# Vacuum Physics

# 9


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Chapter 9


W. Demtröder, *Mechanics and Thermodynamics*, Undergraduate Lecture Notes in Physics, DOI 10.1007/978-3-319-27877-3_9

The importance of vacuum physics for the development of modern physics and technology can be hardly overestimated. Only after the realization of a sufficiently low vacuum, many experiments in atomic, molecular and nuclear physics became possible. These experiments have essentially contributed to the understanding of the micro-structure of matter, of electrons and nuclei as the building blocks and of the internal structure of atoms and nuclei. Based on the results of these experiments the quantum theory of matter could be successfully developed (see Vol. 3).

Without vacuum technology, the manufacturing of semiconductor elements and integrated circuits would have been impossible and therefore we would be still without computers.

Besides for basic research vacuum technology is nowadays used as indispensable tool in many technical applications, which reach from vacuum melting of special metal alloys over the production of thin optical films to the dry freezing of food. It is therefore essential for every physics student to study at least some basic facts of vacuum physics and technology.

In this chapter we will discuss, after a summary of the most important fundamentals, some techniques for the generation of vacuum and the measurement of low pressures. More detailed presentations can be found in [9.1, 9.2, 9.3].



## 9.1 Fundamentals and Basic Concepts

Vacuum is produced in a container, when most of the gases or vapours have been removed and the pressure $p$ in the volume $V$ becomes small compared to the atmospheric pressure $p_0 \approx 1\,\text{bar}$. Devices, that can achieve such a reduction of the pressure, are called **vacuum pumps**, because they pump part of the gases or vapours in the volume $V$ into other containers or into the open air (Fig. 9.1). The achieved pressure, given in the unit Pascal ($1\,\text{Pa} = 1\,\text{N/m}^2 = 10^{-2}\,\text{hPa}$) or often quoted in millibar ($1\,\text{mbar} = 1\,\text{hPa} = 100\,\text{Pa}$) (see Tab. 7.1) depends essentially on the type of vacuum pumps used for the evacuation. At low pressures ($p < 10^{-4}\,\text{hPa}$) the walls of the vacuum container and the gas molecules attached to the walls play an important role for further evacuation because their outgasing essentially influence the achievable vacuum pressure.

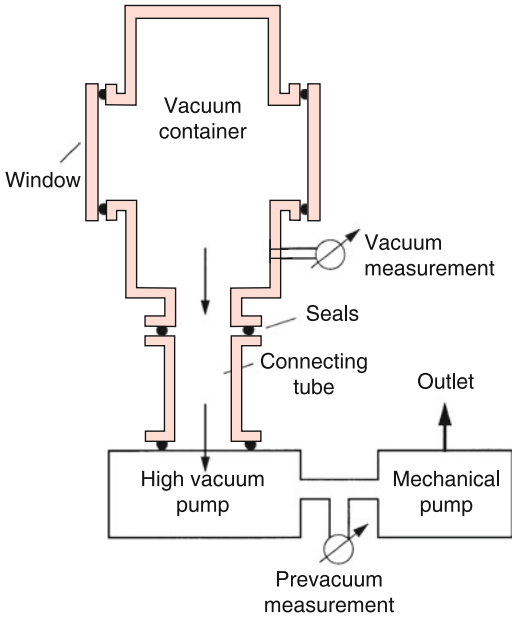


**Figure 9.1** Schematic drawing of a vacuum apparatus

### 9.1.1 The Different Vacuum Ranges

We distinguish four different vacuum ranges, depending on the lower pressure limit of the achievable vacuum.

- Low *vacuum*
  $1\,\text{hPa} < p < 1000\,\text{hPa} = 1\,\text{bar}$
- Medium *vacuum*
  $10^{-3}\,\text{hPa} < p < 1\,\text{hPa}$
- *High vacuum*
  $10^{-7}\,\text{hPa} < p < 10^{-3}\,\text{hPa}$
- *Ultrahigh Vacuum*
  $p < 10^{-7}\,\text{hPa}$.

The best vacuum, achievable today is about $10^{-13}\,\text{hPa}$.

In order to give an impression how empty an evacuated container really is, Tab. 9.1 compiles the number of gas molecules per $\text{m}^3$ for different pressures. It is illustrative to compare these numbers with the number $n_w$ of molecules sitting per $\text{m}^2$ in a monomolecular layer on the surface of the container walls. With a mean distance of 0.3 nm between the molecules of a monomolecular layer we get $n_w = 10^{19}/\text{m}^2$. A cubic vacuum container with $V = 1\,\text{m}^3$ has a wall surface of $6\,\text{m}^2$. At a pressure of $2 \cdot 10^{-5}\,\text{hPa}$ the number of molecules on the wall therefore equals the number of all molecules in the volume of the container. For pressures below $10^{-5}\,\text{hPa}$ the number of molecules on the wall therefore exceeds the number in the volume and in order to reach a much lower vacuum the walls have to be outgassed by heating.

Generally there are different gases ($N_2$, $O_2$, He, Ar with pressures $p_i$) and vapours (water, oil or other liquids with saturation

**Table 9.1** Particle density $n$ of air molecules, mean free path $\Lambda$ and particle flux density $\phi$ onto the container surface for different pressures at room temperature

| $p$/hPa | $n/\text{m}^{-3}$ | $\Lambda$/m | $\phi/\text{m}^{-2}\text{s}^{-1}$ |
|---|---|---|---|
| $10^3$ | $2.5 \cdot 10^{25}$ | $6 \cdot 10^{-8}$ | $3 \cdot 10^{27}$ |
| 1 | $2.5 \cdot 10^{22}$ | $6 \cdot 10^{-5}$ | $3 \cdot 10^{24}$ |
| $10^{-3}$ | $2.5 \cdot 10^{19}$ | $6 \cdot 10^{-2}$ | $3 \cdot 10^{21}$ |
| $10^{-6}$ | $2.5 \cdot 10^{16}$ | 60 | $3 \cdot 10^{18}$ |
| $10^{-9}$ | $2.5 \cdot 10^{13}$ | $6 \cdot 10^4$ | $3 \cdot 10^{15}$ |

pressures $p_{si}$) in the vacuum container. The total pressure

$$p = \sum (p_i + p_{si}) \tag{9.1}$$

is then the sum of all partial pressures. The saturation pressure which adjusts itself at the equilibrium between liquid and vapour depends on the temperature (see Sect. 10.4.2).

For planning an experiment in the vacuum chamber the mean free path $\Lambda$ of the molecules is of great importance. It determines the collision probability between the molecules in the chamber (see Sect. 7.3). Table 9.1 shows that in the fine vacuum range $\Lambda$ is small compared with the dimensions of commonly used vacuum chambers. Collisions can be therefore not neglected. On the other hand, in the high vacuum range for $p < 10^{-6}$ hPa, $\Lambda$ becomes large compared with the dimensions of the chamber and the molecules fly freely through the chamber without suffering collisions until they hit a wall.

### 9.1.2 Influence of the Molecules at the Walls

The number of molecules, hitting per sec an area of 1 m$^2$ of the walls of a vacuum container (particle flux density $\Phi$, last column of Tab. 9.1) depends on the particle density $n$ in the evacuated volume $V$ and on the mean thermal velocity $\overline{v}$ (see Sect. 7.3). A molecule with the velocity $\boldsymbol{v} = \{v_x, v_y v_z\}$ with the distance $z$ from the surface can reach the surface within the time $\Delta t \geq z/v_z$ as long as $z$ is smaller than the mean free path $\Lambda$ (Fig. 9.2). For a mean particle density $n$ the number of wall collisions per second of molecules in the upper half volume is

$$Z = \frac{nA\overline{v}}{4\pi} \int_0^{\pi/2} \sin\vartheta \, \cos\vartheta \, \mathrm{d}\vartheta \int_0^{2\pi} \mathrm{d}\varphi \, . \tag{9.2a}$$

The first integral gives the value $1/2$, the second gives $2\pi$. The particle flux density $\Phi = Z/A$ onto the unit area of the wall surface is then

$$\Phi = (1/4) n \cdot v \, . \tag{9.2b}$$

The numerical values in Tab. 9.1 show, that at a pressure of $p = 3 \cdot 10^{-6}$ hPa and a mean velocity $v = 500$ m/s nearly as many molecules hit the surface per second as are contained in a mono-molecular layer on the surface. If all impinging molecules would stick at the surface a clean surface would be covered within 1 s with a monomolecular layer. This illustrates that a really clean surface can be only realized at very low pressures (ultrahigh vacuum) and if the molecules do not stick on the surface. This can be achieved, when the surface is heated, which causes all impinging molecules to leave the surface immediately.

With decreasing temperature the evaporation decreases and the inner wall of a vacuum chamber is therefore at low temperatures always covered by a layer of adsorbed molecules. An equilibrium adjusts itself which depends on the temperature of the surface, on the density $n$ in the chamber and on the molecular species, where the rates of adsorbing and desorbing molecules become equal.

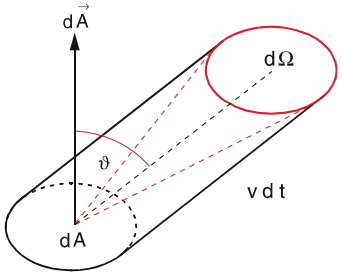


**Figure 9.2** Illustration of the collision rate with the wall

Our example above has shown that at pressures $p \leq 10^{-3}$ hPa the number of molecules adsorbed on the wall becomes larger than the number in the evacuated volume. When a vacuum chamber is evacuated, the pressure in the chamber below $10^{-3}$ hPa will be at first essentially determined by the rate of molecule desorbing from the wall, until the desorbing rate becomes smaller than the pumping rate that removes the molecules out of the vacuum chamber.

### 9.1.3 Pumping Speed and Suction Capacity of Vacuum Pumps

When a vacuum chamber is evacuated the gas in the chamber has to pass through an opening and through pipes in order to reach the vacuum pump. The **volume flow rate** of the pipe (often given in the unit litre per second = l/s or cubic meter per hour = m$^3$/h) is the gas volume that flows per sec through a cross section of the pipe at a given pressure $p$ and temperature $T$.

**Note**, that the molecular density $n = N/V$ decreases with the pressure according to

$$p \cdot V = NkT \rightarrow N = \frac{pV}{kT} \rightarrow n = \frac{p}{kT} \, . \tag{9.3}$$

Therefore even for a constant volume flow rate the number of molecules passing per second through the cross section decreases with $p$! This means for equal volume flow rates $\mathrm{d}V/\mathrm{d}t$, the number $\mathrm{d}N/\mathrm{d}t$ of molecules pumped out of the vacuum chamber depends on pressure $p$ and temperature $T$.

The **suction capacity**

$$S_\mathrm{V} = \frac{\mathrm{d}V}{\mathrm{d}t} \text{ given in [l/s] or in [m}^3\text{/h]} \tag{9.4}$$

of a vacuum pump is defined as the volume flow rate $\mathrm{d}V/\mathrm{d}t$ at the suction intake of the pump.

The total mass flow of molecules with mass $m$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \varrho \cdot \frac{\mathrm{d}V}{\mathrm{d}t} = \frac{m}{kT} p \cdot \frac{\mathrm{d}V}{\mathrm{d}t} \, , \tag{9.5}$$

that is pumped per second out of the vacuum chamber is the mass suction capacity. It depends on the pressure and the volume flow rate through the chamber opening and the pipes.

Manufacturers of pumps generally give the suction capacity or pumping speed of a pump in the unit

$$S_L = p \cdot \frac{dV}{dt}\,, \qquad [S_L] = \text{hPa} \cdot \text{l/s} \tag{9.6}$$

as the product of pressure $p$ and volume flow rate $dV/dt$.

**Example**

With a suction capacity $S_V = 500\,\text{l/s}$ about $10^{22}$ molecules per sec are pumped out of a vacuum chamber at room temperature and $p = 1\,\text{hPa}$. At the lower pressure $p = 10^{-6}\,\text{hPa}$ these are only $10^{16}$ molecules per second at the same value of $S_V$.

The suction capacity is for the first case $S_L = 500\,\text{hPa} \cdot \text{l/s}$ (corresponding to 50 Watt) while for the second case $S_L$ is only $5 \cdot 10^{-4}\,\text{hPa} \cdot \text{l/s}$ (50 µW). ◀

### 9.1.4 Flow Conductance of Vacuum Pipes

The dimensions of vacuum pipes play an important role for the design of a vacuum apparatus. The mass flow

$$\frac{dM}{dt} = L_m \cdot (p_2 - p_1) \tag{9.7a}$$

through a vacuum pipe is proportional to the pressure difference $(p_2 - p_1)$ between entrance and exit of the pipe. The proportionality factor $L_m$ is the coefficient of mass flow conductance given in the unit [1 m · s]. Generally the pumping speed

$$p \cdot \frac{dV}{dt} = L_S \cdot (p_2 - p_1) \tag{9.7b}$$

is used with the unit [hPa · m³/h]. Because of $p \cdot V = N \cdot kT \rightarrow p = (\varrho/m)kT$ with $m = M/N =$ mass of one molecule the coefficient of volume flow conductance $L_S$ can be related to the mass flow conductance by

$$L_S = \frac{kT}{m} \cdot L_m\,. \tag{9.7c}$$

$L_S$ depends on the mass $m$ of the molecules, on the mean free path $\Lambda$ (because $\Lambda \propto 1/p$) and on the geometry of the vacuum pipes. For simple geometries it can be calculated. For complex geometries it must be determined experimentally. The values are compiled in special tables [9.1].

The gas flow through pipes

$$\frac{dV}{dt} = C_S \frac{\Delta p}{p} \tag{9.7d}$$

strongly depends on the pressure. Here $C_S = L_S$ is named the volume flow conductance. The different pressure ranges are characterized by the Knudsen number

$$\text{Kn} = \frac{\Lambda}{d}\,, \tag{9.8}$$

which gives the ratio of mean free path $\Lambda$ and the diameter $d$ of openings or pipes. According to the magnitude of Kn we distinguish between three ranges:

- Range of laminar gas flow (for Reynolds numbers Re $<$ 2200) or turbulent flow (for Re $>$ 2200) which occurs for Kn $\ll 1$. Here is $\Lambda \ll d$.
- Range of Knudsen flow (also called transition range) where Kn $\approx 1$ and $\Lambda \approx d$.
- Range of free molecular flow where Kn $\gg 1$ and $\Lambda \gg d$.

In the range Kn $\ll 1$ the gas flow is essentially governed by collisions between the gas molecules, which means that the viscosity plays an important role. The flow can be described by hydro-dynamical models (see Chap. 8). Depending on the magnitude of the Reynolds number Re and the viscosity $\eta$ the flow is laminar for Re $<$ 2200 or turbulent for Re $>$ 2200. Under the conditions relevant for most vacuum systems the Reynolds number is generally smaller than 2200 and the flow is therefore laminar.

In the range Kn $\gg 1$ collisions between the molecules can be neglected. The viscosity $\eta$ does no longer influence the gas flow and collisions with the wall determine the suction capacity. The flow conductance becomes independent of the pressure.

We will illustrate these conditions by some examples:

**Examples**

1. Volume flow conductance $C_S$ of a circular opening with diameter $d$ in the range of molecular flow ($\Lambda \gg d$). According to Eq. 9.2 the number of molecules passing per sec through the hole with area $A = \pi d^2/4$ is

$$Z = \tfrac{1}{4} A \cdot n \cdot \overline{v}\,,$$

with $p \cdot V = N \cdot kT$ and $Z = dN/dt$ we obtain for the volume gas flow through the hole

$$\frac{dV}{dt} = \frac{1}{4} A \cdot \frac{n}{p} kT\,\overline{v} = \frac{1}{4} A \cdot \overline{v},$$

since $n = N/V = p/kT$.
Since $n \sim p$ the volume flow $dV/dt$ becomes independent of pressure. Inserting numerical values of $v$ for air at $T = 300\,\text{K}$ gives $dV/dt = 11.6 \cdot A$ in l/s if $A$ is given in cm². A circular opening with $d = 10\,\text{cm}$ has therefore at low pressures ($\Lambda \gg d$) the volume flow conductance $C_S = 900\,\text{l/s}$.
2. Flow through a pipe with length $L$ and diameter $d$ in the range of laminar flow ($\Lambda \ll d$). The pressures at

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the two ends of the pipe are $p_1$ and $p_2$. According to the Hagen-Poisseuille-law (8.32)

$$p \cdot \frac{dV}{dt} = \frac{\pi \cdot d^4}{128\,\eta L} \cdot \frac{p_1 + p_2}{2}(p_1 - p_2)\,, \qquad (9.9)$$

we obtain for $d = 5\,\text{cm}$, $L = 1\,\text{m}$, $p_1 = 2\,\text{hPa}$, $p_2 = 0$, $\eta_{air} = 0.018\,\text{mPa}\cdot\text{s}$, the numerical value $p \cdot dV/dt = 170\,\text{Pa}\cdot\text{m}^2/\text{s}$. According to (9.7) the volume flow conductance then becomes $C_S = 0.85\,\text{m}^3/\text{s} = 850\,\text{l/s}$. At a lower pressure of $10^{-1}$ hPa, where $\Lambda = 0.06\,\text{cm}$ (Tab. 9.1) which is still smaller than $d$ the flow conductance decreases according to (9.7) and (9.9) to $C_S = 42\,\text{l/s}$. Equation 9.9 is in this range, however, only approximately valid and the accurate value is $C_S = 80\,\text{l/s}$.
In the range of molecular flow ($\Lambda > d$) $C_S$ converges with decreasing pressure towards the value $C_S = 16\,\text{l/s}$. ◀

The reciprocal of the flow conductance

$$R_S = 1/C_S \qquad (9.10)$$

is the flow resistance. Completely analogue to the electrical resistance in electricity the *flow resistance* of consecutive flow pipes is the sum of the individual resistances, while for flow pipes in parallel arrangements the individual *flow conductances* add to the total conductance, as can be immediately seen from (9.7).

### 9.1.5 Accessible Final Pressure

Every vacuum chamber has openings that allow access to the experimental setup in its inside. They are closed by flange seals. However, there are always leaks which are often difficult to find and to close. Through these leaks molecules can penetrate from the outside into the vacuum chamber. We define the gas rate $dG_L/dt = p_0 \cdot dV_L/dt$ ($p_0$ = atmospheric pressure) which penetrates through all leaks into the vacuum chamber as the **leak rate**. It is given in the same units $\text{hPa}\cdot\text{l/s}$ as the pumping speed defined in (9.6).

As has been previously discussed molecules can also be desorbed from the inner walls and delivered into the volume of the vacuum chamber. This leads without pumping to a pressure increase $\Delta p$.

For the rate $dN_d/dt$ of desorbing molecules we obtain with $p \cdot V = N \cdot kT$ the pressure increase per second

$$\frac{dp}{dt} = \frac{kT}{V}\frac{dN_d}{dt}\,. \qquad (9.11)$$

The total rate of desorbed gas is

$$\frac{dG_d}{dt} = V \cdot \frac{dp}{dt} = kT\frac{dN_d}{dt}\,. \qquad (9.12)$$

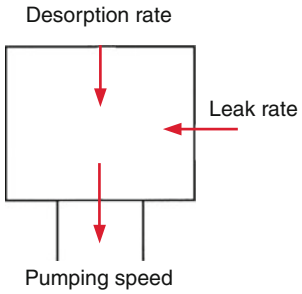


**Figure 9.3** The achievable final pressure is determined by the compensation of pumping speed by leak rate + desorption rate

The final pressure achieved in the vacuum chamber is determined by the pumping speed, the leak rate and the total rate of desorbing molecules (Fig. 9.3). At the final pressure the pumping speed just equals the sum of leak rate and desorbing gas rate.

$$S_L^{\text{eff}}(p) = \frac{dG_L}{dt} + \frac{dG_d}{dt}\,, \qquad (9.13)$$

where $S_L^{\text{eff}}$ is the effective pumping speed at the outlet opening of the chamber to the pumping pipes. It is equal to the pumping speed of the pump minus the flow conductance of the vacuum lines between chamber and pump.

The attainable final pressure $p_f$ results then from (9.13) with (9.6) and (9.12):

$$p_f = \frac{dG_d/dt + dG_L/dt}{S_V}\,, \qquad (9.14)$$

where $S_V = dV_p/dt$ is the effective suction capacity at the exit of the vacuum chamber.

**Example**

For a suction capacity $S_V = 10^3\,\text{l/s}$, a leak rate of $10^{-4}\,\text{hPa}\cdot\text{l/s}$ and a desorbing gas rate of $10^{-3}\,\text{hPa}\cdot\text{l/s}$ a final pressure of $p_f = 1.1 \cdot 10^{-6}\,\text{hPa}$ can be reached. After heating the walls the desorbing rate sinks below the leak rate and a final pressure of $p_f = 10^{-7}\,\text{hPa}$ can be achieved. ◀

## 9.2 Generation of Vacuum

In order to remove gas particles out of the vacuum chamber vacuum pumps are used. The different types can be divided into three classes (Tab. 9.2):

- Mechanical pumps,
- Diffusion pumps (fluid acceleration vacuum pump),
- Cryo pumps and sorption pumps.

We will briefly discuss these three classes. In Fig. 9.4 the pressure ranges are compiled where the different pumps can be used.

**Table 9.2** Classification of the most important types of vacuum pumps

| Mechanical pumps | Fuel acceleration pumps | Condensation pumps, sorption pumps |
|---|---|---|
| Rotary vane pumps | Liquid jet pumps | Cool traps |
| Roots pumps | Vapor jet pumps | Kryo pumps, sorption pumps |
| Turbopumps | Diffusion pumps | ion getterpumps |

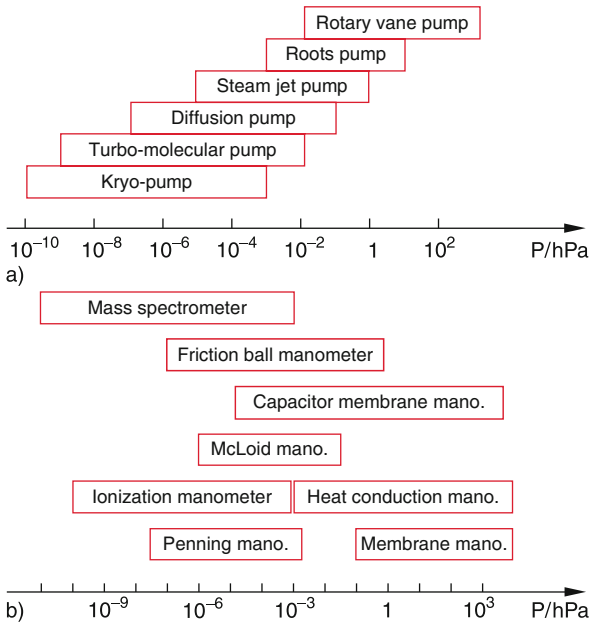


**Figure 9.4** Pressure ranges **a** of the differrent types of vacuum pumps, **b** of pressure detectors

## 9.2.1 Mechanical Pumps

Already around 1600 Galileo Galilei has produced a low vacuum in a container by using a movable piston. More detailed experiments were performed in 1643 by Evangelista Torricelli, who was Galileo' successor in Florence. In honour of Torricelli the unit of pressure has been named torr (1 torr is the pressure of 1 mm mercury column = 133.3 Pa). The unit torr has been used for several centuries before the SI unit 1 Pa was introduced.

Spectacular experiments with evacuated spheres were performed 1645 by Otto von Guericke, the major of the German city Magdeburg. He put two hemi-spheres together, sealed them up with leather gaskets and evacuated the interior. This pressed the two hemi-spheres tightly together. In order to demonstrate the force on the hemi-spheres due to the external pressure he roped 8 horses in on each side who tried unsuccessfully to separate the hemi-spheres. The large auditorium was very much astonished that 16 horses could not separate the hemi-spheres although they could be readily separated after the evacuated sphere was filled again with air at the external pressure. Superstitious people believed in a ghost inside the sphere. An engraving of Caspar Schott illustrates this spectacular experiment (Fig. 9.5). At that time the evacuation with piston air pumps (Fig. 9.6) was tedious, because the seals were imperfect.

**Figure 9.5** The demonstration experiment by Otto von Guericke. Engraving by Caspar Schott

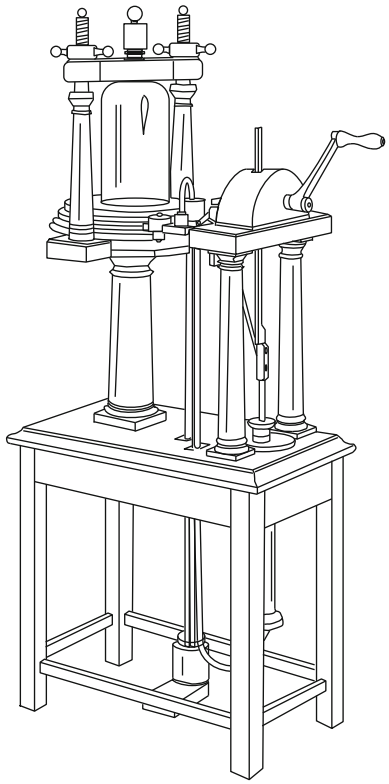

**Figure 9.6** Ancient mechanical vacuum pump

Nowadays the mechanical pumps are mainly rotary vane pumps, Roots pumps or turbo-molecular pumps, which are all driven by electro motors.

### 9.2.1.1 Rotary Vane Pumps

The basic principle of rotary vane pumps is schematically illustrated in Fig. 9.7. An eccentrically mounted rotor $R_1$ rotates in a cylindrical bore with an inlet $S_1$ from the vacuum chamber and an outlet $A_1$ into the open air at atmospheric pressure. The rotor has a slit in which two sliders are pushed by a coil spring against the wall of the bore. When the rotor rotates in the direction of the arrow the right side of the sliders sucks the gas from $S_1$ and drives it during half of a rotation period towards $A_1$. This is repeated every half turn thus continuously evacuating the vacuum chamber behind $S_1$.

For single-stage pumps the outlet $A_1$ is connected to the open air (or an exhaust gas line) and the pressure $p$ in $A_1$ equals the atmospheric pressure. Due to the pressure difference between $A_1$ and $S_1$ always some gas can flow back from $A_1$ to $S_1$ because the slider in the rotor does not completely seal the connection between $A_1$ and $S_1$. This limits the attainable final pressure in $S_1$. In order to keep the leak rate as small as possible the pump is filled with oil which forms a film between slider and wall and not only gives a better seal but also acts as lubricant that prevents jamming of the rotor. With such single-stage pumps final pressures of $10^{-1}$–$10^{-2}$ hPa are reached.

In order to obtain lower final pressures the outlet $A_1$ can be connected to a second pump (Fig. 9.8), which produces in $A_1$ already a pressure of $10^{-1}$ hPa, thus reducing the back-streaming considerably. This leads to a final pressure of permanent gases in $S_1$ of about $10^{-3}$ to $10^{-4}$ hPa. However, now the saturation vapour pressure of the pump oil ($p_s \approx 10^{-3}$ hPa at $T = 350$ K) is the limiting factor for the final pressure. Using a cool trap between $S_1$ and the vacuum chamber can reduce the saturation pressure and realizes an oil-free vacuum in the chamber.

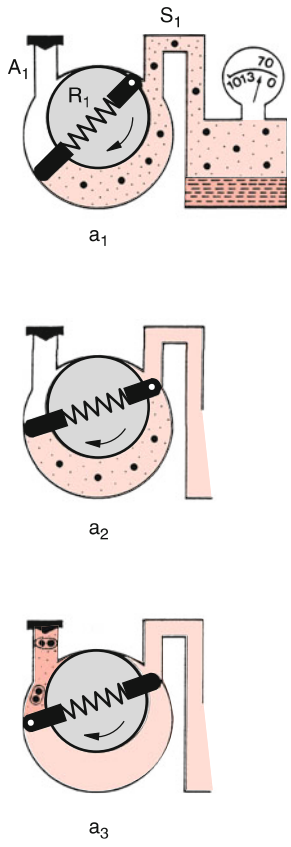


**Figure 9.7** Principle operation of a rotating vane pump [9.1]. With kind permission of Leybold GmbH

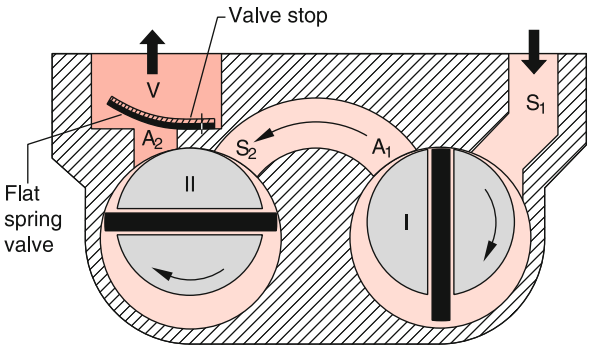


**Figure 9.8** Two stage rotary vane pump [9.1]. With kind permission of Leybold GmbH

Typical pumping speeds of such rotary van pumps reach from 1 $m^3/h$ for small pumps to 60 $m^3/h$ for larger ones. To prevent back streaming of atmospheric pressure from $A$ to $S$ in case of an accidental standstill of the pump a blocking valve $V$ is built in at $A_2$.

### 9.2.1.2 Roots-Pump

The principle of a roots pump is shown in Fig. 9.9. Two symmetrically shaped rotors $R_1$ and $R_2$ rotate with opposite directions about two axes. They are arranged in such a way that their surfaces nearly touch each other. The gap width between the two rotors and between the rotors and the wall are only a few tenth of a millimetre. For the momentary situation shown in Fig. 9.9 the gas volume $V_1$ enclosed by the left rotor $R_2$ is compressed and pushed to the outlet $A$ when the rotor rotates counterclockwise. A quarter of a full turn later the oppositely turning rotor $R_1$ pushes gas from $S$ to a similar enclosed volume on the right side and presses it to $A$. Since the rotors do not touch, there is no

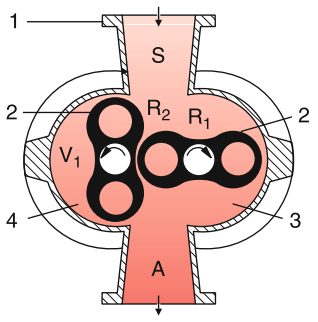


**Figure 9.9** Principle operation of roots pump [9.1]. With kind permission of Leybold GmbH

material abrasion and roots pumps can rotate with high angular velocities, thus increasing the pumping speed. The disadvantage of the gap between the rotors is the backstream of gas from $A$ to $S$. With decreasing pressure in $A$ the flow resistance of the gaps with width $d$ becomes larger as soon as $\Lambda \gg d$. Therefore the pressure in $A$ should be lowered by a one-stage rotary vane pump. Roots pumps need a forepump. Large roots pumps reach pumping speeds of up to $10^5\ \mathrm{m}^3/\mathrm{h}$.

#### 9.2.1.3 Turbo-Molecular Pumps

The turbo-molecular pump, developed 1958 by W. Becker [9.5] is based on the principle that molecules hitting a fast moving surface, gain momentum in the direction of the surface motion (Fig. 9.10).

The turbo pump consists of a staple of fast rotating rotors with many blades (Fig. 9.11). Assume a gas molecule $M$ with the thermal velocity $\boldsymbol{v}$ impinges on a blade of the rotor which has the same temperature $T$ as the gas. For a resting rotor the molecule $M$ would desorb from the blade after a short time with the velocity $\boldsymbol{v}'$ which has about the same magnitude as $v$, ($|\boldsymbol{v}| \approx |\boldsymbol{v}'|$) while its directions are distributed around the surface normal.

If the rotor blade moves with the velocity $u$ the total velocity of the desorbing molecules is the vector sum $\boldsymbol{v}^* = \boldsymbol{v}' + \boldsymbol{u}$. Due to the direction of $\boldsymbol{u}$ to the left in Fig. 9.10, the number of impinging molecules from the left half space is larger than that of molecules from the right one. Because of the inclined blades the velocities $v'$ are preferentially directed into the downward direction. The rotating blades therefore transport molecules from the upper space (inlet of the pump) to the lower space (outlet of the pump).

This is illustrated in Fig. 9.10b. If the rotor blade moves with the velocity $\boldsymbol{u}$ to the left, molecules moving with the velocity $v' < u$ from the upper space 1 can hit the blade only on the left side.

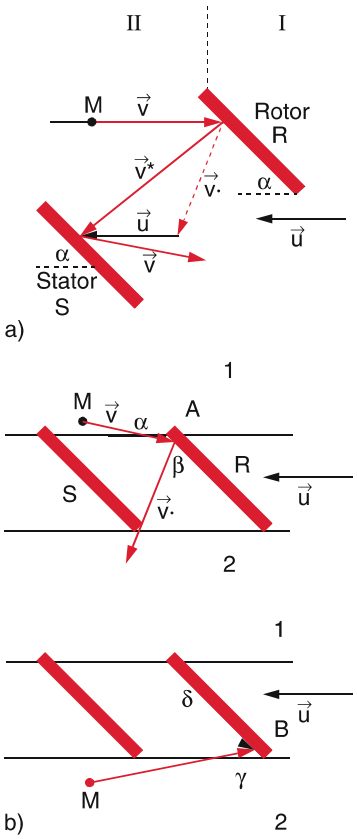


**Figure 9.10** **a** Momentum transfer at the reflection of molecules $M$ at a fast moving surface; **b** basic principle of turbo pump

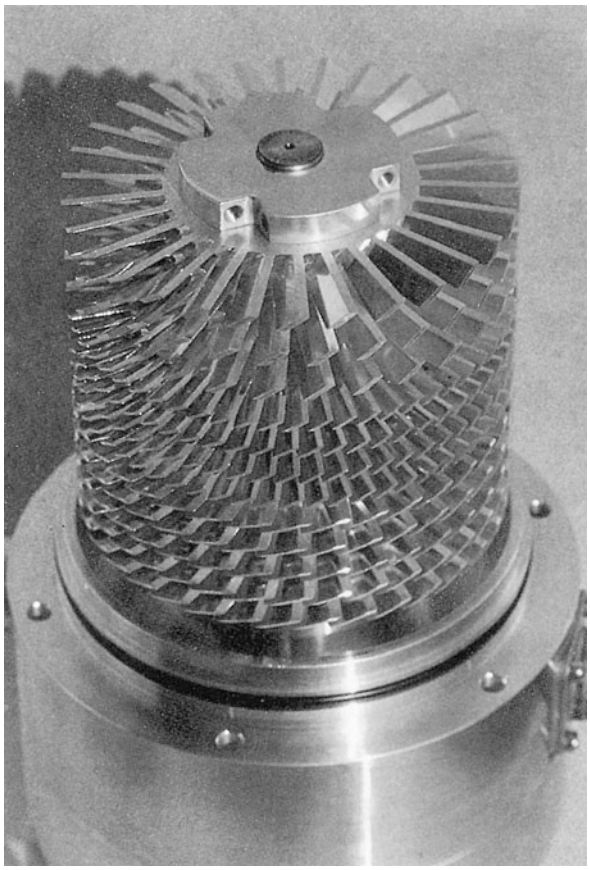

**Figure 9.11** Rotor of a turbo pump. With kind permission of CIT Vacuum Technique

### 9.2.2 Diffusion Pumps

Diffusion pumps are used for the generation of high- and ultrahigh-vacuum. Their principle is shown in Fig. 9.12. A pumping fluid 2 (oil or mercury) is evaporated by the heater at the bottom of the pump. The vapour rises in the inner part of the pump and leaves it at the upper end through nozzles where it gains supersonic speed forming fast vapour jets, which are directed downwards. Molecules from the vacuum chamber diffuse into the vapour jets and are pushed downwards by collisions

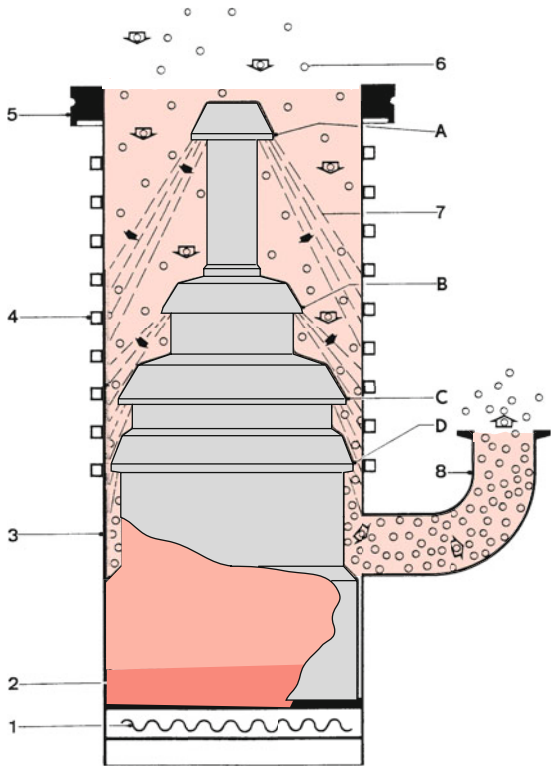


**Figure 9.12** Operation principle of a diffusion pump. *1* = Heating, *2* = boiling region, *3* = pump body, *4* = water cooling, *5* = high vacuum side, *6* = particles from high vacuum side, *7* = vapor jet, *8* = pre vacuum tube, *A–D* = nozzles for vapor jets. With kind permission of Leybold GmbH [9.1]

with the vapour molecules. Since the vapour jets are initially free of gas, the diffusion rate into the jet is higher than out of the jet.

After diffusion into the vapor jet the gas molecules experience by collisions with the jet molecules an additional momentum downwards into the direction of the jet. They come into lower regions where they diffuse into the lower jets where they experience more collisions and are transported farther downwards. Finally they reach the outlet of the diffusion pump where they are pumped away by a mechanical pump. A pressure ratio $p_i/p_0 \approx 10^{-7}$ between the pressure $p_i$ at the input and $p_0$ at the outlet of the diffusion pump can be reached. When the forepump maintains a pressure $p_0 = 10^{-2}$ hPa a pressure as low as $10^{-9}$ hPa can be realized at the high vacuum side.

The hot vapor jets hit the cooled wall of the pump where they condense and flow as liquid film down to the heater. Here they are again vaporized. In order to form oil vapor jets the free mean path $\Lambda$ must be sufficiently large, i.e. the pressure sufficiently low. Diffusion pumps therefore can operate only at pressures below $10^{-2}$–$10^{-3}$ hPa. They do need a forepump, which generates the necessary minimum starting pressure.

The total pressure at the high vacuum side of the diffusion pump is the sum of all partial pressures, including the saturation pressure of the pump fuel. For mercury as fuel the saturation pressure is $10^{-3}$ hPa at room temperature. For mercury pumps

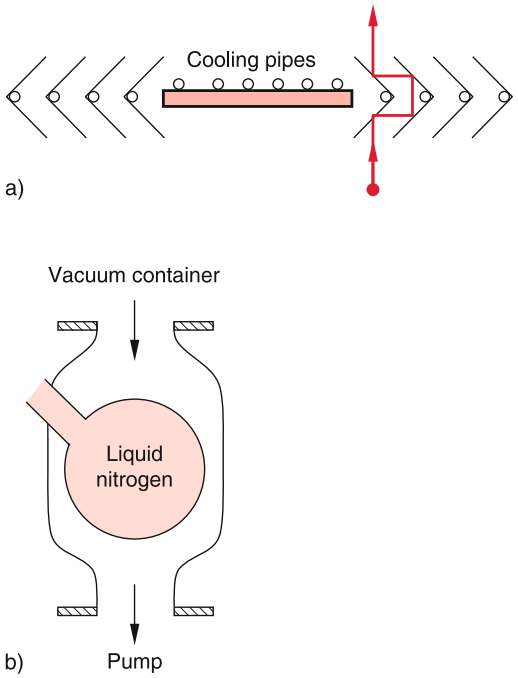


**Figure 9.13** **a** Cooled baffle for reduction of oil return flow. **b** Liquid nitrogen condensation trap

therefore liquid nitrogen cool traps above the diffusion pump are necessary in order to obtain a better high vacuum. Oil-diffusion pumps operate with special oils that have saturation pressures below $10^{-7}$ hPa. Therefore nowadays mainly oil diffusion pumps are used.

In order to prevent oil molecules from reaching the vacuum container a cooled baffle is mounted above the pump (Fig. 9.13a) which blocks the direct way of the molecules. Another solution is a liquid nitrogen trap (Fig.9.13b) where every oil molecule on its way to the vacuum container hits at least one cooled wall where the molecules are adsorbed.

The pumping speed of modern vacuum diffusion pumps ranges from 60 l/s (for a small pump with 20 cm heights) to 50 000 l/s (about 4–5 m high). Diffusion pumps are the favorite types of high vacuum pumps. In Fig. 9.14 the pumping speed of medium sized diffusion pumps as a function of the pressure on the high vacuum side is compared with the performance of a turbo pump. Important for the optimum performance of a pumping system is

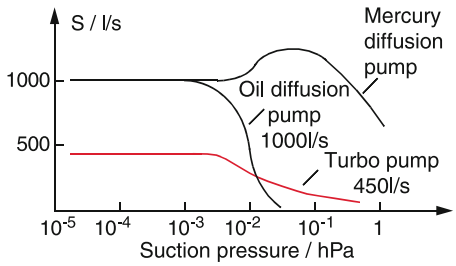


**Figure 9.14** Pumping speed $S(p)$ of different types of pumps

the choice of the best forepump, which should be always able to maintain a pressure below $10^{-2}$ hPa on the high pressure side of the diffusion pump.

**Example**

A diffusion pump with a pumping speed of 2000 l/s should maintain a pressure of $10^{-5}$ hPa in a container into which continuously a gas streams. A gas volume of 2000 l at $p = 10^{-5}$ hPa corresponds to a volume of 2 l at a pressure of $10^{-2}$ hPa. Therefore the forepump must have at least a pumping speed of 2 l/s $= 7.2\,\mathrm{m^3/h}$. Since the vacuum pipe between forepump and diffusion pump reduces the pumping speed, a forepump with a pumping speed of $12\,\mathrm{m^3/h}$ should be used. ◀

### 9.2.3 Cryo- and Sorption-Pumps; Ion-Getter Pumps

A cryopump consists essentially of one or several cooled surfaces inside the vacuum container. All gases or vapors with condensation temperatures above the temperature of the surfaces condense and are adsorbed as liquids or solids on the surfaces. Liquid nitrogen cooltraps therefore can condense all gases and vapors except hydrogen and helium which need liquid helium traps. Most cryo-pumps use closed cycle lquid helium cooling systems (Fig. 9.15), which reach temperatures down to about $T = 10\,\mathrm{K}$.

The achievable final pressure is determined by the equilibrium of the rate of molecules impinging onto the cold surface and the rate of evaporating molecules. The latter is determined by the vapor pressure of the component with the lowest evaporation temperature. The impinging molecules have a mean velocity $\overline{v} \sim \sqrt{T_\mathrm{w}}$ which depends on the temperature $T_\mathrm{w}$ of the walls of the vacuum chamber, while the mean velocity of the evaporating molecules $\overline{v} \sim \sqrt{T_\mathrm{c}}$ depends on the lower temperature $T_\mathrm{c}$ of the cold surface.

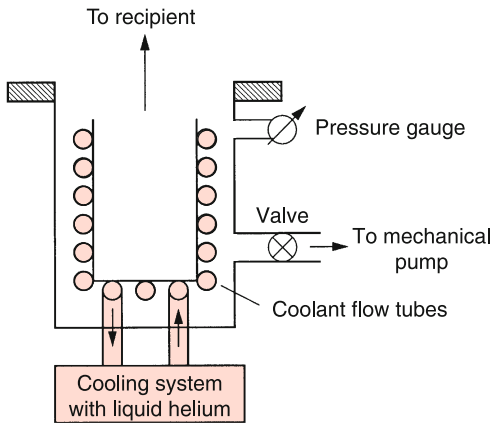


**Figure 9.15** Principle of cryo pump with closed cooling cycle

The rate of molecules impinging onto the area $A$ is

$$Z = \frac{1}{4} n \cdot \overline{v_\mathrm{w}} \cdot A \,, \tag{9.15}$$

which equals the desorbing rate under equilibrium conditions. With $p = nkT$ and $\overline{v} \sim \sqrt{T}$ we obtain the partial pressure of the $i$-th vapor component in the container

$$p_\mathrm{e}(i) = p_\mathrm{s}(i) \cdot \sqrt{T_\mathrm{w}/T_\mathrm{c}} \,, \tag{9.16a}$$

where $p_\mathrm{s}$ is the saturation pressure. The attainable final pressure is then

$$p_\mathrm{total} = \sum p_\mathrm{e}(i) \cdot \sqrt{T_\mathrm{w}/T_\mathrm{c}} \,. \tag{9.16b}$$

Cryo-pumps need a forepump which lowers the pressure in the container down to about $10^{-3}$ hPa, because for $p > 10^{-3}$ hPa the mean free path $\Lambda$ is smaller than the dimensions of the container and the heat conduction from the cold surfaces to the wall of the container becomes too large (see Sect. 7.5). Furthermore at low pressures the layer of condensed gases becomes too thick which lowers the heat conduction from the surface of this layer to the cooling body and increases the temperature of the surface.

The pumping speed of a cold surface $A_\mathrm{c}$ at a pressure $p$ in the vacuum container is according to (9.2) and (9.15)

$$\begin{aligned} L_s &= \frac{1}{4} A_\mathrm{c} \overline{v} \left(1 - \frac{p_\mathrm{s}}{p} \sqrt{T_\mathrm{w}/T_\mathrm{c}}\right) \\ &= \frac{1}{4} A_\mathrm{c} \overline{v} \cdot \alpha \cdot \frac{1 - p_\mathrm{e}}{p} \,, \end{aligned} \tag{9.17}$$

where $\alpha \leq 1$ is the sticking propability of an impinging molecule on the cold surface, and $p_\mathrm{s} = \sum p_\mathrm{s}(i)$ is the sum of the saturation pressures of all vapor components at the temperature $T_\mathrm{c}$ of the cold surfaces.

**Example**

$\overline{v} = 400\,\mathrm{m/s}$, $\alpha = 1$, $P_\mathrm{e} \ll p$, $A = 1\,\mathrm{cm^2} \rightarrow L_\mathrm{s} = 10\,\mathrm{l/s}$, i.e. the cold surface has a maximum pumping speed of 10 l/s per $\mathrm{cm^2}$. ◀

The growth rate $\mathrm{d}\Delta/\mathrm{d}t$ of the adsorbed layer with thickness $\Delta(t)$ on the cold surface depends on the density $n = N/V$ of molecules with mass $m$ in the container and on their mean velocity $\overline{v} = (8kT/m\pi)^{(1/2)}$ at the temperature $T$.

According to Fig. 7.28 the number of molecules with mass $m$ hitting per sec the area $\mathrm{d}A$ is

$$\mathrm{d}Z = \frac{1}{4} n \cdot \overline{v} \mathrm{d}A \,. \tag{9.18a}$$

With $\overline{v} = \sqrt{8kT/m\pi}$ we get the mass increase of the layer per sec

$$\begin{aligned} \frac{\mathrm{d}M}{\mathrm{d}t} &= \mathrm{d}Z \cdot m = \frac{1}{4} n \cdot m \cdot \overline{v} \cdot \mathrm{d}A \\ &= \frac{1}{4} n \cdot \sqrt{8kTm/\pi} \,. \end{aligned} \tag{9.18b}$$

Chapter 9

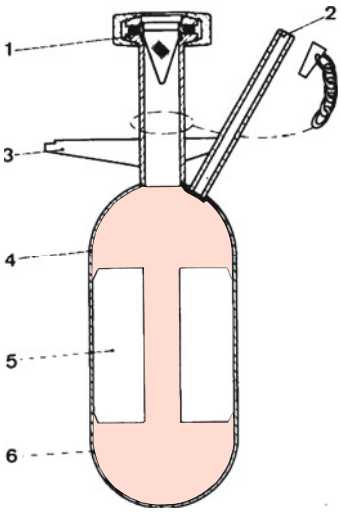


**Figure 9.16** Setup of a sorption pump. *1:* inlet connector; *2:* degasing connector; *3:* mechanical support; *4:* pump body; *5:* heat conduction sheets; *6:* adsorption material [9.1]

The mass $M$ of the layer with thickness $\Delta$ and density $\varrho$ is $M = \varrho \cdot \Delta \cdot dA$.

This gives finally the growth rate of the layer

$$\frac{d\Delta}{dt} = \frac{n}{\varrho}\sqrt{kTm/2\pi} \qquad (9.18c)$$

**Example**

For $N_2$-molecules at a pressure of $10^{-5}$ hPa the growth rate is 5 µm/h. ◀

The adsorbed layer should not be too thick, because the heat conduction becomes worse with increasing thickness $\Delta$ and the surface temperature of the layer increases. This increases the evaporation rate of the adsorbed molecules.

The adsorbing surface can be greatly increased by using molecular sieves (zeolites = alkali-aluminum silicate)). They consist of small balls with many fine pores, into which the molecules can diffuse and are then adsorbed. The effective surface of Zeolith is about $10^3$ m$^2$ per gramm. For Zeolith the diameter of the pores is about 1.3 nm. For typical sizes of 0.5 nm for molecules 1 g Zeolith can adsorb about $2.5 \cdot 10^{21}$ molecules in a monolayer. This corresponds to a gas volume of 10 000 l at a pressure of $10^{-2}$ hPa.

The adsorption of the molecular sieves depends strongly on the temperature. They can be therefore used at low temperatures (liquid nitrogen temperature = 78 K) as a cryopump and later on they can be degassed at higher temperatures and used again as pumps. Such a sorption pump is shown schematically in Fig. 9.16.

Another solution for high vacuum pumps are ion-getter pumps. In a gas discharge ions are produced which are accelerated onto the cathode. Here they sputter the cathode material (e.g. Titanium) which is adsorbed on cold surfaces, where already a layer of condensed gases has been formed. The titanium atoms form a film, that covers the layer of adsorbed atoms and burries it completely. A new fresh metal surface is formed where further gas molecules can be adsorbed. Since the vapor pressure of titanium is very low, even at room temperature very low pressures can be obtained.

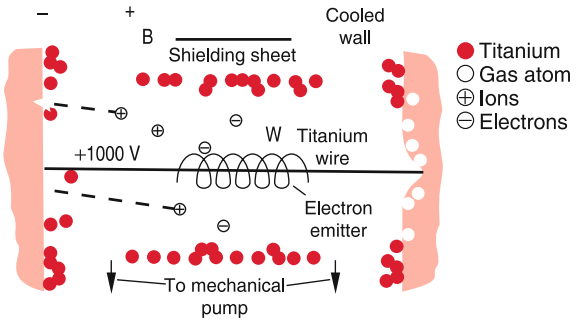


**Figure 9.17** Principle of getter ion pump [9.1]

Such ion-getter pumps (chemical getter pumps) are useful for the generation of oil-free ultrahigh vacuum ($p < 10^{-6}$ hPa). In Fig. 9.17 a possible realization is shown. A titanium wire is heated by direct electric current or by electron bombardment. The sputtered titanium atoms are ionized by collisions with electrons and are accelerated onto the cooled walls, which are kept at ground potential. Here they push the adsorbed molecules deeper into the wall and burry them under a metallic film of neutral titanium atoms. A sputter rate of 5 mg/min represents at $p = 10^{-6}$ hPa a pumping speed of 3000 l/s.

## 9.3 Measurement of Low Pressures

For the measurement of pressures a variety of different measuring techniques and instruments have been developed. We will present only a small selection. Table 9.3 compiles some of these devices suitable for the different pressure ranges.

**Table 9.3** Pressure ranges of different pressure measuring devices

| Device | Pressure range/mbar |
|---|---|
| Liquid manometer | 0.1–$10^3$ |
| Mechanical spring vacuum meter | 1–$10^3$ |
| Membrane manometer | 1–$10^3$ |
| Capacity manometer | $10^{-4}$–$10^3$ |
| Heat conduction manometer | $10^{-3}$–1 |
| Heat conduction manometer with control feedback | $10^{-3}$–100 |
| McLeod manometer | $10^{-6}$–$10^{-1}$ |
| Penning ionization manometer | $10^{-7}$–$10^{-3}$ |
| Ionization manometer | $10^{-12}$–$10^{-3}$ |
| Friction manometer | $10^{-7}$–$10^{-1}$ |

### 9.3.1 Liquid Manometers

Liquid manometers (Fig. 7.3) are simple devices for pressure measurements, that have been already used in 1643 by Torricelli. Here the height difference $\Delta h$ of a liquid with density $\varrho$ in the two legs of a U-shaped tube are measured. The pressure difference $\Delta p = p_2 - p_1$ between the two ends of the U-tube is then

$$\Delta p = \varrho \cdot g \cdot \Delta h \; . \tag{9.19}$$

**Example**

With oil ($\varrho = 900\,\mathrm{kg/m^3}$) a pressure difference $\Delta p = 1\,\mathrm{hPa}$ causes a height difference $\Delta h = 11.3\,\mathrm{mm}$. For mercury ($\varrho = 13{,}546\,\mathrm{kg/m^3}$) one obtains $\Delta h = 1\,\mathrm{mm}$ for $\Delta p = 1.33\,\mathrm{hPa} = 1\,\mathrm{torr}$. ◀

When one leg of the U-tube is closed and evacuated (Fig. 7.2) the volume above the liquid is filed with the vapour of the liquid with the vapour pressure $p_s(T)$, that depends on the temperature $T$. The height difference is then

$$\Delta h = \frac{1}{\varrho \cdot g}(p - p_s) \approx \frac{1}{\varrho g} p \quad \text{for} \quad p_s \ll p \; , \tag{9.19a}$$

which gives directly the pressure $p$ above the open leg of the U-tube.

The accuracy and sensitivity of liquid manometers can be considerably increased with a device, developed by McLeod (Fig. 9.18), which is based on the Boyle–Mariotte Law (see Sect. 7.1). At the beginning of the measurement, the container $B$ is lowered until the liquid level in the left leg is at $h_1$. The pressure $p_1$ above $h_1$ is the pressure in the vacuum chamber. Now $B$ is lifted again until the liquid level rises above the point $z$. The volume $V = V_0 + V_c$ of $G$ and the capillary above $G$ is now separated from the vacuum chamber. The container is lifted up to a height where the liquid level in the very left tube (pressure $p_1$) is by $\Delta h$ higher than in the capillary above $G$ where the higher pressure $p_2$ is present due to the compression of the closed volume $V$ to the much smaller volume $V_c = \pi r^2 \cdot x$. According to the Boyle–Marriot law we obtain

$$p_1 \cdot (V_0 + V_c) = p_2 \cdot \pi \cdot r^2 \cdot x \; .$$

The measured height difference of the liquid between the left tube and the capillary

$$\Delta h = \frac{p_2 - p_1}{\varrho \cdot g} = \frac{p_1}{\varrho \cdot g}\left(\frac{V_0}{\pi r^2 x} + \frac{L}{x} - 1\right) \tag{9.20}$$

yields the pressure $p_1$ in the vacuum chamber, after the volumes $V_0$, $V_c = \pi \cdot r^2 \cdot L$ and the length $x$ of the gas-filled part of the capillary have been determined. in case of mercury one has to take into account the capillary depression to mercury (see Sect. 6.4).

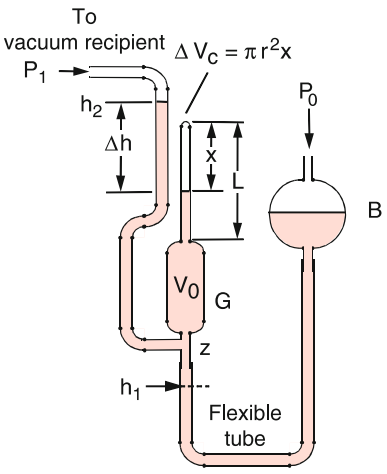


**Figure 9.18** Principle of McLeod vacuum meter

### 9.3.2 Membrane Manometer

To measure the pressure in the low vacuum range robust and simple membrane manometers are available (Fig. 9.19b). A thin membrane separates the vacuum from the upper part at atmospheric pressure. A wire is connected at one end with the centre of the membrane and at the other end with a hand that can rotate around a fixed axis. Due to the pressure difference, the membrane sags and turns the hand by an angle that is proportional to the pressure difference, which can be read on a calibrated scale.

Another realization (Fig. 9.19a) uses a bent thin hollow tube that is connected to the vacuum chamber. The bending radius is

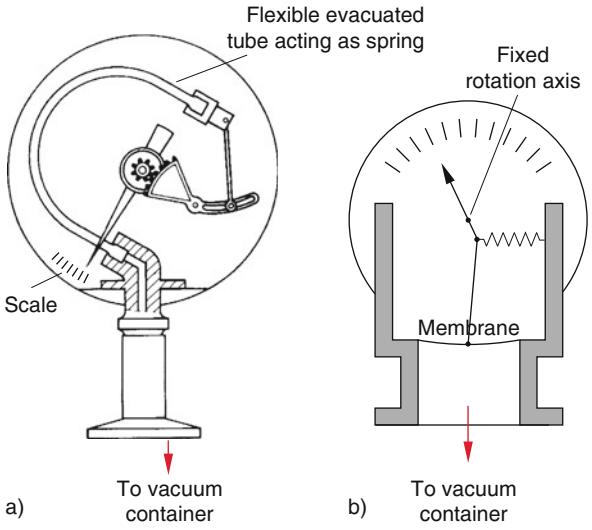


**Figure 9.19** Two designs of robust and compact pressure detectors. **a** Spring pressure gauge; **b** membrane pressure gauge

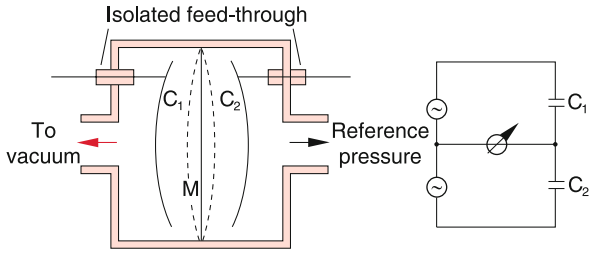


**Figure 9.20** Membrane capacitor vacuum gauge. A thin membrane *M* provides together with two curved fixed plates two capacities $C_1$ and $C_2$, which are arranged in a bridge circuit (see Vol. 2, Chap. 2). They are fed by two identical ac-voltage sources

dependent on the pressure. When it changes the upper end of the tube moves a hand which indicates the pressure on a calibrated scale.

For lower pressures in the high vacuum range ($p < 10^{-5}$ hPa) capacitance membrane manometers (Fig. 9.20) can be used. Here a thin membrane which separates the vacuum chamber from a chamber with a fixed reference pressure. It forms one electrode of two electric capacitors $C_1$ and $C_2$, When the pressure in the vacuum chamber decreases the membrane bends to the left side and decreases the electrode separation of $C_1$ but increases that of $C_2$, thus increasing the capacitance of $C_1$ and decreases that of $C_2$. This changes their AC resistance in an opposite direction, which can be measured with an electric bridge arrangement where the two capacitors are charged by two identical AC voltage supplies (see Vol. 2. Chap. 1).

### 9.3.3 Heat Conduction Manometers

As has been shown in Sect. 7.5 the heat conduction of a gas in the pressure range where the mean free path $\Lambda$ is larger than the dimensions of the vacuum chamber, is proportional to the pressure $p$. This fact is used in the heat conduction manometer (Fig. 9.21) for measuring pressures. A filament of length $L$, heated by an electric current $I$, is clamped between to yokes along the axis of a small cylindrical tube. Its temperature $T_d$ is determined by the supplied electric power $I^2 \cdot R$ and the power loss due to heat conduction.

$$\frac{dW}{dt} = 2\pi r \cdot L \cdot \kappa (T_d - T_w) \,, \tag{9.21}$$

which is given by the surface $2\pi r \cdot L$ of the filament, the heat conduction $\kappa$ of the gas and the temperature difference $\Delta T = (T_d - T_w)$ between filament and wall (see Sect. 7.5.3). Stationary conditions are established, when the supplied power equals the power loss. This yields

$$I^2 \cdot R = 2\pi r \cdot L \cdot \kappa \cdot \Delta T \,. \tag{9.21a}$$

The coefficient of heat transfer

$$\kappa = n \cdot v \cdot k \cdot f/8 = v \cdot p \cdot f/8T \,, \tag{9.21b}$$

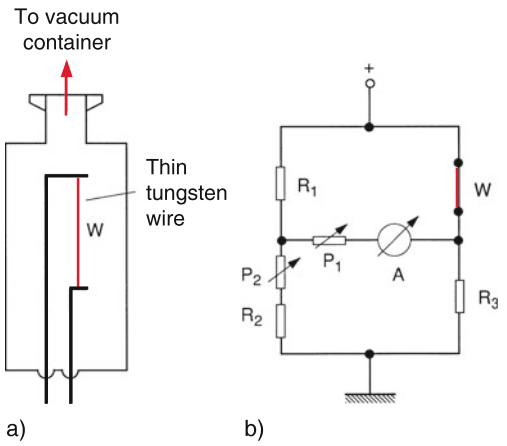


**Figure 9.21** Heat conduction vacuum gauge. **a** Mechanical design; **b** electric circuit

(7.49a) is proportional to the gas density $n = p/kT$ and therefore to the pressure p and to the degrees of freedom $f$ of the gas molecules. The electric resistance then becomes

$$R(T_d) = \frac{2\pi r \cdot L \cdot p \cdot v \cdot f \cdot (T_d - T_w)}{4(T_d + T_w)} \,. \tag{9.21c}$$

It depends on the temperature $T_d$. It can be measured with an electric bridge (Fig. 9.21b) (see Vol. 2, Sect. 2.4.3) and yields the wanted pressure measurement.

Since the heat conduction in the low vacuum range ($\Lambda \ll d$) is independent of the pressure (see Tab. 9.1) heat conduction manometers can be used only in the medium vacuum range ($1 - 10^{-3}$ hPa), for instance between diffusion pump and backing pump. For pressures below $10^{-3}$ hPa the heat conduction through the gas becomes smaller than other heat leaks (for example through the yokes of the filament). Therefore the accuracy of pressure measurements decreases strongly below $p = 10^{-3}$ hPa.

### 9.3.4 Ionization Gauge and Penning Vacuum Meter

The vacuum meters that are used most often in the high vacuum range are the ionization gauge (Fig. 9.22) and the Penning vacuum meter (Fig. 9.23). The ionization gauge consists of a heated filament as cathode K emitting electrons that are accelerated onto the anode *A*. On their way from *K* to *A*, they collide with gas molecules and ionize them (see Vol. 3). When the free mean path of the electrons is larger than the distance *K*–*A* the number $N_{ion}$ of produced ions is proportional to the density $n$ of the gas molecules in the manometer and therefore also to the pressure $p = n \cdot kT$. It is

$$N_{ion} = N_{el} \cdot \sum_i n_i \cdot \alpha_i(E_{el}) \,, \tag{9.22}$$

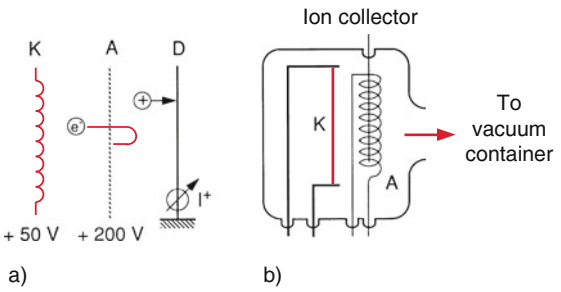


**Figure 9.22** Ionization vacuum meter. **a** Schematic principle; **b** design of Bayard–Alpert tube

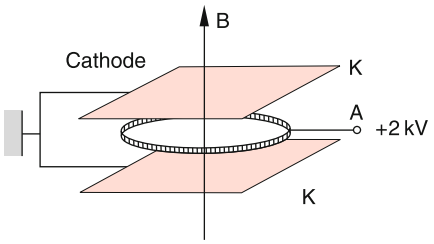


**Figure 9.23** Penning vacuum gauge

where $n_i$ is the partial density of molecules of type $i$ and $\alpha_i(E_{el})$ the ionization probability, which depends on the energy $E_{el}$ of the electrons. The positive ions are collected on a wire $D$ at a negative potential against the anode.

The minimum of still detectable pressure is limited by several factors: Firstly, the ion current decreases with decreasing pressure, which demands good current amplifiers. Secondly, the electrons impinging onto the anode generate X-rays that can release electrons from the ion collector. Their number is independent of the pressure and form an underground current that overlaps the wanted signal current.

Typical pressure ranges where the ionization gauge can be used are $10^{-3}\,\text{hPa} \geq p \geq 10^{-12}\,\text{hPa}$, where for the lower pressures special designs have been developed which minimize the underground current (Bayard–Alpert tube Fig. 9.22b).

Instead of the thermionic emission of electrons from a heated filament at higher voltages ($\approx$ 1000 V) also a cold electron emission between two metal plates can be realized. Since the ionization probability is small at such high electron energies, the ionization path must be enlarged. This is achieved by a permanent magnet with a magnetic field $B$ that forces the electrons on spiral paths until they reach the anode (Fig. 9.23).

These Penning manometers are robust but not as accurate as the ionization gauges. They can be used in the vacuum range from $10^{-3}$ to $10^{-7}$ hPa.

### 9.3.5 Rotating Ball Vacuum Gauge

The principle of this vacuum gauge is based on the deceleration of a rotating ball due to friction with the rest gas molecules. A small steel hollow sphere is contact-free hold in its position by a magnetic field (Fig. 9.24). A rotating magnetic field produced by special coils is superimposed onto the static magnetic field. It causes the ball to rotate with an angular velocity of about $\omega = 2\pi \cdot 400\,\text{s}^{-1}$. After shut off the rotating field, the ball rotates freely and is only decelerated by friction due to collisions with the gas molecules. The slowing down time depends on the rate of collisions and therefore on the gas pressure.

The angular momentum of the rotating ball is

$$L = I\omega = \frac{2}{5}MR^2\omega = \frac{8}{15}\pi\varrho R^5\omega\ . \tag{9.23}$$

The retarding collisions produce a mean torque

$$D = \frac{\mathrm{d}L}{\mathrm{d}t} = I\cdot\dot{\omega}\ , \tag{9.24}$$

onto the ball which is proportional to the gas pressure. The decrease rate of the angular velocity $\omega$ is then

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{D}{I} = a\cdot\omega\cdot p\ . \tag{9.25}$$

The proportionality factor a depends on the radius $R$ of the ball, on the density $\varrho$ and on the mean molecular velocity $v$. After calibrating the system the factor a can be measured. The pressure $p$, which is proportional to the density $\varrho$ can then be determined from the relative deceleration $\mathrm{d}\omega/\mathrm{d}t/\omega$. The accuracy of the measurement is about $\Delta p/p = 3\%$. Therefore the rotating ball gauge is the most accurate vacuum meter in the vacuum range 0.1–$10^{-7}$ hPa [9.6].

For more detailed and recent information on modern techniques of vacuum physics, the reader is referred to the literature [9.7].

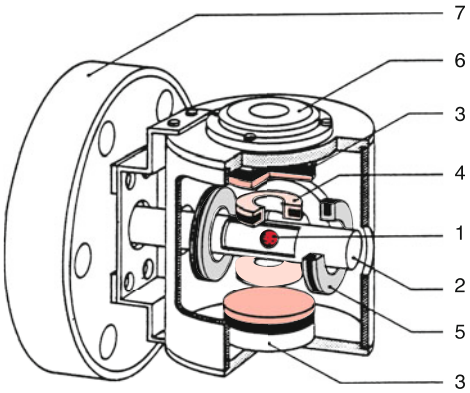


**Figure 9.24** Section through the gauge head of a friction vacuum gauge. *1* = Steel ball, *2* = gauge tube with one open end, which is welded to the flange *7*, *3* = permanent magnet, *4* = stabilization coils, *5* = four driving coils, *6* = horizontal position detector. With kind permission of Leybold GmbH

## Summary

- A volume $V$ is called evacuated if the total gas pressure in $V$ is small compared to the atmospheric pressure.
- The different vacuum ranges are:
  Low vacuum ($1\,\text{hPa} \le p \le 10^3\,\text{hPa}$)
  Medium vacuum ($10^{-3}\,\text{hPa} \le p \le 1\,\text{hPa}$)
  High vacuum ($10^{-7}\,\text{hPa} \le p \le 10^{-3}\,\text{hPa}$)
  Ultrahigh vacuum ($p \le 10^{-7}\,\text{hPa}$)
- Vacuum is generated with vacuum pumps. The most important types are mechanical pumps (rotary vane pumps) and roots-pumps, (which are used as fore pumps for the generation of fine vacuum), turbo-molecular pumps for the generation of oil-free high- and ultrahigh vacuum, oil- and mercury diffusion pumps, cryo-pumps and ion getter pumps for the generation of ultrahigh vacuum.
- The gas pressure in a vacuum chamber can be measured with one of the following devices:
  liquid barometer ($0.1\,\text{hPa} \le p \le 10^3\,\text{hPa}$)
  membrane manometer ($p \ge 1\,\text{hPa}$)
  heat conduction manometer ($p \ge 10^{-3}\,\text{hPa}$)
  capacitance manometer ($p \ge 10^{-5}\,\text{hPa}$)
  friction vacuum manometer ($p \ge 10^{-7}\,\text{hPa}$)
  ionization gauge ($p \ge 10^{-12}\,\text{hPa}$)
- The suction capability $S_V = dV/dt$ is the gas volume flow through the suction connection of a pump. Often the product $S_L = p \cdot S_V$ of pressure and suction capability is called the pumping speed.
- The vacuum lines (tubes and pump connectors) between vacuum chamber and pump reduce the total suction capability. Their flow conductance $L_S = p \cdot dV/(p_2 - p_1)$ should be as high as possible, in order to make the pressure difference between entrance and exit of the vacuum line small.
- The achievable final pressure in the vacuum chamber is determined by the pumping speed of the pump, by the leak rate and the desorption rate of molecules from the inner walls of the chamber.



## Problems

**9.1** A vacuum chamber is connected to the outside at atmospheric pressure through a capillary tube with length $L = 10\,\text{cm}$ and 0.5 mm inner diameter. What should be the effective suction capacity of the vacuum pump in order to maintain a pressure of $10^{-3}\,\text{hPa}$?

**9.2** Which force was necessary to separate the two hemispheres of Guericke's demonstration experiment, when the diameter of the spheres was 60 cm and the inner pressure 100 hPa?

**9.3** In a cubic vacuum chamber with a volume $V = 0.4\,\text{m}^3$ a pressure of $p = 10^{-5}\,\text{hPa}$ is maintained. What are the particle density $n$, the mean free path $\Lambda$ and the mean time $\tau$ between two successive collisions between particles at room temperature? How large is the ratio $Z_1/Z_2$ of the rate $Z_1$ for mutual collision between particles to the rate $Z_2$ for collision of particles with the walls? How large is the total mean path length that a particle traverses within 1 s, and what is the sum of the path lengths of all particle in the chamber?

**9.4** Assume, the vacuum chamber of Probl. 9.3 is operated under ultrahigh vacuum and the inner walls are free from all adsorbed molecules. At $t = 0$ oxygen is let in until the pressure rises to $10^{-7}\,\text{hPa}$. How long does it take until the walls are covered by a monomolecular layer, if each oxygen molecule covers an area of $0.15 \times 0.2\,\text{nm}^2$ and its sticking probability is 1?

**9.5** A vacuum chamber should be evacuated down to a pressure of $10^{-6}\,\text{hPa}$ using a diffusion pump with the effective pumping speed of 3000 l/s. What is the minimum effective pumping speed of the mechanical fore pump in order to maintain a vacuum of 0.1 hPa at the outlet of the diffusion pump?

**9.6** The ionization cross section of nitrogen molecules $N_2$ for collisions with electrons of 100 eV energy is $\sigma = 1 \cdot 10^{-18}\,\text{cm}^2$. How large is for an electron current of 10 mA the ion current at a pressure of $10^{-7}\,\text{hPa}$ in the ionization gauge when the path length of the electrons is 2 cm?

**9.7** Through the heated filament of a thermal conductivity gauge flows the electric current $I = U/R(T)$ at a constant voltage $U$. The heating power under vacuum conditions is $P_{el} = U^2/R_0$. What is the dissipation power due to heat conduction in a cylindrical chamber with diameter of 2 cm at a gas pressure of $p = 10^{-2}\,\text{hPa}$ when the temperature of the filament is $T_1 = 450\,\text{K}$ and that of the wall is $T_2 = 300\,\text{K}$? (The length of the filament is 5 cm, its diameter 0.5 mm, the distance filament-wall is 1 cm). Which fraction of the electric energy $E_{el} = U \cdot I$ is dissipated by heat conduction if $U = 0.5\,\text{V}$ and $I = 2\,\text{A}$?

**9.8** The total angular momentum transfer onto a ball at rest in a gas at thermal equilibrium is zero. Why is the rotating ball in a Langmuir friction gauge slowed down? Estimate the torque that the gas molecules transfer to a ball with a radius of 1 cm rotating with the angular velocity $\omega = 2\pi \cdot 400\,\mathrm{s}^{-1}$ at a temperature of $T = 300\,\mathrm{K}$ and a pressure of $p = 10^{-3}\,\mathrm{hPa}$. How long does it take until $\omega$ has decreased by 1%?

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