{1013} = 0.0547 \frac{\text{kg}}{\text{m}^3} \text{ and in accordance with Formula 1-10:}$$

$$Re = \frac{\rho}{\eta} \cdot v \cdot d = 1.822, \text{ i.e. laminar flow.}$$

We use Formula 1-21 to calculate pressure p_1 :

$$L_{Rl} = \frac{\pi \cdot d^4}{256 \cdot \eta \cdot l} \cdot (p_1 + p_2) = \frac{\pi \cdot d^4}{128 \cdot \eta \cdot l} \cdot \bar{p}$$

and multiply by $\Delta p = p_1 - p_2$ to obtain the gas throughput:

$$Q = L_{Rl} \cdot \Delta p = \frac{\pi \cdot d^4}{256 \cdot \eta \cdot l} \cdot (p_1^2 - p_2^2).$$

Since $p_2 = 4,285 \text{ Pa}$ and $Q = 127 \text{ Pa} \cdot \text{m}^3/\text{s}$ it is possible to directly determine p_1 from these values:

$$Q_{diff} = q_{diff} \cdot A_d \sqrt{p_2^2 + \frac{Q \cdot 256 \eta \cdot l}{\pi \cdot d^4}} = 4,287.2 \text{ Pa}$$

We have a pressure loss Δp of merely 2.2 Pa, a very low value.

The conductivity of the piping is obtained from Formula 1-14:

$$L_{Ri} = \frac{Q}{\Delta p} = 57.73 \frac{\text{m}^3}{\text{s}}$$

The effective volume flow rate

$$S_{eff} = \frac{S_v \cdot L_{Ri}}{S_v + L_{Ri}} = 0.029707 \frac{\text{m}^3}{\text{s}}$$

is only slightly lower than the volume flow rate without the piping: $S_v = 0.029722 \text{ m}^3/\text{s}$.

7.3.2 Molecular conductivity

Now let us also consider the conductivity of the same piping in the molecular flow range.

The piping has a diameter of 0.07 m and a length of 2 m. The elongated length of 0.235 each of the two 90° pipe bends, i.e. a total length of 2.47 m is taken into consideration [20].

In accordance with Formula 1-22, the piping resistance is

$$L_{Rm} = \frac{\bar{c} \cdot \pi \cdot d^3}{12 \cdot l} = 0.017123 \cdot \frac{\text{m}^3}{\text{s}}$$

where $\bar{c} = 471 \text{ m/s}$ for air at $T = 293 \text{ K}$. The orifice conductivity of the pipe inlet has already been taken into account.

The effective volume flow rate is obtained in accordance with the following formula:

$$S_{eff} = \frac{S_v \cdot L_{Rm}}{S_v + L_{Rm}} = 1.0864 \cdot 10^{-2} \frac{\text{m}^3}{\text{s}} \text{ where } S_v = 2.9722 \cdot 10^{-2} \text{ m}^3/\text{s}.$$

In the molecular flow range, the pumping speed of the backing pump would be reduced to nearly one third! In this range, it is absolutely necessary to pay strict attention to short runs and large piping cross sections between pump and recipient. This applies in particular with respect to turbopumps that are ideally flanged directly to the recipient.

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