Vacuum I

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Abstract
This is an introduction to the basics of vacuum. It is intended for a reader unfamiliar with the topic, more advanced treatments are left to the dedicated CERN Accelerator School of vacuum in accelerators, and to the specialized bibliography. It is here reviewed the kinetics of gases, and gas flows through pipes and pumps. The topic of pumps is continued in the proceeding of the Vacuum II lecture.

1 Vacuum, mean free path, and beam lifetime

In accelerators the beam dynamics has the general purpose to control beam particles. For a charged particle this happens through the Lorenz force

$$\frac{dm\gamma\vec{v}}{dt} = q\vec{E} + q\vec{v} \times \vec{B}. \tag{1}$$

Here q is the charge of the particle, and m is the particle mass. The time and space structure of the electric and magnetic fields $\vec{E}, \vec{B}$ in an accelerator has the purpose of guiding beam particles along a design trajectory. However, in a particle accelerator is also present a jungle of unwanted particles, which creates a damaging background for beam operation and experiments. These particles are referred as "residual gas". As the particles composing the "vacuum" are not controlled by an electromagnetic field, they are in general treated as a gas in a thermodynamic sense which is therefore characterized by macroscopic quantities as pressure P, temperature T, particle density $\tilde{n}$, and composition. The statistical behavior of vacuum particles is described by the kinetic theory [1, 2]. In accelerators the aim of all the vacuum systems is to minimize the interaction of the beam with the residual gas. In Table 1 are listed typical values of particle density for different types of vacuum.

Table 1: Example of particle densities (from Ref. [3]).

	Particles m^{-3}
Atmosphere	2.5×10^{25}
Vacuum Cleaner	2×10^{25}
Freeze dryer	10^{22}
Light bulb	10^{20}
Thermos flask	10^{19}
TV Tube	10^{14}
Low earth orbit (300km)	10^{14}
H_2 in LHC	$\sim 10^{14}$
SRS/Diamond	10^{13}
Surface of Moon	10^{11}
Interstellar space	10^{5}

A fundamental process in a gas is the particle wall collisions. The velocity of a particle after the interaction with a wall depends on the particle-wall processes. In any case this process is responsible for creating the macroscopic pressure. The SI unit of the pressure is the Pascal = [N/m^2]. Although this standard definition there are also other units of common use, as Bar, Torr, and Atmosphere, which are

Table 2: Classification of vacuum.

Low vacuum	Atm. pressure to 1 mbar
Medium vacuum	1 to 10^{-3} mbar
High Vacuum (HV)	10^{-3} to 10^{-8} mbar
Ultrahigh vacuum (UHV)	10^{-8} to 10^{-12} mbar
Extreme high vacuum (XHV)	less than 10^{-12} mbar

related each other as 1 Pa $= 10^{-2}$ mbar = 7.5×10^{-3} Torr = 9.87×10^{-6} atm. In Table 2 is shown the classification of the vacuum in terms of the pressure.

Another important process in a gas is the particle-particle collisions. This process is the most probable process as collisions between 3 or more particles are possible but quite unlikely. For elastic collisions two fundamental quantities are preserved: Energy, and Momentum. The particle-particle collisions are responsible for creating a distribution of velocities in the gas particles. The temperature of the gas is related to the mean kinetic energy of a particle: for mono atomic particles $\frac{1}{2}m\langle v^2\rangle = \frac{3}{2}k_BT$, with $k_B = 1.38 \times 10^{-23}$ J K^{-1} the Boltzmann constant. For example for air, assumed mainly composed by nitrogen N_2, at $T = 20\,^\circ$C we find $\sqrt{\langle v^2\rangle} = 511$ m/s. This is not the average velocity v_a, which is slightly smaller, in fact $v_a = \langle v\rangle = 0.92\sqrt{\langle v^2\rangle} = 470$ m/s. When the gas is at equilibrium the velocity distribution among the molecules follows the Maxwell-Boltzmann distribution

$$\frac{1}{N}\frac{dN}{dv} = \frac{4}{\sqrt{\pi}}\left(\frac{m}{2k_BT}\right)^{3/2} v^2 e^{-\frac{mv^2}{2k_BT}}. \tag{2}$$

This distribution is shown in Fig. 1. The most probable velocity is $v_\alpha = \sqrt{\frac{2k_BT}{m}}$, while the average velocity is $v_\alpha = \sqrt{\frac{8}{\pi}\frac{k_BT}{m}}$. As we previously discussed, the gas is characterized by pressure, temperature,

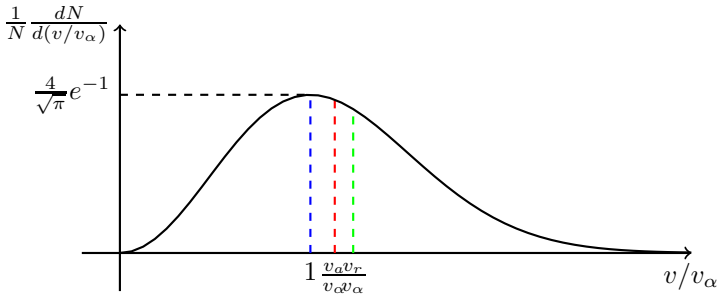

Fig. 1: Maxwell-Boltzmann distribution.

and volume. When the gas is at equilibrium, i.e. in a stationary state, these quantities are bounded by the equation of state $PV = nR_0T$, with $R_0 = 8.31$ N m/(mole K). The pressure is measured in Pascal, the volume in m^3, n is the number of moles (1 mole is a number of particles equal of the Avogadro's number N_a); also $R_0 = N_ak_B$, and T is the absolute temperature expressed in Kelvin. In vacuum physics the concept of mean free path plays an important role for determining the behavior of the gas. Consider a set of particles at rest, let the particle density of this distribution be $\tilde{n}$. Now consider N test particles distributed on a plane of area A. If now this plane moves "orthogonal" through the rest gas, when the plane is displaced of a distance Δl, the test particles will have spanned the volume $A \times \Delta l$ (see Fig. 2). On the other hand these particles have a cross-section with respect to the rest gas of $\sigma = \pi r^2$, where r is the radius of the cross-section. Then the particles present in the spanned volume will cover (with respect to the interaction with the test particles) the available area by the amount $\Delta A = A \times \Delta l\tilde{n}\sigma$. Therefore

the number of particles that will go, without collision, through the portion of rest gas of length Δl is $N - N(A \times \Delta l \tilde{n}\sigma)/A$. We obtain the differential equation

$$\frac{dN}{dl} = -N \times \tilde{n}\sigma. \tag{3}$$

Integrating this equation we find the survival of the test particles $N(l)$ at distance l. This quantity can be interpreted as the number of particles that did not collide for a distance l, and of these particles certainly $N(l) \times \Delta l \tilde{n}\sigma$ will collide with the rest gas between l and $l + \Delta l$. Therefore the probability that a particle will travel for a distance l and then collide with the rest gas in the space between l and $l + dl$ is then $dP(l) = \frac{N(l)}{N_0}\tilde{n}\sigma dl$, where N_0 is the initial number of particle in the plane considered. The average distance that a test particle will travel between two collisions is then $\lambda = \int_0^\infty l dP(l) = \frac{1}{\sigma\tilde{n}}$. Note that in this argumentation it is assumed that the particles of the gas are at rest, which is not true in a real gas. Maxwell computed the effect of the reciprocal motion among particles of the same species, and it adds a factor to the formula, which becomes

$$\lambda = \frac{1}{\sqrt{2}\sigma\tilde{n}}. \tag{4}$$

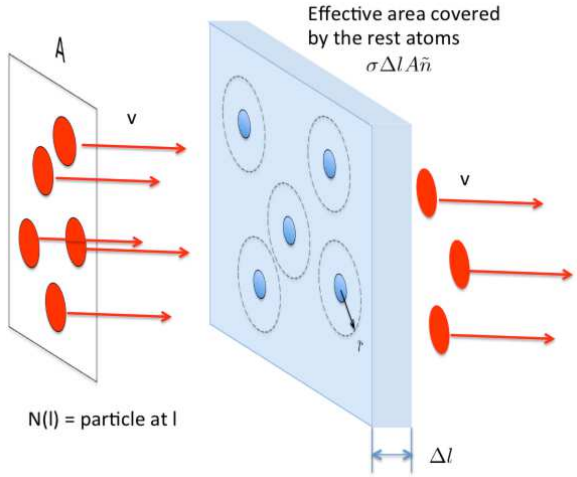

Fig. 2: Conceptual discussion for the mean free path.

For example if we consider air at $T = 20\,^\circ$C and pressure of $P = 1$ atm, we find from the equation of state $\tilde{n} = P/(k_B T) = 2.47 \times 10^{25}$ atom/m^3. The diameter of a molecule air is $d = 3.74 \times 10^{-10}$ m (from Ref. [2]) from which $\sigma = \pi d^2 = 4.39 \times 10^{-19}$ m^2. Therefore the mean free path is $\lambda = 6.51 \times 10^{-8}$ m. Below in Table 3 we show the relation of mean free path with pressure and viscosity for N_2 at $T = 20\,^\circ$C taking $d = 3.15 \times 10^{-10}$ m (obtained from measurement of viscosity [4]).

In accelerators, synchrotrons or colliders, the circulating beam is disturbed by the presence of residual gas. The importance of the residual gas is of high relevance for circular accelerators where the beam circulates for large number of turns. The situation is here of a beam formed by a number of a certain ion species which traveling may collide with the residual gas molecules, get ionized, and lost because of the wrong charge state with respect to the machine rigidity. The number of particles surviving a path of length Δl is

$$N(l + \Delta l) = N(l) - N(l)\sigma\tilde{n}\Delta l.$$

Assuming that all beam particles have the same longitudinal velocity v_0, we change the space variable into a time variable so we find

$$N(t + \Delta t) = N(t) - N(t)\sigma\tilde{n}v_0\Delta t,$$

Table 3: Mean free path, particle density, viscosity.

	P	$\tilde{n}$	ρ	η	λ
	Pa	m^{-3}	Kg m^{-3}	m^{-2} s^{-1}	m
atm	10^5	2.5×10^{25}	1.16	2.9×10^{27}	9×10^{-8}
primary vacuum	1	2.5×10^{20}	1.16×10^{-5}	2.9×10^{22}	9×10^{-3}
	10^{-1}	2.5×10^{19}	1.16×10^{-6}	2.9×10^{21}	9×10^{-2}
high vacuum	10^{-4}	2.5×10^{16}	1.16×10^{-9}	2.9×10^{18}	9×10^{1}
	10^{-7}	2.5×10^{13}	1.16×10^{-12}	2.9×10^{15}	9×10^{4}
UHV	10^{-10}	2.5×10^{10}	1.16×10^{-12}	2.9×10^{12}	9×10^{7}
XHV	10^{-11}				

therefore

$$\frac{dN}{dt} = -N(t)\sigma\tilde{n}v_0.$$

As the particle density of the residual gas is $\tilde{n} = P/(k_B T)$, the previous equation becomes

$$\frac{dN}{dt} = -N(t)\frac{\sigma P v_0}{k_B T}.$$

The constant of time of this equation defines the beam lifetime

$$\tau = \frac{k_B T}{\sigma P v_0}.$$

For example for LHC the residual gas, among the other species, is composed by molecules of hydrogen H_2 in thermical equilibrium with the cold surfaces at the temperature of $T = 5\,^{\circ}\mathrm{K}$. The cross-section with the energetic protons circulating at 7 TeV sets the cross-section to $\sigma = 9.5 \times 10^{-30}$ m^{-2}.

Therefore for a beam lifetime of $\tau = 100$ hours, we find the requirement for the pressure of H_2 inside the vacuum chamber of $P = 6.7 \times 10^{-8}$ Pa. Clearly, for other molecules composing the gas the requirement will vary, in Table 4 are shown the pressures foreseen for LHC for the different vacuum gas components [5].

Table 4: Pressure of different vacuum components in LHC for a target beam lifetime of $\tau = 100$ hours.

Gas	Nuclear scattering σ [cm^2]	Gas density [m^3]	Pressure [Pa] at 5K
H_2	9.5×10^{-26}	9.8×10^{14}	6.7×10^{-8}
H_e	1.26×10^{-25}	7.4×10^{14}	5.1×10^{-8}
CH_4	5.66×10^{-25}	1.6×10^{14}	1.1×10^{-8}
H_2O	5.65×10^{-25}	1.6×10^{14}	1.1×10^{-9}
CO	8.54×10^{-25}	1.1×10^{14}	7.5×10^{-9}
CO_2	1.32×10^{-24}	7.0×10^{13}	4.9×10^{-9}

A special note has to be reserved here to the electrons. In fact also electrons can be accounted as residual gas. Due to their lightness, electrons are strongly influenced by the electric field of the circulating beam in the accelerator. The electrons in the vacuum chamber are often referred as the “electron cloud”. A review of the complex processes of build up and interplay with the circulating bunches are found in Refs. [6–8].

As previously mentioned the molecules of the vacuum are subjected to collisions among them generating a Maxwellian distribution of velocity. A relevant feature of a gas is the so called impingement

rate J. This quantity measures the number of molecules that hits a unit of surface per unit of time. For a Maxwell-Boltzmann velocity distribution we find [2, 9]

$$J = \frac{1}{4}\tilde{n}v_a,$$

where $v_a = \sqrt{\frac{8}{\pi}\frac{k_B T}{m}}$ is the average velocity of a gas molecule.

2 Gas flows in pipes

The properties of the gas to the transport through pipes depend very much on the spatial scale considered which is set by the size of the pipe or vessel. If the size of the vessel D is much larger than the mean free path λ, then the gas will be dominated by the collisions among the gas molecules while the effect of molecule-wall collisions will be negligible. In this regime the gas will effectively behave as a continuum medium as a local change of properties will be propagated as a wave (like sound in air at room pressure and temperature). If the size of the vessel is instead much smaller than the mean free path, the vacuum molecules will mainly collide with the vessel walls. In this case continuum processes are not possible and motion of gas particles is dominated by particle wall collisions. This regime is referred to as the "molecular regime". The Knudsen number characterizes the type of regime in which a gas is found

$$K_n = \frac{\lambda}{D} \begin{cases} K_n < 0.01 & \text{Continuous regime} \\ 0.01 < K_n < 0.5 & \text{Transitional regime} \\ K_n > 0.5 & \text{Molecular regime} \end{cases}$$

2.1 The throughput and conductances

The creation of vacuum requires the extraction of the air from a vessel, which is made via a system of pumps connected to vessels through pipes.

We next present a short discussion of gas flow in pipes. The gas flow through a pipe can be expressed in terms of a number of particles per second dN/dt passing through a reference surface across the pipe. On the other hand the measurement of the gas flow is better expressed in terms of macroscopic quantities characterizing the thermodynamic state of the gas. If in a pipe a gas flows with velocity v through the surface A, the rate of particles per second dN/dt is

$$\frac{dN}{dt} = \tilde{n}vA = \frac{P}{k_B T}vA = \frac{P}{k_B T}\frac{dV}{dt} = \frac{1}{k_B T}\frac{d}{dt}PV. \tag{5}$$

Note that the quantity $Q = PV$ is here a product of a pressure times a volume. The result of Eq. 5 can be re-expressed so that the particle flow is

$$\frac{dN}{dt} = \frac{1}{k_B T}\dot{Q}.$$

The quantity $\dot{Q}$ is called throughput and is expressed in Pa m^3/s. In absence of adsorption or desorption, the rate of particles through a cross-section of a pipe does not change along the pipe, hence the throughput does not change either.

It is now useful to introduce the concept of conductance of a pipe. If in a pipe there is a flow of particles from a section 1 with pressure P_1, to a section 2 with pressure P_2 $(< P_1)$, the relation between the throughput and the difference of pressure between the two sections is expressed as

$$C = \frac{\dot{Q}}{P_1 - P_2}. \tag{6}$$

Here C is the conductance and it is a geometric property of the pipe and of the gas flow. The units of C are m^3/s. For a composed structure formed by several pipes, based on the assumption that the throughput is conserved, it is possible to prove that for N pipes each having conductance C_i, the conductance C of the composition in series is given by

$$\frac{1}{C} = \sum_{i=1}^{N} \frac{1}{C_i}.$$

For the composition of pipes in parallel the conductance of the composed structure becomes

$$C = \sum_{i=1}^{N} C_i.$$

Note that the law of composition of pipes in series can be used to obtain an indication of how the conductance of a long pipe scales with the length. In fact if C_1 is the conductance of one pipe, by connecting N of these pipes in series we find the conductance $C = C_1/N$. Therefore it is expected that the conductance scale as the inverse of the pipe length.

Till now the concept of conductance alias of the relation of the throughput with the pressure gradient was discussed without considering the physical behavior of the gas itself. It is therefore to be expected that a pipe exhibit different conduction properties according of whether the gas is in a molecular or in a continuous regime.

2.2 Molecular flow

The particle-wall collision characterizes the molecular flow of a gas in a pipe. For example in a vessel of $D = 0.1$ m, the molecular regime $K_n > 0.5$ is obtained for a pressure of $P < 1.3 \times 10^{-3}$ mbar (at room temperature).

Due to the imperfections of the pipe surface, the collision "gas molecule - wall" becomes a very complex process. However, the experimental evidence found by Knudsen [10] suggested that a particle hitting a surface at an arbitrary angle with respect to the normal to the surface, will emerge after the interaction with an angle not correlated to the incident direction with probability according to the cosine-law. This law states that the probability that a particle will have direction within the solid angle $d\omega$ is

$$dP = \frac{1}{\pi} \cos\theta \, d\omega.$$

See Fig. 3 for a schematic of the Knudsen law.

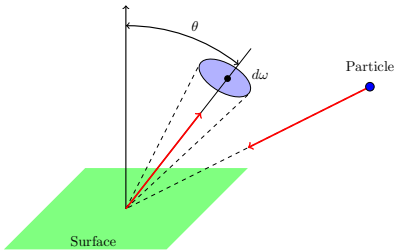

Fig. 3: Description of the cosine-law.

As consequence a particle launched inside a pipe will have a certain probability α of going through the pipe, hence a probability $1 - \alpha$ to return back. Here we also assume that no processes of capture by surfaces take place (no sticking). If N_1 particles per unit of time enters the pipe, then $N_1\alpha$ will go out and $N_1(1 - \alpha)$ will return back. Therefore in a molecular regime inside a pipe there are always two opposite fluxes of particles simultaneously coexisting.

The simplest example of conductance is the conductance of an aperture. Consider the situation shown in Fig. 4. There are two attached vessels connected by an aperture of area A. On the left vessel the pressure is P_u, and in the other the pressure is P_d. In both vessels the gas has the same temperature T. The rate of particles from the vessel with pressure P_u to the other vessel is $I_u = J_u A$. The gas throughput is obtained as $\dot{Q}_u = P_u \dot{V}_u$, where $\dot{V}_u$ is the volumetric flow of gas from the vessel with P_u. The volumetric flow is obtained as $\dot{V}_u = I_u/\tilde{n}_u$, therefore $\dot{Q}_u = P_u I_u/\tilde{n}_u$. The same argument can be repeated for the gas flow from the right vessel to the left. Therefore the total throughput across the aperture is then $\dot{Q} = \dot{Q}_u - \dot{Q}_u = P_u I_u/\tilde{n}_u - P_d I_d/\tilde{n}_d$. Here we also recall that $I = AJ = A\tilde{n}v_a/4$, therefore $I_u/\tilde{n}_u = I_d/\tilde{n}_d = v_a A/4$. Finally

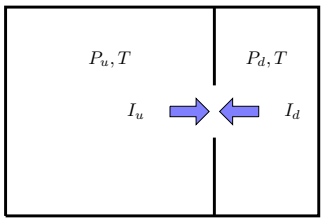

Fig. 4: Schematic of a conductance of an aperture.

$$\dot{Q} = A\frac{1}{4}v_a(P_u - P_d);$$

comparing this formula with Eq. 6 we find that the conductance of the aperture is

$$C_a = A\sqrt{\frac{1}{2\pi}\frac{R_0 T}{M}},$$

where M is the molar mass of the gas.

Usually the conductances of all types of pipe are referred to the conductance of an aperture C_a. For example, for a long pipe the conductance is [2, 10]

$$C_L = \frac{4}{3}\frac{d}{L}C_a.$$

Note that C_L scales as the inverse of the pipe length L as already inferred by the law of composition of pipes in series.

Observation. The expression of the conductance is in these formulas depending on the geometrical properties of the pipes, and by the type of molecules the gas is composed of. This property stems from the flow regime, which is here molecular.

2.2.1 Continuum flow regime

For $K_n < 0.01$ there are approximately in average 100 collisions among particles before a particle will collide with a wall. In this case perturbations of $\tilde{n}, P, T$ propagate through a continuum medium. In this regime, collisions among the particles create the phenomena of viscosity, which will affect the gas behavior in pipes.

If a fluid is propagating into a pipe with "small" speed, the fluid is in the laminar regime and the motion of the particles is parallel to the pipe axis (see in Ref. [11] for extensive discussions of flow in pipes). The velocity of the fluid is zero at the surfaces of the pipe, and is the largest at the center of it. If the velocity of the fluid is increased beyond a certain threshold, the fluid changes properties and its

motion becomes turbulent. The quantity that defines the transition from the viscous laminar regime to the turbulent one is the Reynold number

$$Re = \frac{\rho v D_h}{\eta},$$

where ρ is the density of the fluid in Kg/m^3, v is the average velocity of the gas in m/s, and D_h is the hydraulic diameter in m, expressed as $D_h = 4A/B$, with A the cross sectional area, B the perimeter of the pipe. Finally η is the viscosity in Pa-s. If $Re < 2000$ the fluid is in the laminar regime, while for $Re > 3000$ the fluid is in the turbulent regime.

In terms of the throughput the Reynold number can be expressed as

$$Re = 4\frac{\dot{Q}}{B}\frac{M}{R_0 T}\frac{1}{\eta}.$$

For air (N_2) at $T = 20\,^{\circ}\mathrm{C}$, taking $\eta = 1.75 \times 10^{-5}$ Pa-s, we find $Re = k_R \dot{Q}/B$ with $k_R = 2.615$ s/(m^2 Pa). Therefore the transition to a turbulent flow ($Re \sim 2000$) takes place at the transition throughput $\dot{Q}_T = 24d$, with $\dot{Q}_T$ in mbar l/s. For a pipe of $d = 25$ mm, we obtain $\dot{Q}_T = 600$ mbar l/s, which at atmospheric pressure corresponds to a speed of $v = 1.22$ m/s.

2.2.1.1 Laminar Regime

A complexity in characterizing a fluid flow in a pipe stems from the compressibility of the fluid. However, it is possible to prove that if the velocity of the fluid has Mach number Ma < 0.2, then the fluid in a pipe behaves as if it were incompressible, i.e. the Bernoulli equation takes a form very similar to that of the equation for incompressible fluids.

It is now important the characterization of pipes in terms of the conductance when the flow regime in pipes is laminar. The conductance is given under some assumptions of the laminar flow: 1) The fluid is considered incompressible; 2) The fluid is fully developed, that is it reaches a velocity distribution which does not change along a pipe of constant cross-section (see in [2] for a further discussion); 3) The particle motion is laminar (Re < 2000); 4) The velocity of the fluid at the pipe walls is zero. Under these assumptions we find that the throughput is given by $\dot{Q} = C(P_u - P_d)$, where now the conductance is given by

$$C = \frac{\pi D^4}{128 \eta L}\overline{P}$$

with $\overline{P} = (P_u + P_d)/2$. Here P_u is the pressure upstream, P_d the pressure downstream, D the diameter of the pipe, L its length, and η the fluid viscosity. This finding is directly obtained from the Hagen-Poiseuille equation [11]. We conclude that in a continuum laminar regime the conductance depends on the pressure at which the fluid transport is operated.

2.2.1.2 Turbulent regime

In a turbulent regime, for a long pipe, the expression of the throughput becomes

$$\dot{Q} = A\sqrt{\frac{R_0 T}{M}}\sqrt{\frac{D_h}{f_D L}}\sqrt{P_u^2 - P_d^2}$$

where f_d is the Darcy friction factor, a quantity which depends non-linearly from the Reynold number [12].

3 Sources of vacuum degradation

After air has been pumped out from a chamber, vacuum can anyhow degrade because new molecules may still enter into the vessel.

One phenomenon contributing to spoil the vacuum is the evaporation/condensation of liquids present on surfaces (because not cleaned). If on a surface of a high vacuum vessel there is a spot of liquid, from the surface of the liquid particles evaporate increasing the pressure in the vessel. At the same time vapor particles in the vessel will impinge on the liquid surface bringing molecules into the liquid. There are therefore two fluxes of particles: one is of evaporation and the other of condensation. The process of condensation depends on the pressure in the vessel, while the evaporation process depends only on the temperature. Waiting long enough the pressure in the vessel will stabilize to the saturate vapor pressure P_E, which value is given by the Clausius-Clapeyron equation [13]. Therefore we conclude that both fluxes of evaporation J_E and condensation J_C are equal. Hence the evaporation flux is

$$J_E = P_E N_a \frac{1}{\sqrt{2\pi R_0 MT}}.$$

A spot of liquid in a vacuum chamber will therefore emit the flux of particles J_E. This is equivalent to a throughput into the vessel equal to $\dot{Q}_E = AJ_E k_B T$, where A is the area of the surface of the liquid exposed to the vacuum in the vessel.

Another source of vacuum degradation is the phenomenon of the outgassing. The outgassing is the passage of the gas from the wall of the vessel or pipe to the vacuum. The outgassing is the release of the gas molecules previously adsorbed by the surfaces. The locations where gas molecules are captured (and later released) are called adsorption sites. When molecules hit one of these sites, there is a certain probability of capture (see discussion on "sticking coefficients" in Ref. [2]). Clearly when an adsorption site is occupied, it cannot accommodate another molecule, and the mount of gas absorbed by the surface is proportional to the fraction of the occupied adsorption sites Θ. Typically a molecule captured in an adsorption site remains there for a time called "mean stay time" τ_d before being released. Therefore in

Table 5: Table of mean stay time, at $T = 20\,^{\circ}\mathrm{K}$.

E_d [Kcal/mole]	Cases	τ_d [s]
0.1	Helium	1.18×10^{-13}
1.5	H_2 physisorption	1.3×10^{-12}
3-4	Ar, CO, N_2, CO_2 physisorption	1.6×10^{-11}
10-15	Weak chemisorption	2.6×10^{-6}
20	H_2 chemisorption	66
25		3.3×10^{5} (half week)
30	CO/Ni chemisorption	1.6×10^{9} (50 years)
40		4.3×10^{16} (half age of earth)
150	O W chemisorption	1.35×10^{98} (larger than the age of the universe)

the time interval dt of the total sites present of the surfaces, the fractional quantity $\Theta dt/\tau_d$ will become free and release gas. The time evolution of Θ, neglecting the re-adsorption, follows then the equation

$$\frac{d\Theta}{dt} = -\frac{\Theta}{\tau_d}.$$

The mean stay time is strongly related to the surface temperature and of the binding energy, which capture the gas molecule. As shown in [14] we find $\tau_d = \tau_0 \exp[E_d/(R_0 T)]$, with $\tau_0 = 10^{-13}$ seconds. Table 5 provides the sojourn time of the molecules according to the binding energy E_d. The number of adsorption sites is $N_s = A \times 3 \times 10^{15}$, where A is the area of the surface in cm^2. The outgassing, in terms of throughput, becomes then

$$\dot{Q}_G = k_B T \frac{N_s \Theta}{\tau_d}.$$

A third source of vacuum degradation comes from the presence of leaks. If in a vessel with high vacuum a small hole is created (small channel) then the throughput of gas from outside towards

the inside of the vessel is given by $\dot{Q} \simeq C_a P_0$, with P_0 the atmospheric pressure (or outer pressure). Considering air mainly composed by N_2 and at room temperature of $T = 293\,^\circ$K: for a small hole with diameter $d = 10^{-10}$ m we find a conductance of $C_a = 9.17 \times 10^{-19}$ m^3/s. Therefore the throughput is $\dot{Q}_L = 9.17 \times 10^{-14}$ Pa m^3/s = 9.17×10^{-13} mbar l/s. For a hole with $d = 10^{-9}$ m, $\dot{Q}_L \simeq 10^{-10}$ mbar l/s, therefore 1 cm^3 of air needs 317 years to enter inside the vessel. According to the throughput, the leaks of a vacuum system can be distinguished in [15]: very tight if $\dot{Q}_L < 10^{-6}$ mbar l/s, in tight if $10^{-6} < \dot{Q}_L < 10^{-5}$ mbar l/s, with leaks if $10^{-5} < \dot{Q}_L < 10^{-4}$ mbar l/s.

We mention at last among the sources of vacuum degradation the phenomenon of the permeation: this process happens because gases are adsorbed and diffused through the material composing the walls and later desorbed into the vessel. The throughput depends on surface temperature, thickness and composition of walls, and the composition of gases. A discussion of this effect is in Ref. [2].

4 Pipes and pumps

The creation of vacuum is made via pumps that are connected to vessels via pipes. An ideal pump behaves such that all the gas particles that enter into the pump inlet never return back. The pumping speed of a pump is referred to the volumetric speed S of the gas through the inlet, it is expressed in units m^3/s. If the inlet of a pump has diameter D, then the gas flow through the ideal pump aperture is given by $I = JD^2\pi/4$, here I is the number of molecules per second passing through the inlet surface. The volumetric pumping speed is then $S = dV/dt = I/\tilde{n} = v_a D^2\pi/16$. For example for N_2 at $T = 20\,^\circ$C if $D = 0.1$ m we find a volumetric pumping speed of $S_0 = 0.92$ m^3/s. Of course this pumping speed is ideal and the effective pumping speed of a real pump will be smaller. The situation is summarized in Fig. 5. The throughput in the section AA is $\dot{Q} = PS$, which will be the same throughout

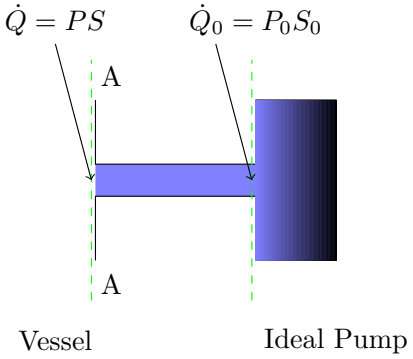

Fig. 5: Effective pumping speed S and its relation with the pumping speed S_0 of an ideal pump.

the pipe, and will be equal to the throughput of gas entering to the pump $\dot{Q}_0 = P_0 S_0$. At the same time $\dot{Q} = C(P - P_0)$, with C the conductance of the pipe connecting the vessel with the pump. From these relations we find

$$\frac{1}{S} = \frac{1}{C} + \frac{1}{S_0},$$

which gives the effective pumping speed of an ideal pump. For example taking a long pipe, $C_L = 4D/(3L)C_a$, and noting that the volumetric speed of the ideal pump is $S_0 = C_a$, we find

$$S = \frac{S_0}{1 + 3L/(4D)}.$$

Therefore pumps should be placed as close as possible to vessels in order to exploit the nominal pumping capability of the pump.

5 Making the vacuum: pump-down time, ultimate pressure

We now put together all the different sources of vacuum degradation, which are summarized in Fig. 6. The quantity of gas inside a vessel Q varies according to

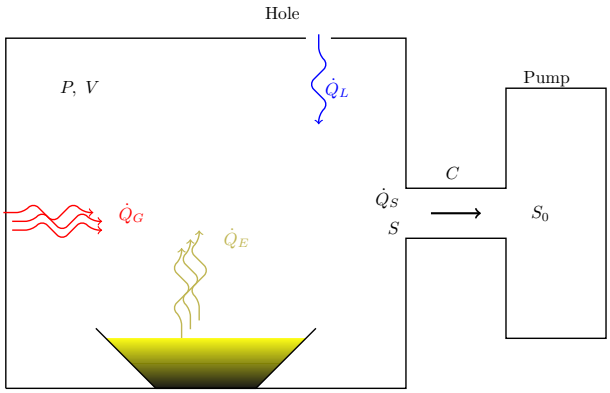

Fig. 6: Summary of the vacuum degradation sources.

$$\dot{Q} = \dot{Q}_T - \dot{Q}_S,$$

where $\dot{Q}_S$ is the throughput removed by the pump, and $\dot{Q}_T$ is the total throughput entering into the vessel because of the source of vacuum degradation. The previous equation becomes

$$\frac{dP}{dt}V = \dot{Q}_T - \dot{Q}_S, \tag{7}$$

where V is the volume of the vessel. If the sources of vacuum degradation and the pumping speed are independent on the pressure in the vessel, the evolution of the pressure, i.e. the solution of Eq. 7, is

$$P = P_u + (P_0 - P_u)e^{-\frac{S}{V}t},$$

where P_0 is the initial pressure at $t = 0$, and $P_u = \dot{Q}_T/S$. The constant of time of the process $\tau_{pd} = V/S$ is the pump-down time. From the previous equation we see that for $t \to \infty$ the pressure in the vessel converges to $P \to P_u$ called the ultimate pressure. This pressure is determined by the equilibrium between the throughput of the degradation sources, and the throughput removed by the pump.

The requirement on vacuum varies from project to project. In Tab. 6 is reported an example of the vacuum requirement in SNS, LHC, and FAIR [5, 16, 17].

6 Pumps

The control/creation of vacuum is obtained via a proper system of pumps. The classification of pumps is made according to their functioning principle.

6.1 Positive Displacement Pumps

The principle of this type of pumps is the based on a displacement of a volume $\mathcal{V}$ of vacuum gas from the vessel to the outside. This process implies that the action of the pump is to seal a volume $\mathcal{V}$ and to open it out of the vessel. Clearly when the volume $\mathcal{V}$ of gas is displaced and opened, in order for the gas to flow out, the pressure in the volume $\mathcal{V}$ has to be larger than the outside pressure P_{outlet}. Therefore it is always necessary that the pump compresses the volume $\mathcal{V}$ so that the gas initial pressure, equal to the vessel pressure P_{inlet}, will become larger than P_{outlet}. If the gas pressure in the vessel is so low that the

Table 6: Example of vacuum pressure in some accelerators.

SNS	Front End	1×10^{-4} to 4×10^{-7} Torr
	DTL	2×10^{-7} Torr
	CTL	5×10^{-8} Torr
	SCL	$< 10^{-9}$ Torr
	HEBT	$< 5 \times 10^{-8}$ Torr
	Ring	10^{-8} Torr
	RTBR	10^{-7} Torr
LHC		$10^{-10} - 10^{-11}$ mbar
FAIR	HEBT	10^{-9} mbar
	SIS100	10^{-12} mbar

compression made by the pump is not enough to reach a pressure larger than P_{outlet}, then the gas will be transported from outlet to the inlet! This reasoning shows that a positive displacement pump will be able to extract the gas only if the ratio P_{outlet}/P_{inlet} can be reached by the compression process.

6.1.1 Piston Pump

In this type of pump a piston moves in a cylinder creating a variable volume from V_{min} to V_{max}. The ideal volumetric pumping speed is $S_0 = V_{max}N_c$, where N_c is the number of cycles per second of the piston. When the piston creates the minimum volume V_{min} the pressure inside the chamber is equal to P_{outlet}. Next the piston expands the volume, and for an isothermal process when the volume is $V_i = P_{outlet}V_{min}/P_{inlet}$ the gas will start flowing from the vessel into the piston chamber. The volumetric amount of gas, which enters into the piston chamber is $V_{max} - V_i$, and this is the amount of gas later expelled. The effective pumping speed is therefore $S = N_c(V_{max} - V_i)$, that is

$$S = S_0 \left(1 - \frac{P_{outlet}}{P_{inlet}} \frac{V_{min}}{V_{max}}\right).$$

Figure 7 shows a pattern of the volumetric pumping speed versus the inlet over outlet pressure. This

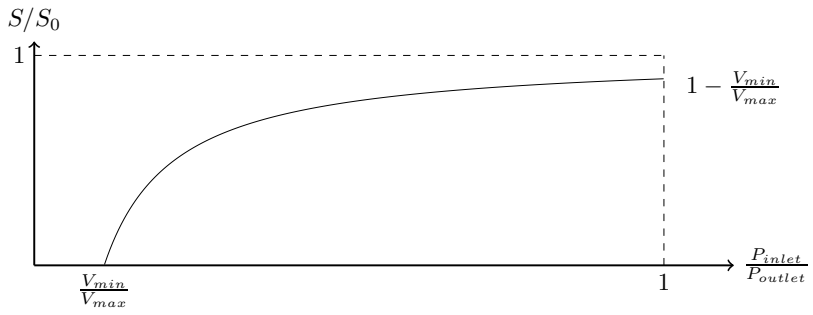

Fig. 7: Pumping speed in a piston pump.

discussion shows that the pump stops pumping at a limit inlet pressure that depends on the compression made by the pump. The higher the compression, the lower the limit pressure. If the thermodynamic process characterizing the compression is of different nature the dependence of S from P_{inlet}/P_{outlet} will be different: for example for an isentropic compression we find $S = S_0[1-(P_{outlet}/P_{inlet})^{1/\gamma}V_{min}/V_{max}]$. The result is anyway that there exists a limit pressure at which the pump stops functioning. Note that this feature sets an ultimate pressure in a vessel+pump system independently of the presence of source of vacuum degradation.

In general, from the point of view of gas flow, a pump is an object that absorbs a throughput $P_{inlet}S_0$ through the inlet, but due to other uncontrolled processes, is also subjected to a back-flow $\dot{Q}_b$. The total throughput is then $\dot{Q} = P_{inlet}S_0 - \dot{Q}_b$. In order to characterize the back-flow, it is useful to define the **zero load compression ratio**. This quantity is obtained as follows: the inlet is closed and the pressure P_{i0} is measured at the entrance of the pump. This is the inlet pressure at zero load. It is therefore defined the zero load compression ratio as $K_0 = P_0/P_{i0}$, which is a quantity measurable as function of the outlet pressure P_0 and of the pumping speed. As in this special setting at the inlet the throughput is $\dot{Q} = 0$, we find the back-flow throughput as $\dot{Q}_b = S_0P_0/K_0$.

For technical reasons, the compression rate of a pump cannot be made arbitrarily large. Hence other techniques were developed to improve the lower limit pressure.

6.1.2 Rotary Pumps

These pumps are characterized by a pumping speed of $S = 1 - 1500$ m^3/h. The lower pressure reaches $P = 5 \times 10^{-2}$ mbar for the one stage pumps, and $P = 10^{-3}$ mbar for the 2 stages pumps. An illustration of this type of pump is shown in Fig. 8. These pumps make the compression via a rotation of a rotor,

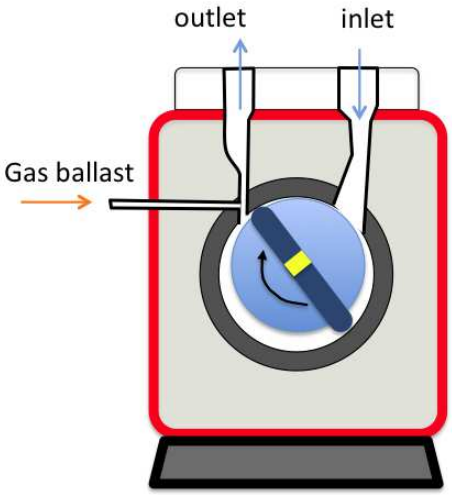

Fig. 8: Illustration of a rotary pump.

which creates a moving vane that compresses the gas to a high compression rate. However, during the compression, there can be some gas component (G), which partial pressure P_G becomes too high starting then a process of condensation of that component. The problem is avoided by injecting a non-condensable gas during the compression phase. By doing so the maximum partial pressure P_G will be lowered below the condensation point. This process is called gas ballast [18].

6.1.3 Liquid ring pumps

Liquid ring pumps are constituted by a rotating impeller, which axis is off center the case (see the illustration in Fig. 9). The centrifugal force pushes the liquid against the case creating a liquid ring, which seals the impeller creating vanes with variable volume. The typical pumping speed is $S = 1 - 27000$ m^3/h, and the gas can be pumped for pressures $P = 1000$ mbar to $P = 33$ mbar. A problem related to this type of pumps arises when the gas expands in the cavities and the pressure becomes lower than the vapor pressure P_s of the liquid (typically water). At that point the water boils, but the motion of the impeller further compresses the gas causing the vapor bubbles to implode creating shock waves through the liquid medium. This phenomenon is called cavitation and it creates an anomalous functioning of the

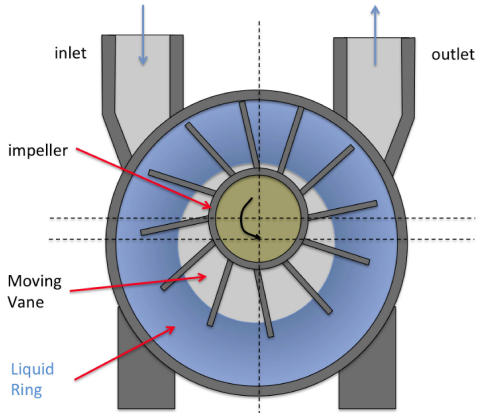

Fig. 9: Illustration of a liquid ring pump.

pump setting the limit pressure at which the pump can work. At $T = 15\,^{\circ}\mathrm{C}$ the vapor pressure of water is 33 mbar, which becomes a typical limit pressure for this type of pump (to avoid cavitation). For a review of liquid ring pumps see Ref. [19].

6.1.4 Dry vacuum pumps: Roots

These pumps are formed by two rotating elements which are separated from the case and among each other by ~ 1 mm. They rotate in opposite direction and in their motion they create a moving vane, which brings a gas volume from the inlet to the outlet. The pumping speed is $S = 75 - 30000$ m^3/h and the operating pressure is $10 - 10^{-3}$ mbar. An illustration of this type of pump is shown in Fig. 10. For a general reference see in Ref. [20].

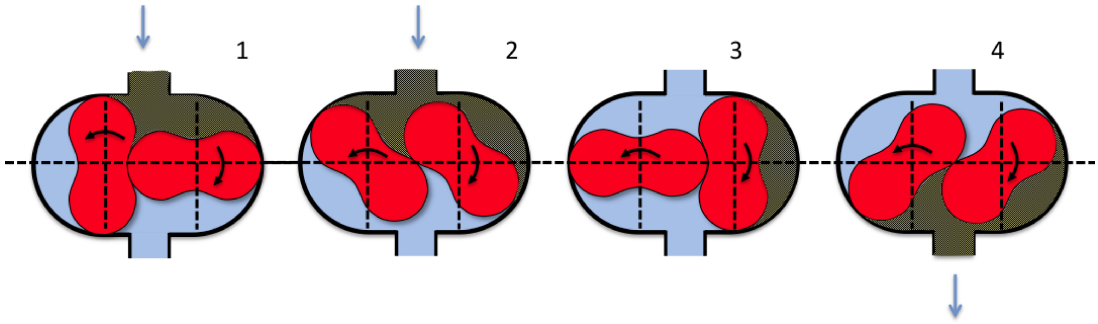

Fig. 10: Illustration of the Roots pump.

7 Kinetic vacuum pumps

A different class of pumps based on a different principle is that of the kinetic vacuum pumps. These pumps give a momentum to particles so that they are moved from the inlet to the outlet.

7.1 Molecular drag pump

This pump is based on the molecular drag effect. If a gas molecule hits a surface, it will emerge from it with a direction probability determined by the cosine law. However, if the surface is in motion with velocity tangent to the surface itself, the particle will emerge from the reflection with the moving surface also with an additional velocity component equal to the speed of the surface. This effect is called drag effect, and it is used to create a pump [21]. Consider an open long channel of transverse cross-section

$h \times w$ closed by a surface moving with velocity U [Fig. 11 (top)]. A gas molecule when hitting the

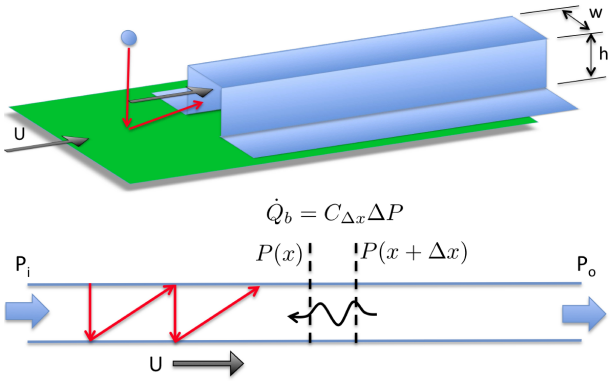

Fig. 11: Principle of the drag pump (top), and schematic of gas flow in the drag pump channel (bottom).

moving surface will acquire a velocity U due to the drag effect. When the particle hits the other walls of the channel, by the cosine-law, it will be reflected in average orthogonal to that surface, see Fig. 11 (bottom). Therefore a volumetric flow of $S_0 = whU/2$ is established into the vane of the channel. Taking into account of the back-flow the pumping speed at the inlet is

$$S_i = S_0 \frac{K - K_0}{1 - K_0},$$

where $K_0 = P_{outlet}/P_{inlet,0}$ is the zero load compression ratio, and $K = P_{outlet}/P_{inlet}$. It can be shown that the compression rate at zero load takes the form $K_0 = \exp(S_0/C)$ where C is the conductance of the channel. For a long tube $S_0/C = 3UL/(4hv_a)$, where v_a is the average thermal velocity, and L is the length of the channel. For example for $L = 250$ mm, and $h = 3$ mm, then $S_0/C > 10$ and $K_0 \gg 1$ so that we retrieve the form

$$S = S_0 \left(1 - \frac{K}{K_0}\right).$$

An illustration of the functioning of a molecular drag pump is shown in Fig. 12. The typical pumping

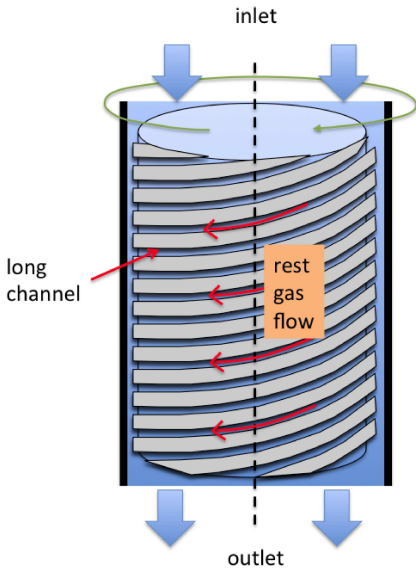

Fig. 12: Illustration of the functioning of a molecular drag pump.

speed of a molecular drag pump is $7 - 300$ l/s, at an operating pressure of $10^{-3} - 10^{3}$ Pa. The ultimate pressure reachable is 10^{-5} to 10^{-3} Pa. For references see Refs. [9, 22].

7.2 Turbo-molecular pump

The turbomolecular pump is based on the rotation of a set of blades at a velocity U. The blades are tilted with an angle ϕ. The gas molecules enter into the inlet and the motion of the blades imparts a momentum to the gas. The situation is illustrated in Fig. 13. When particles go out of the set of rotating blades, the gas has acquired a rotating velocity, which makes difficult the use of a subsequent series of rotating blades (as they should run at similar velocity of the gas). For this reason a stator formed by blades at rest is put after the rotating blades so to remove the rotational component of the particle velocity. By using this strategy several blocks of rotor+stator can be placed in a multistage pumping structure.

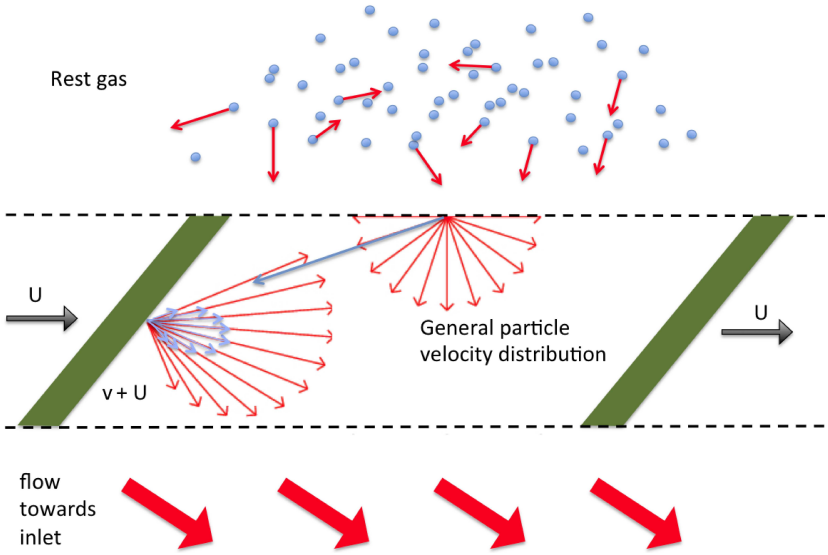

Fig. 13: Principle of the turbo-molecular pump.

The probability that molecules entering in the pump will be pushed out is $W = \dot{N}/(J_i A)$, where J_i is the impingement rate of molecules into the surface of the inlet. The maximum probability W_{max} is found when $P_{outlet} = P_{inlet}$. In an analogous way to the molecular drag, the pumping probability W is given by

$$W = W_{max} \frac{K_0 - K}{K_0 - 1},$$

with K_0 the compression at zero load. In Ref. [9, 23] it is shown that $K_0 \propto g(\phi) \exp(U/v_a)$, therefore $K_0 \propto \exp(\sqrt{M})$, with M the molar mass of the gas. This means that different gas species have different pumping probability. In addition the maximum probability W_{max} is $W_{max} \propto U/v_a \propto \sqrt{M}$. Therefore the maximum pumping speed $S_{max} = W_{max} J$ is independent from the molecular mass of the gas, and

$$\frac{S}{S_{max}} = \frac{K_0 - K}{K_0 - 1}.$$

See also in Ref. [2, 22] for more details. In Fig. 14 (left) is shown an example the maximum compression as function of the foreline pressure for several gas species [2]. The typical pumping speed of these types of pump is $35 - 25000$ l/s [Fig. 14 (right)], and the ultimate pressure reachable is 10^{-8} to 10^{-7} Pa.

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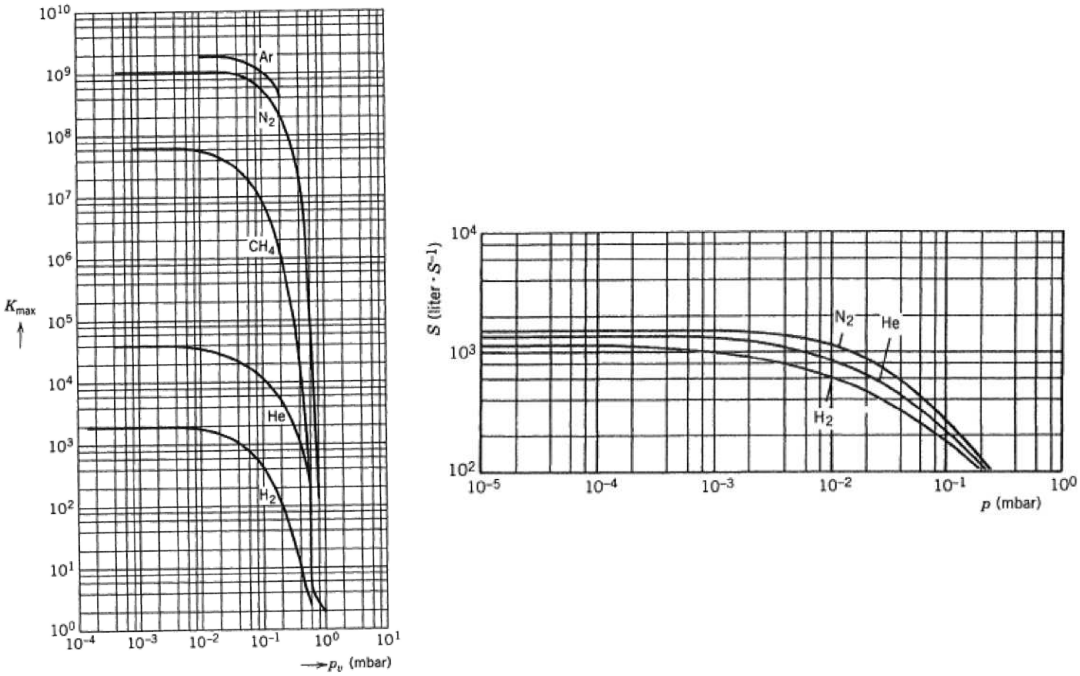

Fig. 14: Maximum compression rate as function of the foreline pressure (left) and pumping speed (right) (Blazer Pfeiffer).

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