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VACUUM GUIDE FOR SCIENTIFIC APPLICATIONS

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Edwards, a world leader and expert in vacuum solutions, has been delivering complete vacuum solutions for scientific, laboratory and R&D applications for more than 100 years.

At Edwards we have a deep understanding of the role that vacuum plays at different stages in a myriad of scientific processes. This experience, coupled with innovative technologies and collaborative engineering, enables us to offer a comprehensive range of vacuum solutions. These will enhance performance across a broad range of applications, helping science improve our lives.

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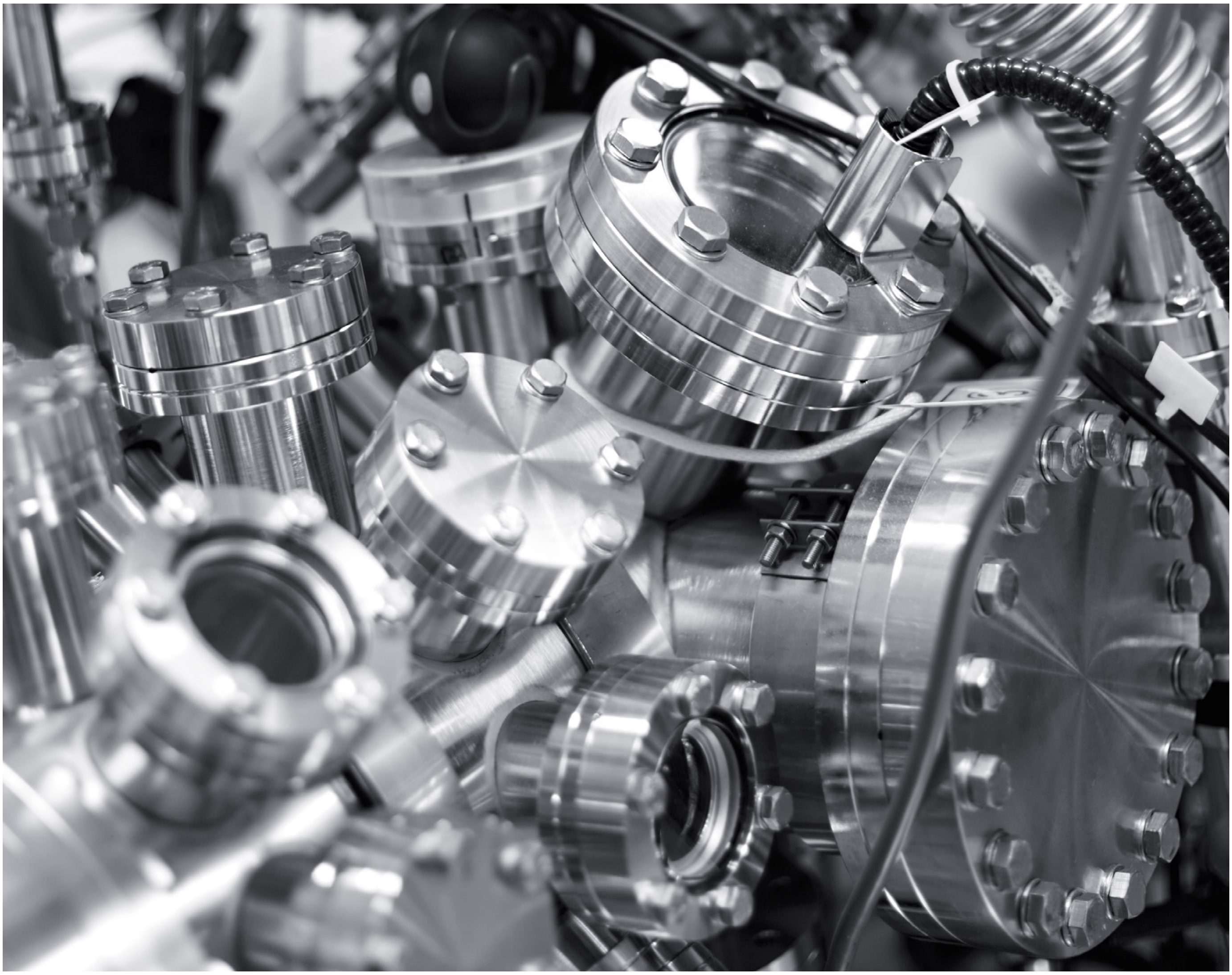
1. INTRODUCTION

Vacuum is at the heart of research and development, in pioneering fields such as high energy physics and space simulation; and at grass roots level, where we foster experimentation in the laboratories of schools and universities. At Edwards we have a deep understanding of research processes and the role that vacuum plays at every stage. This experience, coupled with innovative technologies and collaborative engineering, allows us to create vacuum equipment to meet these exacting demands, through off-the-shelf or bespoke solutions; from initial advice through to implementation and support, we deliver safe, stable vacuum environments that keep up with the complex and evolving demands on both analysis and discovery. From the smallest school laboratory, to international R&D projects, our products and application know-how are facilitating educational development and scientific evolution across the globe.

With more than 100 years of expertise in developing vacuum pumps, our experience safeguards a reliable and stable vacuum environment. To us, partnership-like customer relationships are fundamental. Therefore, this vacuum guide is meant to provide an overview of vacuum technology in an easy to read manner.



2. FOUNDATIONS OF VACUUM TECHNOLOGY

2.1 DEFINITION OF VACUUM

Let us start by giving you some perspective. A practical vacuum is achievable from 10^3 to < 10^{-12} mbar(a) – a dynamic range of no less than 15 orders! There are few disciplines of science that fall within such a wide working range.

The selection process for pumps therefore necessitates a familiarity, appreciation and understanding of the basic principles and terminology of vacuum science which is what will be discussed next.

A vacuum is described as a space in which the pressure is below the surrounding atmospheric pressure. Within a gas the total pressure is defined as the rate of transfer of the normal component of momentum of the constituting molecules to a plane per unit area. The SI unit of pressure being the Pascal (Pa), which is the pressure exerted by a force of one Newton perpendicular to a plane surface of 1 m^2.

By definition:

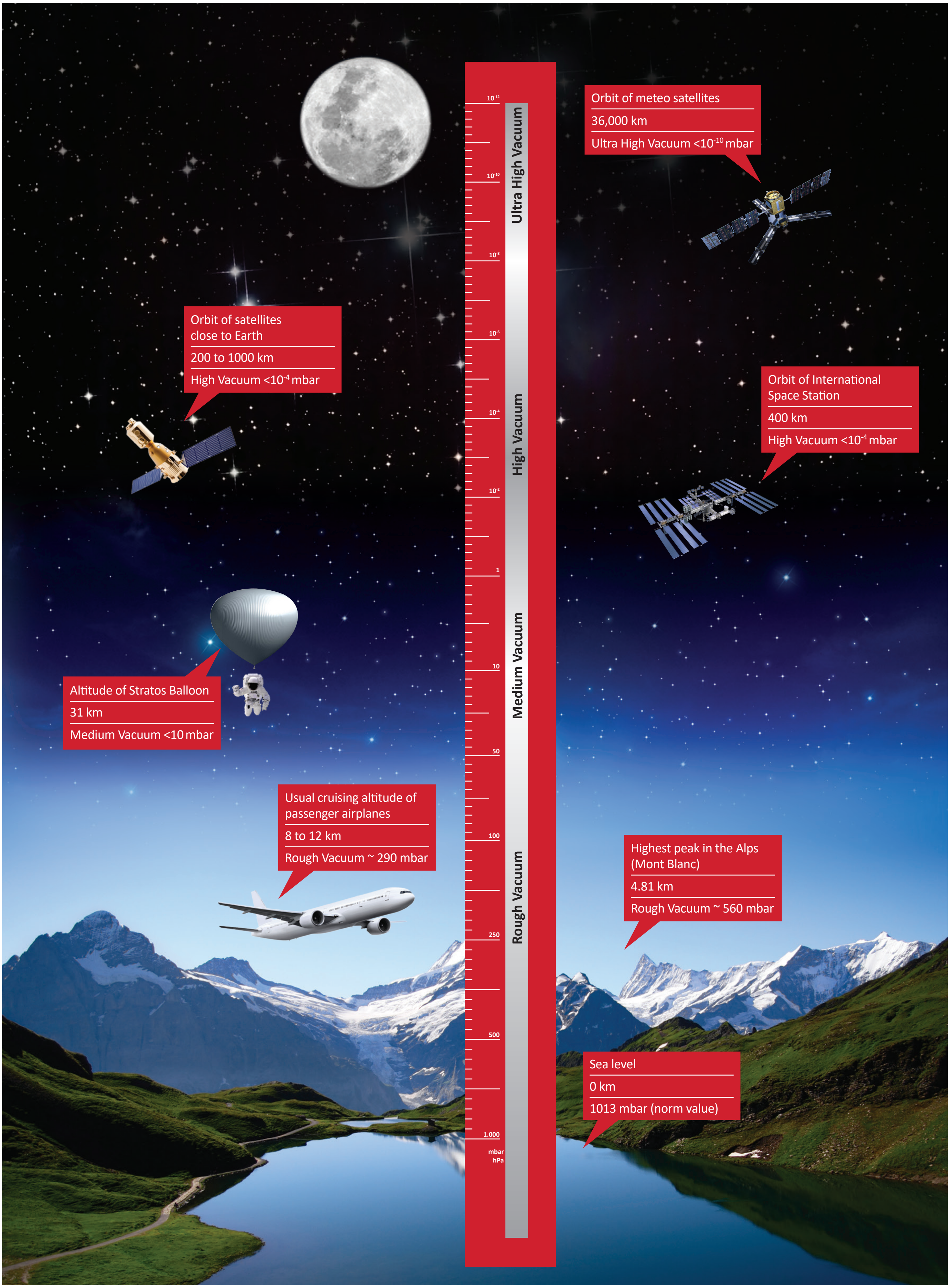
1 standard atmosphere = 1.01325×10^5 Pa
= 1013.25 mbar(a)
= 760 Torr

N.B. increasingly the unit hPa is used where 1 hPa = 1 mbar(a)

A common scheme of the vacuum range is shown in Table 2.1:

Low or Rough Vacuum (LV)	Atmospheric to 1 mbar(a)
Medium or Fine Vacuum (MV)	1 to 10^{-3} mbar(a)
High Vacuum (HV)	10^{-3} to 10^{-7} mbar(a)
Ultra High Vacuum (UHV)	10^{-7} to 10^{-12} mbar(a)
Extreme High Vacuum (XHV)	<10^{-12} mbar(a)

Table 2.1: Definition of vacuum ranges.



Orbit of meteo satellites
36,000 km
Ultra High Vacuum $<10^{-10}$ mbar

Orbit of satellites close to Earth
200 to 1000 km
High Vacuum $<10^{-4}$ mbar

Orbit of International Space Station
400 km
High Vacuum $<10^{-4}$ mbar

Altitude of Stratos Balloon
31 km
Medium Vacuum <10 mbar

Usual cruising altitude of passenger airplanes
8 to 12 km
Rough Vacuum ~ 290 mbar

Highest peak in the Alps (Mont Blanc)
4.81 km
Rough Vacuum ~ 560 mbar

Sea level
0 km
1013 mbar (norm value)

2.2 CONCEPTS & TERMINOLOGY

In this section we discuss some important vacuum concepts and illustrate how they impact the mechanism, choice and use of vacuum pumps.

The vacuum environment is essentially a gas at a reduced pressure. Theories of vacuum must therefore account for the laws which have been shown to hold true for gases. To describe the properties of a gas, the equation of state for ideal gases is commonly used. It relates the pressure, p, volume, V, and temperature, T, of a gas. One form of the equation of state of ideal gases is:

$$p = nk_0T \qquad (2\text{-}1)$$

where:

p = the pressure,

n = the number density,

k_0 = the Boltzmann's constant, and

T = the absolute thermodynamic temperature

The number density, n, is the number of molecules, N, per unit volume, V:

$$n = \frac{N}{V} \qquad (2\text{-}2)$$

and $n = 2.5 \times 10^{16} \times p$ per cm^3 at 20°C where p is in mbar(a) as illustrated in Table 2.2:

Pressure (mbar(a))	Number density (molecules/cm^3)
10^3	2.5×10^{19}
1	2.5×10^{16}
10^{-6}	2.5×10^{10}
10^{-10}	2.5×10^{6}

Table 2.2: Pressure with according number density.

Depending on the physical parameters, the behaviour of real gases can deviate from that of an ideal gas. For example, with air under ambient conditions, the value of the product pV is about 0.02% smaller than assumed for an ideal gas. At higher pressures and lower temperatures, deviations from ideal gas behaviour become larger. Since vacuum technology deals with diluted gases at ambient or elevated temperatures, in which the particle density is small and the mean thermal velocity is high, the intrinsic volume and intrinsic pressure (caused by van-der-Waals force) of the gas particles can be neglected.

Aside - a more convenient expression of equation (2-1) is shown below, derived using $k_o = R_o/N_A$ where n_m is the number of moles of the gas ($n_m = N/N_A$), R_o is the gas constant and N_A is Avogadro's number:

$$pV = n_mR_0T \qquad (2\text{-}3)$$

It can be seen that the product pV is proportional to the number of moles present and equals the 'quantity', Q, of the gas. This important concept will be discussed further below. Even at low pressures there are still a very large number of entities (molecules) allowing significant statistical analysis.

Kinetic Theory gives several relevant outcomes for vacuum science:

i. The mean thermal velocity $\bar{v}$ is given by

$$\bar{v} = \left(\frac{8R_0T}{\pi M}\right)^{1/2} \qquad (2\text{-}4)$$

where M is the molar mass of the gas.

For example, at 20^{o}C, $\bar{v}$ for a helium molecule is 1,245 m/s compared to 470 m/s for nitrogen and 394 m/s for argon.

ii. We can view gases as moving at random with relatively high velocities and collisions occurring between them as shown below in Fig. 2.1.

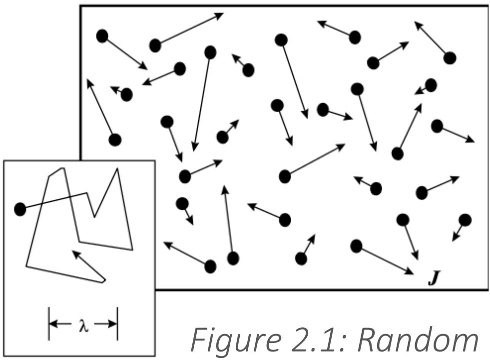


Figure 2.1: Random movement of molecules.

This allows us to consider the concept of mean free path which is defined as the mean distance travelled by molecules between collisions:

$$\lambda = \frac{k_0T}{\sqrt{2}\pi p d_m^2} \qquad (2\text{-}5)$$

where:

λ = the mean free path, and

d_m = the molecular diameter.

Additionally, we can define the impingement rate, J, as the number of molecules intersecting or impinging on a vacuum surface where:

$$J = 0.25 \cdot n\bar{v} \qquad (2\text{-}6)$$

Extending this analysis we develop the monolayer formation time, t_{mono}, which is the time taken for the formation of one (uniform) adsorbed layer of gas on a vacuum surface.

These parameters are summarised in Table 2.3:

Pressure (mbar(a))	Impingement rate (cm^{-2}.s^{-1})	Mean free path	Monolayer formation time
10^3	3×10^{19}	66 nm	3 ns
1	3×10^{16}	0.066 mm	3 µs
10^{-3}	3×10^{13}	6.6 cm	3 ms
10^{-6}	3×10^{10}	66 m	3 s
10^{-10}	3×10^{6}	660 km	8 hours

Table 2.3: Parameters for the monolayer formation time (for N_2 at 20°C).

iii. Flowing gas

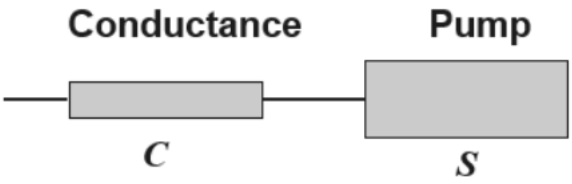
We define the flowrate or throughput, Q, of a gas as the quantity/unit time (in mbarm³/h, kg/h or slm):

$$Q = pV = pS \qquad (2\text{-}7)$$

where speed, S = volume rate and the conductance, C, is a measure of the ease of gas flow between two regions with a pressure difference of Δp of such that:

$$C = \frac{Q}{\Delta p} \qquad (2\text{-}8)$$

The effective or net pumping speed (volumetric flowrate), S_{net}, can be significantly affected by the conductance of connecting components.



Pumping speed can be combined with a conductance in the same way as conductances in series.

$$\frac{1}{S_{net}} = \frac{1}{S} + \frac{1}{C} \qquad (2\text{-}9)$$

Fig. 2.2 shows the restrictive effect of a 1 m length NW40 connecting pipe on the net pumping speed ($S_{upstream}$) of various speed turbomolecular pumps ($S_{downstream}$):

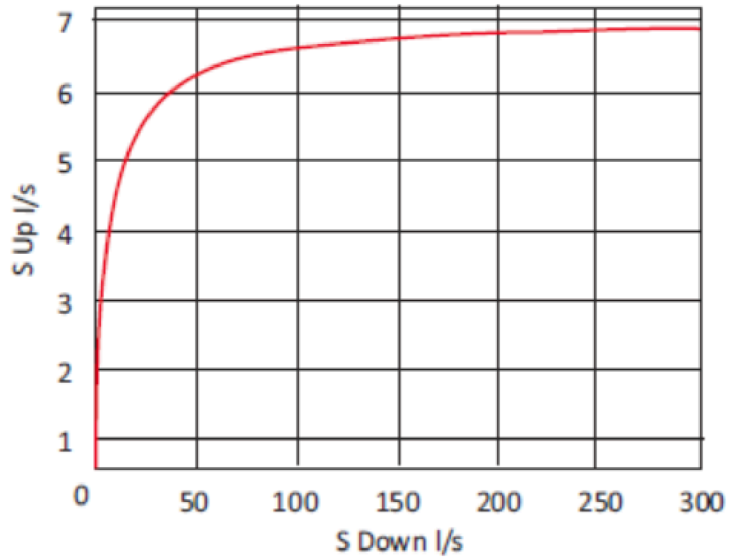


Figure 2.2: Restrictive effect of a 1 m length NW40 pipe on the net pumping speed.

iv. Flow regimes

We have developed a picture of gas molecules moving randomly at high velocities with a wide range of defining parameter values, across the vacuum spectrum. To deliberately induce flow, *i.e.* to create a pumping effect, we need to exploit and influence these.

Reconsidering the concept of mean free path we can see that for a typical vacuum component with a dimension, *d*, of 7 cm (*i.e.* the diameter of an ISO63 pipe) molecules will be more likely to collide with other molecules than with the pipe wall, but decreasingly so as the pressure reduces to 10^{-3} mbar(a).

- We introduce the concept of the Knudsen number, K_n:

$$K_n = \frac{\lambda}{d} \qquad (2\text{-}10)$$

- As shown in Fig. 2.3, as vacuum improves (and system pressure decreases), collisions within the volume become relatively few compared with surface collisions.
- The ratio of surface to volume collisions can be shown for a box to be ~ 3 x K_n allowing us to define flow regimes as below:

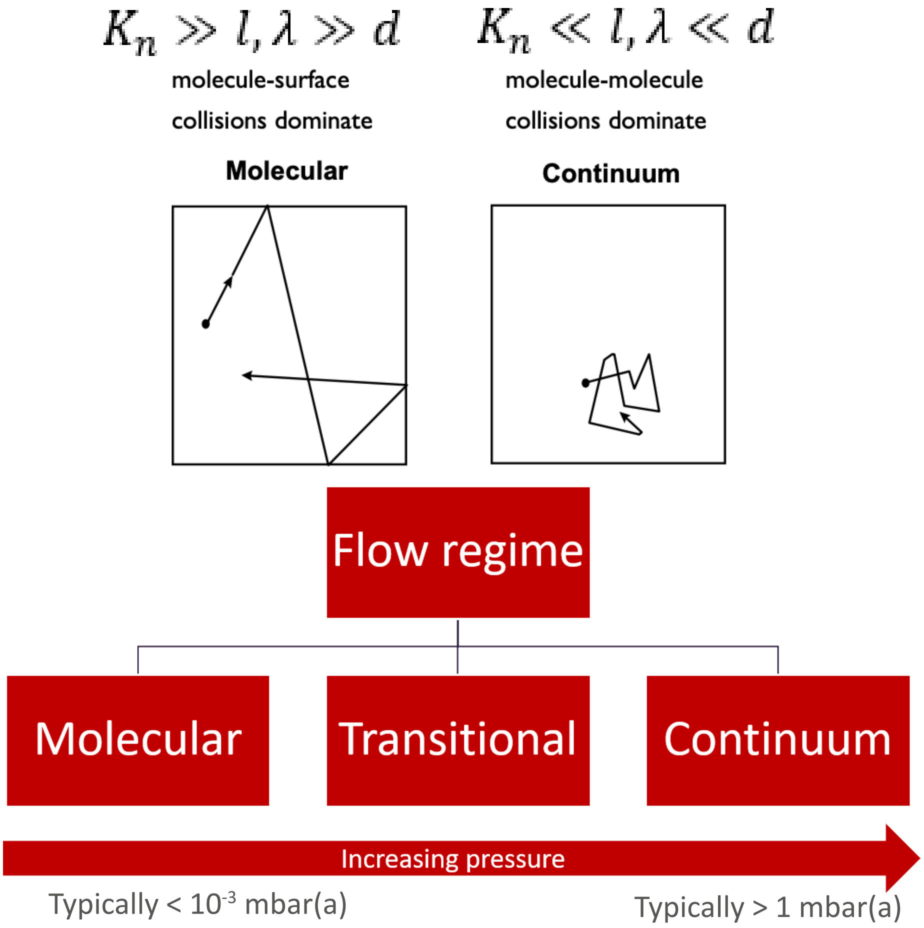


Figure 2.3: Different flow regimes dependent on the pressure.

The understanding of flow types is a fundamental requirement in the design of vacuum pumps and systems, both in terms of the different mechanisms employed to create controlled gas flow at different pressures and also the optimisation of system design.

v. Compression ratios

The pumping process relies on the compression of gas. The pressure ratio of a pump mechanism's exhaust pressure and the inlet pressure is known as the compression ratio, $K = P_{exhaust}/P_{inlet}$. The maximum compression ratio is referred to as K_o and is the compression with no gas flow at the inlet. The theoretical definition of compression for a given pump or pumping stage depends on the type of mechanism producing the compression; the compression ratio or a pump mechanism may be different for different gases. It is important to consider the effect and mitigation of the internal heat of compression within any compressing mechanism.

2.3 CLASSIFICATION OF PUMP TECHNOLOGIES

A consequence of the kinetic nature of gases is that there are different flow types across the vacuum spectrum, and these are exploited accordingly in the design of suitable pumping mechanisms for given vacuum and process conditions. The diagram shown in Fig. 2.4 is a schematic representing the most common pump classifications and families.

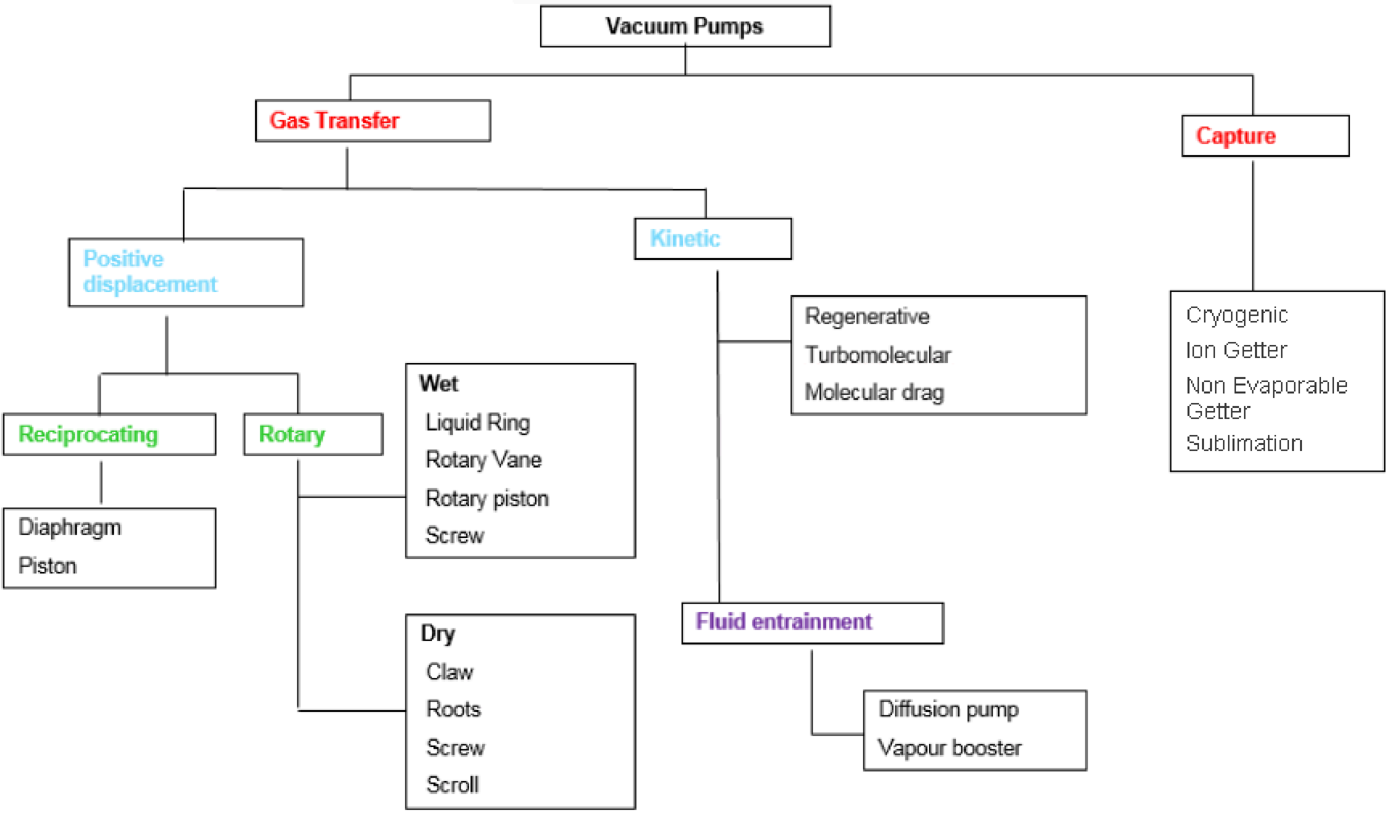
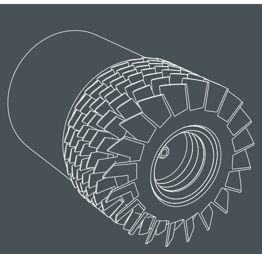
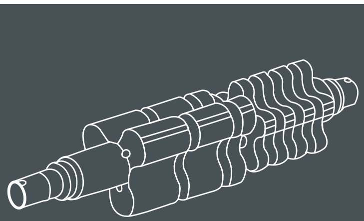


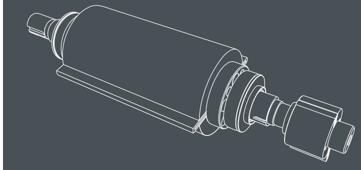
Fig. 2.4: Most common types of vacuum pumps.

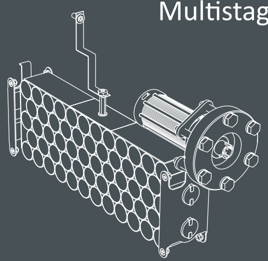
Typically, the different pressure ranges in vacuum technology are defined as follows: rough vacuum (from 10^3 mbar(a) to 1 mbar(a)); medium vacuum (1 mbar(a) to 10^{-3} mbar(a)); high vacuum (10^{-3} mbar(a) to 10^{-7} mbar(a)); ultra-high vacuum (10^{-7} mbar(a) to 10^{-12}); and extreme high vacuum (less than 10^{-12} mbar(a)) *(see Table 2.4 with working ranges)*.

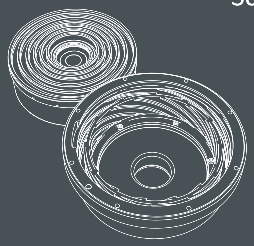

Mechanical Turbomolecular


Multistage roots


Scroll


Rotary vane


Ion Getter / NEG


Regenerative

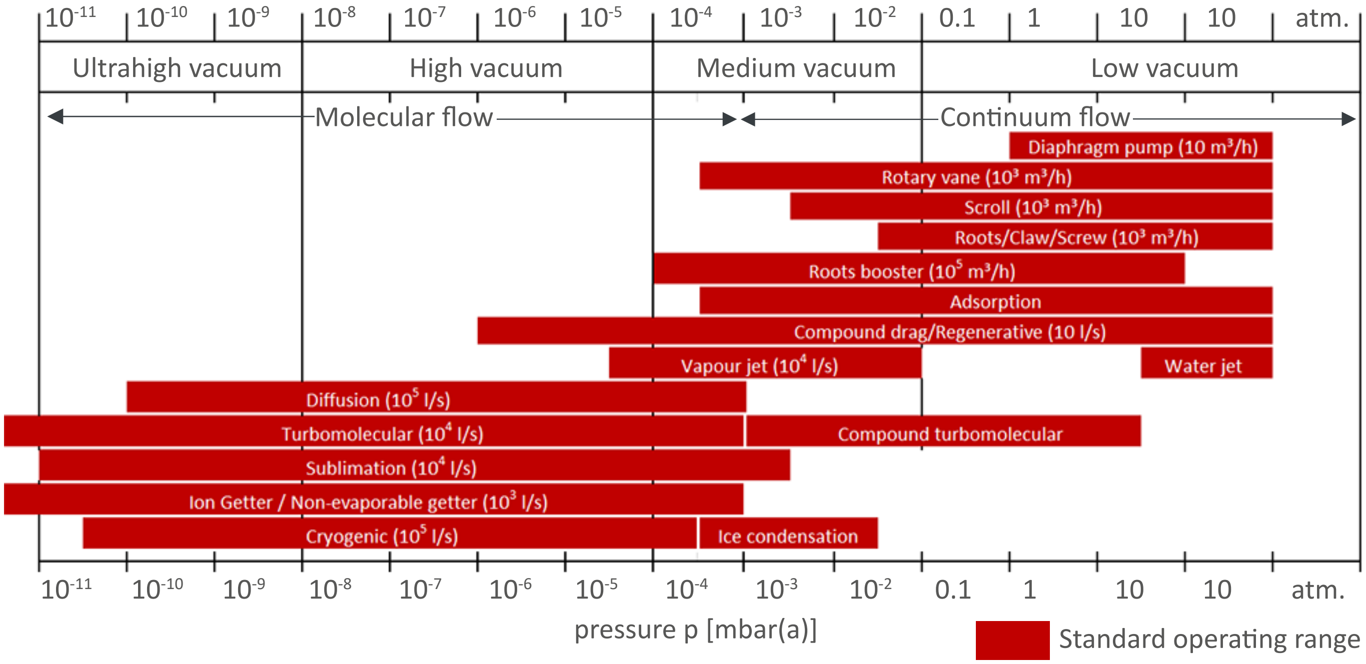
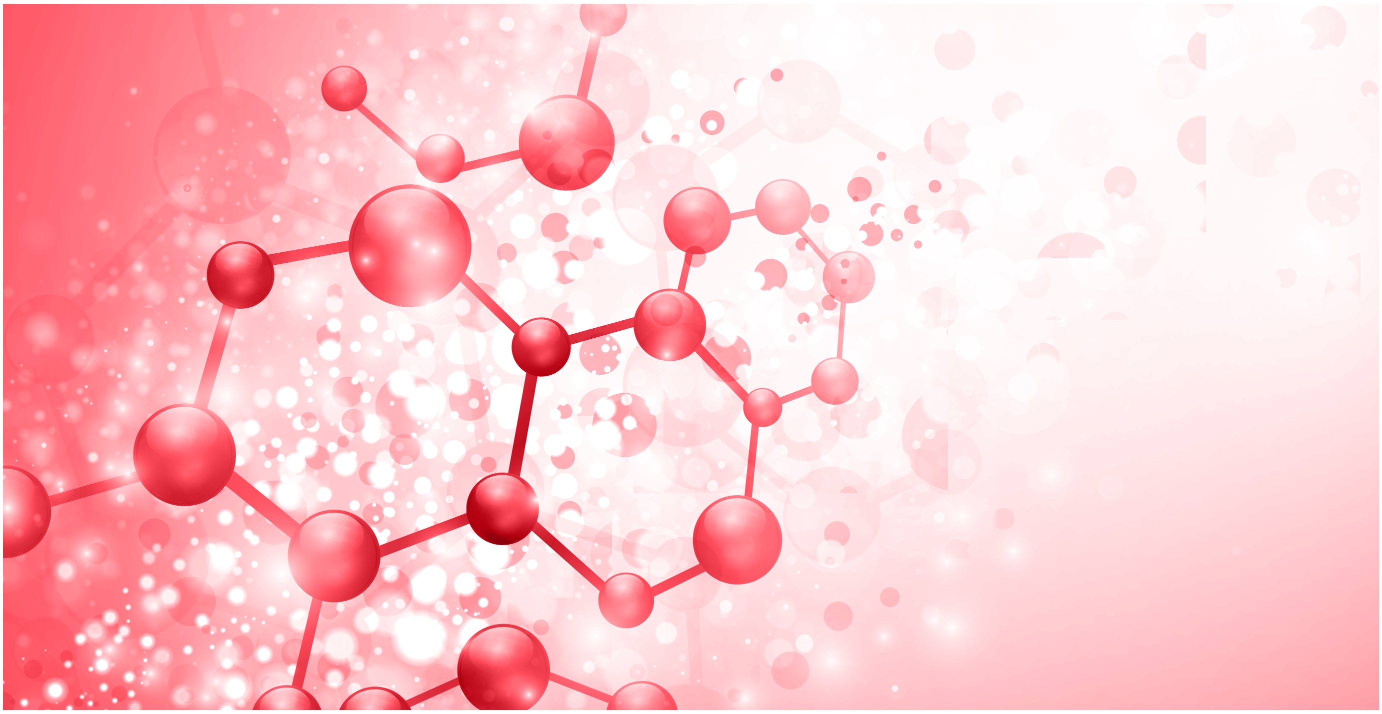


Table 2.4: Working ranges of different pump technologies.

Besides the vacuum pressure ranges that can be obtained, it is also important to consider the performance envelope of different pump technologies. Depending on the size of the vacuum system, the economic perspective will further reduce the selection of applicable pump technologies.

Primary vacuum pumps (mainly working in the rough and medium vacuum range) are exhausting to atmospheric pressures and thus can act in isolation. Secondary pumps (typically working in the high and ultra-high vacuum range) continuously exhaust to a primary pump or require a primary pump to create a level of vacuum they can operate from.



3. VACUUM PUMP TECHNOLOGIES

3.1 PRIMARY PUMPS

3.1.1 DIAPHRAGM PUMPS

Diaphragm pumps operate in the low vacuum regime. Due to their design, they do not achieve high compression ratios with a single stage. Thus, we often find two-, three- and even four-staged diaphragm pumps which make them useful as compact and environment-friendly pumps e.g. in lab applications and for backing turbomolecular pumps (TMPs). Diaphragm pumps can produce a standard operating range from 10^3 down to the low mbar range.

Operating principle: These pumps employ a diaphragm which is moved backwards and forwards by a rod. This oscillating motion compresses the medium and activates the valves. The gas moves in through an inlet valve and (when the diaphragm moves back), the inlet valve is closed and the gas is pressurised before being expelled out through the exit valve.

The diaphragm and the valves are usually made of polytetrafluoroethylene, which makes them resistant to corrosives and less vulnerable to vapour damage. Since diaphragm pumps are “dry” by design, they provide a hydrocarbon-free vacuum. Further advantages of diaphragm pumps are that they are easy to clean and maintain, are suitable for pumping many gases and laboratory chemicals, diaphragm pumps do not use any oil, so their operational and maintenance costs are low.

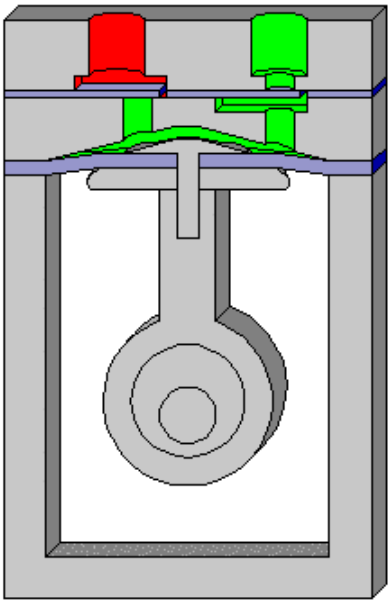


Figure 3.1: Schematic of a diaphragm pump.

Application area	• Chemistry and laboratory applications (vacuum filtration, distillation, drying,...) • Fore vacuum pump for turbomolecular pumps (with compound stage)
Pressure range	2000 to 0.5 mbar
Disadvantages	**Advantages**
• Only relatively small pumping speeds available. • Suitable for many gases & applications. • Able to pump liquid drops when pump is in horizontal position.	• Easy maintenance / Cleaning • Ultimate pressures only approx. 1mbar • Short diaphragm life time

3.1.2 ROTARY VANE PUMPS

Rotary vane pumps are the most common type of positive displacement vacuum pumps. As a very mature technology, they offer excellent reliability, robustness, compact design and low costs of investment.

Operating within a pressure range from atmosphere down to approx. 10^{-4} mbar(a), makes them ideal backing pumps for any kind of medium and high vacuum pumps.

Fig. 3.2 shows the operating principle of a rotary vane pump. As the rotor with the vanes rotates, the gas is moved from the inlet and compressed towards the outlet.

Whereas the oil-sealed operation is a disadvantage for some applications, the use of oil enables higher compression ratios, better internal cooling behaviour and makes the pump resistant to dirt, dust and condensate.

Of course, the need for servicing the pumps regularly (oil changes) means higher costs of ownership – compared to dry pumps of similar size.

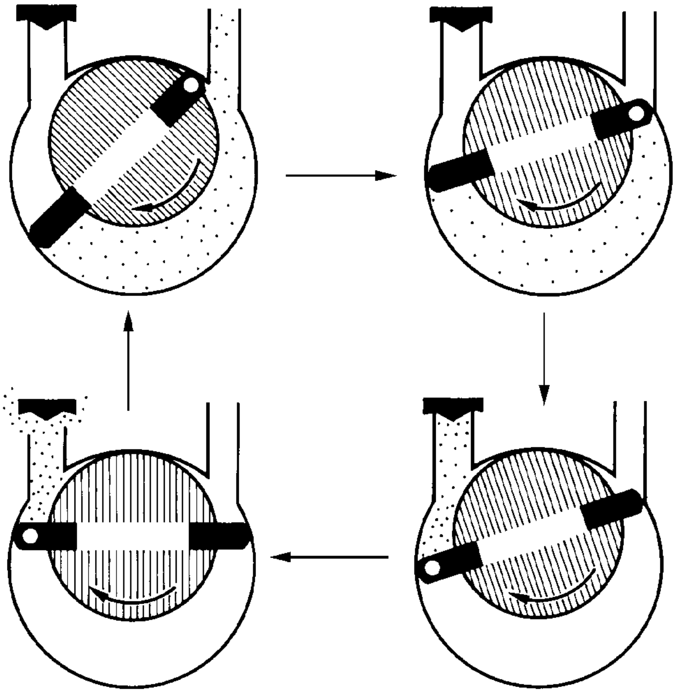


Figure 3.2: Schematic of a rotary vane pump's operating principle.

Application area	• Industrial & coating applications • Analytical instruments (mass spectrometers, leak detectors,...) • Research & development • Semiconductor and solar applications (special versions)...
Pressure range	10^3 to 10^{-4} mbar(a)
Disadvantages	**Advantages**
• No contamination-free vacuum (hydrocarbons) • High cost of ownership (oil changes, maintenance)	• Very low ultimate pressure • High pumping speed (from atm) • Low power consumption • Low capital costs

3.1.3 SCROLL PUMPS

Scroll pumps use two interleaved Archimedean spiral-shaped scrolls to pump or compress gases. One of the scrolls is fixed, while the other orbits eccentrically without rotating, thereby trapping and compressing pockets of gas between the scrolls which move the trapped gas from the outside (i.e. inlet) part to the inner (i.e. outlet) part of the scroll.

Scroll pumps are used in a diverse range of applications where clean, dry vacuum pumping is required. Furthermore, scroll pumps are frequently used as backing pumps for turbomolecular pump systems.

Scroll pumps have many advantages over other vacuum pumps: possibly the most significant is that although they have higher initial costs compared to oil-sealed rotary vane pumps, their operating costs are low because they do not require oil (which also makes them environmentally friendly). In addition, their maintenance needs are low (requiring intervention only every 1 to 2.5 years). Other advantages and disadvantages are listed below. However, wearing of tip seals can lead to particle emission, and the tip seals can have a low tolerance to introduced debris.

Figure 3.3: The two spiral-shaped scrolls.

Application area	• Analytical instruments (e.g. leak detectors, electron microscopes) • Clean fore vacuum applications
Pressure range	10^3 to 10^{-3} mbar
Disadvantages	**Advantages**
• Low particle tolerance • Possibility of particle emission	• High pumping speed • Good ultimate pressure • Low noise level & vibrations • Low power consumption • Pump bearings isolated from vacuum space - no contamination risk • Compact design & low weight

3.1.4 MULTI-STAGE ROOTS PUMPS

Multistage Roots pumps combine a series of Roots pump stages to overcome the pressure difference limitations of a single roots pump stage. Multistage roots pumps can compress from atmospheric pressure down to pressures in the low 10^{-2} mbar range and are a dry pumping alternative to scroll pumps where particle-free pumping is desired.

Multi-stage Roots pumps are typically used in dry and clean applications like analytical instruments, R&D as well as in many industrial applications.

Advantages of multi-stage roots pumps include their compact design and little or no wear due to the fact that there are no contacting parts. However, the assembly time is typically longer and suppliers may charger higher service costs.

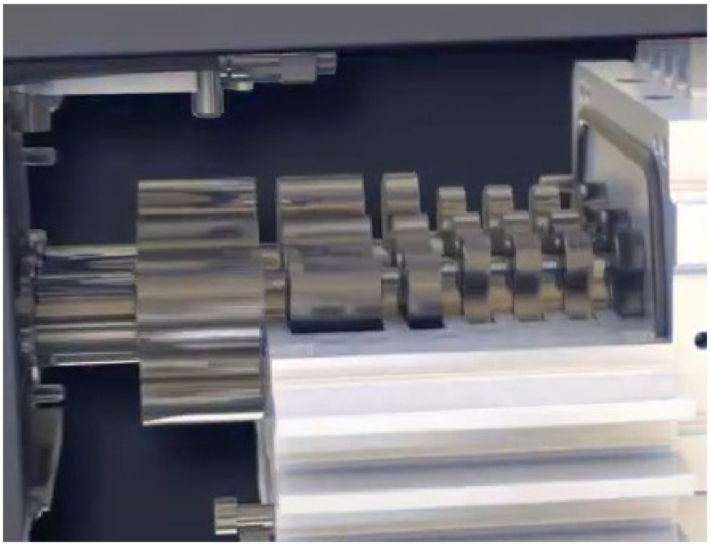


Figure 3.4: Multi-stage roots

Application area	• Dry and clean applications (Analytical instruments, R&D) • Clean applications in semiconductor and solar industry • Coating and industrial applications
Pressure range	10^3 to 10^{-2} mbar
Disadvantages	**Advantages**
• Higher service costs/assembly time • Lower pumping performance from atmosphere	• Compact design • Frequency controlled motor • Long service interval • No contacting parts - no wear • Clean pumping - no particles, no oil

3.2 SECONDARY PUMPS
3.2.1 TURBOMOLECULAR PUMPS

Turbomolecular pumps (TMPs) are kinetic units which operate using a very fast spinning rotor (usually between 24,000 and 90,000 rpm). Their working parts are similar to a multi-bladed turbine, with pairs of rotor/stator stages along the shaft.

TMPs operate by transferring the high-speed impact of their blades directly onto gas molecules, which biases the motion of these molecules towards the "exit" of the pump. As their name indicates, TMPs typically operate in the molecular flow range between 10^{-3} and 10^{-11} mbar. When coupled with a drag pumping mechanism this range can be extended to 10^{-2}mbar. Since they cannot compress against atmospheric pressure, all TMPs require appropriate backing pumps.

Figure 3.5: Turbomolecular rotor

Different bearing concepts are exist for TMPs, with the most common concepts in the market being:

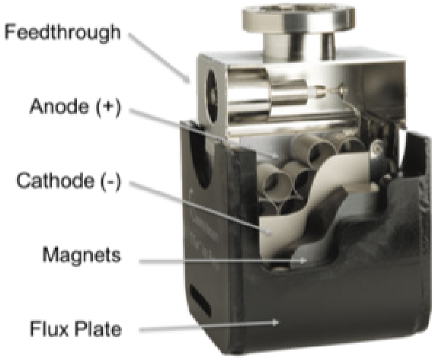
- Fully (5-axis) active magnetic levitated bearing design
- All mechanical bearing design
- Combination of passive magnetic and mechanical bearing design

Application area	• Analytic instruments (Mass Spectrometer, Electron Microscopes, Surface analyzers,...) • Research & Development (High energy physics, UHV systems, MBE systems,...) • Coating & Industrial applicationss
Pressure range	10^2 to $<10^{-10}$ mbar
Disadvantages	**Advantages**
• Relatively low pumping speeds for light gases • Moving parts => source of vibration & (electrical) noise • Sensitive to mechanical shocks/ particulate matter • Requires backing pump	• High pumping speed at HV/UVH • Starts working at high pressures (molecular regime) • Easy operation • Hydrocarbon free operation • Low maintenance • No regeneration required

3.2.2 ION GETTER PUMPS

Ion Getter (or Sputter Ion) Pumps (IGP) can be considered as an array of Penning cells in which a gas discharge is established. Two parallel cathode plates are position normal to an anode cylinder.

A high magnetic field and electrical potential create and maintain the Penning discharge where gas molecules are ionised. The pumping action is via ion implantation in the cathode and the concurrent sputtering of material from the cathode which forms an active gettering layer.



The advantages of IGPs are that they are capable of producing very low ultimate pressures, they are absolutely hydrocarbon free, are high temperature tolerant, have a high tolerance to radiation/magnetic fields, there are no moving parts (and thus no vibrations or electrical noise), no regeneration is required, such units are low-maintenance and there are no valves involved. IGPs require a roughing pump to supply the suitable starting pressure in the high vacuum pressure range.

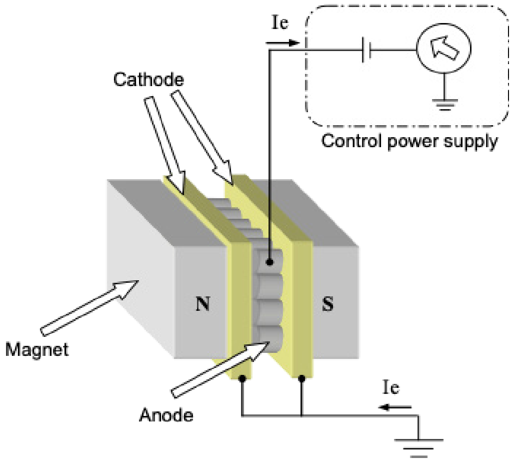


Figure 3.6: Ion Getter pump set-up

Application area	• UHV/Storage rings • MBE - systems • Electron microscopes • Surface analysis
Pressure range	10^{-5} to 10^{-12} mbar
Disadvantages	**Advantages**
• Decreasing pumping speed in UHV range • Needs high voltage and magnetic field • Needs roughing pump to supply start pressure (10^{-5} mbar range) • Heavy weight	• Very low ultimate pressures • Absolutely hydrocarbon free • High temperature tolerance; bakeable • High tolerance to radiation and magnetic fields • No moving parts => no vibration & (electrical) noise • No regeneration • No valves needed • Low Maintenance

3.2.3 CRYO PUMPS

Cryo pumps work by either condensing or adsorbing gases on cold surfaces resp. activated charcoal. The low-temperatures required are usually provided by a dual-stage cold head, where the first stage typically attains temperatures between 50 and 80K at the cryopanels, and about 10K at the second stage.

A thermal radiation shield with the baffle is closely linked to the first stage of the cold head- here mostly H_2O and CO_2 are condensed. The remaining gases penetrate the baffle, where gases like N_2, O_2 or Ar will condense at the second stage. H_2, He and Ne cannot be pumped by the cryopanels but will be adsorbed by the activated charcoal coated on the inside of the cryopanels attached to the second stage.

Cryo pumps are used in ultra-high vacuum systems, such the ones listed below. A main advantage of a cryopump is the very high pumping efficiency and thus pumping speed for water vapor.

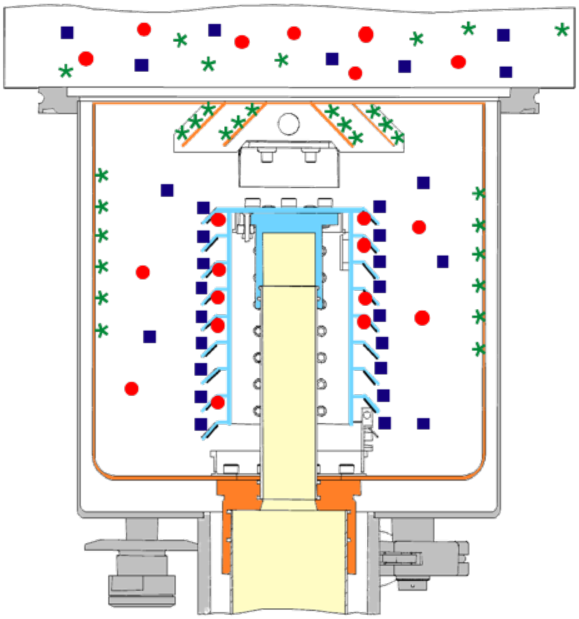


Figure 3.7: Cryo pump schematic

Application area	• Space simulation & General R&D • UHV systems/beamlines • MBE (Molecular Beam Epitaxy) • Electron beam welding systems • Coating systems & Load lock chambers
Pressure range	10^{-5} to 10^{-11} mbar
Disadvantages	**Advantages**
• Relatively lower pumping efficiency for H2, He, Ne • Medium to strong vibrations • Very sensitive to heat & dust • Regeneration required • Backing pump needed (for start and regeneration) • Relatively high costs	• Very low ultimate pressures • Absolutely hydrocarbon free operation • Very high pumping speed for water vapour • No moving parts in vacuum

4. VACUUM MEASUREMENT

The measurement of vacuum pressure plays an extensive and important role in all vacuum applications including for quality and safety.

When measuring a vacuum pressure, it must be remembered that there is no universal vacuum gauge – one that will respond accurately throughout the range from atmospheric pressure to 10^{-12} mbar(a). Therefore, understanding the application and the pressure measurement required is crucial to making the correct choices. Important considerations are the materials of construction, method of measurement (both direct and indirect), and electronics; all contributing to the limitation of each type of gauge.

Additionally, the environment which the gauge is situated can dictate the type suited *e.g.* radiation, magnetic fields, temperature and corrosive atmospheres.

4.1 SELECTION CRITERIA

The main criteria to consider when selecting a vacuum gauge are:

1. Pressure range: Ask yourself what the desired pressure range is that you want to measure, as different pressure ranges require the use of different gauges. Also consider the allowed measurement uncertainty / requested accuracy.

2. Application: Consider the specific application and process conditions you are using the vacuum gauge for. This includes amongst others:

> **a. Special operating conditions:** dirt/dust or vapours, vibrations and/or mechanical impact, strong gas flows, radiation, magnetic fields etc. have to be taken into account as some gauges are more sensitive towards environmental conditions than others.
> **b. Temperature:** Some gauges are more sensitive to temperature variations than others – so make sure the chosen gauge can withstand either hot or cold conditions if required, and the effect on accuracy which a change in temperature can give.
> **c. Gases:** Finally, if any special gases are involved in the system this also needs to be considered. The right correction factors must be used and materials selected to avoid any unwanted chemical reactions or media compatibility issues.

3. Communication & Control: This covers questions around how to control the measurements (*e.g.* controller type, cable length), the type of interface needed (*e.g.* RS232, Profibus, Devicenet,…), whether trigger points (set points, switching points) shall be used and so on.

4. Size, cost, serviceability

4.2 DIRECT OR INDIRECT GAUGES

“Direct” gauges measure the force associated with pressure independently of the composition of the gas being measured. “Indirect” gauges are dependent on the gas species being measured, since they measure a pressure dependent property such as the thermal conductivity or ionization characteristics. Manufacturers offer combination gauges to overcome the measurement range limitations of some of the technologies. For instance, a combination Pirani-Penning gauge can operate from atmosphere to 10^{-10} mbar(a). Fig 4.1 gives an overview on the types of gauges.

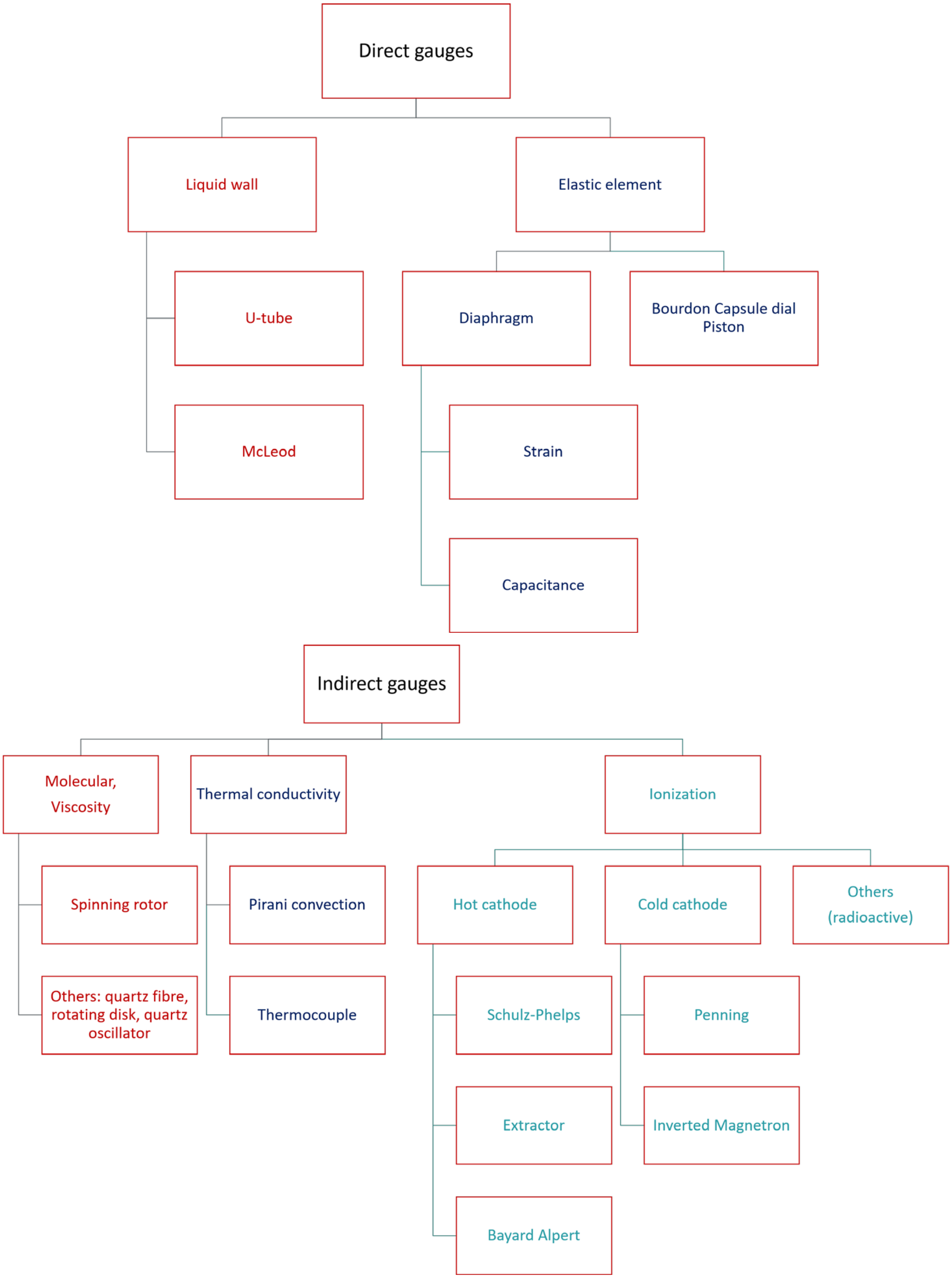


Figure 4.1: Classification of vacuum gauges.

4.3 MEASUREMENT RANGES

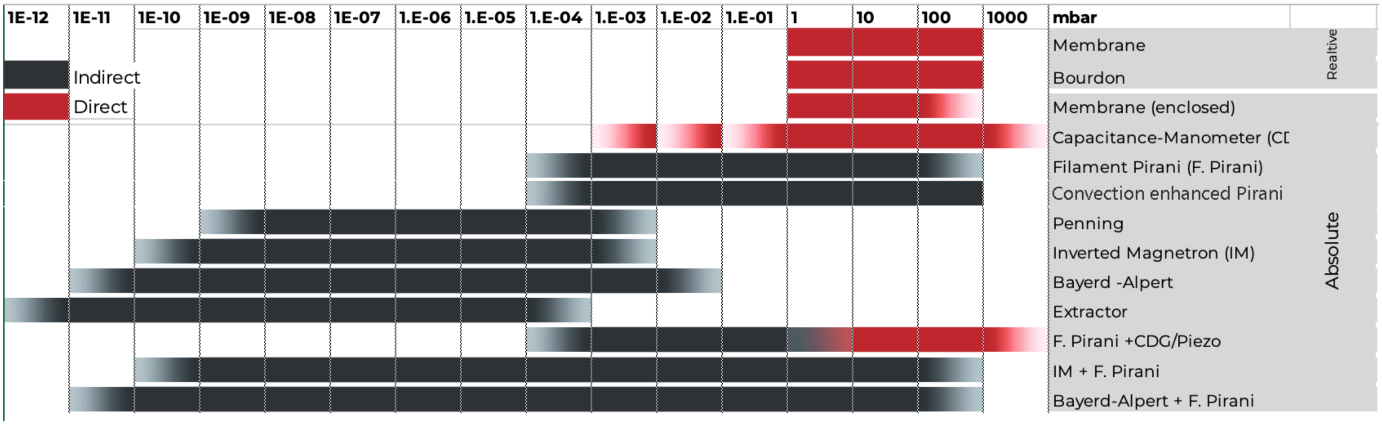


Figure 4.2: Operating range of different gauges.

Mechanical dial gauges are used in the pressure range from atmosphere to 1 mbar(a); however, these gauges offer only limited accuracy and can only be read directly at the point of installation. Diaphragm vacuum gauges (piezo sensors or capacitive sensors) are used to obtain more accurate measurements and for remote display of readings.

Pirani thermal conductivity vacuum gauges are used between 10 and 10^{-4} mbar(a). It is also possible to use special high-pressure hot cathode ionization vacuum gauges at pressures $< 10^{-2}$ mbar(a).

Either cold cathode ionization vacuum gauges or hot cathode ionization vacuum gauges are used for pressures of less than 10^{-3} mbar(a), the latter in the case of clean conditions and rigorous accuracy requirements. It is also a good idea to use a combination of two or more sensors to cover the entire pressure range in use.

In the case of diaphragm vacuum gauges and Pirani vacuum gauges, pressure switch points are generated to activate ionization vacuum gauges only if the pressure is sufficiently low, thus protecting them against contamination or burn-out of the hot, thermionic, cathode. An overview on the operating range of different gauges is given in Fig. 4.2.

4.4 ACTIVE OR PASSIVE GAUGES

Vacuum gauges can be either active, passive or digital. “Active” gauges (as shown in Fig. 4.3) incorporate the electronic sensor, which transforms the pressure measured into an electrical signal with a compact electronic control and evaluation unit. They indicate the pressure measured either in the form of an analogue measurement signal or a numerical value through a standardized digital interface.

A “passive” gauge (as shown in Fig. 4.4) does not feature an integrated electronic unit, so they need to be connected to control units by a cable.

Figure 4.3: APG200 active pirani gauge.

This control unit will deliver power to the gauge head, evaluate the transmitted data and the evaluation and display of the resulting pressure reading.

The control units are normally also equipped with analogue voltage outputs, digital interfaces and relay contacts for switch-points.

Figure 4.4: PRG20K passive pirani gauges.

4.5 DIRECT GAUGES

Elastic element vacuum gauges: A sealed and evacuated vacuum chamber is separated by a diaphragm from the vacuum pressure to be measured. This serves as the reference quantity. With increasing evacuation, the difference between the pressure which is to be measured and the pressure within the reference chamber becomes less, causing the diaphragm to flex. This movement may be transferred by mechanical means to a dial, or electrically by means of a strain gauge or a bending bar for conversion into an electrical measurement signal. Different types of elastic element gauges are shown in Fig. 4.5.

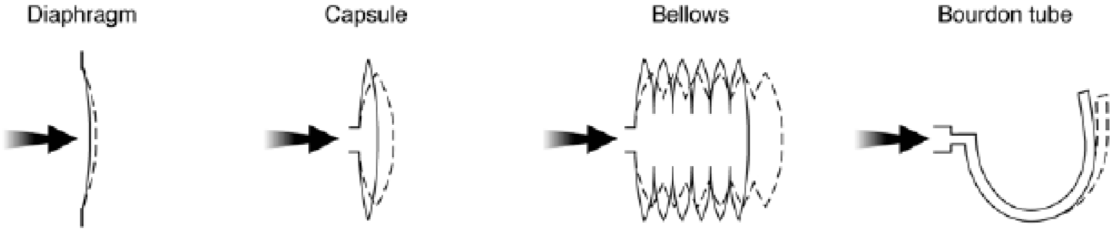


Figure 4.5: Types of elastic element gauges.

Bourdon vacuum gauge: The simplest direct gauges fall under the category of dial gauges. The most common is a Bourdon vacuum gauge that derives from the inside of a tube that is bent into a circular arc and connected to the vacuum system. Because of the external atmospheric pressure, the end of the tube bends more or less during the evacuation process. This actuates the pointer arrangement which is attached to this point. The corresponding pressure can be read off on a linear scale. With Bourdon gauges it is possible to roughly determine pressures between 10 mbar(a) and atmospheric pressure.

Capsule vacuum gauge:
This vacuum gauge contains a hermetically sealed, evacuated, thin-walled diaphragm capsule that is located within the instrument (see Fig. 4.6). As the vacuum pressure reduces, the capsule bulges. This movement is transferred to a dial via a system of levers and can then be read off as the pressure on a linear scale. It is independent of atmospheric pressure changes.

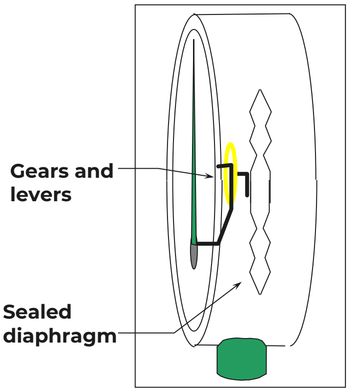


Figure 4.6: Schematic of a capsule vacuum gauge.

Capacitance diaphragm gauge (CDG): The term capacitive measurement means that a plate capacitor is created by the diaphragm with a fixed electrode behind the diaphragm. A schematic of a CDG is shown in Fig. 4.7. When the distance between the two plates of this capacitor changes, a change in capacitance will result. This change, which is proportional to the pressure, is then converted into a corresponding electrical measurement signal. An evacuated reference chamber serves as the reference for the pressure measurements. With capacitance gauges it is possible to accurately measure pressures from 10^{-5} mbar(a) to well above atmospheric pressure, whereby different capacitance gauges having diaphragms of different thickness, and therefore sensitivity, will have to be used.

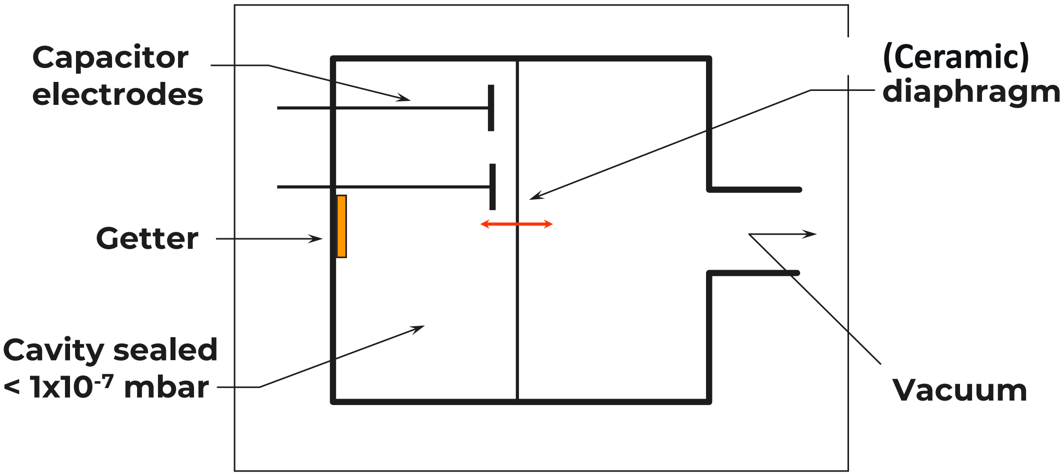


Figure 4.7: Schematic of a CDG.

4.6 INDIRECT GAUGES

Pirani gauge: The Pirani, or thermal conductivity gauge, uses the thermal conductivity of gases to measure pressure in the range from 10^{-4} mbar(a) to atmospheric pressure. The filament within the gauge head forms one arm of a Wheatstone bridge (see Fig 4.8).

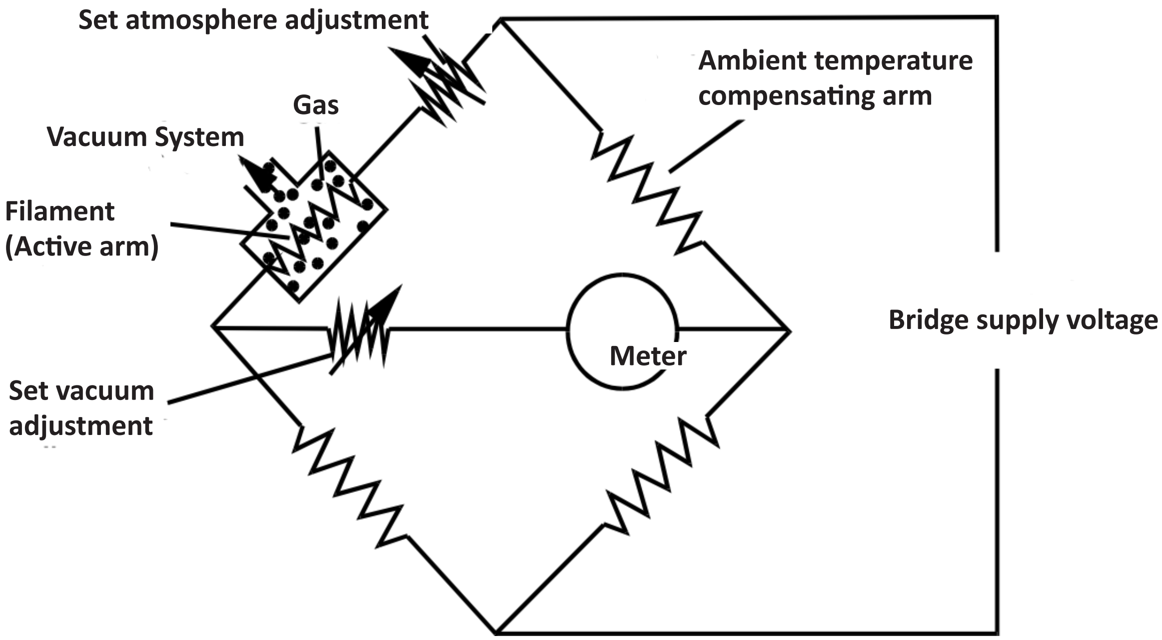


Figure 4.8: Schematic of a pirani gauge with a Wheatstone bridge.

In one operating mode the heating voltage which is applied to the bridge is controlled in such a way, that the filament resistance and thus the temperature of the filament remains constant regardless of the quantity of heat given off by the filament. Since the heat transfer from the filament to the gas increases with increasing pressures, the voltage across the bridge is a measure of the pressure (see Fig. 4.9).

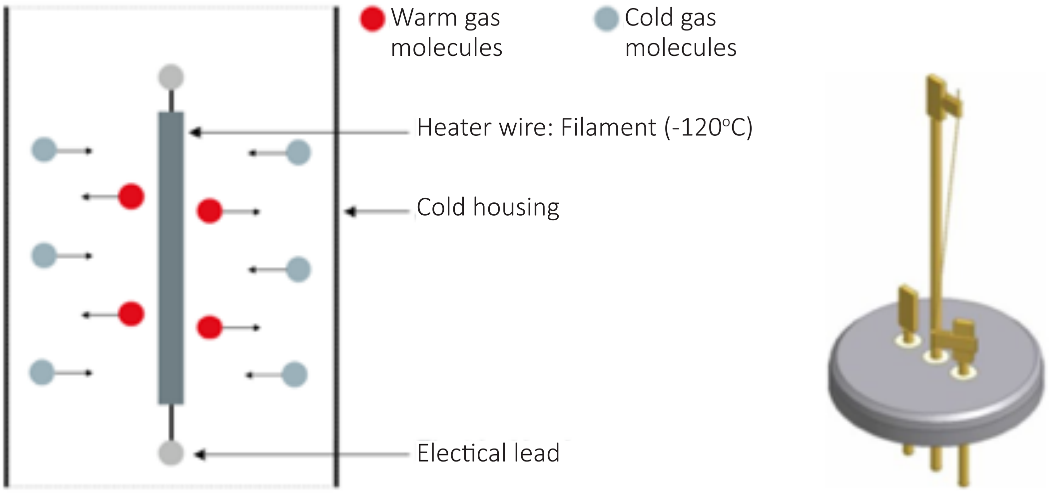


Figure 4.9: Operating principle (left) and set-up (right) of a pirani gauge.

The pirani gauge is an indirect gauge since thermal conductivity varies with gas species as shown in the calibration chart in Fig. 4.10.

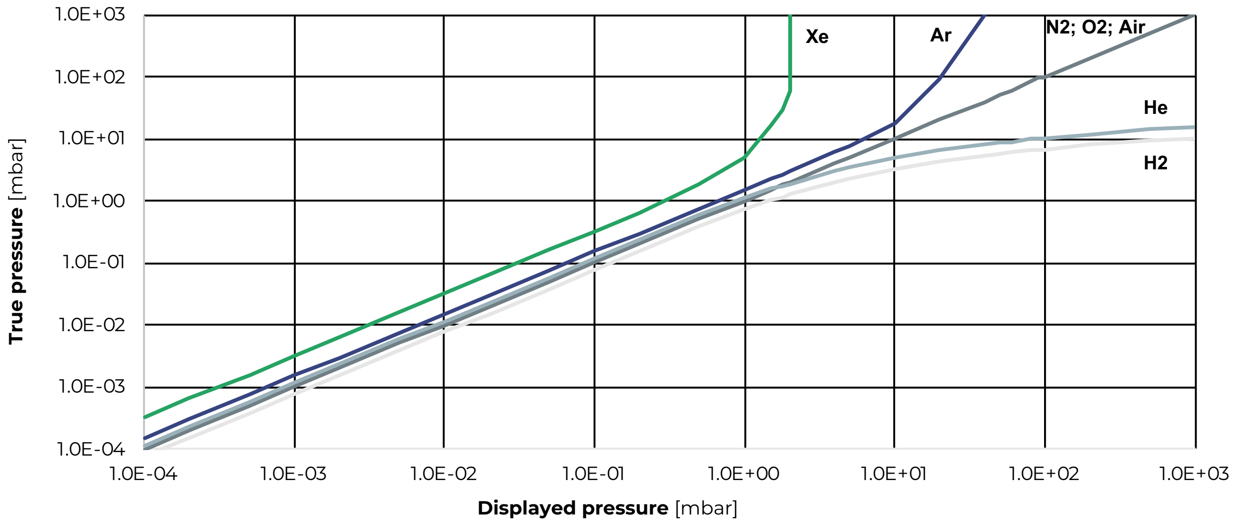


Figure 4.10: Gas dependency of thermoconductivity gauges.

Hot cathode ionisation vacuum gauge: this gauge emits electrons from a heated cathode which are attracted to a positively charged anode. During their flight they ionize gas molecules; the ion current produced being proportional to the gas pressure.

The hot cathode sensors which are mostly used today, are based on the Bayard-Alpert (BA) principle. A BA vacuum gauge collects positive ions on a thin ion collector wire (see Fig. 4.11) and measures the resulting current to the ion collector to determine the number of molecules present, and indicates a pressure based on that measurement. The Bayard-Alpert gauge was invented by R.T. Bayard and D. Alpert in 1950 to overcome a limitation in vacuum pressure measurement by the triode gauge of ~10^{-8} mbar(a).

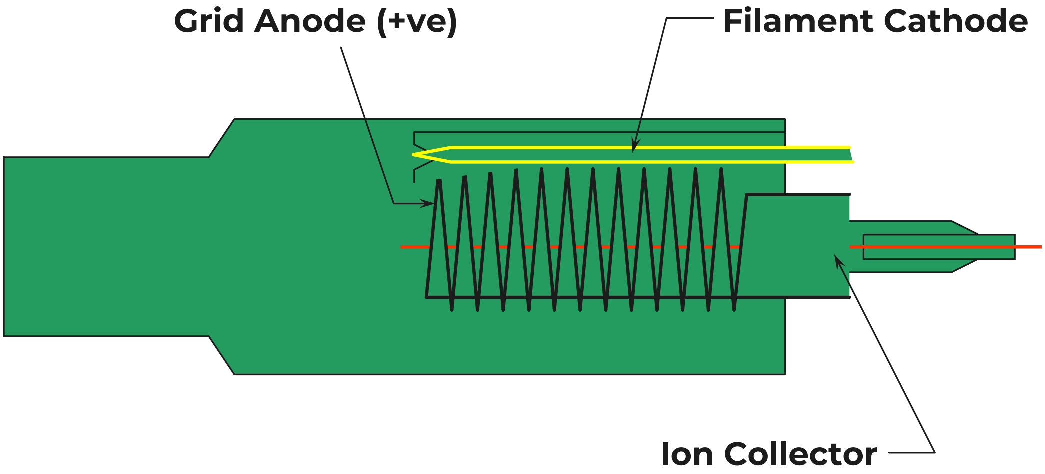


Figure 4.11: Schematic of a BA gauge.

This is because electrons striking the grid anode create low-energy X-rays, which emit photoelectrons when they strike the ion collector. The current that results from the photoelectrons leaving the collector is what causes the lower pressure limit of the triode gauge. The solution proposed by Bayard and Alpert was to reconfigure the collector and grid of the triode gauge to lower the current from this X-ray effect.

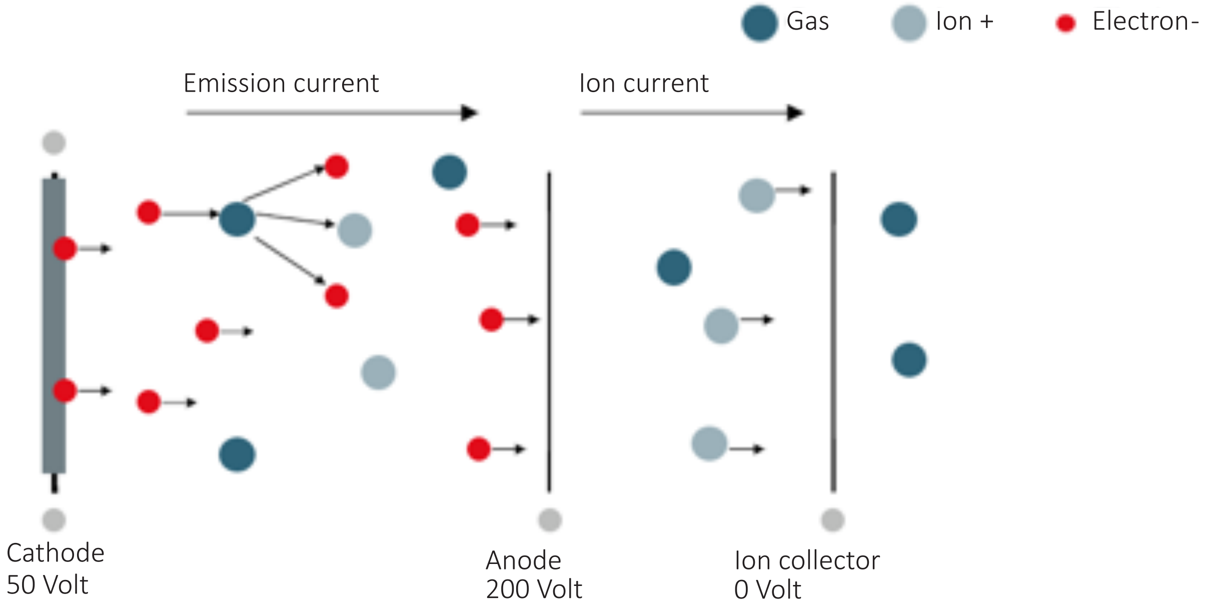


Figure 4.12: Operating principle of extractor ionization gauge.

With the modern electrode arrangement, it is possible to make measurements in the pressure range from 10^{-10} to 10^{-4} mbar(a); other electrode arrangements permit access to a higher pressure of 10^{-2} mbar(a). For the measurement of pressures below 10^{-10} mbar(a), so-called "extractor" ionization gauges are employed in which ions are focused onto a very thin and short ion collector (see Fig 4.12). Due to the geometrical arrangement of this system, interfering influences such as X-ray effects and ion desorption can be almost eliminated. The extractor ionization gauge permits pressure measurements in the range from 10^{-4} to 10^{-12} mbar(a).

Cold cathode ionization gauges: A cold cathode ionization gauge is so named as the cathode is not heated and commonly operates on the inverted magnetron principle. In this device a gas discharge is ignited by applying a high voltage. The resulting ion current is output as a signal which is proportional to the prevailing pressure. The gas discharge is maintained at low pressures with the aid of an applied magnetic field.

A cold cathode system requires a high ignition voltage of up to 3.5 kV DC. With this high acceleration voltage, the electrons fly on the shortest path to the positive anode ring or pin. The electrons are forced into tight spiral paths by the directed permanent magnetic field. This considerably extends the residence time of the electrons, which also considerably increases the probability of the ionization of gas atoms. This creates a permanent ion current whose size is proportional to the pressure.

While the cold cathode ionization gauge uses a closed magnetic field in the sensor, another variant of cold cathode gauge uses an outwardly open magnetic field as an inverted magnetron. This is always indicated from the outside by a warning sign for pacemakers.

Although applications are widely varied, the basic parameters for choosing a gauge are similar. Most users want the most accurate reading possible and settle for a gauge that covers the ranges that are important to them. There are a lot of different vacuum gauge types available, but with a full understanding of the required application, it should be possible to select the right gauge and controller for any operation.

5. VACUUM LEAK DETECTION

5.1 CREATING A LEAK TIGHT SYSTEM

Wherever and whenever a vacuum needs to be created, it is essential to ensure as far as possible, the integrity (*i.e.* the leak-tightness or simply "tightness") of the system. If the system is not tight, then both time and effort are pointlessly squandered trying to create and maintain a vacuum in an "open system" which could never support a vacuum in the first place. Of course, this is an extreme case, but as vacuum pressures get lower and lower, even the most seemingly secure and pristine of systems will soon show that they are less than tight.

Leaks can appear in various ways and their effect differs based on their size and form. A leak allows the gas to transport from one place to another. As gas is compressible, the pressure of the gas influences the amount of the transported gas. That is why the leak rate is always specified in mbar(a)l/s or equivalent units.

Being able to produce a system which is completely devoid of any leaks is virtually impossible and, therefore, it is necessary to work towards achieving a leak rate that is acceptable to the application in question, *i.e.* "sufficiently" leak-tight.

Tightness (or "the absence of leaks") is required for numerous reasons, including:

- for operator safety (*e.g.* egress of toxic materials)
- to guarantee a long lifetime of products
- to ensure and maintain the pressure/vacuum
- to guarantee product safety (*e.g.* to stop air entering a system to create an unsafe mixture)
- for environmental and/or quality standards
- and for process efficiency.

There are multiple ways of detecting vacuum leaks, which are shown in Table 5.1.
The method to be employed for detecting and measuring leaks depends on the lowest likely detectable leak rate required. The leak rate is the amount of gas that flows through a leak at a given pressure differential per unit time.

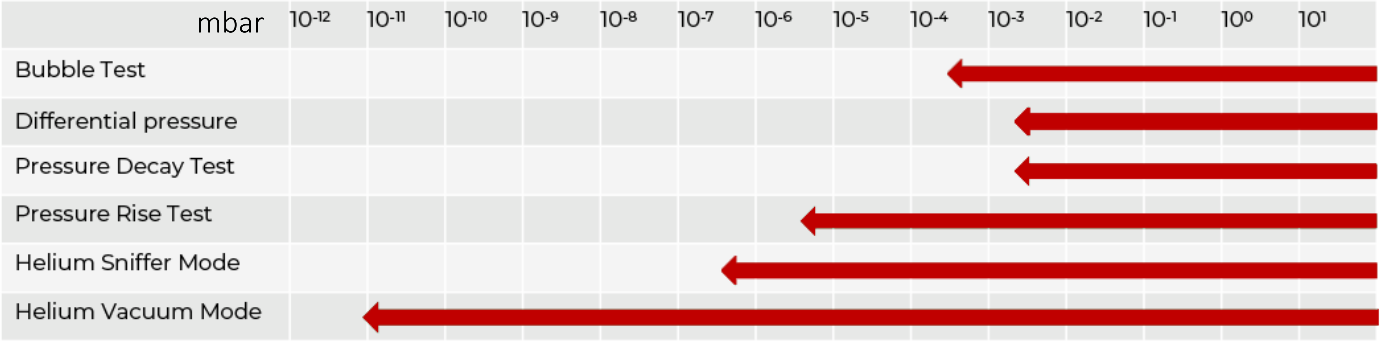


Table 5.1: Different methods of leak detection and their application range.

Leak testing generally aims to identify the position of a leak and/or measure the flowrate of gas through a leak.

5.2 TYPES OF VACUUM LEAK DETECTION

Bubble and foam-spray tests

There is no single detection method suitable for every eventuality. Which one to employ is usually based upon the pressure/vacuum range and the system under examination. The most simple is the bubble test, which is best illustrated by placing a punctured bicycle tube under water, trying to inflate it, and noting where the bubbles come from.

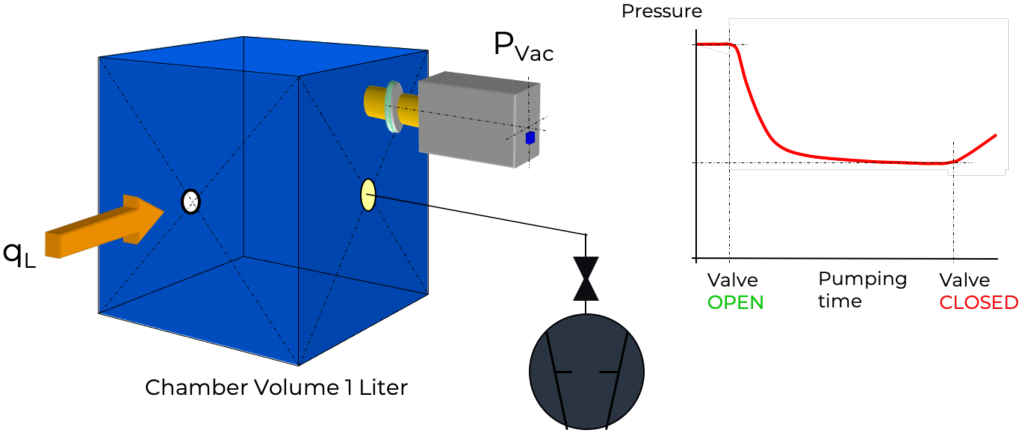
A slight variation of this, the foam-spray test, involves brushing or spraying a surfactant or liquid soap solution around the joint/connection of an active water/gas pipe, and observing if the liquid forms a foam. Both the bubble and foam-spray test are reliable ways of detecting a leak, however, they are time consuming and depend on the attentiveness of the inspector.

Additionally, whilst simple and effective at detecting the locations of leaks, quantifying a leak rate measurement is not practical without a great deal of additional equipment.

Pressure rise tests

The pressure rise tests are conducted by:

A. Evacuating a closed vacuum vessel under test until a certain pressure is obtained, then closing the pump's inlet valve. Fig. 5.1 shows the schematic set-up. After a pre-determined period of time, the inlet valve is again opened, and the time is recorded for the pump to return the pressure to the original evacuated level. This process is repeated a number of times. If the time to return the pressure to the original level remains constant, then a leak is present. If this time period decreases, this indicates reduced gas liberation (outgassing) on the inside of the system (a "virtual" leak) on each successive pump-down but does not exclude a leak from being present.

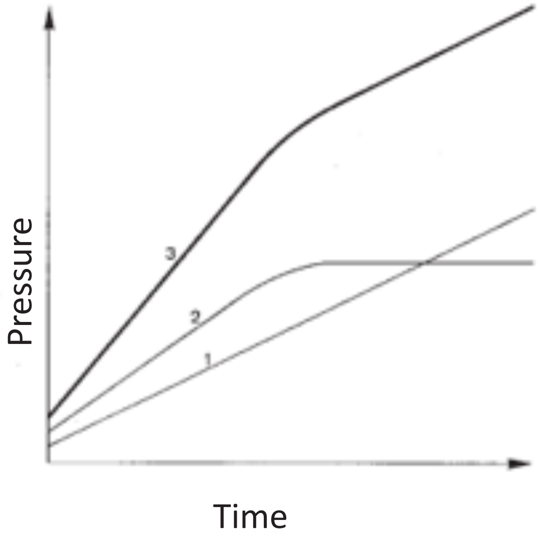


1. Pump down starts with valve open, P_{Vac} decreases
2. Valve closes, P_{Vac} should be stable
3. The leak q_L delivers a continuous gas flow into the chamber
4. P_{Vac} increases with valve closed

Figure 5.1: Schematic set-up for a pressure rise test.

B. Then plot the pressure against time for an evacuated and then isolated system. The curve for the rise in pressure will be a straight line if a leak is present and will tend to atmospheric pressure. However, if the pressure rise is due to gas liberation from the system walls, the pressure rise will gradually taper off to reach a final, stable value (refers to Fig. 5.2).

In most instances both phenomena occur simultaneously, which makes separating one from the other almost impossible. If the volume of the chamber or item under test is known, then the leak rate can be calculated as the volume x (measured change in pressure)/time taken.



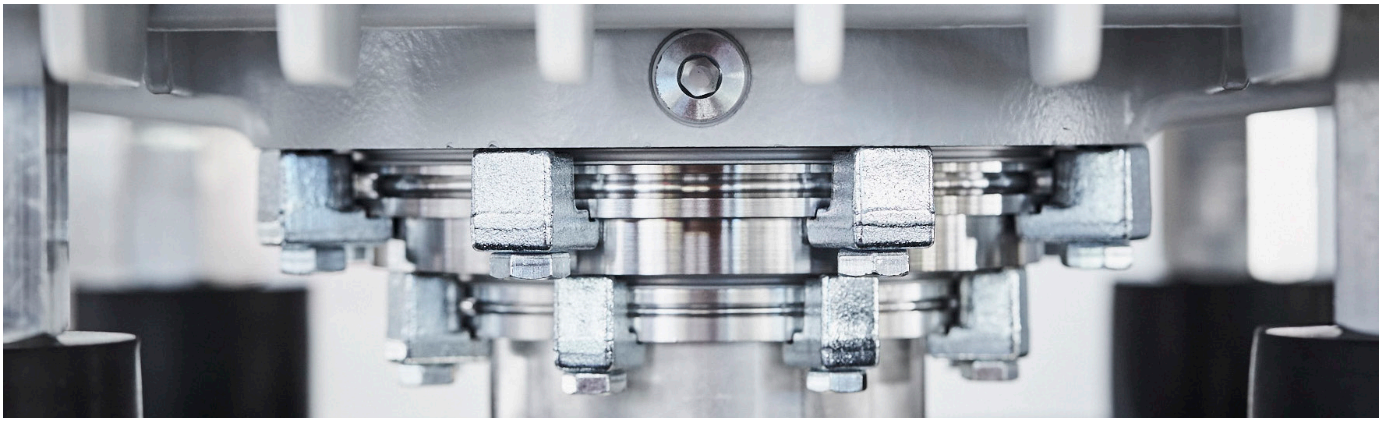
1. Leak
2. Gas evolved from the container walls
3. Leak + gas evolution

Figure 5.2: Pressure development for an evacuated and isolated system.

Pressure drop test

This test is not dissimilar to the pressure rise test. It is only rarely used to check leaks in vacuum systems, and only when the (positive) gauge pressure does not exceed 1 bar, since the flange connections used in vacuum technology will not tolerate a higher pressure.

However, the pressure drop test is frequently employed in tank engineering. Pressure drop tests allow leak rate measurements to 10^{-4} mbar(a)l/s but can be distorted if condensation occurs.



Helium leak testing

Other leak test methods are employed but the only method to detect leaks smaller than 1×10^{-6} mbar(a)l/s is with a helium leak detector (HLD). The most accurate and rapid leak detection methods employ helium as the tracer gas, coupled with a mass spectrometer for identification and quantification typically to minimum detectable leak of 10^{-12} mbar(a)l/s.

The reasons for using helium (mass, $M = 4$) for leak detection are compelling: It is unequivocally detectable by a mass spectrometer, it is chemically inert, non-explosive, non-toxic, present in normal air in a concentration of only 5 ppm, and is relatively economical.

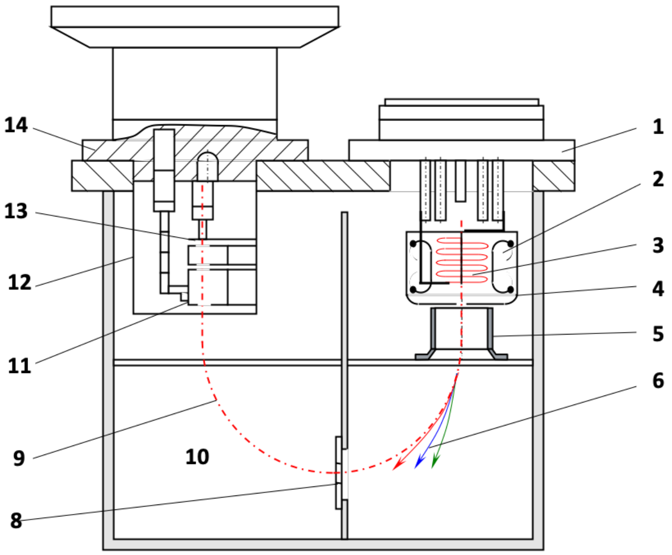


Figure 5.3: Schematic of a He leak detector.

Ion source (1-4)

1. Ion source flange
2. Cathode (Two cathodes Ir + Yt_2O_3)
3. Anode
4. Shielding ion source and aperture

Deflection system (5-9)

5. Extractor
6. Ion path M > 4
8. Intermediate aperture
9. Ion path M =4
10. Magnetic field (vertical to drawing)
11. Suppressor
12. Shielding of ion trap
13. Ion trap
14. Flange of ion trap with pre-amplifier

Leak detection using helium: working principles

Leak detection using helium is achieved in the following ways: The unit being checked is either pressurised from within with helium or else pressurised/sprayed from without with helium. The gases from any potential leaks are collected and pumped into the mass spectrometer for analysis, and any value above the background trace of helium is evidence of a leak. The mass spectrometer is by far the most sensitive leak detection method, as well as the one most widely used for detecting the smallest leaks. In principle, it is possible to detect all gases using mass spectrometry, however, helium as a test gas has proved to be especially practical.

The mass spectrometer itself works in the following way: any helium molecules entering into the spectrometer will be ionized, and these helium ions will then travel into the ion trap, where the resulting ion current is analysed and measured. Based on the ionization current, the leak rate can be calculated. Fig. 5.3 shows a schematic of a He leak detector.

The reference (or background) reading for helium is a crucial part of the leak measurement procedure. This reference reading is the “background noise” for helium, which can be thought of as the ambient level of helium in the air.

The background reading can be influenced and constituted by the increases in the ambient helium concentration (from the act of using helium itself), helium being trapped and permeated from polymers or a memory/clean-up effect in the HLD itself. Modern HLDs constantly measure and calculate this internal (background) level and automatically subtract this from the leak rate measurement.

Helium leak detection measurement methods

There are two HLD methods: integral testing and local testing. The choice of which method to use depends on the configuration and leak rate to be measured too. The “integral” method shows if there is a leak present whilst the “local” method shows where a leak is located (however, the exact pin-pointing of the leak location, is difficult). Both of these detection methods can each be sub-divided down into two further parts: “sample under pressure”, and “sample under vacuum”.

The first of the two integral testing procedures is called the **“integral (sample under pressure)” method**, with the chamber under investigation being placed in a sealed container. The chamber (or sample under test) is pressurised up with helium and the container is connected to the leak detector. A sample of gas from within the container is drawn and passes through the mass spectrometer where any increase (over the background reading) in helium levels is indicative of a leak.

In the **“integral testing (sample under vacuum)” method**, the chamber is again placed within a container but in this instance the container is pressurised with helium – and the test chamber is directly connected to the leak detector. A sample of the gas within the chamber is drawn off and passes through a mass spectrometer where again, any increase in helium (above the background reading) is indicative of a leak. Fig. 5.4 shows the general set-up for the two methods.

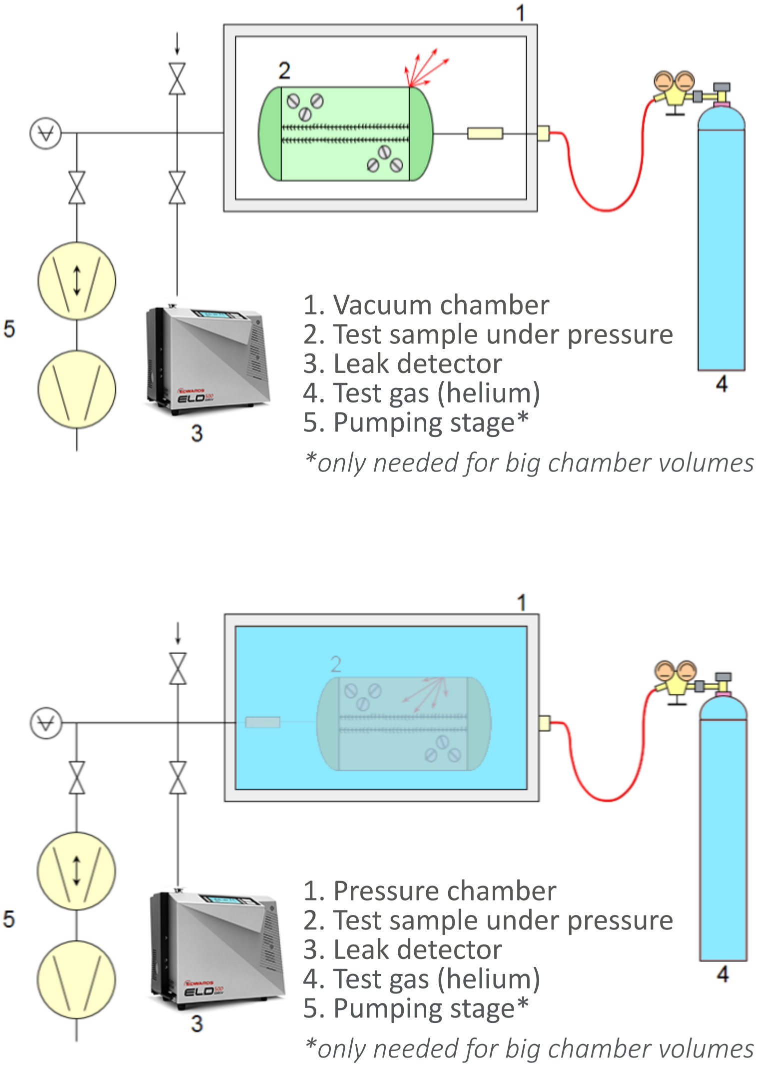
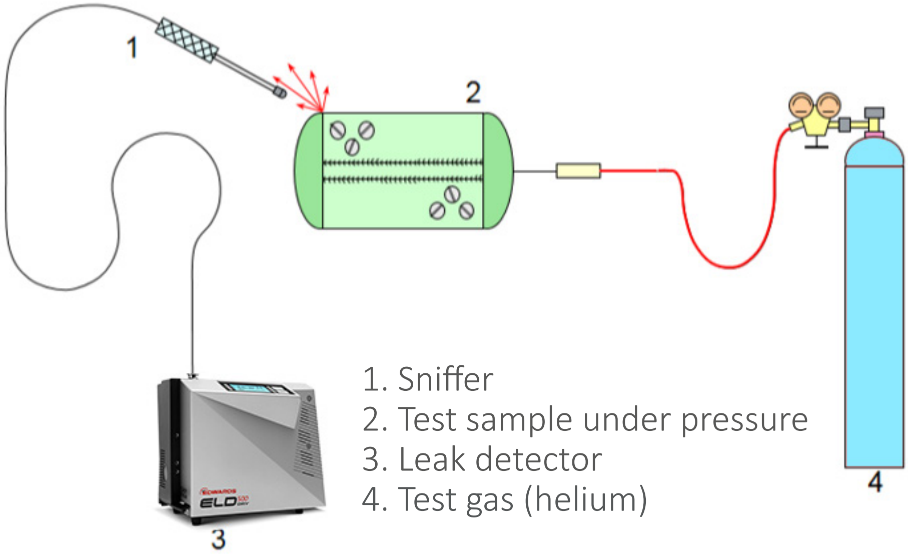


Figure 5.4: Helium leak detection methods. "Sample under pressure" (top) and "sample under vacuum" (bottom).

Sniffer or spraying testing

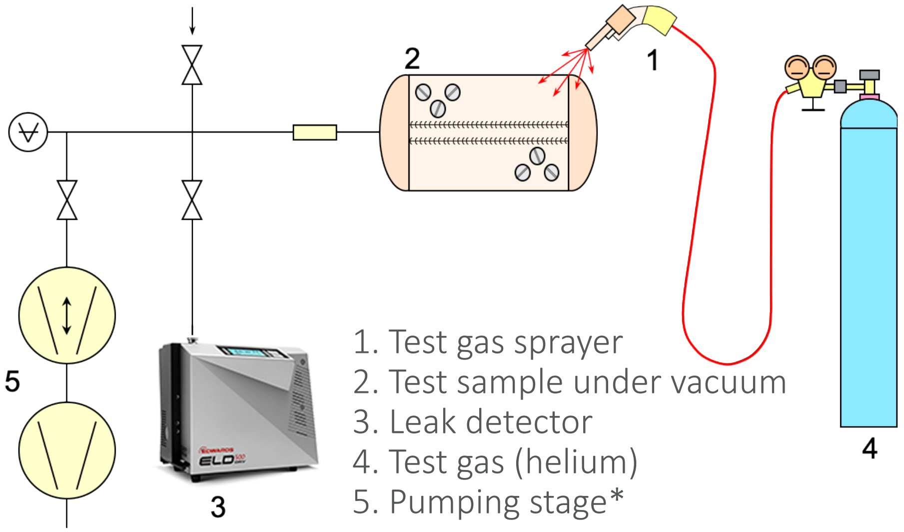
The second set of procedures are sometimes referred to as the “sniffer” or “spraying” tests. In the **“local-sniffer (sample under pressure)” method**, the chamber is pressurised with helium and a sniffer device is passed around the chamber’s likely leak points (welds, flanges, portals, instrument ducts etc.) to capture any escaping tracer gas. This “sniffed” gas is passed to a mass spectrometer to record any elevated (*i.e.* above background) helium levels (see Fig. 5.5).



1. Sniffer
2. Test sample under pressure
3. Leak detector
4. Test gas (helium)

Figure 5.5: Schematic set-uo the "local-sniffer" method.

In the **“local-spraying (sample under vacuum)” method**, the chamber is vacuum pumped and helium gas is liberally spray-directed towards likely leak points, with the intention that some of this pure helium will be transported into the chamber (see Fig. 5.6). The gas, from within the chamber, is passed into a spectrometer to record any elevated helium levels.



1. Test gas sprayer
2. Test sample under vacuum
3. Leak detector
4. Test gas (helium)
5. Pumping stage*

**only needed for big chamber volumes*

Figure 5.6: Schematic set-up the "local-spraying" method.

In summary the HLD integral method requires the chamber or part under test to be placed inside a leak-tight unit (which is not always a possibility). In contrast in the local testing method the chamber is either internally pressurised with helium or internally evacuated and helium being sprayed onto the surface of the chamber at suspected leak points. In both tests, helium enters the leak detector via possible leaks and passes to the spectrometer for analysing.

6. APPLICATION OF VACUUM TECHNOLOGY

6.1 WHY USE VACUUM?

There is an almost infinite number of applications that need a vacuum for one reason or another, but all these different uses of vacuum come down to one of the following basic requirements:

- To produce clean surfaces and clean environments
    - o For precision in material processing and analysis
- To control processes by pressure
    - o For processes such as Coating or Chemical Vapour Deposition where outcomes vary by pressure
- To remove atmospheric constituents
    - o That might cause an adverse reaction or process interference e.g. in electric lights, during melting of metals
- To achieve a pressure difference
    - o For holding, lifting and transportation & in vacuum forming of plastics etc
- To decrease energy transfer
    - o Thermal and electronic insulation
- To remove gas or liquid from material
    - o In degassing or freeze drying
- To extend particle paths before hitting another (mean free path)
    - o For coating, particle accelerators, electron beam welding

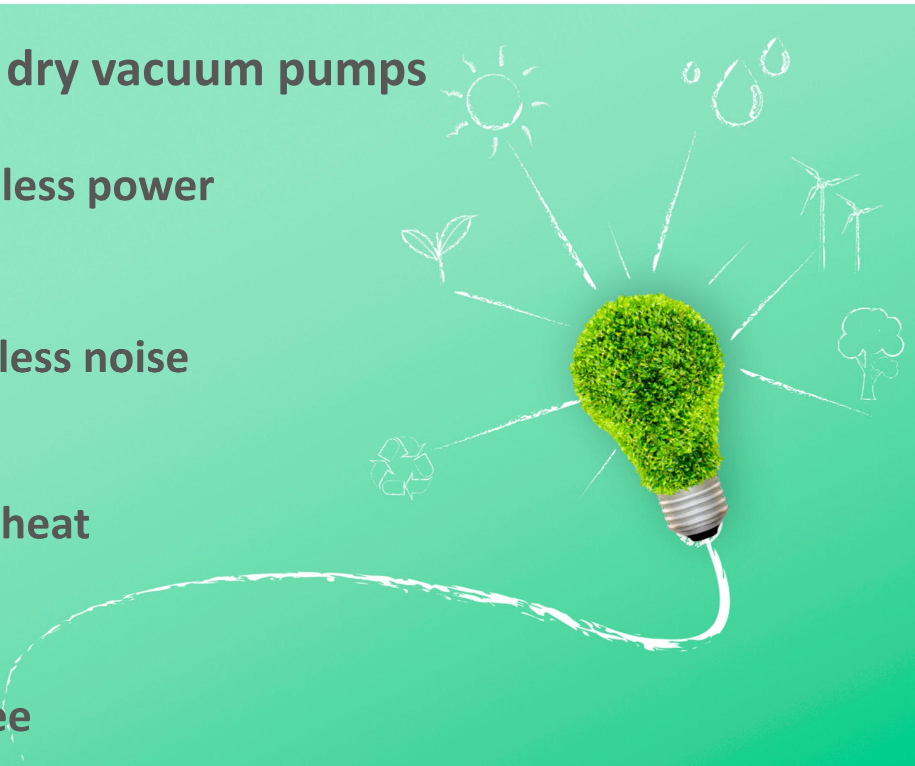
6.2 ENVIRONMENTAL CONSIDERATIONS

Of late, environmental considerations are becoming more important in terms of choosing the optimum vacuum pump for your experiment. This trend is set to intensify going forward.

Our modern dry vacuum pumps consume less power, generate less noise, emit less heat into the lab and of course have no oil to become contaminated.
The above means less use of valuable resources and reduced waste making them better for the environment and as an added bonus running costs are also reduced.

Edwards' modern dry vacuum pumps

- **consume less power**
- **generate less noise**
- **emit less heat**
- **are oil-free**



In the past it was common practice to vent the exhaust pipe from your pump out the window or into an unfiltered extraction system. This can mean releasing waste that is damaging to the environment.

As a company we also offer exhaust gas abatement systems that treat waste reducing its impact on the environment. Figure 6.1 shows one of Edwards' products in this broad portfolio: the Atlas abatement system.

Please contact one of our experts if this could be beneficial for your application.

Figure 6.1: Edwards' Atlas abatement system

6.3 BASIC SCIENTIFIC VACUUM SET-UP

Due to the huge number of very different vacuum applications in the scientific realm, it is impossible to show a system set-up that can work in all circumstances. Vacuum pumping systems are selected according to the required operating pressure, the size of the vacuum chamber and to be able to cope with any process flows.

A typical basic high vacuum system is shown in Figure 6.2. Not all elements of this are always utilised, for example often there is no roughing line and all pumping is done through the secondary pump.

This schematic can easily be converted for medium vacuum applications by eliminating the secondary pump and pumping only through the roughing line, or for UHV applications with the addition of an Ion Pump.

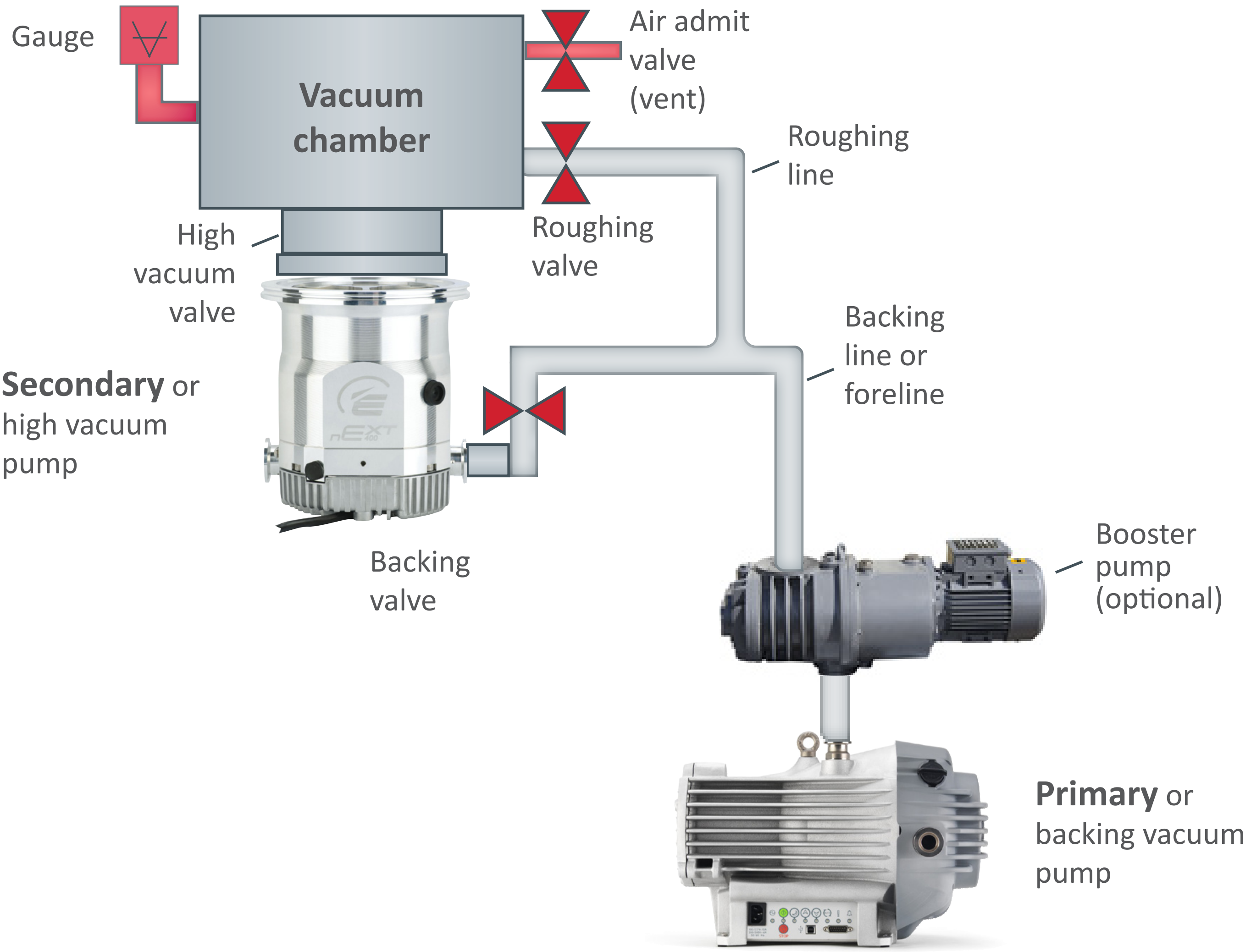


Figure 6.2: Basic scientific vacuum set-up.

6.4 APPLICATION CHART

Below you can find a non-exhaustive overview of some of our vacuum pumps and for which application they are suitable.

APPLICATION	nXDS/XDS dry scroll pumps	nXRi multistage roots pumps	EM/RV rotary vane pumps	nEXT/EXT turbomolecular pumps	Turbomolecular pumping stations	STP magnetically levitated turbomolecular pumps	EPX high vacuum primary pumps	UHV pumps	Measurement and control	Leak Detection and Measurement	Components and hardware
Backing diffusion pumps	●		●						●	●	●
Backing turbomolecular pumps	●	●	●		●		●		●	●	●
Centrifugal concentration	●		●						●	●	●
Coating technology	●		●	●	●	●	●		●	●	●
Distillation and extraction apparatus	●		●						●	●	●
Electron microscopes	●	●	●	●	●	●		●	●	●	●
Freeze dryers	●		●						●	●	●
Fume hoods and glove boxes	●		●						●	●	●
Gas recovery & recirculation	●	●	●	●	●	●			●	●	●
Gel dryers	●		●						●	●	●
High energy physics	●	●	●	●	●	●	●	●	●	●	●
Initial pump down and regeneration of cryopumps	●		●	●	●	●	●		●	●	●
Lasers	●	●	●	●	●	●	●	●	●	●	●
Leak detectors	●	●	●	●	●				●	●	●
Load locks	●		●	●	●		●		●	●	●
Mass spectrometers	●	●	●	●	●	●		●	●	●	●
Mass spectrometry inlet systems	●	●	●						●	●	●
Molecular beam epitaxy	●		●	●	●	●	●	●	●	●	●
Particle size analysers	●		●	●					●	●	●
Refrigeration and air conditioning	●		●						●	●	●
Rotary evaporation	●		●						●	●	●
Sample preparation	●		●						●	●	●
Surface science	●	●	●	●	●	●	●	●	●	●	●
UHV and XHV systems	●	●	●	●	●	●	●	●	●	●	●
Ultra high-speed centrifuges	●		●						●	●	●
Vacuum filtration	●	●	●						●	●	●
Vacuum ovens	●	●	●						●	●	●

6.5 PUMP SIZING

The size of the vacuum pump or vacuum pump system is governed by two independent questions:

1. What effective pumping speed is needed to pump down a given volume of a vessel or reactor to a desired pressure in a given time?
2. What effective pumping speed is needed during a vacuum process with a given load of gases or vapours to maintain the desired operating pressure?

The effective or net pumping speed of a vacuum pump is thereby defined as the actual pumping speed that prevails at the vessel taking into account the flow resistance (conductance) of any baffles, condensers or catch pots, valves, filters and pipes installed between the pump and the vessel (for calculating the net pumping speed refer to Sec. 2.2, equation (2-9)). Depending on the system design, the effective pumping speed can differ significantly from the nominal pumping speed of the vacuum pump.

6.5.1 AIR LEAKAGE

Leak tightness is a significant factor when sizing a vacuum system. The gas load of non-condensables is often underestimated. Air entering the system through leakage is usually the most significant load of non-condensables in a vacuum process. This may result in a significantly over-sized vacuum system, due to:

1. The required capacity of the system being increased by the amount of air that needs to be pumped "away" to maintain the process pressure. This will be reflected in capital costs as well as running costs.
2. The efficiency of condensers being reduced as the air passing through the condenser will be saturated with process vapours, thus increasing the total gas load.
3. Vapour emissions from the system being increased. Depending on the solvents used, this may be subject to environmental concerns.

Therefore, minimizing the load of non-condensables and air resulting from leakage can have a significant impact on process efficiency and costs.

To minimize air leakage the following points should be considered:

1. High quality process vessels should be used for vacuum duties.
2. Equipment connections should be minimized and all-welded connections should be used where possible.
3. Equipment seals should be inspected regularly and replaced whenever deterioration is observed.
4. The air leakage should regularly be determined by measuring the rate of pressure rise (refer to chapter 5.2 on how to do a pressure rise test).

Once the rate of pressure rise has been determined, the air leakage can be estimated according to BS3636 by using the formula:

$$L = 0.07 \cdot V \cdot \Delta p \tag{6-1}$$

where:

L = leak rate [kg/h],

V = total volume of the system to be evacuated, including pipes, receivers, etc., [m³],

Δp = pressure rise, [mbar(a)/min]

Air from leakage may not be the only source of non-condensables. For specific purposes air or nitrogen is deliberately introduced to the system to prevent condensation, control the pressure, improve the vapour handling capacities of a primary pumps.

6.5.2 PUMP SIZING FOR VESSEL EVACUATION (WITHOUT ANY PROCESS GASES OR VAPOURS)

The pumpdown time is calculated using the below equation, assuming the system is leak free, and the pump selected can achieve a vacuum level at least one decade lower than the required operating pressure, (*i.e.*, $p_u < 0.1p_T$).

$$t = \frac{V}{S} \cdot \ln \frac{p_a}{p_T} = \frac{V}{S} \cdot \ln \frac{1013}{p_T} \tag{6-2}$$

where:

t = time [h, min, s],

V = system volume [m³, l],

S = effective pump speed [m³/h, l/min, l/s],

p_a = atmospheric or initial pressure [1013 mbar(a), etc.], and

p_T = operating pressure [mbar(a), etc.].

Incorporating leak rates, (L in mbar(a)l/s and outgassing rates (G in mbar(a)l/s), complicates the pumpdown calculations, as given in below equation.

$$t = \frac{V}{S} \cdot \ln \frac{(p_a - p_u) - Q/S}{(p_T - p_u) - Q/S} \tag{6-3}$$

where:

Q = gas load, $L + G$ [mbar(a)l/s],

V = system volume [m³, l],

S = effective pump speed [m³/h, l/min, l/s],

P_u = ultimate (lowest) pressure of pump [mbar(a)]

p_a = atmospheric or initial pressure [1013 mbar(a), etc.], and

p_T = operating pressure [mbar(a), etc.].

Finally check by calculating the lowest system pressure (p_i) achievable using the below equation, by using consistent units.

$$p_i = \frac{Q}{S} \frac{[\mathrm{mbar\,s^{-1}}]}{[\mathrm{l\,s^{-1}}]} \qquad (6\text{-}4)$$

p_i should be lower than p_T.

The time needed to evacuate a chamber can be calculated given the system volume, pump speed, the initial pressure and the required pressure. Edwards can assist in pump down calculations with its in-house calculation software. If air leakage is significant, it needs to be taken into account.

6.5.3 PUMP SIZING TO MAINTAIN PROCESS PRESSURE (WITH FLOW OF GASES OR VAPOURS)

In a typical chemical or pharmaceutical process, the pump down time is not the only critical parameter for the process. It is also important to size the vacuum pump in such way that it will be able to maintain the required pressure during the process, where process gases and vapours are present.

To size the pump system accordingly the total amount of gas, *i.e.* condensable vapours and non-condensable gas (incl. air leakage), needs to be determined. The total volume of gas can be calculated from the Ideal Gas Law:

$$V_i = \frac{\dot{n}_i RT}{p_{tot}} \qquad (6\text{-}5)$$

$$\dot{V}_{tot} = \sum \dot{V}_i \qquad (6\text{-}6)$$

where:

V_i = volume of gas, *i* (condensable and non-condensable arriving at the pump inlet) per time unit (m³/h) $= \frac{dV_i}{dt}$

V_{tot} = total gas volume per time unit (m³/h)

n_i = number of kmoles of gas, *I* ,per time unit $= \frac{\dot{m}_i}{M_i}$

R = universal gas constant

m_i = mass of gas, *i* ,per time unit

M_i = molecular weight of gas, *i*

T = temperature at the pump inlet [K]

p_{tot} = total system pressure at the pump inlet [kPa]

p_{tot}	V	T	R
Pa (Nm^{-2})	m^3	K	8.314 J $mol^{-1}K^{-1}$
mbar(a)	dm^3	K	83.14 mbar(a) litres $mol^{-1}K^{-1}$
dyne cm^{-2}	cm^3	K	8.314 x 10^7 ergs $mol^{-1}K^{-1}$
mmHg (Torr)	dm^3	K	62.364 mmHg litres $mol^{-1}K^{-1}$
atm	cm^3	K	82.058 atm cm^3 $mol^{-1}K^{-1}$

Note: 1 mm Hg = 1 Torr

Table 6.1 Values of R (for 1 mol) in Various Systems of Units. Calculated for STP.

When a condenser is used at the pump inlet, the amount of vapours condensing out at the given condenser operating conditions (cooling temperature, pressure) can be subtracted from the total gas load. Edwards can assist in assessing the total amount of condensables saturating the non-condensable gas load using a condenser.

The throughput needed to maintain the required process pressure, can be calculated using equation (2-7):

$$Q = p \cdot \dot{V}_{tot} = p \cdot S_{net}$$

where:

Q = flowrate or throughput [mbar.m³/h]

p = process pressure

V_{tot} = total gas volume per time unit [m³/h]

S_{net} = effective or net pumping speed [m³/h]

Therefore, the required net pumping speed can be obtained by rewriting the equation:

$$S_{net} = \frac{Q}{p}$$

Note, that this gives the net or effective pumping speed for the system. Any losses, due to conductance of inlet piping or pressure drops caused by a condenser need to be taken into account and added to the required pumping speed of the vacuum pump.

6.6 PRESSURE CONTROL

Controlling the pressure during a process run can be essential to assure the quality and yield of the product. There are three methods commonly used to achieve this:

a) Air bleed – A defined amount of air or nitrogen is introduced to the system to maintain a constant pressure.

b) Throttling – A throttling or control valve is placed at the inlet of the pump to control the pressure. This is only possible, if a vacuum pump is used that can run continuously against a closed inlet valve. Most dry pumps will happily do so. In cases where a dry pump is used in combination with a mechanical booster, it may be possible to place a control valve between pump and booster.

c) Variable speed drive – State-of-the-art technology are dry pumps equipped with a variable speed drive. By varying the frequency, the capacity of the pump and hence the pressure of the system can be controlled. For a pump/booster combination, either the dry pump itself or the mechanical booster or both can be run on an inverter.

6.7 HANDLING VAPOURS

When vapours are pumped, working pressure and pumping speed are not the only two factors that need to be considered. A third factor, namely the partial pressure of the vapour, becomes important for determining the vacuum system arrangement. The partial pressure of the vapour may vary considerably during a process. Additionally, condensation inside the swept volume of the vacuum pump should be avoided. This can be done by several different means. This chapter will describe the use of gas ballast and purge gas, as well as the use of condensers to pump vapours and condensables.

6.7.1 USE OF GAS BALLAST & PURGE GAS

Gas ballast (GB) is a constructional feature widely applied in many primary vacuum pumps for the pumping of vapours. Wolfgang Gaede invented the gas-ballast principle in 1935 and was originally focussed on primary oil-sealed pumps. Gas ballast is useful in reducing the extent of vapour contamination in the oil (and/or other parts) thus extending oil life and, at a more fundamental level, permitting the pump to operate on a vapour duty at nearly full specifications. Put simply, depending on the percentage make-up of vapour in the pumped load, then without gas ballast the pump can 'stagnate'.

A typical physical representation of the gas ballast configuration is shown in Fig. 6.3 below:

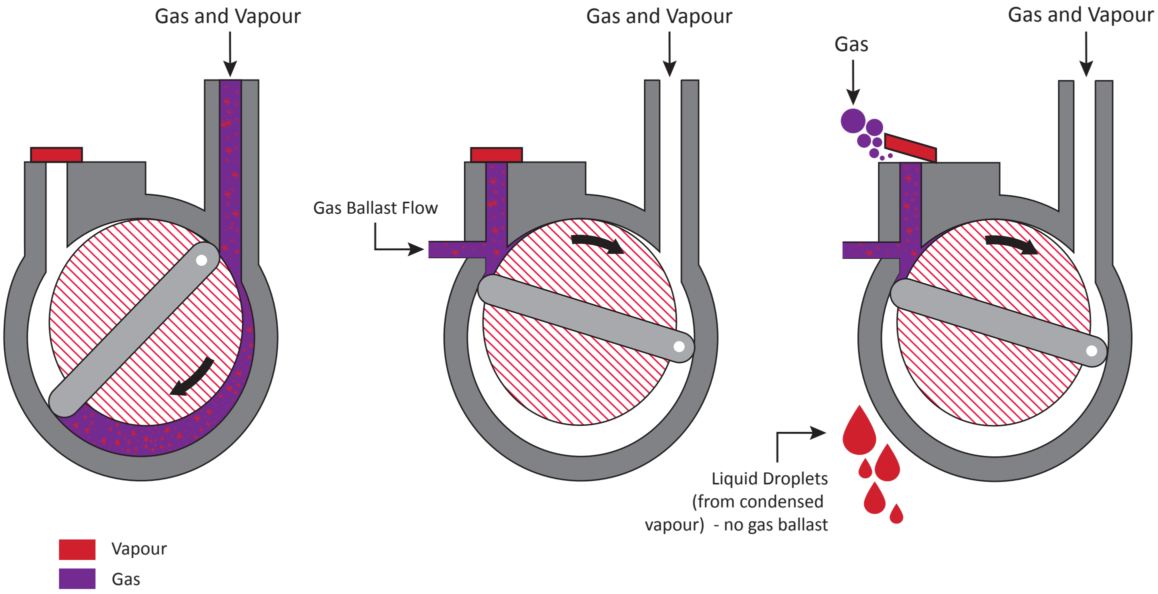


Figure 6.3: Gas ballast configuration

The basic principle of ballast is that atmospheric air (or CDA or inert gas) is admitted into a pump during the (late) compression stages (as above). This increases the percentage of non-condensable gas such that the partial pressure of the vapour being pumped is below its saturated vapour pressure when the exhaust valve opens (typically at a pressure of 1.05 to 1.2 bar(a)). This means that the vapour is discharged from the pump without liquefaction.

Note that the term vapour pressure usually refers to the saturated vapour pressure.

The maximum vapour handling capacity (MVHC) of a pump is the maximum amount of vapour that can be pumped without condensation in the pump (as discussed above); the vapour being compressed such that it just avoids saturation at the point of exhaust. The Maximum Water Vapour Handling Capacity (MWVHC) refers to the specific case of water vapour handling and this is a measure quoted for pump performance and is used a relative measure.

Note that the speed of the pump is not a determining factor to the MVHC. However it does influence the degree of degradation of the inlet pressure and the operating pressure at a given vapour flowrate. The operating temperature of the pump, the exhaust valve opening pressure and the gas ballast flowrate are the major factors in maximising the MVHC.

The gas ballast flowrate will be determined by a combination of the considerations of the vapour capacity required and the degrading effect the ballast flow has on the inlet pressure. The positioning of the gas ballast introduction point to the pumping medium (*e.g.* ensuring the correct point in the wraps of a scroll pump) is crucial: It has to be close enough to the pump inlet to ensure no condensation during the progressive compression, but at a point where the ultimate pressure during ballast flow is not overly corrupted.

Comments

- MVHC is independent of pump speed/displacement: the operating temperature of the pump, the exhaust valve opening pressure and the gas ballast flowrate are the major factors in maximising the MVHC.
- Gas ballasting can also be used 'retrospectively' to purge condensed and dissolved vapours from the oil/other materials of the pump's mechanism.
- Generally a pump should be operated with ballast and allowed to reach full temperature (~30-60 mins) before any condensable vapours are introduced. Similarly after vapours have been processed the pump should be operated on GB for another 30-60 mins before turning the pump off (this prevents condensation in a non-running, cooling pump).
- Gas ballast should be introduced at the point where it has least effect on the ultimate pressure, but avoids condensation occurring in compression.
- When using GB on an oil-sealed rotary vane pump an oil return kit may be needed as there will be carry over oil loss.
- The effect of ballast humidity is small and is neglected (usually in the case of pumps running at a temperature > 70°C).

Purge gas

In some cases using the gas ballast port is not sufficient to prevent condensation inside the pump; in particular when high loads of vapours are pumped. Then, alternatively or in addition to the GB, air or an inert purge gas can be introduced at the pump inlet. This allows for higher gas flows and hence higher dilution of the vapour. Subsequently, a lower partial pressure of the vapour is achieved.

Note that a higher flow of inlet purge gas will also impact the ultimate pressure of the pump. For oil-sealed pumps a higher gas flow also means a higher carry over oil loss. Therefore, inlet purge is commonly used with mechanical dry pumps.

Applying an exhaust purge is an effective way to prevent condensation at the pump exhaust and the exhaust line.

6.8 HANDLING FLAMMABLES & EXPLOSIVES

When pumping chemicals in a lab, it is often required to pump potentially flammable or explosive atmospheres. Therefore, it is necessary to consider the possibility of ignition sources resulting from failure conditions of the equipment. When installing vacuum pumps, a safety strategy needs to be developed that should include the following steps:

1. Identification of explosive atmospheres
2. Avoiding explosive atmospheres
3. Eliminating possible ignition sources
4. Limiting the effects of a potential ignition

The below sections will look into the specific aspects of each of these steps.

6.8.1 IDENTIFICATION OF EXPLOSIVE ATMOSPHERES

Understanding what the explosive atmosphere is and where an ignition might take place is a vital first step. Therefore, the internal atmosphere from the process interface and inside the vacuum pump, as well as the external atmosphere surrounding the pump must be taken into account. The source of explosion hazard is generally an oxidant (*e.g.* O_2, O_3, F_2), a flammable or explosive material (*e.g.* H_2, solvent vapours, fine metal dust) or pyrophoric materials (*e.g.* silane, phosphine).

6.8.2 AVOIDING EXPLOSIVE ATMOSPHERES

A flammable material will only create a potentially explosive atmosphere, if it is combined with air, oxygen or other oxidants and its concentration lies between the Lower Flammability Limit - LFL (or Lower Explosion Limit - LEL) and the Upper Flammability Limit - UFL (or Upper Explosion Limit - UEL). The explosion hazard can be avoided by ensuring that the concentration of the potentially flammable mixture is kept outside the flammable zone. Hence, an explosion will not occur even with an ignition source present. There are a number of strategies that can be used to avoid operating with gas mixtures in the flammable zone. The choice of strategy will depend on the outcome of the risk assessment (hazard analysis) for the process and the pumping system:

a) Maintain the flammable gas concentration below the LFL (LEL)

To minimize the risk of the flammable gas accidentally entering the flammable zone, a safety margin for below-LFL (LEL) operation should be used. A safety margin should be determined following a risk assessment. Some authorities suggest maintaining the concentration at below 25% LFL (LEL). The commonly used method of maintaining a suitable concentration below LFL (LEL) is dilution with an inert gas purge (*e.g.* nitrogen), introduced into the pump inlet and/or purge connections. The required integrity of the dilution system and of any alarms or interlocks will depend on the hazardous zone which would result if the dilution system were to fail.

b) Maintain the oxygen concentration below the MOC (LOC)

This mode of operation requires the use of oxygen concentration monitoring of the pumped gases to ensure safe operation. To minimize the risk of the flammable gas accidentally entering the flammable zone, a safety margin for the Minimum Oxygen Concentration - MOC (or Limiting Oxygen Concentration - LOC) operation should be used. Available industry standards indicate that where the oxygen concentration is continuously monitored, it should be maintained at less than two volume percentage points below the lowest published MOC (LOC) for the gas mixture. Unless the MOC (LOC) is less than 5%, the oxygen concentration must be maintained at no more than 60% of the MOC (LOC). If monitoring is only undertaken in the form of routine oxygen level checks, the oxygen level should not be allowed to exceed 60% of the lowest published MOC (LOC) unless the MOC (LOC) is less than 5%, in which case the oxygen concentration must be maintained below 40% of the MOC (LOC).

The preferred method of maintaining the oxygen level below the lowest published MOC (LOC) is by the rigorous exclusion of air and oxygen from the process and pump system, together with dilution of the pumped gas with an inert purge gas (such as nitrogen), introduced into the pump inlet and/or purge connections, if needed. The required integrity of the air/oxygen exclusion measures and of any alarms and interlocks will depend on the hazardous zone that would result were the exclusion and dilution systems to fail. Precautions typically required to rigorously exclude air from the process and pump system are given at the end of this section.

c) Maintain the flammable gas concentration above the UFL (UEL)

Where flammable gas concentrations are high, then operation above UFL (UEL) can be more suitable. To minimize the risk of any accidental incursion into the flammable zone, a safety margin for above UFL (UEL) operation should be used. It is recommended that the residual oxygen level in the gas should be maintained at less than 60% of the absolute oxygen level normally present at the flammable gas UFL (UEL) concentration.

The preferred method of maintaining the oxygen level below this safety margin, is rigorous exclusion of air and oxygen from the process and pump system. Dilution of the pumped gas with an inert purge gas (such as nitrogen) or with additional flammable gas ('padding' gas), introduced into the pump inlet and/or purge connections, may also be needed. The required integrity of the air exclusion measures, of any purge gas introduction system, and of any alarms and interlocks will depend on the hazardous zone that would result were the exclusion and dilution systems to fail.

d) Maintaining the flammable gas concentration below the minimum explosion pressure

Every flammable material has got a minimum pressure below which an explosion can't be sustained. If the pressure at the inlet of the vacuum pump can be maintained securely below this pressure then ignitions starting inside the vacuum pump will not be able to spread. Precautions, however, must be taken for the exhaust of the vacuum pump. Edwards research has proven that it is not possible to sustain a burn in a potentially explosive atmosphere below 60 mbar(a).

Precautions typically required to rigorously exclude air from the process and pump system are as follows:

Elimination of air leaks

Use a leak detector or conduct a pressure rise test (refer to section 5.2). Before admitting flammable materials into the process chamber, it is possible to perform a test to establish that air (oxygen) leakage into the vacuum system is within allowable limits.

To perform a pressure rise test, the empty process chamber is evacuated to a pressure just below the normal operating pressure, and is then isolated from the vacuum pump. The pressure in the process chamber is then recorded over a fixed period of time. As the volume of the process chamber is known along with the maximum allowable air leakage, it is possible to calculate a maximum allowable pressure rise that can occur over the fixed period of time. If this maximum pressure limit is exceeded, action must be taken to seal the source of the air (oxygen) leakage into the process chamber; the test must then be repeated successfully before the admission of flammable materials into the process chamber is allowed. In some cases, the ability of the vacuum system to achieve a good base pressure can be used to indicate system leak tightness.

Remove all air from the system before the start of the process

Before any flammable gas is admitted into the process, the system should be fully evacuated and/or purged with inert gas (such as nitrogen), to remove all air from the system. At the end of the process, this procedure should be repeated to remove any flammable gas before the system is finally vented to air.

Reverse flow

The system operating procedures and facilities need to protect the system from any reverse air flow, which might result from a pump failure. Any pumped flammable gases need to be safely disposed of at the final vent from the pump exhaust. Flammable gas mixtures should not be able to arise in the exhaust pipeline. This can be achieved by the use of suitable inert purging of the pipeline before the start of and after the end of the flammable gas process, and by the use of adequate inert gas purging.

6.8.3 ELIMINATING POSSIBLE IGNITION SOURCES

Where vacuum pumps are used to pump flammable mixtures, all possible sources of ignition must be considered. Below are some areas of consideration, which can be used as part of an overall review. Depending upon the process it might be possible to avoid some or all ignition sources. If it is not possible to avoid the ignition source because of process conditions or system requirement, the system needs to be designed accordingly.

Mechanical contact - Mechanical contact of rotating and stationary parts inside the vacuum pump and system could provide an ignition source. All Edwards vacuum pumps are designed and built to keep the correct running clearances inside the pump during all operating conditions. To avoid this ignition source it is important to avoid deposition of materials on the internal surfaces or to clean the pump. The bearings must be kept in good condition, have sufficient lubrication and suitable purge gas to eliminate contact with process gases. The recommended maintenance regime for the bearings must be followed to ensure safe and reliable operation.

Particle ingestion - All pumping mechanisms have the potential to ingest particles which have been created by the process or which are a result of the system manufacturing process. Where these are rolled between a moving surface and a static one, it is possible to generate heat. A suitable inlet screen (mesh) or filter will prevent the ingress of particles into the vacuum pump to reduce the size and volume of particles to a safe amount. Care must be taken to have a suitable maintenance regime for the inlet screen.

Dust build-up - The build-up of fine compacted dust within internal clearances can occur where any pumping mechanism is placed on a dust generating process. Even with the use of inlet dust filters, it is still possible for small dust particles to enter the pump. With small dimensional changes due to thermal changes, compacted dust can touch a moving surface and create heat.

Heat of compression (auto-ignition) - The internal heat of compression within any compressor must be considered in relation to the auto-ignition temperature of any gases or vapours which are pumped. It must be ensured that the pump has a temperature classification that is at least the same or higher than the gases being pumped.

Hot surfaces - Where flammable gases or vapours are allowed to come into contact with a hot surface, they may ignite if the auto-ignition temperature is exceeded. Note: Edwards pumps and flame arrestors should not be thermally insulated if this could cause increased surface temperatures internally (and externally) leading to auto-ignition.

Externally applied heat - Externally applied heat can occur, for example, in the event of a fire in the immediate area of the vacuum equipment. Under this condition, it is possible to generate internal pressures in excess of the maximum static pressure of the system, and temperatures in excess of auto-ignition temperature. This should be considered as part of the system hazard analysis.

Hot process gas flow - High inlet gas temperatures can lead to internal (or external) surfaces exceeding the auto-ignition temperature of the materials being pumped. High temperature inlet gas can also lead to rotor/stator seizure. For maximum allowable internal gas temperatures, the vacuum pump instruction manual should be consulted.

Catalytic reaction - The presence of certain materials can lead to catalytic ignition. All materials of construction in the vacuum system should be considered for their potential to act in this way with the pumped gases or vapours.

Pyrophoric reaction - The heat of combustion of pyrophoric materials caused by air or oxidant ingress could act as an ignition source for any flammable material present.

Static electricity - Certain conditions can occur where static electricity can build up on insulated components before discharging to earth in the form of a spark. The potential for static build-up should be considered as part of the system design.

Lightning - Where located in an outdoor location, a lightning strike can provide ignition energy. The potential of this event occurring should be considered as part of the system design.

6.8.4 LIMITING THE EFFECTS OF A POTENTIAL IGNITION

Where it is not possible to avoid the flammable zone, the equipment needs to be designed to avoid or to contain any resulting explosion without rupturing or transmitting a flame to the outside atmosphere. If the external atmosphere of the vacuum system is hazardous, all equipment must be suitably rated for it.

Within the European Union the ATEX directive gives clear guidance on the design of equipment that is to be used in potentially explosive atmospheres.

a) ATEX directive

ATEX is an amalgamation of the French words ‘Atmospheres‘ and ‘Explosibles’ which means ‘Explosive Atmospheres‘ and was realised with the introduction of the ATEX directive 94/9/EC in 2003 and recently updated with the new directive 2014/34/EU in 2016. This European Union (EU) legislation standardises the way to use any equipment (mechanical or electrical) in potentially explosive atmospheres safely; to ensure that no harm can come to the people in the vicinity and to the environment.

ATEX is an EU legislation and as such is law and adherence to it is mandatory within the European Union. Before the directive came into force the use of equipment in explosive atmospheres was mandated by national laws and working practices. Most of these are historically evolved from the experience gathered in the mining industry and were mostly limited to electrical equipment.

So how is compliance to the ATEX directive shown?

Depending on the type of equipment (mechanical or electrical) and on the equipment category (category 1, 2 or 3) the ATEX directive dictates that in some cases a notified body has to certify compliance to the directive whereas in other cases the manufacturer or importer into the EU can self-certify the equipment. Table 6.2 shows which type of equipment can be self-certified by the manufacturer and which ones need the involvement of a notified body.

	Mechanical equipment	Electrical equipment
Category 1	Notified Body	Notified Body
Category 2	Self-Certification	Notified Body
Category 3	Self-Certification	Self-Certification

Table 6.2: Certifiers of ATEX equipment.

Notified bodies are conformity assessment bodies nominated by the European Commission, which is the legislative body within the EU.

In order to aid both the notified bodies and the manufacturers of equipment destined to be used in explosive atmospheres, harmonized standards have been written. Whilst the directive is law and defines the level of safety to be applied, standards give practical guidance to show how to comply with the directive, taking into account state of the art technical solutions. EU standards are written and reviewed on a constant basis by groups of technical experts in each EU member country.

The very basis of every ATEX certification for mechanical equipment is the Ignition Hazard Assessment based on EN80079-36 (EN= European Norm) in which the manufacturer assesses the possible ignition sources based on the likelihood that they become active. Vacuum pumps can be classed as mechanical equipment.

Depending on the equipment category required, measures have to be put in place to ensure that the ignition sources cannot become active during normal operation and during foreseeable or rare malfunctions.

A good example is the overall thermal state of a ‘dry,’ *i.e.* oil free mechanical vacuum pump. If the temperature of the pump exceeds a certain pump specific value, thermal seizure can occur due to thermal expansion of the rotor. If the rotor expands to a point where it touches the stator, sparks with potentially enough energy to ignite a flammable atmosphere present inside the pump can be created. In order to avoid this happening, the thermal state of the pump needs to be controlled. Several measures, depending on the pump design, can be put in place, for example:

- Using a temperature transmitter to measure the case temperature of the pump,
- Using a temperature transmitter to measure the exhaust gas temperature of the pump,
- Monitor the cooling media supply to the pump.

Each of these measures give one level of protection.

Thermal seizure must not be allowed to occur when the pump is running within the pre-defined operating conditions given in the relevant pump instruction manual. However, during malfunctions like loss of cooling media, there is a risk of too high a thermal load remaining inside the pump leading to expansion of the rotor until the pump seizes. The loss of cooling media can be considered as an expected malfunction. By mounting a flow switch into the cooling media line, this potential failure mechanism has been prevented.

In order to designate a level of safety to the equipment, different categories have been defined. Depending on the explosive zone present, the correct equipment has to be chosen.

As illustrated in Table 6.3, category 3 equipment will only assure safety during normal operation. However, in the zone it is placed (zone 2) an explosive atmosphere will not occur during normal operation and if it does only for a short period of time. The likelihood of the explosive atmosphere being present at the same time as the malfunction is occurring in the pump is considered by the ATEX directive to be an 'acceptable risk'.

For vacuum pumps the internal zone - defined as all areas inside the pump that can come into contact with the pumped media (gases or vapours) - and the external zone - the atmosphere outside of the vacuum pump - are considered separately.

Area classification		Equipment classification	
Zone (European & IEC Classification)	Definition of Zone	Definition of Category	Equipment Classification
Zone 0	An area in which an explosive mixture is continuously present or present for long periods (most of the time)	Protection assured in the case of two independent failures	Category 1
Zone 1	Explosive atmosphere will be present for some of the time	Protection is assured in the event of foreseeable malfunctions	Category 2
Zone 2	Explosive atmosphere is not expected to be present during normal operation and if so only for short amount of time (for example once a month and then for 30 minutes only)	Protection is assured during normal operation	Category 3

Table 6.3: Classification of ATEX zones and according equipment categories.

Once either the manufacturer or the notified body is assured that all ignition sources cannot become active, taking into account the level of protection required for the equipment category to be achieved, the equipment can be marked as being ATEX certified. All ATEX certified equipment must be marked to make them easily identifiable for use in explosive atmospheres.

The following information can usually be found on the equipment rating label:

- Ex All equipment suitable for use in potentially explosive atmosphere must show this symbol,

- Equipment category: I for mining and II for non-mining equipment,
- Explosion protection concept used to prevent ignition sources from igniting a potentially explosive atmosphere,
- If applicable the gas group the equipment can be used in,
- Auto ignition temperature.

A typical marking found on an Edwards ATEX vacuum pump Ex h IIB T4 Gb is described in Table 6.4.

The ATEX directive is applicable to the EU but increasingly non-EU countries/users are choosing it as a measure to ensure safety in explosive atmospheres. It is to be noted that the end-user is responsible for the correct assessment of their zoning requirements.

Ex	Symbol for an explosion-protected device
h	Conformity to EN80079-36
IIB	Gas group IIB
T4	Gases with an auto ignition temperature of > 135 °C
Gb	Gas and category 2

Table 6.4: Explanation of the ATEX markings.

6.9 APPLICATION EXAMPLES

6.9.1 SCHLENK LINES

A Schlenk Line is a tubular glass apparatus commonly used in chemistry or material laboratory research to carry out experiments under a vacuum and an inert atmosphere (like nitrogen or argon). It is used when samples are sensitive to air/moisture and the vacuum is also often used to remove the last traces of solvent from a sample. A Schlenk Line typically contains a dual glass manifold with multiple ports; the number of ports is configurable. One manifold is connected to an inert gas source, while the other one is connected to a vacuum pump (see Figure 6.4).

A vessel with the sample is connected to the manifold e.g. by a rubber vacuum tube with each port access controlled by a tap. One backing line of the Schlenk manifold is always kept under vacuum, the other one under inert gas, controlled by valves.

A cold trap of liquid nitrogen or dry ice/acetone is used between the Schlenk Line and the vacuum pump to protect the pump e.g. from the solvents which are present in the experiment. The typical vacuum pressure can go down to 1×10^{-3} mbar.

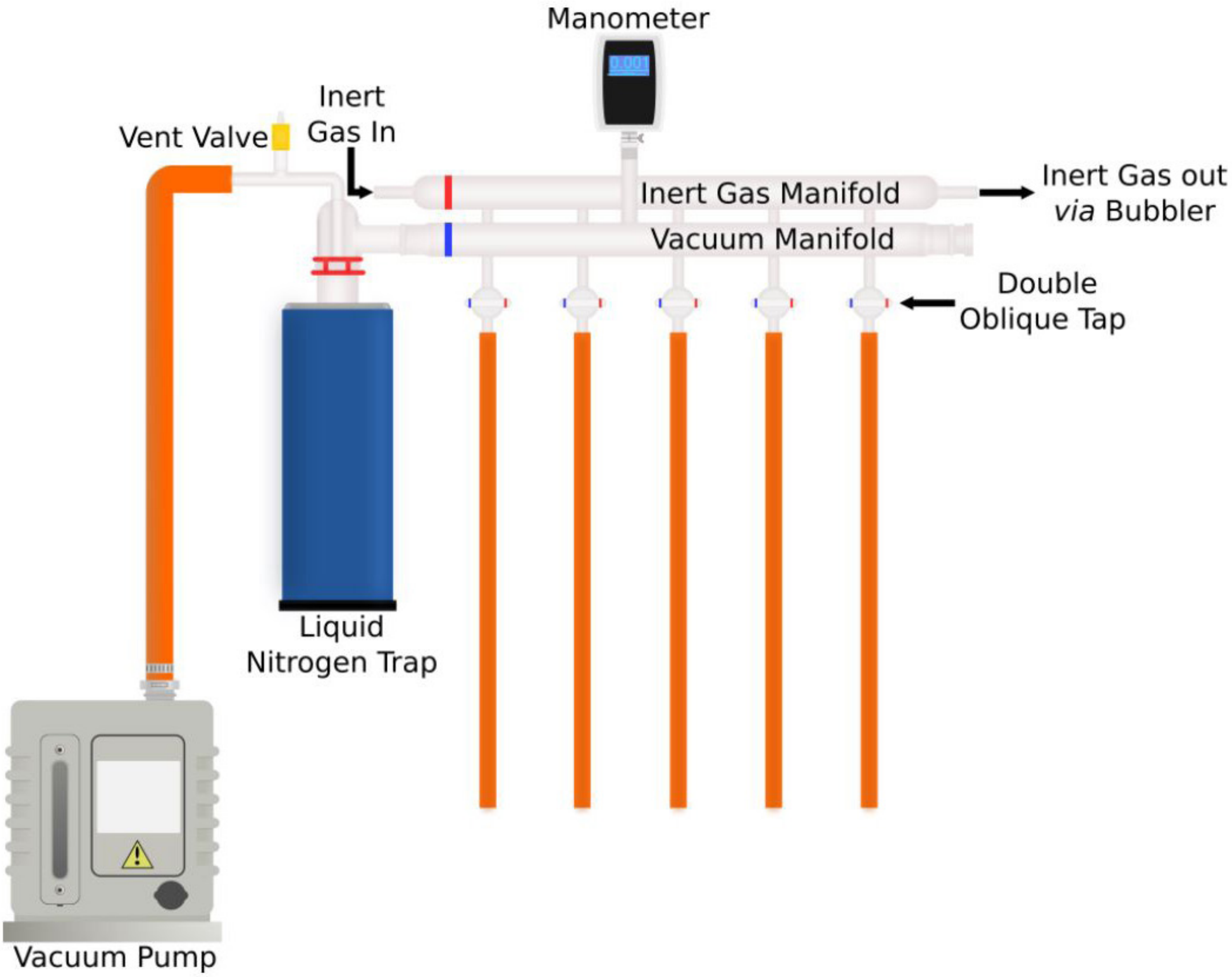


Figure 6.4: A typical Schlenk line. Source: schlenklinesurvivalguide.com

1. Challenges	2. Solution	3. Main benefits / novel step
Pumping condensable vapour from the process. Potential for corrosive or aggressive gases/ vapours.	Small fore vacuum pump with a typical size of 3 to 12 m³/h. nXDS (dry scroll vacuum pumps) and RV (oil sealed rotary vane vacuum pumps) could be used for this application. **For RV versions:** The robust RV pumps can be operated in the unique high throughput mode and with inert gas ballast to avoid condensation of vapours and dilute solvents entering the pump. An installed cold trap in the vacuum line, which is often already part of the Schlenk Line, captures most condensable vapours and minimizes vapours entering the vacuum pump. The installation of an EMF filter safely protects the working environment if the pump is not being used inside a fume cupboard. **For nXDS pumps:** The dry running nXDS vacuum pumps should be operated with inert gas ballast to avoid condensation of vapours and dilute solvents entering the pump. C-versions should be used if slightly corrosive or aggressive gases/vapours are to be pumped. In addition, a cold trap which is often already part of the Schlenk Line, could further protect the pump.	**For RV versions:** Well-proven solution in Schlenk Line applications. Cost-effective basic solution with efficient performance/price ratio. Long maintenance intervals because of excellent vapour handling and good capability to handle slightly corrosive or aggressive gases. **For nXDS pumps:** Well-proven solution in Schlenk Line applications. No oil contamination risk because of dry technology; no oil to be contaminated by process gases. Long maintenance intervals because of excellent vapour handling. High up-time because of good capability to handle slightly corrosive or aggressive gases/vapours with special C-versions.

Figure 6.5: An Edwards nXDS scroll pump & RV rotary vane pump.

6.9.2 MASS SPECTROMETRY

One of the most ubiquitous uses of vacuum pumps in laboratories is in mass-spectrometry (MS). The pumps associated with such MS units are at the vanguard of the high-tech vacuum industry in terms of automation, control, compactness, resolution, efficiency, quiet operation, low-maintenance and cost effectiveness.

MS enables the near-immediate identification and measurement of thousands of types of molecules (e.g. metabolites, lipids, proteins, small molecules etc.), whilst also providing a detailed picture of how cells and tissues respond to drug treatment, but without the use of expensive reagents.

Figure 6.6: A typical split flow turbopump as used in mass spectrometers

Furthermore, by combining MS with other technologies, it has been possible to make significant advances in a number of important medical fields including: the characterisation of advanced cell models; biomarker identification; drug distribution/tissue penetration; isotope tracing; as well as observing spatial changes in drug and metabolite distribution. Such MS developments have helped to unravel the mysteries of effective drug treatments and bio-medical science in general…and yet they all rely upon the humble vacuum pump.

The development of mass spectrometer technology demands the constant evolution of vacuum systems. Leading the world in vacuum solutions, we bring expertise in both the fundamentals of the technology and all aspects of the development and production of specific integrated systems.

Figure 6.7: An example of a mass spectrometer: Waters Corporation's Xevo™ TQ Absolute Tandem Quadrupole Mass Spectrometer.

Core to the Edwards advantage is its Applications and Derivatives team.

A partnership approach to system design starts with a vacuum expert using our TransCalc HSM development software to optimise your systems. Developed in-house, TransCalc HSM is a unique program used to simulate the complete vacuum system from atmosphere to ultra-high vacuum (UHV).

This software has been developed to give rapid simulation of the behaviour of the proposed vacuum solution to ensure it perfectly meets your requirements.

Accurate computer simulation offers you the chance to streamline your development cycle, avoiding a costly iterative approach and delivering a quicker time to market.

With Edwards you can quickly and flexibly create the perfect solution for your needs.

When an off the shelf pump will not meet your requirements for space or performance our A&D department will develop a bespoke vacuum solution to turn the proposed modelled system into reality.

Our focus on technological advancement in vacuum as well as investment in R&D enables us to develop the innovative products that meet customer specific application requirements.

6.9.3 LAB SCALE FREEZE DRYING

Freeze drying (lyophilization) is a dehydration technique where a product is dried under vacuum at low temperature. The water or any other solvent that is contained in the sample is thereby frozen to a solid (ice) and then removed by turning the ice into vapour. Conducting this process under vacuum allows the solvent to be evaporated without having to pass through the liquid phase. The major advantage of freeze drying is that thermo-labile components are preserved and the original size and shape of the sample is maintained. This is only possible by keeping the material in a frozen state at low temperatures during the entire drying process.

The absence of solvent in the final dried product minimizes the effects of oxidation and other degradation processes, thus allowing it to be stored over long periods without the risk of infections by micro-organisms or compositional changes (genetically or enzymatically).

The steps required to lyophilize (freeze-dry) a product in a batch type process are as follows:

1. Pre-treatment / formulation.
2. Freezing at atmospheric pressure (thermal treatment).
3. Primary drying under vacuum (sublimation).
4. Secondary drying under vacuum (desorption).
5. Backfilling & stoppering.

Typical pre-freezing temperatures are in the range of -40 to -60 °C. During primary drying, the frozen liquid (ice) is removed by the process of sublimation (directly turned into vapour). Primary drying is typically conducted at a pressure of 1 to 0.01 mbar(a) depending on the characteristics of the respective product. For an effective freeze drying process the temperature of the product must be higher than the temperature of the condenser. The temperature difference creates a pressure differential, which forces the water vapour molecules out of the material and towards the condenser.

The secondary drying process has begun, when the product reaches a temperature above its eutectic point. During this step the remaining liquid is desorbed. The removal is controlled and optimized by decreasing the pressure down to about 10^{-3} mbar(a), while increasing the shelf temperature to its allowed maximum, just before denaturation of the product occurs. In order to optimize drying cycle times, the end of the primary and secondary drying step is usually determined by conducting a pressure rise test.

Plant and systems

A typical freeze drying set-up (see Fig. 6.8) consists of four basic components: product chamber, refrigeration system, condenser and vacuum pump, whereas the vacuum pump is pumping the chamber through the condenser to protect it from moisture.

The pressure during the freeze drying process is measured by a pressure gauge; usually a pirani or capacitance manometer. Accuracy and repeatability of the pressure measurements are essential for the control of the freeze drying process.

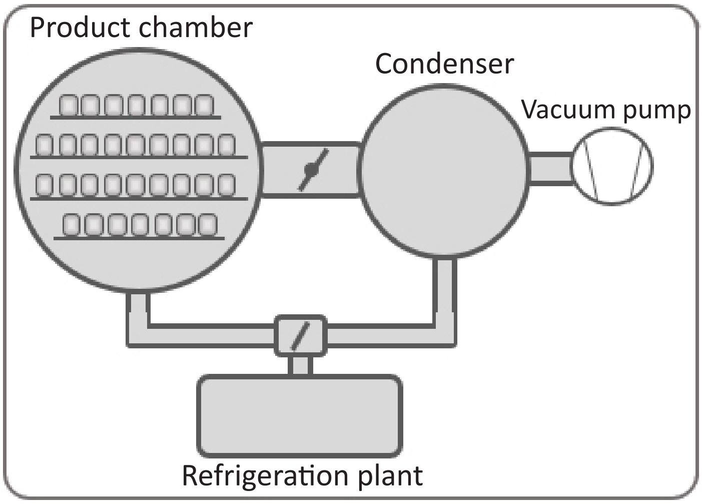


Figure 6.8: Schematic of a freeze drying set-up.

Vacuum pumping

Together with the refrigeration system, the vacuum system forms the heart of a freeze dryer; its main purpose being to evacuate the system down to the processing working pressure. Furthermore, the vacuum system removes all non-condensable gases during the drying process. Pump sizing for shelve freeze dryers can be related back to the actual shelve area, thus a pump capacity of 50 m^3/h per 1 m^2 will give acceptable performance. For general laboratory dryers again 50 m^3/h per 10 l of product should be satisfactory. For dryer applications where an externally frozen product is handled, rapid chamber evacuation becomes necessary to avoid excessive temperature rises or thawing. The pump size must than be selected for the required chamber pump down time.

Usually two-stage oil-sealed rotary vane pumps have been used for laboratory and pilot plants. For the larger industrial plants mechanical booster/rotary pump combinations are common. For certain units with exceptionally low condensation temperature, such as liquid nitrogen, vapour booster/diffusion pump backed by a roots/rotary combination have found a place.

As more and more modern pharmaceuticals contain solvents and acids in their formulation it is now quite common to fit dry pump combinations to new and existing drying facilities. This overcomes contamination with hydrocarbons from oil-sealed pumps.

Common pump issues

In the past, two-stage oil-sealed rotary vane pumps have been used and - provided a low temperature condenser was used and only water vapour was being pumped - the pump stood up quite well over time. Frequent oil changes are needed to overcome accumulative contamination and therefore loss in performance. Gas-ballasting provides limited protection.

Lately formulations to be freeze dried contain various solvents other than water. Ethanol, methanol and acidic acid are the most common solvents. These will thin and degrade the pump oil, thus increasing the risk of pump seizure unless the oil is carefully monitored and change frequently. In those cases dry pumps, such as Edwards nXDS dry scroll pumps, are the accepted way forward as they offer several advantages over oil-sealed solutions.

Pump sizing information needed

- Material processed,
- Vapours other than water to be condensed/removed,
- Solvents (corrosive / flammable),
- Capacity of dryer in litres or square-meters,
- Plant volume (incl. condenser and pipe work),
- Leak rate if known,
- Evacuation time,
- Condenser temperature (max load condition).

6.9.4 PUMPING CONDENSABLE VAPOURS

Condensable vapours, such as water vapour, can be easily handled by a modern laboratory vacuum pump, provided that an effective pumping protocol is followed to allow the water to remain in vapour phase within the pump. This applies to both oil sealed pumps and dry pumps.

Allowing vapour to condense inside the pump will result in performance degradation, failure to achieve ultimate, slow pump-down and cause mechanical problems. Not following a good pumping protocol will mean a very long time to pump down to target pressures. Once vapour condenses inside a vacuum pump it can lead to reduced reliability via accelerated corrosive effects; condensation can also increase pump-down times and limits ultimate pressures.

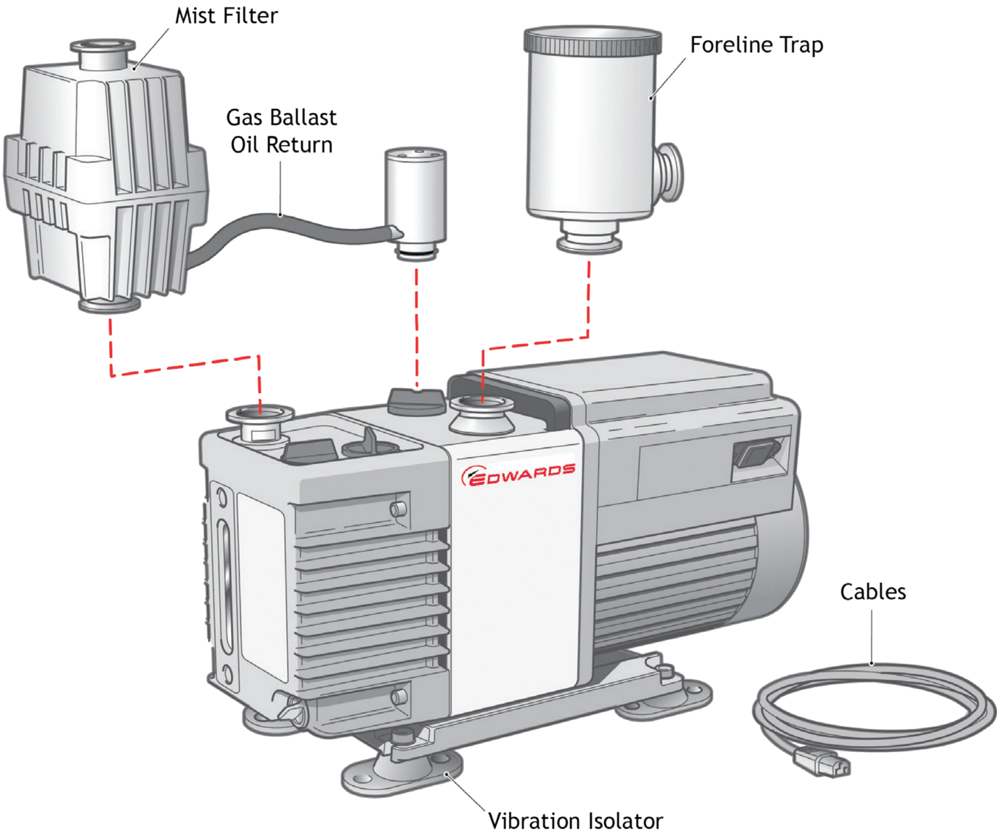


Figure 6.9: Edwards RV rotary vane pump with accessories

Firstly it is important for the pump to warm - up to its normal operating temperature before exposing it to condensable vapour, this will typically take up to 60 minutes. This will prevent water vapour condensing inside the relatively cool pump. “Blanking” the inlet of the pump, by closing a valve, and allowing the pump to run pumping “nothing” is all that is required. Running gas ballast during this process will help the pump warm up faster.

Secondly the ballast should generally be run all the time that vapour is being passed through the pump. While the vapour being pumped is saturated, the vacuum pump’s ultimate pressure will be limited, not by ultimate pressure performance of the pump itself, but by the vapour pressure of the material being processed. For example, water has a saturated vapour pressure of ~24 mbar (18 Torr) at 20 oC (70 oF), this is the best pressure the pump can achieve until all the water has been pumped away.

Allowing water vapour to condense inside a pump will make the time to recover ultimate pressure much longer than if it remains in vapour phase because it has to be re-evaporated before it can be pumped out. Condensed water can reduce oil sealed rotary vane oil life-time and in all pumps condensed vapour can 'accelerate' corrosive effects of other materials being processed.

Figure 6.10: Gas Ballast control on Edwards RV oil-sealed rotary vane pump

Allowing the pump to "clean up" after pumping vapours will extend pump life and performance. If the pump is switched off as soon as the procedure producing vapour is finished, vapour will remain inside the pump, condense and lead to accelerated wear by allowing the inside of the pump to corrode. Running the pump with the inlet "blanked off" with a valve will allow the pump to exhaust any residual vapours will give the longest life and fastest recovery when it is used next.

It is recommended the pump is run for a minimum of 20 to 30 minutes after finishing the vacuum process as best practice. Running gas ballast during "clean up" will ensure that the condensable vapours are expelled from the pump. Very importantly when pumping potentially flammable vapours inert gas such as nitrogen should be used as the ballast gas.

Figure 6.11: Edwards RV oil-sealed rotary vane pump range

Using exhaust mist filters for oil-sealed rotary vane pumps

Oil sealed rotary vane pumps emit oil mist from the exhaust ports when they are operated regardless of their manufacturer. This “mist”, sometimes referred to erroneously as “smoke”, is actually a fine aerosol of the vacuum pump oil that forms as the oil is squeezed through the tiny clearances that are inside the pump mechanism and as an effect of the heightened temperature of operation. This hydrocarbon oil mist may represent a flammable hazard.

When an oil sealed rotary vane pump has high gas through put, for example when roughing a large chamber down from atmospheric pressure, oil mist will be seen at the pump’s exhaust. Examples of other occassions to generate oil mist at the exhaust include pumping a high gas flow introduced in the vacuum system or when running gas ballast. Over time, this oil mist can cause the pump to lose a significant amount of its oil charge, possibly emptying the pump’s oil. In a laboratory this can cause oil to be drawn into an exhaust ducting system or into the environment.

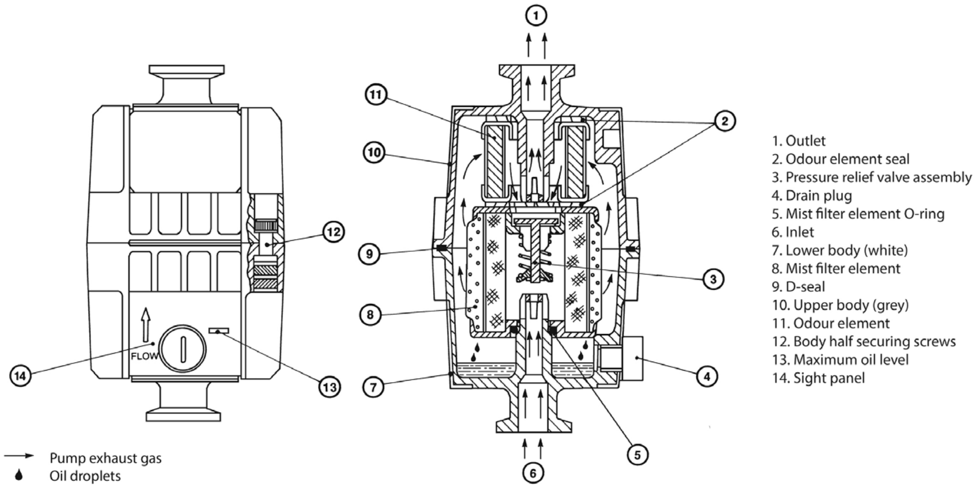


Figure 6.12: Edwards exhaust mist filter

Even with a vacuum pump that is operating at its ultimate pressure there is generally a small amount of oil mist seen at the exhaust. Most modern oil sealed rotary vane pumps use an ‘air bleed’ internally that does not affect the vacuum performance, but prevents hydraulic “knocking” at very low pressures. This air bleed causes a small amount of oil mist to pass to the exhaust even with a pump that is apparently not pumping any gas.

It is recommended that all oil sealed rotary vane pumps be fitted with an exhaust mist filter to capture oil mist and allow it to drain back into the pump oil box. Most exhaust mist filters are coalescing filters that allow the mist to form droplets which can’t “float” in the air like an aerosol. Gravity drains the oil back into the mist filter body. This oil can then either be manually returned to the pump or returned automatically using an ‘oil return’ accessory.

Oil mist filters should incorporate some form of over-pressure device that will allow the filter to be “by-passed” if it becomes blocked. This prevents over pressure of the pumps oil box which will cause external oil leaks and poor pump performance and may lead to a dangerous ‘over-pressure’ situation.

A high quality exhaust mist filter will also contain an odour adsorbing element, usually activated charcoal, which will adsorb the oily “smell” from the exhaust of the pump too.

It should be noted that exhaust mist filters do not change the nature of exhaust gas and so if hazardous gases are pumped, they still need to be managed once exhaust mist filter has performed its duty. It is necessary also to assess the suitability and/or chemical compatibility of the exhaust mist filter with the gases being pumped.

The filtration elements are consumables and should be replaced periodically. A good guide would be to change them during routine oil changes to ensure efficient and effective operation.

6.9.5 CHEMICAL REACTIONS

Chemical reactions such as the synthesis of compounds in the chemical and petrochemical industries as well as the fragrance and pharmaceutical industries are widely used. Some of the reactions require reduced pressure in order to avoid high process temperatures, to remove reaction products mainly gases and vapours, or to shift the equilibrium to improve performance and yield.

The effect of pressure on reversible gas phase reactions is covered by Le Chatelier’ principle, which states that a system in equilibrium will readjust, if possible to relieve any stress on the system. If one considers the following:

$$3H_2 + N_2 \leftrightarrow 2NH_3$$

The left to right reaction producing ammonia is accompanied by a reduction in volume from four moles of reactants to two moles of product, resulting in the system pressure decreasing during the reaction. If the pressure is now increased (*i.e.* stress is applied) the chemical equilibrium shifts so as to reduce the pressure by producing more ammonia. Conversely if it was desirable to shift the reaction to the left, the reaction will be operated under reduced pressure *i.e.* vacuum. To maintain the required vacuum condition, and therefore the reaction process, the reaction by-products such as water, hydrogen, alcohols, glycol etc. must be removed continuously. The pressure range for reactions can vary between 50 to 10^{-2} mbar(a).

Vacuum pumping

Past experience and experimental data are usually required to determine the optimum size and operating pressure of a vacuum pump. Data such as reaction rate, reaction order, effect of pressure changes, gas/liquid/vapour ratios etc. need to be considered. The capacity or speed of the pump will have to cope with large quantities of non-condensable reaction gases, including H_2 as well as the usual leakage air associated with such equipment. As the air leakage rate can be very high, especially for older equipment, and as most vapours pumped are flammable, potentially flammable mixtures may be present during the whole or part of the process cycle.

The capacity or speed of the pump will have to cope with large quantities of non-condensable reaction gases, including H_2 as well as the usual leakage air associated with such equipment. As the air leakage rate can be very high, especially for older equipment, and as most vapours pumped are flammable, potentially flammable mixtures may be present during the whole or part of the process cycle.

When non-condensable gases in equilibrium with a liquid phase leave the reactor, vapour saturation in addition to any reaction vapour generation must be considered. In most cases the mass transfer data will be known from previous reactor processes and the sizing of the vacuum pump becomes a matter of mass transfer calculations.

Hitherto nearly all types of vacuum producing equipment have been used such as steam ejector + liquid ring pumps using glycol, all types of oil-sealed rotary pumps (pure gas pumping), right up to the more advanced pumps like vapour booster and turbomolecular pumps. The latter pump is of interest for the reaction of organometallic compounds. The type of vacuum pump best suited for any reactor application depends not only on the required operating pressure and capacity, but also on the type of gas and/or vapour reaching the pump. Although numerous protection means, such as condensers, knock-out pots, filters and cyclone separators can provide effective protection, some contamination will penetrate through to the pump.

Common pump issues

As previously mentioned the choice of the vacuum equipment will depend on the compatibility of all the materials in contact with the reaction gases or vapours.

Oil-sealed mechanical pumps cannot tolerate polymeric or oil soluble materials and acids as these cause further reactions, loss of lubrication, excessive wear, swelling of blades etc. within the pump. Similar considerations apply to once-through oil-lubricated pumps unless very high and uneconomical oil flowrates are set creating possible problems in the disposal of relatively large quantities of waste oil.

Well engineered dry pumping arrangements provide reliable means for even the most arduous of reactor applications. Well engineered means the incorporation of appropriate protection means as well as safety measures in accordance with the pumped vapours and/or gases. As mentioned above flammable gas/vapour mixtures will be present during the process cycle, therefore the appropriate correct explosion protection must be provided.

Pump sizing information needed

- Operating pressure of all process phases,
- Vapour/gas loads/mass flowrates to be pumped from each process phase,
- Physical data of process materials, especially vapour pressures,
- Operating/vapour temperature,
- Experimental leak rate,
- Pump protection devices available within the plant.

6.9.6 VACUUM EQUIPMENT IN LABORATORIES

Five key questions to ask yourself if you are using vacuum in a lab environment:

Do I regularly check the oil quality when using an oil-sealed pump?

Particularly in harsh processes, oil should be checked regularly and changed when necessary. When the oil is turning into an amber colour, it is due for a change. If the oil is allowed to deteriorate too much, your pump may be damaged and a full service will be required.

Are my filters clean?

Your exhaust filters need to be in a good condition and free of any blockages. Oil or dust saturation in these filters can cause a back pressure in your pump which can have a drastic effect on both the performance and reliability.

Does my pump have enough space around it and is the cooling fan clear?

Most of our scientific pumps are air cooled, which means they have cooling fans that pull the heat away from the body. If the pump is placed in a space with no ventilation or in an area with poor airflow, this can cause your pump to overheat and damage components. Therefore, you regularly need to check your fan and make sure that it is free of dust and that the inlet is not blocked by anything else in the lab.

Is my pipework connected effectively?

A good seal is crucial to achieve the desired vacuum levels. A poor inlet seal will allow atmosphere into the pump, which will increase your pump's down time and make your pump work harder (meaning more maintenance will be required).

Exhaust seals are just as important. If these are not sealed properly it will allow whatever substances that are being pumped, to go in to the atmosphere. Even if your pumps are running a clean application, oil vapours and tip seal dust can still be harmful to your health if you breath them in.

Am I dealing with condensable vapours?

Vapours condensing in pump oil leads to poor lubrication, increased wear of moving parts and loss of vacuum performance. Work through our recommendations on the checklist to minimize condensation. Our primary pumps are designed to pump vapours and have the highest gas ballast flow rates of any similar sized pumps.

A consideration to make: Loss of oil from oil-sealed rotary vane pumps

If we consider a typical laboratory system where a 1 litre volume flask is being evacuated from atmospheric pressure every hour.

- At a temperature of 295 K the mass of air transferred/pumped in each cycle is ~ 1.2 g
- A typical 'small' Oil sealed rotary vane pump has an oil charge of approximately 1 litre. With unit density this is a mass of ~ 1,000 g

If 25% of the mass of oil, compared to the mass of the pumped air, is carried over (i.e. transferred with the pumped air) during each flask evacuation then during each cycle the oil loss ~ 0.3 g

This suggests that in ~ 3300 cycles all the oil will be lost from the pump. At a rate of one cycle per hour this occurs in approximately 4 to 5 months. (Note that this could be confirmed by checking how often the oil in the Oil sealed rotary vane pump needs to be re-filled) and or we can surmise that in 3 months we would expect > 600 g of oil to be lost from the pump.

This will result in a layer of aromatic (smelly) oil of 0.1 mm thickness coating an area of 60,000 cm2 of the laboratory.

As a comparison operating a pump at ultimate pressure (< 1 Pa) the mass flow of air is <0.001 g/h

Two smart oil-free alternatives

nXDS scroll pumps are completely oil-free, hermetically sealed. They have no oil in the gas pathway so there is no potential contamination of the process nor of the laboratory environment. They can be configured to pump a wide range of laboratory applications and maintenance intervention is 2.5 years or more.

nXRi multi-stage roots pumps guarantee clean processes and clean results being totally oil and contaminant free. Additionally, it's delivering the highest pumping density for pumps of this size. Their reduced power usage, compact size, low vibration and noise levels and 5-year service intervals make them another ideal partner for your lab.

7. PRODUCT OFFERING

Edwards offers a broad range of vacuum products to meet the challenges presented by today's scientific applications. Whatever your vacuum pumping requirements, Edwards has the product solution.

nEXT Turbomolecular Pumps

nEXT turbomolecular pumps are drawing from our tried and trusted EXT and STP ranges. They offer superior performance, reliability and end user serviceability, setting the benchmark for scientific turbomolecular pumps. Available in pump sizes from 55 up to 1250 l/s pumping speeds for Nitrogen.

STP Magnetically Levitated Turbomolecular Pumps

Edwards STP maglev turbomolecular pumps are at the forefront of vacuum for R&D institutes and high energy physics. The multi-axis, non-contact magnetic bearing system ensures there is no risk of contamination, while minimising noise and vibration. This also means zero maintenance for most applications and low cost of ownership, making the STP maglev turbomolecular pumps the ideal choice for critical and demanding applications.

Gamma Ion Pumps

Also known as sputter ion pumps or ion getter pumps, are capture pumps that ionize gases using an anode/cathode array. Ion pumps can operate from 10^{-5} to 10^{-12} mbar and range in size from 0.2 to 1,200 l/s of nitrogen.

Non-Evaporable Getter Pumps

Newly introduced into the Gamma portfolio, a range of Non-Evaporable Getter Pumps (NEG) pumps further extends the Edwards UHV capable product offering. NEGs have the capability to run without power (once activated) for extended periods of time and are particularly useful both for rapid pump-down to UHV pressures and for maintaining vacuum once achieved. NEGs can be integrated within an IGP for an extremely efficient pump combination.

T-Station Turbomolecular Pumping Station

The Edwards turbomolecular pumping stations are a comprehensive range of products providing versatile vacuum solutions in many different applications. All our nEXT turbomolecular pumping stations are supplied fully assembled and ready to run straight out of the box with nEXT turbomolecular pumps and backing pumps that are user serviceable. There are 2 models in the turbomolecular pumping stations range the entry level T-Station 85 and the higher capacity T-Station 300.

nEXT Turbomolecular Pumping Stations

nEXT turbomolecular pumping stations have been developed to provide a comprehensive vacuum solution with the latest technological advances for easy installation and operation. With speeds of 47 ls^{-1} to 400 ls^{-1}, and now available with the nXDS dry scroll pump, the nEXT turbomolecular pumping station enables you to configure the most appropriate combination of turbomolecular and backing pump for your application.

Customised Turbomolecular Pumping Stations

In applications where one of our standard turbomolecular pumping stations does not fulfil your needs, Edwards also offer custom built turbomolecular pumping stations to meet your exact requirements. These can incorporate any of our nEXT turbomolecular pumps or our STP maglev turbomolecular pumps plus our full range of backing pumps and accessories.

nXDS Dry Scroll Pumps

The nXDS has taken scroll vacuum technology to the next level. Improved performance, quiet operation and extended service intervals make nXDS the ultimate dry choice.

RV Oil Sealed Rotary Vane Pumps

The RV series of rotary vane pumps are the result of more than 75 years' experience and a clean sheet design programme to produce the ultimate range of small oil sealed rotary vane pumps. These rugged vacuum pumps offer an excellent ultimate, with good pumping speeds as well as superior vapour handling capabilities and quiet operation.

nXRi Dry Multistage Roots Pumps

Designed to deliver unrivalled pump speeds of 30 to 120m^3h^{-1}: that is six times more pumping speed than a similar sized dry pump. With lower input power and zero maintenance the nXRi brings real performance improvements and cost benefits across a range of applications.

Measurement and Control

We offer a wide choice of vacuum measurement and control products – from dial gauges to microprocessor based gauge controllers. Within each product range, there is a family of models designed to meet the widest user specification.

8. SERVICE SOLUTIONS

Edwards understands the importance of local support. We have a number of major service facilities located around the world as well as a network of Authorised Service Distributors, each location supported by an extensive team of engineers and technicians to provide local, rapid response and great value service. In addition, you can buy spare parts and maintenance kits directly from Edwards with delivery to any country around the globe.

- Comprehensive service
- Extended warranties
- Repair
- Service Contracts
- Refurbished products

All our service operations are conducted at the highest international standards in accordance with ISO 9001 (quality), ISO 14001 (environmental) and OHSAS 18001 (workplace safety).

9. UNIT CONVERSIONS

Pressure Units

	mbar	bar	Torr	Pa (Nm^{-2})	atm	lbf inch^{-2}
1 mbar =	1	1 x 10^{-3}	0.75	10^{2}	9.87 x 10^{-4}	1.45 x 10^{-2}
1 bar =	10^{3}	1	7.5 x 10^{2}	1 x 10^{5}	0.987	14.5
1 Torr =	1.33	1.33 x 10^{-3}	1	1.33 x 10^{2}	1.32 x 10^{-3}	1.93 x 10^{-2}
1 Pa (Nm^{-2}) =	0.01	1 x 10^{-5}	7.5 x 10^{-3}	1	9.87 x 10^{-6}	1.45 x 10^{-4}
1 atm =	1.01 x 10^{3}	1.01	7.6 x 10^{2}	1.01 x 10^{5}	1	14.7
1 lbf inch^{-2} =	68.9	6.89 x 10^{-2}	51.71	6.89 x 10^{3}	6.80 x 10^{-2}	1
1 kgf cm^{-2} =	9.81 x 10^{2}	0.98	7.36 x 10^{2}	9.81 x 10^{4}	0.97	14.2
1 inch Hg =	33.9	3.39 x 10^{-2}	25.4	3.39 x 10^{3}	3.34 x 10^{-2}	0.49
1 mm Hg =	1.33	1.33 x 10^{-3}	1	1.33 x 10^{2}	1.32 x 10^{-3}	1.93 x 10^{-2}
1 inch H_2O =	2.49	2.49 x 10^{-3}	1.87	2.49 x 10^{2}	2.46 x 10^{-3}	3.61 x 10^{-2}
1 mm H_2O =	9.81 x 10^{-2}	9.81 x 10^{-5}	7.36 x 10^{-2}	9.81	9.68 x 10^{-5}	1.42 x 10^{-3}

	kgf cm^{-2}	inch Hg	mm Hg	inch H2O	mm H2O
1 mbar =	1.02 x 10^{-3}	2.95 x 10^{-2}	0.75	0.40	10.2
1 bar =	1.02	29.53	7.5 x 10^{2}	4.01 x 10^{2}	1.02 x 10^{4}
1 Torr =	1.36 x 10^{-3}	3.94 x 10^{-2}	1	0.54	13.6
1 Pa (Nm^{-2}) =	1.02 x 10^{-5}	2.95 x 10^{-4}	7.5 x 10^{-3}	4.01 x 10^{-3}	0.10^{2}
1 atm =	1.03	29.92	7.6 x 10^{2}	4.07 x 10^{2}	1.03 x 10^{4}
1 lbf inch^{-2} =	7.03 x 10^{-2}	2.04	51.71	27.68	7.03 x 10^{2}
1 kgf cm^{-2} =	1	28.96	7.36 x 10^{-2}	3.94 x 10^{2}	1 x 10^{4}
1 inch Hg =	3.45 x 10^{-2}	1	25.4	13.6	3.45 x 10^{2}
1 mm Hg =	1.36 x 10^{-3}	3.94 x 10^{-2}	1	0.54	13.60
1 inch H_2O =	2.54 x 10^{-3}	7.36 x 10^{-2}	1.87	1	25.4
1 mm H_2O =	10^{-4}	2.90 x 10^{-3}	7.36 x 10^{-2}	3.94 x 10^{-2}	1

Note also: 1 dyn cm^{-2} (barye) = 0.1 Pa (Nm^{-2}) = 10^{-3} mbar

Leak Rate Units

	mbar ls^{-1}	Torr ls^{-1}	atm cm^{3} s^{-1}	lusec	atm ft^{3}min^{-1}
1 mbar ls^{-1} =	1	0.75	0.99	7.5 x 10^{2}	2.09 x 10^{-3}
1 Torr ls $^{-1}$ =	1.33	1	1.32 x 10^{3}	103	2.79 x 10^{-3}
1 atm cm^{3} s^{-1} =	1.01	0.76	1	7.6 x 10^{2}	2.12 x 10^{-3}
1 lusec =	1.33 x 10^{-3}	1 x 10^{-3}	1.32 x 10^{-3}	1	2.79 x 10^{-6}
1 atm ft^{3}min-^{1} =	4.78 x 10^{2}	3.59 x 10^{2}	4.72 x 10^{2}	3.59 x 10^{5}	1

Pumping Speed Units

	ls^{-1}	l min^{-1}	ft^{3}min^{-1}	m^{3}h^{-1}
1 ls^{-1} =	1	60	2.119	3.60
1 l min^{-1} =	0.017	1	0.035	0.06
1 ft^{3}min^{-1} =	0.472	28.317	1	1.699
1 m^{3}h^{-1} =	0.278	16.667	0.589	1

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