

INTRODUCTION TO THE PRINCIPLES OF VACUUM PHYSICS

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Abstract

Vacuum physics is the necessary condition for scientific research and modern high technology. In this introduction to the physics and technology of vacuum the basic concepts of a gas composed of atoms and molecules are presented. These gas particles are contained in a partially empty volume forming the vacuum. The fundamentals of vacuum, molecular density, pressure, velocity distribution, mean free path, particle velocity, conductivity, temperature and gas flow are discussed.

1. INTRODUCTION — DEFINITION, HISTORY AND APPLICATIONS OF VACUUM

The word "vacuum" comes from the Latin "vacua", which means "empty". However, there does not exist a totally empty space in nature, there is no "ideal vacuum". Vacuum is only a partially empty space, where some of the air and other gases have been removed from a gas containing volume ("gas" comes from the Greek word "chaos" = infinite, empty space). In other words, vacuum means any volume containing less gas particles, atoms and molecules (a lower particle density and gas pressure), than there are in the surrounding outside atmosphere. Accordingly, vacuum is the gaseous environment at pressures below atmosphere.

Since the times of the famous Greek philosophers, Demokritos (460-370 B.C.) and his teacher Leukippos (5th century B.C.), one is discussing the concept of vacuum and is speculating whether there might exist an absolutely empty space, in contrast to the matter of countless numbers of indivisible atoms forming the universe. It was Aristotle (384-322 B.C.), who claimed that nature is afraid of total emptiness and that there is an insurmountable "*horror vacui*". Therefore, he doubted and even rejected an absolute vacuum. He assumed, for example, that the idea of empty space would invite the concept of motion without resistance, i.e. a motion at infinite velocity. This opinion became a paradigm for almost 2000 years. It was believed by famous writers, like Roger Bacon (1214-1299) and René Descartes (1596-1650) and was strongly supported also by the church.

Only in the 17th century were vacuum physics and technology born. Galileo (1564-1642) was among the first to conduct experiments attempting to measure forces required to produce vacuum with a piston in a cylinder. Torricelli (1608-1647), an associate of Galileo's, succeeded in 1644 to produce vacuum experimentally by submerging a glass tube, which was filled with mercury and closed at one end, with its open end in a pool of mercury. By using mercury instead of water, he was able to reduce the size of the apparatus to convenient dimensions. He demonstrated that the mercury column was always 760 mm above the level in the pool, regardless of size, length, shape or degree of tilt of the tube (see Fig. 1) and, in this way, he measured for the first time the pressure of atmospheric air. Also, by other experiments, performed by the French scientist and philosopher Blaise Pascal (1623 - 1662), the idea of the "*horror vacui*" was definitely proved to be wrong (see Fig. 2). Pascal also measured, for example, the altitude with the Hg barometer (invented by Torricelli), contributed significantly to our understanding of vacuum physics and made many other important discoveries in physics. The unit of measure of the degree of vacuum of the International Standards Organization, i.e. the SI-unit of pressure, was called in honour of Pascal :

$$1 \text{ Pa} = 1 \text{ N/m}^2 = 7.501 \times 10^{-3} \text{ Torr} = 10^{-2} \text{ mbar} .$$

At the same time, the mayor of the city of Magdeburg, Otto von Guericke (1602-1686; see Fig. 3), modified the water pumps, invented the manometer (1661), constructed the first air pump (1650) and made many other discoveries in physics and astronomy. For instance, from the astronomical observation of the constancy of the time of orbit revolution of the planets, he concluded

that there is no friction in space, but vacuum instead. On the occasion of the Reichstag at Regensburg/Germany he performed publicly in 1654 his famous and most spectacular experiment with the two empty, gasketed copper "Magdeburg Hemispheres" of about 50 cm in diameter (see Fig. 4). By this experiment he demonstrated that it is impossible to pull the two halves apart against the air pressure, even by using 2×8 horses (the counter-pressure by air in the interior of the sphere is missing). During this time, it became clear that we are living on the bottom of a huge ocean of air and that the mass of the atmosphere corresponds to a pressure of about 1 kg per cm^2 or 10 tons on an area of 1 m^2 . This is the reason, why the 16 horses of von Guericke were unable to pull the hemispheres apart. The reason, why we don't feel anything of this tremendous pressure is simply that there is the same pressure inside our body. To determine the mass of air, Otto von Guericke performed his spectacular gallows experiment, shown in Fig. 5.



Fig. 1 Experiments of Torricelli (1608-1647), observing the height of a mercury column in one-sided glass tubes to be independent of the shape and inclination of the tubes. In the volume above the mercury meniscus was the first experimentally generated vacuum, the "Torricelli Vacuum" (taken from an engraving of P. Gasparis Schotti "Technica Curiosa", Nürnberg, 1664. Courtesy C. Edelmann [11]).

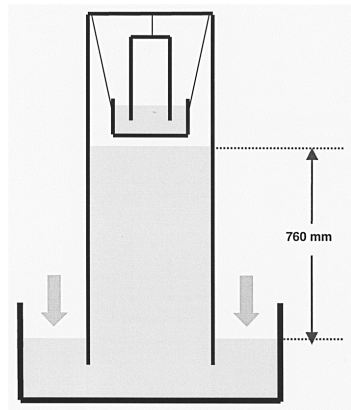


Fig. 2 Experiment by Blaise Pascal proving the action of atmospheric pressure and the existence of vacuum.



Fig. 3 Portrait of Otto von Guericke (1602-1686), (Courtesy "Otto von Guericke Society" in Magdeburg).

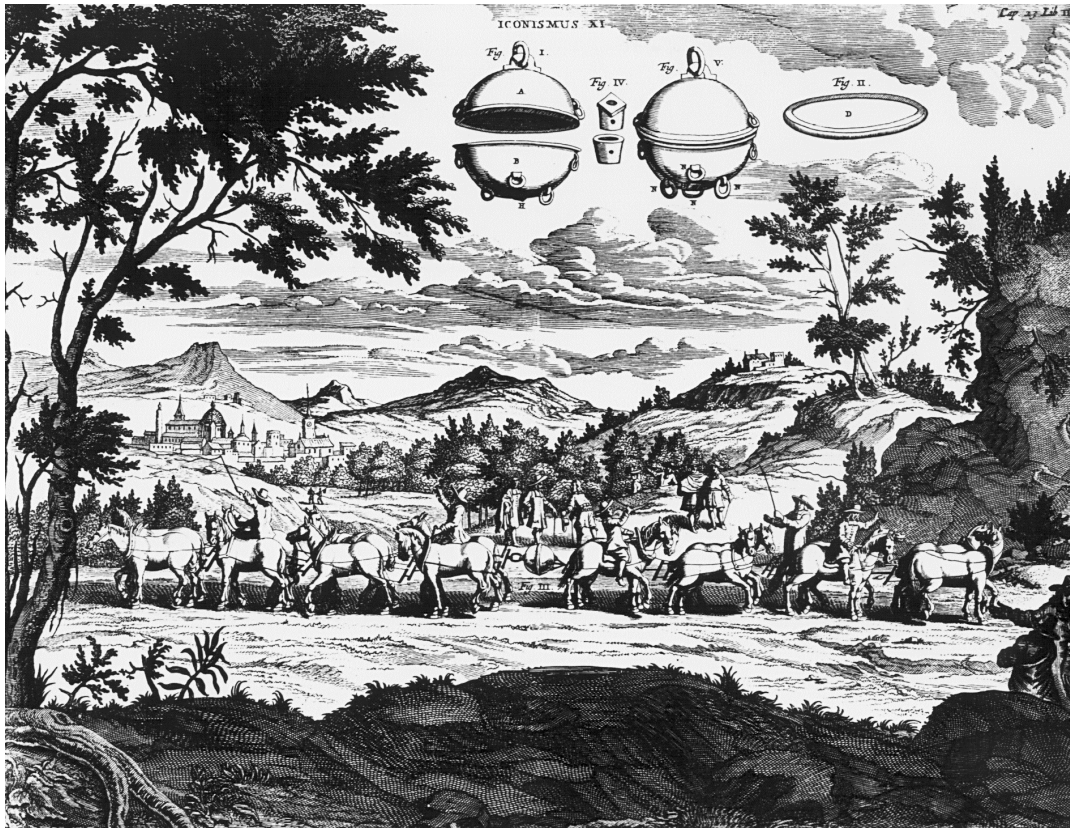


Fig. 4 Experiment with the "Magdeburger Hemispheres" (1654) by Otto von Guericke (taken from an engraving of P. Gasparis Schotti "Technica Curiosa", Nürnberg, 1664. Courtesy Otto von Guericke Society in Magdeburg).

Another important discovery was made by Robert Boyle (1627-1691, who built an improved vacuum pump, and Edme Mariotte (~1620-1684). They derived *the law of Boyle-Mariotte*, the fundamental equation of gas laws, valid for so-called "ideal gases" being in thermodynamical equilibrium :

$$p V / T = \text{constant} \quad (\text{with } p = \text{pressure, } V = \text{volume and } T = \text{absolute temperature of the gas}).$$

Many technical inventions, concerning various pumps for vacuum generation, were made in the last, and until the middle, of our century, leading for instance to the discovery of the electron in 1897 by J.J. Thomson (1856-1940) and the invention of the X-ray tube by Wilhelm Conrad Röntgen (1845-1923) with his discovery of short-wavelength X-ray radiation on November 8, 1895. Finally, in the thirties of our century, the invention of the wide variety of particle accelerators started and went on till today with the construction of huge machines. With accelerators, nuclear and high-energy elementary-particle physics began. All the inventions and sophisticated technological developments of today would have been unthinkable without high vacuum and its technology. Therefore, vacuum physics and techniques paved the way for the development of modern high-technology and our industrial society.

What characterises vacuum? The particles in a volume are in constant motion. They hit the walls of the container and exert a force on its surface area, which is called "pressure". One can measure this force per unit area of the vessel, called pressure, by comparing it to the atmospheric pressure or by determining it in absolute units. Therefore, by a pressure measurement one obtains the number and intensity of particle impacts on a unit of surface area.

The highest pressures ever obtained in a laboratory happened in the European Laboratory for High Energy Nuclear Physics CERN during head-on collisions of two fast lead nuclei. This is the unimaginably large pressure of 10^{30} bar, which is estimated to be about 5-times larger than before a supernova explosion. Compared with this value, the maximum static pressure of about 3.5×10^6 bar, reached in experiments with diamond stamps, is very small. On the other hand, the lowest pressure or

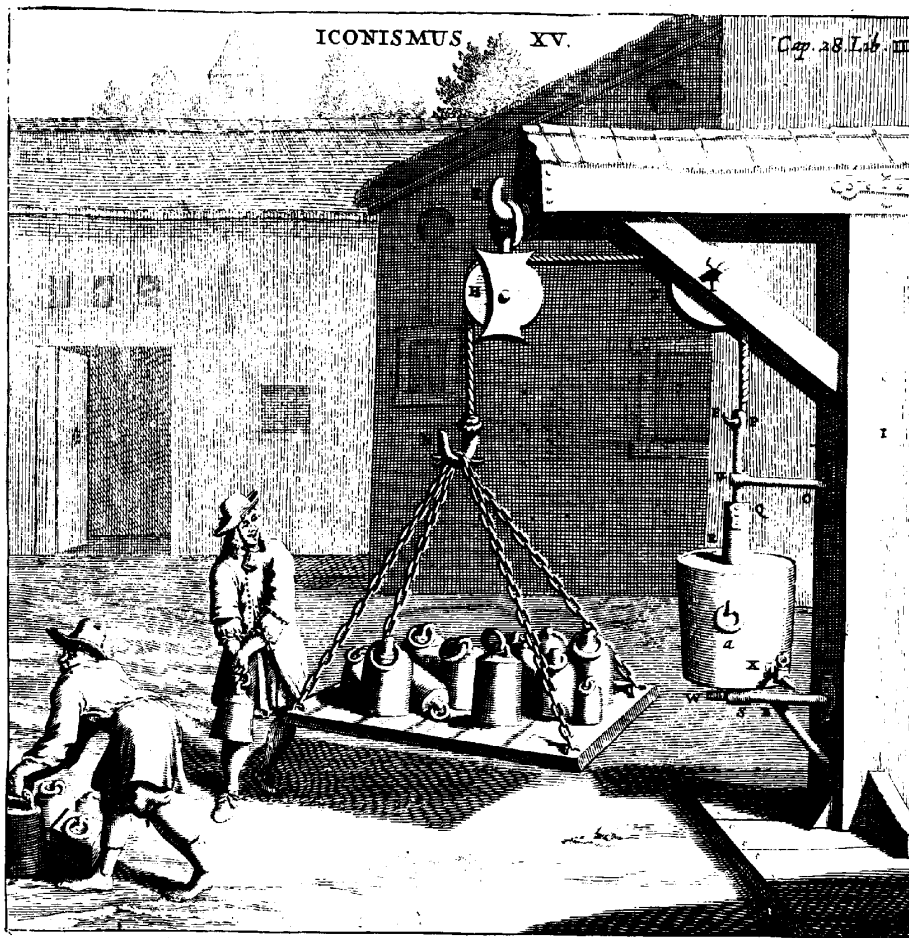


Fig. 5 Gallows experiment of Otto von Guericke (1602-1686), in order to determine the mass of air (taken from an engraving of *Otonis de Guericke "Experimenta nova (ut vocantur) Magdeburgica de vacuo spatio"*). Courtesy C. Edelmann [11]). In a copper cylinder **a**, fixed at the gallows post on the right side of the picture, a piston **Q** can move vertically. The piston is connected with a rope running over two rolls **H** and **T** to a board loaded with several weights. At first, the piston is pulled up with the tap **X** at the bottom of the cylinder open. When evacuating the cylinder with an air pump, tap closed, the piston slides downwards due to the outside air pressure, lifting the weights.

highest vacuum generated by pumps in the laboratory amounts to 10^{-17} bar, which corresponds to just a few hundred particles in one cm^3 and which was also obtained at CERN. One should compare this with a number of $\sim 3 \times 10^{19}$ particles per cm^3 at atmospheric pressure and room temperature. Therefore, between the highest and lowest pressure there are 47 orders of magnitude in between. But even the best vacuum obtained on earth is a high-pressure area compared with the almost total emptiness between stars in space. Accordingly, besides pressure vacuum is characterised by the density of particles. The interstellar particle density in the Milky Way, for instance, consisting of gas, plasma and dust, is only $\sim 5 \times 10^4$ particles per m^3 . Between Galaxies one has only one particle or at most a few of them per m^3 . If one would distribute homogeneously the total matter of the universe in space, one would still have an extremely low particle density of only 3 particles per m^3 . The universal density scale, presented in Table 1, exhibits the enormous range of about 60 orders of magnitude between the maximum density calculated for a black hole and almost totally empty regions in space with the earth somewhere in the middle. Table 2 shows examples of particle densities of various objects. However, even the almost perfect vacuum of interstellar space is not empty at all. There is electromagnetic radiation everywhere or superstrong fields, which are even able to generate new particles. Even if we would succeed to construct an empty volume, totally shielded against radiation from outside and cooled to absolute zero temperature to reduce radiation from its walls, there would still be radiation emitted from the particles of the walls which are never totally at rest (due to Heisenberg's uncertainty principle).

Table 1
Universal density scale

Universal density scale	g/cm^3
Big Bang	∞
Black hole	10^{27}
Neutron Star	10^{14}
White Dwarf	10^6
Solar Center	158
Sun (average density)	1.4
Water on Earth	1
Air	10^{-3}
Vacuum in Laboratory	10^{-18}
Interstellar Space	10^{-24}
Universe	10^{-30}
Empty Regions in Space	10^{-33}

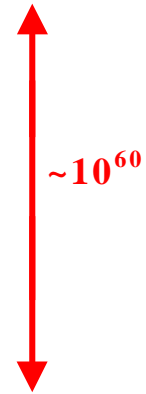


Table 2
Examples of particle densities of various objects.

Object	Number of Particles	Length of Cubic Edge	Mean Free Path
Gold (one of the most dense elements)	60 000 000	0.0001 mm	-
Air (at normal pressure)	30 000 000	0.001 mm	0.000066 mm
Air (on Mt. Everest)	9 000 000	0.001 mm	0.0002 mm
Thermos Flask	5 000 000	0.1 mm	33.6 cm
TV Cathode-Ray Tube	13 000	0.1 mm	134 m
Atmosphere (at the orbit of space shuttle)	1 000	0.1 mm	1.68 km
Interstellar Space	3	1 cm	670 000 000 km
Intergalactic Space	1	10 m	1.7×10^{18} km (=180 000 light years)

In association with the interest in space research, the development of techniques to achieve ultra-high vacuum (UHV) is of utmost importance. The pressure of a conventional vacuum system with diffusion pumps, today normally replaced by turbo-molecular pumps, and elastomer gaskets is normally about 10^{-4} to 10^{-5} Pa, which corresponds to about 10^{14} to 10^{13} molecules of nitrogen arriving each second on each cm^2 of a surface at room temperature. Since an atomic monolayer corresponds to about 10^{15} atoms per cm^2 such conditions result in nitrogen arrival rates of a monolayer every 10 s (assuming that every molecule sticks to the surface). This represents an unacceptable level of contamination for most high-tech applications of today. For surface studies e.g., vacua below 10^{-7} Pa, i.e. UHV, became indispensable, corresponding to the formation of about one monolayer in about a few hours or to a mean free path between collisions of molecules of about 50 000 km. An UHV-system typical for this kind of research is shown in Fig. 6.

Vacuum vessels are fabricated of materials like glass, aluminium, (oxygen-free) copper, stainless steel, titanium etc., which corrode very slowly and have low rates of outgassing of adsorbed gas. Vessels are carefully cleaned by mechanical, chemical or thermal treatments and vacuum sealed by materials of different vapour pressure from rubber, synthetics to metals, depending on the quality of vacuum to be maintained. To obtain UHV conditions, free of organic contaminants, water vapour and hydrocarbons, metal gaskets are necessary, allowing baking of the whole chamber to about 520 K while the vacuum pumps operate. By baking vacuum systems for several hours an accelerated desorption of water vapour and other gases from all internal surfaces is obtained, the necessary condition for UHV. To avoid high vapour pressure, also the materials used inside vacuum chambers have to be chosen very carefully.

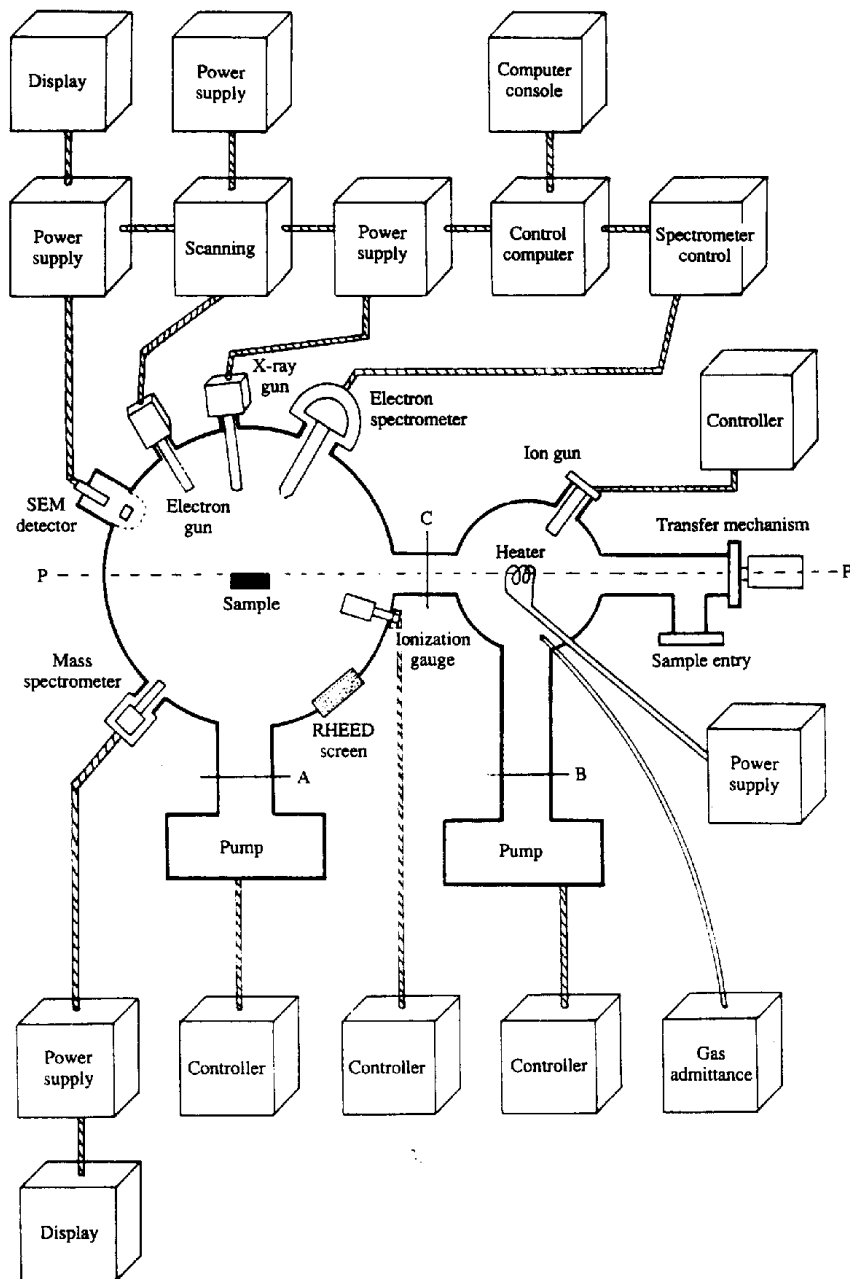


Fig. 6 Arrangement of vacuum components in a typical UHV-system for surface studies [9].

Vacuum is made by removing the various gases from the contained volume. This is done by many different kinds of vacuum pumps, which either remove the particles from the volume by real pumping or trap them by binding them via physical or chemical forces, changing their form and keeping them trapped in the bulk of the pumping material, a so-called getter. This is done by various mechanical and sorption pumps, diffusion pumps, cryo-pumps, ion-sputter pumps, non-evaporable-getter(NEG) pumps or titanium sublimation pumps. As an example for the tremendous development of mechanical pumps during the second half of the 20th century, in particular of fast rotating turbomolecular pumps, Fig. 7 shows the so-called dry (oilfree) wide-range type of such a pump, where the rotor is kept in position by magnetic bearings. Not only pumps for vacuum generation, but also a wide variety of devices for pressure measurements, rest-gas analysis and mass spectrometry have been developed for the various ranges of vacuum. All these highly sophisticated devices for vacuum generation and measurement and the corresponding materials and cleaning techniques form the basis for modern vacuum technology and will be discussed in detail in the following chapters.

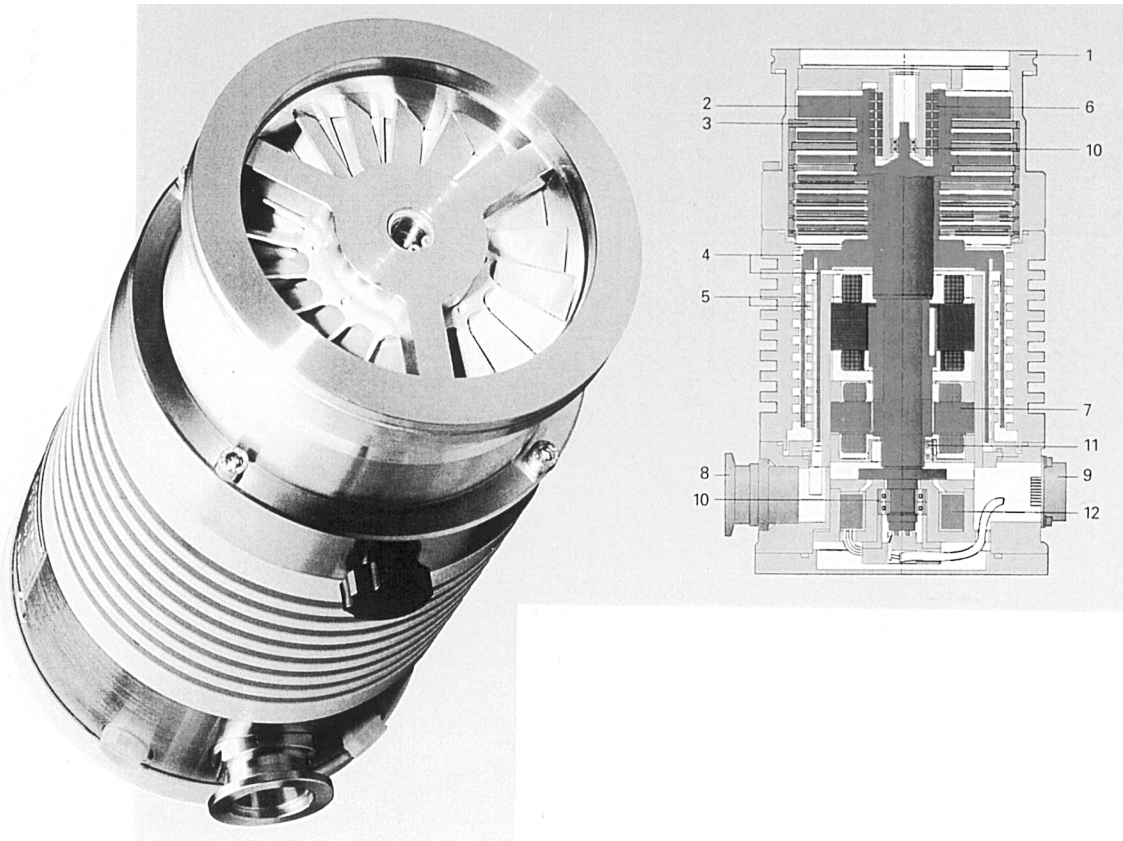


Fig. 7 Magnetic-bearing wide-range turbomolecular pump (from Pfeiffer-Balzars Co.).

There are many people who believe that vacuum technology is just dealing with valves, flanges and other vacuum components. But the science and technology that all this hardware enables are the keys to our high-tech society. Vacuum is used for a huge number of technical processes and products, like vacuum-packed coffee, thermos flasks, light bulbs, microwave and cathode-ray tubes for TV screens. One uses it always when one needs a "clean" space, which is free of gases and contaminants. It led to the development of ion-getter pumps and ultra-high-vacuum (UHV) techniques, to electron and ion microscopes, ion implanters, sensitive leak detectors and space simulation technology. Because its conductivity is lower than any other material, vacuum is best suited for thermal insulation, i.e. to reduce energy transfer or to prevent heat loss. It is used for thermal insulation at low temperatures (below 100 K), in particular. On the other hand, low temperatures are used to generate ultra-high vacuum by cryo-pumping. Contamination by gas particles can disturb or totally prevent processes or spoil products. Therefore, vacuum technology and equipment was essential to the development of electron and microwave tubes, the production of high-purity metals, the separation and storage of gases, any plant producing computer chips and semi-conductor components, displays, thin films, nanostructures, optical and microelectronic coatings, vacuum metallurgy, data storage and hard disk drives. Vacuum technology is growing in importance as more industries introduce advanced materials and devices and as technology goes more and more into the direction of components of micro- and nanometer scale.

Ultra-high vacuum is also of particular importance for chemical and biological techniques, for atomic-physics research and for the operation of modern particle accelerators, used for high-energy elementary-particle physics or synchrotron-radiation research. The development of the so-called 3rd generation synchrotron light sources with their tremendous fluxes of photons of all wavelength, used nowadays in many areas of natural science, would have been impossible without UHV-technology. A comparison of the brightness, i.e. the number of emitted photons in appropriate units, of a simple candle with the brightness of these modern machines, using magnetic undulators for its amplification, is presented in Fig. 8 . The graph shows that synchrotron radiation is about 10 orders of magnitude brighter than the radiation of the sun, which emits the huge amount of energy of ~ 41 ergs per year. A

supernova, however, is radiating in much shorter times more than one order of magnitude more energy. Figure 9 shows how this enormous amount of radiation energy is transferred into the kinetic energy of high-speed acceleration of gas, expanding in all directions of the extreme-high-vacuum of empty space.

For a more detailed study of vacuum physics, a list of a few general textbooks on high-vacuum physics is given at the end of this article.

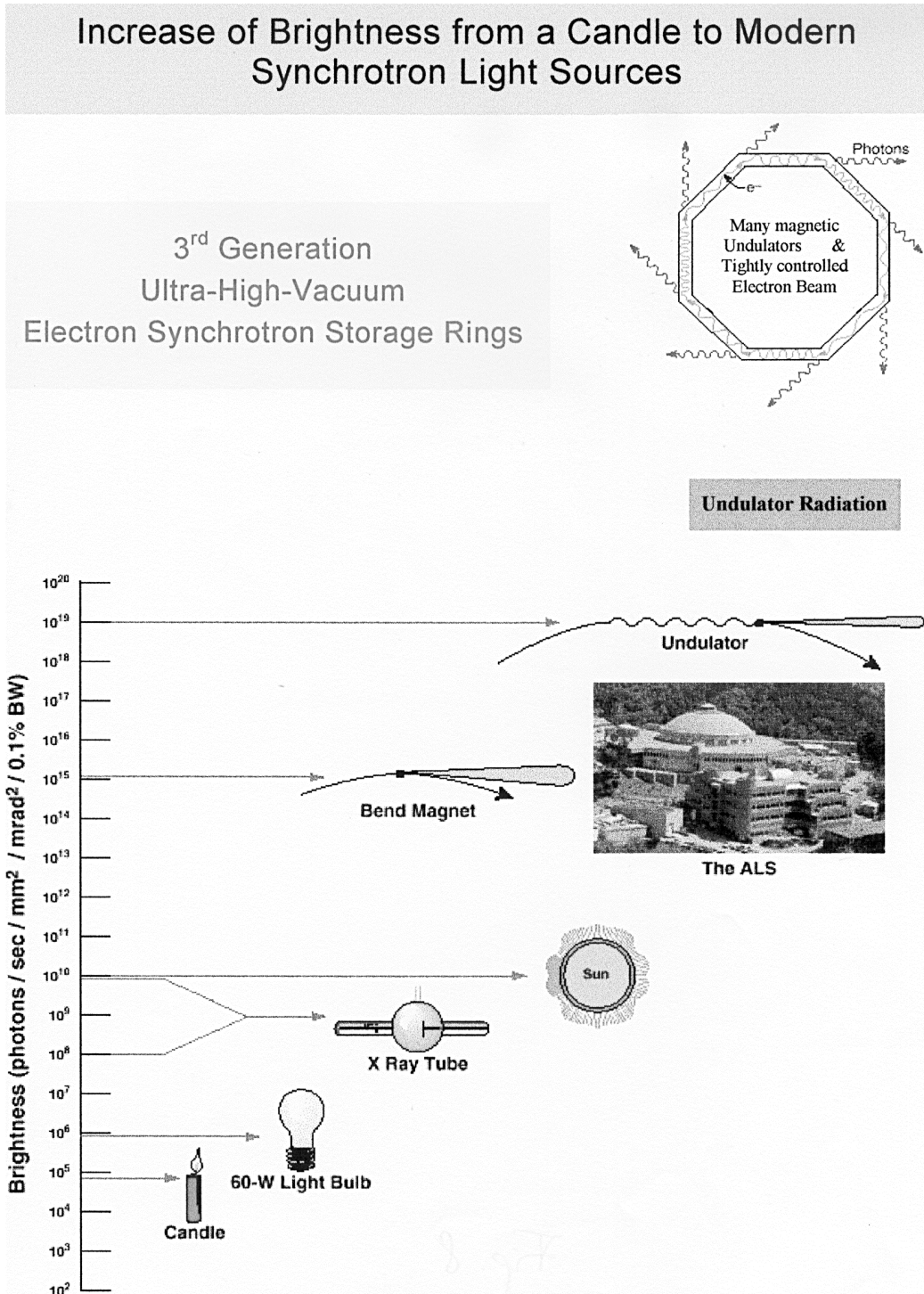


Fig. 8 Comparison of photon intensities emitted by various artificial light sources with the sun. (Courtesy Advanced Light Source, Lawrence Berkeley National Laboratory.)

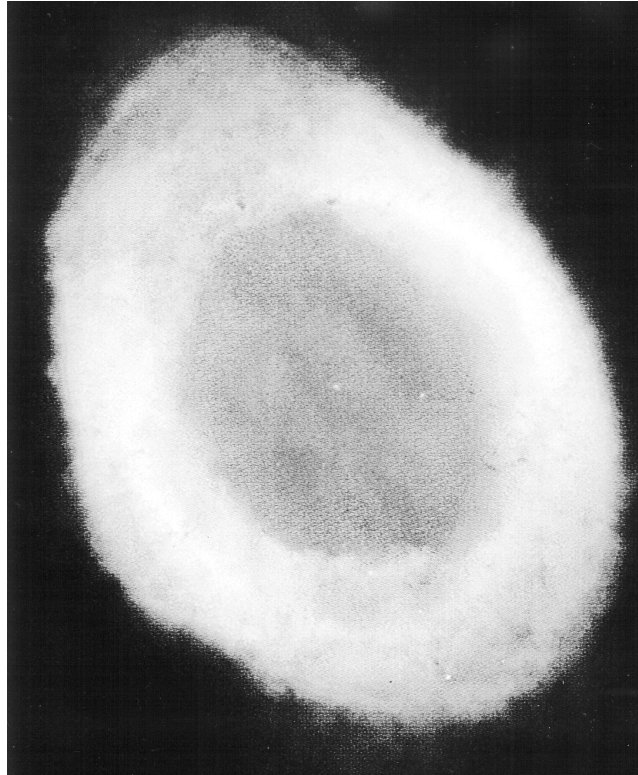


Fig. 9 A ring nebula observed by the Hubble Space Telescope (NASA/ESA, taken from CERN Courier, Vol.39, No.4, May 1999, p.10). The hot gas thrown into space by a supernova explosion travels at more than 100 km/s.

2. CONVERSION FACTORS FOR PRESSURE AND PRESSURE RANGES OF VACUUM, VACUUM GAUGES AND PUMPS

By *pressure* p one means the average force F_{\perp} in Newton (or the rate of normal momentum transfer) exerted by gas molecules impacting on a surface of unit area A (in m^2). Therefore, pressure can be expressed (in so-called "coherent" pressure units) as:

$$p = F_{\perp}/A \quad (\text{Pa}) \quad (\text{see Table 1}).$$

If there is a flow of gas, one has to distinguish between dynamic and static pressure, depending whether the gauge reading the pressure is stationary or moves with the same velocity as the flow. Similarly, one speaks of a steady-state pressure, if the pressure at different locations in a vacuum systems remains constant with time. Derived from the definition above, pressure can be expressed also (in "non-coherent" pressure units) as the height h of a liquid with density ρ (which is mercury for the unit Torr) of a manometer column under the acceleration $g = 9.806 \text{ m s}^{-2}$ due to gravity:

$$p = h g \rho \quad (\text{Torr}).$$

It can also be expressed by the number density of molecules n , the Boltzmann constant k and the temperature T :

$$p = n k T \quad (\text{Pa})$$

or by n , the mass per molecule m , the mean-square velocity v_{ms}^2 of molecules and the gas density ρ :

$$p = (1/3) n m v_{\text{ms}}^2 \quad (\mu\text{bar})$$

$$p = (1/3) \rho v_{\text{ms}}^2 \quad (\text{Torr}).$$

All the quantities used here are further explained in the following sections. As one can see, the gas pressure does not depend on the gas species. The conversion factors for pressure in various systems of units are given in Table 3.

Table 3
Conversion factors for pressure in various systems of units [8].

	Pa (N m ⁻²)	m b a r	T o r r (mm Hg at 0 °C)	Technical Atmospheres (at)	Physical Atmospheres (atm)
Pa (N m ⁻²)	1	1.0×10^{-2}	7.5×10^{-3}	1.02×10^{-5}	9.87×10^{-6}
m b a r	1.0×10^2	1	7.5×10^{-1}	1.02×10^{-3}	9.87×10^{-4}
T o r r (mm Hg at 0 °C)	1.33×10^2	1.33	1	1.36×10^{-3}	1.32×10^{-3}
Technical Atmospheres (at)	9.80×10^4	9.80×10^2	7.36×10^2	1	9.68×10^{-1}
Physical Atm.(atm)	1.01×10^5	1.01×10^2	7.60×10^2	1.03	1

The ultimate pressure of a system designates the limiting pressure approached in a vacuum system after pumping long enough to demonstrate that a further reduction in pressure is negligible. Similarly, the ultimate pressure of a vacuum pump is the limiting low pressure of a pump due to leaks or gases trapped in the various components of the pump. *Pumping speed* means the ratio of the throughput of a given gas to the partial pressure of that gas near the pump intake. The throughput or the amount of gas in pressure-volume units flowing per unit time at a fixed temperature across a specified cross section near the pump intake is often referred to as *pumping capacity*.

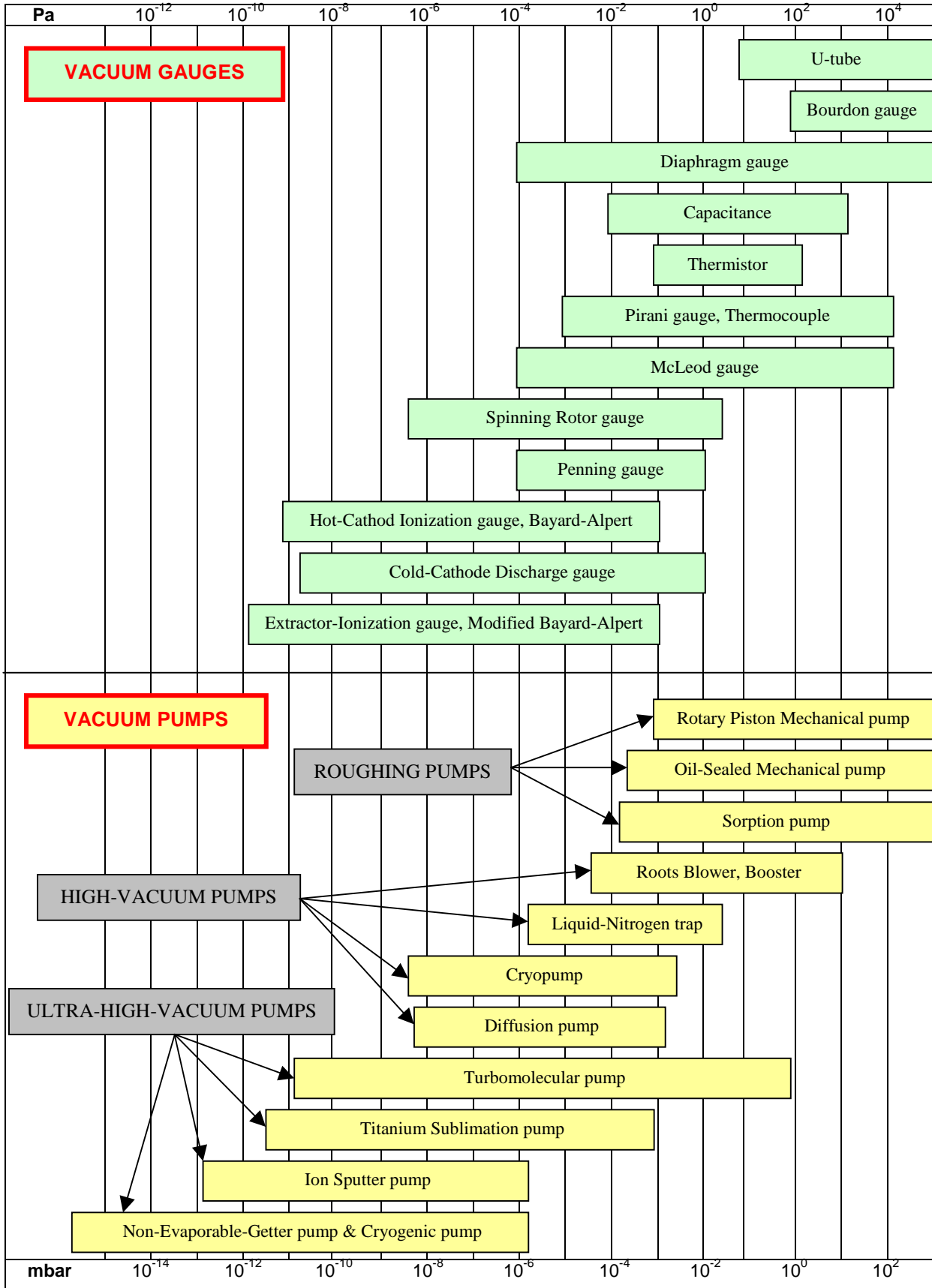
According to the number of particles in a given volume, or to the various regions of pressure correspondingly, there are different degrees or classes of vacuum (see Table 4), ranging from rough vacuum of some ten thousands of Pascal (Pa) to the fine, high (HV) and ultra-high vacuum (UHV) to the extreme high vacuum (XHV) ranging from 10^{10} to less than 10^{12} Pa (almost to 10^{14} Pa). Accordingly, vacuum covers a range of almost 19 orders of magnitude. As always in physics, to reach the extreme values of vacuum, either the generation or measurement of pressures of about 1/100 of a femtobar or less, is particularly attractive, because it pushes science to completely new and undiscovered areas. Pressures measured in space so far, are reaching further down to even lower values, which are at least one or two orders of magnitude smaller. Such pressures correspond to a density of only a few particles per cubic centimetre. Clearly, it is a real challenge for modern techniques to generate and to measure absolutely such low pressures, and it is not obvious at present whether the vacuum or its measurement is better.

Table 4
Classification of vacuum ranges [8].

Vacuum Ranges	Pressure Units			
	Pa		mbar	
	min	max	min	max
Low (LV)	3.3×10^3	1.0×10^5	3.3×10	1.0×10^3
Medium (MV)	1.0×10^{-1}	3.3×10^3	1.0×10^{-3}	3.3×10
High (HV)	1.0×10^{-4}	1.0×10^{-1}	1.0×10^{-6}	1.0×10^{-3}
Very High (VHV)	1.0×10^{-7}	1.0×10^{-4}	1.0×10^{-9}	1.0×10^{-6}
Ultra-High (UHV)	1.0×10^{-10}	1.0×10^{-7}	1.0×10^{-12}	1.0×10^{-9}
Extreme Ultra-High (XHV)	$\leq 1.0 \times 10^{-10}$		$\leq 1.0 \times 10^{-12}$	

According to this wide range of vacuum technology, vacuum measuring and vacuum generating techniques have had to be developed for widely differing magnitudes, exploiting various physical properties of gases. Table 5 shows the pressure ranges of the huge variety of vacuum gauges and vacuum pumps, to be discussed in the following lectures.

Table 5
Pressure ranges of vacuum gauges and vacuum pumps.



3. COMPOSITION OF AIR

Whereas atmospheric air is a mixture of gases with over 99% nitrogen and oxygen (see Table 6, for instance) the rest gas of high and ultrahigh vacuum consists mainly of the lightest gas hydrogen. The reason is that hydrogen easily penetrates walls, is adsorbed by all surfaces surrounding the volume and is less effectively pumped than gases of larger active molecules.

Table 6
Composition of atmosphere (at sea level) [8].

Gas	Percent by Volume	Partial Pressure (mbar)
N ₂	78.08	7.93×10^2
O ₂	20.95	2.12×10^2
Ar	0.93	9.39
CO ₂	3.3×10^{-2}	3.33×10^{-1}
Ne	1.8×10^{-3}	1.87×10^{-2}
He	5.24×10^{-4}	5.33×10^{-3}
Kr	1.1×10^{-4}	1.11×10^{-3}
H ₂	5.0×10^{-5}	5.06×10^{-4}
Xe	8.7×10^{-6}	8.79×10^{-5}
H ₂ O	1.57	1.72×10
CH ₄	2.0×10^{-4}	1.99×10^{-3}
O ₃	7.0×10^{-6}	7.06×10^{-5}
N ₂ O	5.0×10^{-5}	5.06×10^{-4}

4. IDEAL AND REAL GASES

4.1 Ideal gases

The theoretical concept of an ideal gas is very useful for the description of vacuum-physics problems. It assumes that (i) the molecules are small spheres, (ii) the gas density is relatively small, i.e. the volume of molecules is small compared to the total volume occupied by the gas, (iii) the molecules do not exert forces on each other, i.e. the temperature of the gas is not too low, (iv) the path travelled by molecules is linear and random and (v) collisions between molecules are purely elastic. Under these conditions, which are the normal ones, the transition from one state of a gas, specified by its pressure p_1 , volume V_1 and thermodynamic temperature T_1 (measured in degrees Kelvin) to another state with quantities p_2 , V_2 , T_2 can be described by *the Boyle-Mariotte law for an ideal gas* :

$$p_1 V_1 / T_1 = p_2 V_2 / T_2 = \text{const}$$

This means that for a given gas pV/T is a constant value. Under normal conditions this is best fulfilled for H₂ and He. The constant depends for a given temperature only on the number of molecules contained in the volume, i.e. from the amount of gas enclosed.

For a given mass of a gas, three fundamental relations can be derived from Boyle-Mariotte's law, namely:

Boyle's law

$$T = \text{const}$$

$$p_1 V_1 = p_2 V_2 = \text{const}$$

(isothermal phase transition)

Charle's law

$$p = \text{const}$$

$$V_1 / T_1 = V_2 / T_2 = \text{const}$$

(isobar phase transition)

Gay-Lussac's law

$$V = \text{const}$$

$$p_1 / T_1 = p_2 / T_2 = \text{const}$$

(isochore phase transition).

For the case of thermal insulation one has $Q = \text{const}$, with $dQ = 0$ and the (p,V) -relation: $pV^{\kappa} = \text{const}$, corresponding to an adiabatic phase transition ($dQ = dU + pdV$ with the specific heat capacities at $p, V = \text{const}$).

It was observed that by relating pV/T to the concept of mole, its value is the same for any ideal gas. A mole is the weight in grams equal numerically to the molecular weight of a substance. For instance: 1 mole O_2 , H_2 , $H_2O = 32$ g, 2.016 g, 18.016 g respectively. Avogadro found that the mass m (of a standard volume of gas at the same temperature and pressure) is proportional to its molar mass (molecular weight) M . In other words the amount of moles n_M in a given mass m of a substance having a molar mass M is: $n_M = m/M$. It was shown by experiments that under standard conditions of temperature (0°C or 273.16 K) and pressure (1.013250×10^5 Pa or 760 Torr) one mole (or gram molecular weight) of any gas occupies a volume of 22.4 liter (= 22 415 cm^3). It is: $pV = 22.4 m/M$, with m : mass of gas, M : molar mass, V in liters and p in Pa, where the pressure p is proportional to the gas density $\rho = m/V$.

For a gas mixture, the total pressure is the sum of all partial pressures: $p = p_1 + p_2 + \dots + p_i = \sum p_i$ (Dalton's law) and the mean molar mass is: $\langle M \rangle = (m_1 + m_2 + \dots + m_i) / (n_{m1} + n_{m2} + \dots + n_{mi})$ (in g/mol).

The number density n of particles (atoms, molecules etc.) is given by:

$$n = N/V = (N_A/R) (p/T) = n_M (N_A/V) = (m/M) (N_A/V) \text{ (particles/m}^3\text{)},$$

where N is the total number of particles (molecules) and V the volume. Under the same conditions of pressure and temperature, equal volumes of all gases have the same number of particles (Avogadro's law, L.R.A.C. Avogadro : 1776 - 1856). This volume is called a mole, and the number of particles in one mol of a substance is given by Avogadro's number N_A . By independent measurements of the mass of the hydrogen atom (particle mass) of $m_p = 1.67 \times 10^{-24}$ g and the molecular weight of H_2 : $M = 2.016$ g, one can calculate Avogadro's number to be :

$$N_A = M/m_p = 2.016 / (2 \times 1.67 \times 10^{-24}) = F/e = 6.0221367 \times 10^{23} \text{ (molecules/mol)}.$$

One gets the number N_A independently also from the quotient of the value of the Faraday F (defined as the electrical charge necessary to deposit electrolytically one mole of a substance) and the charge e of an electron. One mole of any gas has N_A particles and under standard conditions occupies 22.4 liters. From these values one can calculate that in a standard liter there are:

$$(6.022 \times 10^{23} \text{ particles}) / 22.4 \text{ liters} = 2.69 \times 10^{22} \text{ particles/liter} .$$

R is the *universal (or molar) gas constant*:

$$R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1} \text{ (with } p \text{ in Pa, } V \text{ in m}^3, T \text{ in K)}.$$

Whereas the universal gas constant R is related to moles, Boltzmann's constant k is calculated on a molecular basis:

$$k = R/N_A = 1.3806 \times 10^{-16} \text{ erg/K} = 1.3806 \times 10^{-23} \text{ J/K} , \text{ (with } 1 \text{ J} = 1.0 \times 10^7 \text{ erg} = 2.388 \times 10^{-1} \text{ cal)}.$$

From this the equation of state of an ideal gas is derived, which describes how the measurable quantities of a gas depend on each other:

$$pV = n_M RT = (m/M) RT$$

Again, from Dalton's law one gets for a mixture of gases: $pV_M = (\sum n_{Mi})RT$, with total volume $V_M = \sum V_i$ and total pressure $p = \sum p_i$, if all components have the same pressure.

With $n = N/V$ (molecules/ m^3) and $m = M/N_A$ one obtains for the gas density: $\rho = mn = pM/RT = pm/kT = M/V_M$. The density of gas depends on the two parameters temperature and pressure, which both must be given, if the density is quoted.

The pressure p exerted by a gas depends only on the number density of molecules $n = N/V$ and temperature T of the gas, not on the particular gas. It can be expressed as the force F it exerts on a unit area A or as the number density of molecules $n = N/V$, Boltzmann's constant $k = R/N_A$ and the temperature T (see: section 2).

4.2 Real gases

At low temperatures or high pressures a gas approaches the points of condensation or sublimation, where it changes its phase from the gaseous to the liquid or even solid one. Such a gas is called a real gas (or vapour). Due to the action of interatomic or intermolecular forces under these conditions, the p - V curve of a real gas deviates from that of an ideal gas, exhibiting a flat plateau, which corresponds to the liquid-gas phase transition. Near the critical point (critical temperature and pressure) the behaviour of real gases can be described very satisfactorily by a modified equation of state, *the Van der Waals equation* (J.D. van der Waals: 1837 -1923):

$$(p + n_M^2 a/V^2) (V - n_M b) = n_M RT, \quad (\text{for } n_M = m/M > 1 \text{ mol})$$

The correction term $n_M^2 a/V^2 \sim (m^2/V^2) = \rho^2$ with $a = \text{const}$ takes the forces of intermolecular attraction into account, which brings molecules closer together, acting like an additional pressure. The volume-correction term $n_M b$ is a measure of the actual volume of all molecules of their own, which is four times that of the molecule itself and increases with the molecular diameter. Whereas the isotherms of an ideal gas are hyperbolas, those of a real gas at sufficiently low temperatures exhibit first a maximum and then a minimum with decreasing volume (see Fig. 10). Normally, at critical values of temperature T_c , volume V_c and pressure p_c these extrema merge at a critical point into a curve with horizontal turning tangent. The values of a and b are determined for most gases as a function of the critical point (T_c, V_c, p_c) of the corresponding gas ($a = 3 p_c (V_c/n_M)^2 \sim \rho_c^{-2}$; $b = 3 V_c/n_M$) and are tabulated. The limiting temperature T_B (Boyle's point) up to which a gas can still be described like an ideal one, even up to high pressures, is given by $T_B = a/(bR)$.

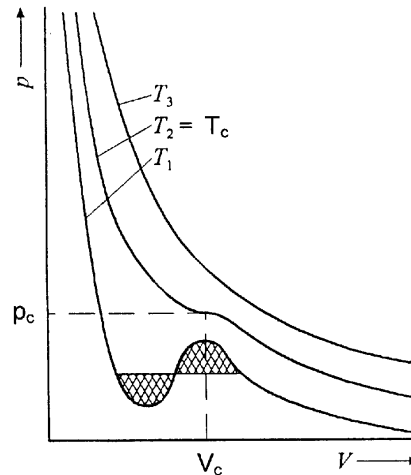


Fig. 10 Isotherms of a real gas according to van der Waals.

5. KINETIC THEORY OF GASES

5.1 Molecular velocities and temperature

Gas molecules are in constant, irregular thermal motion. The velocity of this motion depends on the molar mass M and temperature T only. The higher the molar mass, the lower is the velocity, for a given temperature. Concerning molecular velocities, one distinguishes between the most probable velocity v_p , the arithmetic average velocity v_a (e.g. of a flow of gas), the mean-square velocity v_{ms} and the root-mean-square velocity v_{rms} (normally used, when the kinetic energy of the molecule influences the process), which are simply related in the SI-system of units by :

$$v_{rms} = (v_{ms})^{1/2} = (3RT/M)^{1/2} = (3kT/m)^{1/2}, \quad (\text{m s}^{-1}), \quad \text{with}$$

$$v_p = 129 (T/M)^{1/2} < v_a = 146 (T/M)^{1/2} < v_{rms} = 158 (T/M)^{1/2}, \quad (\text{m s}^{-1}).$$

These velocities are independent of gas pressure and, as can be seen from Table 7, they are greater than the speed of sound of ~ 330 m/s in air.

Table 7
The root-mean-square velocity v_{rms} of different gas molecules at 0 and 23 °C [8].

Gas T (K)	v_{rms} (m s ⁻¹)												
	monoatomic					diatomic					polyatomic		
	He	Ne	Ar	Kr	Xe	H ₂	N ₂	CO	O ₂	Air	NH ₃	C ₂ H ₂	CO ₂
273	1305	581	413	285	228	1838	512	493	461	485	632	511	393
296	1358	605	430	297	237	1914	533	514	480	505	659	533	410

In contrast to the velocity, the concept of temperature of a gas cannot easily be associated with a single molecule. Temperature is understood in terms of the kinetic energy and velocity of motion. If the air, surrounding us, has a molecular velocity below 400 m/s, it appears to us too cold, if it is above 500 m/s it is too hot.

5.2 Velocity distribution and mean free path

The constant motion of molecules and their collisions produce a wide distribution of velocities, from about zero to very large values, which is expressed by the *Maxwell-Boltzmann law* (J.C. Maxwell: 1831 - 1879; L. Boltzmann: 1844 - 1906):

$$(1/n) \, dn/dv = f_v = (4/\pi)^{1/2} (m/2kT)^{3/2} v^2 \exp(-mv^2/2kT)$$

where dn is the number of particles in the velocity range between v and $v + dv$ (per unit of velocity range) and f_v is the fractional number of particles between v and $v + dv$, which is zero for $v = 0$ and $v = \infty$ and has its maximum at the most probable velocity: $v_p = (2kT/m)^{1/2} = (2RT/M)^{1/2} = 0.816 v_{\text{rms}}$. In Fig. 11 f_v is plotted versus v/v_p

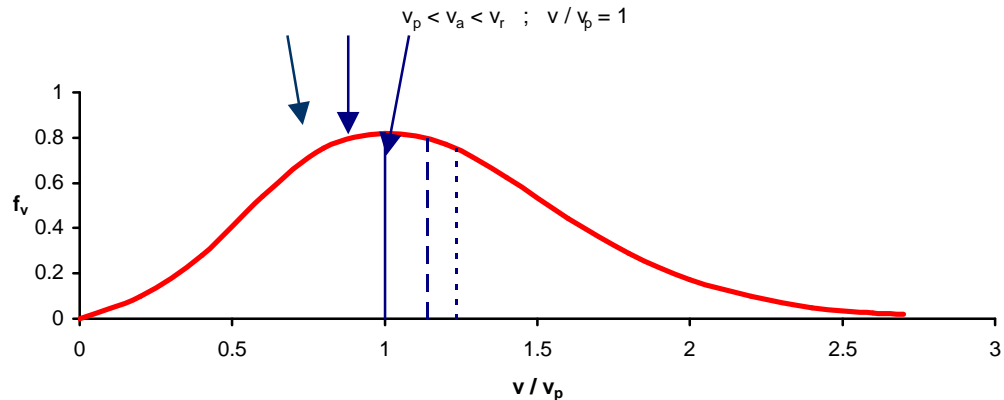


Fig. 11 Maxwell-Boltzmann molecular velocity distribution for a gas at a particular temperature T .

The average distance travelled by all gas molecules between successive collisions is called the *mean free path* λ . It depends on the size and the number of the molecules, i.e. on gas density and pressure. Applying the kinetic theory of gases by using the Maxwell-Boltzmann distribution and the relation $p = nkT$, the average mean free path is given in m by:

$$\lambda = 1/(2^{1/2} \pi d^2 n) = kT/(2^{1/2} \pi d^2 p) = 3.107 \times 10^{-24} T/(d^2 p),$$

where d (m) is the molecular diameter, $n = N/V$ (m⁻³) is the number of molecules per volume, T (K) is the temperature and p (Pa) is the pressure. Accordingly, λ is proportional to the absolute temperature and inversely proportional to the gas pressure.

For air (assuming that all molecules have the same d at room temperature (23 °C), one gets: $\lambda_{\text{Air}}(\text{m}) = 6.5 \times 10^{-3}/p$ (Pa). For common gases, the range of variation of λ is about a factor of 10. When the mean free path becomes greater than the dimensions of the vacuum vessel, the collisions become less frequent and the molecules mostly collide with the walls of the vessel.

The mean free path was derived for pure elastic collisions between the molecules. Taking into account the attractive forces between the molecules, one found empirically that at very high temperature T_{∞} the mean free path is: $\lambda_{\tau} = \lambda_{\infty} / (1 + C/T)$, (with $n, C = \text{const}$).

It is interesting to compare the mean free path of electrons λ_e (cm) and ions λ_{ion} (cm) in a gas with that of neutral molecules λ (cm). One finds approximately: $\lambda_{\text{ion}} = 2^{1/2} \lambda = \lambda_e/4$. Values of mean free path for different pressures or particle densities, respectively, are given below in Table 8.

Table 8

Rough values for characteristic vacuum parameters at a few pressures and gas flow regimes.

	Pressure				
	10 ⁵ Pa 10 ³ mbar	10 ² Pa 10 ⁰ mbar	10 ¹ Pa 10 ⁻³ mbar	10 ⁻⁴ Pa 10 ⁻⁶ mbar	10 ⁻⁷ Pa 10 ⁻⁹ mbar
Particle Density, n (cm ⁻³)	10 ¹⁹	10 ¹⁶	10 ¹³	10 ¹⁰	10 ⁷
Mean Free Path, λ (cm)	10 ⁻⁵	10 ⁻²	10	10 ⁴	10 ⁷ (= 100 km)
Impingement Rate, Z_A (s ⁻¹ cm ⁻²)	10 ²³	10 ²⁰	10 ¹⁷	10 ¹⁴	10 ¹¹
Collision Rate, Z_V (s ⁻¹ cm ⁻³)	10 ²⁹	10 ²³	10 ¹⁷	10 ¹¹	10 ⁵
Monolayer Time, τ	10 ns	10 μ s	10 ms	10 s	3 h
Type of Gas Flow					

From the Maxwell-Boltzmann equation given above, one can derive the number of molecules striking an element of surface perpendicular to their direction of movement, per unit time, the so-called *impingement rate* Z_A as:

$$Z_A = 8.333 \times 10^{22} p / (TM)^{1/2} \text{ (molecules m}^{-2} \text{ s}^{-1}\text{)}, \text{ with } p \text{ (Pa), } T \text{ (K) and } M \text{ (kg/mol),}$$

$$= 2.635 \times 10^{22} p / (TM)^{1/2} \text{ (molecules cm}^{-2} \text{ s}^{-1}\text{)}, \text{ with } p \text{ (mbar), } T \text{ (K) and } M \text{ (g/mol).}$$

Similarly one can calculate the *collision rate* ZV (in molecules cm⁻³ s⁻¹), which is the number of collisions in a unit volume per unit time.

For ultra-high-vacuum systems there is another quantity of interest, namely the *monolayer time* τ , which is defined as the time required for a monolayer to form on a clean, gas-free surface. To derive τ , it is assumed that every impinging gas molecule finds and binds to a vacant site (sticking coefficient $\equiv 1$). The monolayer time τ , in seconds, is inversely proportional to the pressure and can be estimated from:

$$\tau = 3.2 \times 10^{-6} / p, \text{ with } p \text{ in mbar.}$$

Approximate values for particle density n , mean free path λ , impingement and collision rate Z_A and Z_V and monolayer time τ are given for different pressures in Table 8, where also the relevant types of gas flow are indicated (see also section below).

6 THERMAL CONDUCTIVITY AND ENERGY TRANSPORT

So far, all systems discussed have been in thermodynamical equilibrium. If there is a temperature difference in the system, a heat transfer will be observed, from which the specific thermal conductivity of the gas can be determined. Similarly, if differences in pressure or particle density exist, one has a flow of particles from positions of high pressure to low-pressure regions. Pressure differences lead to velocity distributions, which correspond to the transport of particles and are connected to the viscosity of a gas or its coefficient of internal friction of a gas. The *coefficient of viscosity* is given as:

$$\eta = 0.499 n m v_a \lambda ,$$

with the gas density $\rho = n m$, v_a = average molecular velocity and λ = mean free path.

The specific heat conductivity of a gas is proportional to its coefficient of viscosity. Therefore, they have the same dependence on pressure. Differences in particle density in a system lead to mass transport, called diffusion.

The mean free path of gas particles is related to both, the thermal conductivity and the viscosity of gases. Concerning heat conductivity and other phenomena of energy transport, one must distinguish between low and high pressures and, correspondingly, between different states of a gas or types of gas flow, which will be discussed in the following section. Depending on the state of the gas, transport phenomena behave differently. Above approximately 1.3 kPa (= 13.3 mbar = 10 Torr) the heat transfer through a gas inside a small chamber is dominated by convection due to the bulk motion of the gas. In other words, in this so-called *viscous state* of a gas the totality of molecules is responsible for the heat transfer. In this range of gas flow the heat conductivity of gases is independent of pressure, which is also true for the viscosity. At lower pressures, when the mean free path of molecules λ becomes much greater than the dimensions of the container, which is called *molecular state*, the individual molecules carry the heat from wall to wall. Then the gas is no longer characterised by a viscosity. Under this low-pressure condition of so-called free molecular conduction the heat transfer depends only on the number of carriers. Thus the rate of energy transfer, the conductivity, is proportional to the pressure and the temperature difference.

Both, the variation of conductivity and of viscosity with pressure are utilised for pressure measurements, in the first case by monitoring the heat transfer rate from a hot filament to the surrounding walls (thermal conductivity gauges), in the second case by measuring the deceleration of a freely rotating body, a metallic sphere suspended in a permanent magnetic field, due to collisions with the rest gas (viscosity manometers, spinning rotor gauge). Heat transfer in high-vacuum is very low compared to conditions at atmospheric pressure. Therefore, there is very little heat flow for instance between two metal plates in high vacuum. Heat transfer by conduction takes place only through the small areas of contact, if not high clamping forces are used to enlarge the touching area.

7 GAS FLOW

7.1 Gas flow regimes and transport phenomena

When a system is pumped down from atmospheric pressure to high vacuum, the gas in the system goes through various regimes of gas flow. These regimes depend on the size of vacuum components, the gas species and the temperature. One distinguishes the *viscous state* at high pressures from the *molecular state* at low pressures and an *intermediate state* between these two. At atmospheric pressure up to about 100 Pa (= 1 mbar), the mean free path of the gas molecules is very small (see Table 8). Therefore, the gas flow is limited by viscosity and the type of flow is called *viscous*. This type of gas flow is characterised by intermolecular collisions that impart to the gas the appearance of a viscous fluid. At low pressures, however, where the mean free path is similar to the dimensions of the vacuum vessel containing the gas, its flow is governed by viscosity as well as by molecular phenomena. This type of gas flow is called intermediate or sometimes *Knudsen regime*. To specify the types of gas flow, the dimensionless *Knudsen number* (1910, M. Knudsen: 1871-1949) has been defined as

$$K = \lambda/d,$$

with the characteristic dimension of the vessel or the diameter d of a cylindrical pipe (K is proportional to the ratio of Mach and Reynolds number, see below).

$K \ll 1$ holds for the viscous flow regime with the characteristics of a continuous fluid. At very low pressures, where the mean free path is much larger than the dimensions of the vacuum enclosure ($K \gg 1$), the flow is molecular. In this state, the molecules interact mostly with the walls of the vessel not with themselves (rarefied "Knudsen gas").

In the viscous state of a gas, one distinguishes further between *turbulent* and *laminar* flow. When the velocity of the gas flow exceeds certain values, the flowing gas layers are not parallel and cavities are formed between them. Then the viscous flow is turbulent. On the other hand, at lower

velocities the flow is laminar, i.e. the layers are moving parallel, forming e.g. in a pipe a parabolic velocity distribution with increasing velocities from the wall towards the axis of the pipe. Whereas the limit between laminar, intermediate and molecular flow is defined by the value of the Knudsen number, the limit between turbulent and laminar flow with the characteristics of a continuous fluid is described by the value of another dimensionless quantity, the *Reynolds number* (O. Reynolds: 1842-1912), which is expressed by

$$R = d v \rho / \eta$$

the ratio of kinetic energy and frictional work, with d = diameter of the pipe or characteristic size of the vacuum component, v = gas velocity and ρ , η the density and viscosity of the gas at the temperature of the flow.

By evaluating the Knudsen and Reynolds number, one can predict the various flow regimes, which can be distinguished approximately by the following relations :

- | | | | | |
|----------------------|----------------|---|--------------|------------------------|
| (1) $R < 1200$ | ($K < 0.01$) | : | laminar | (viscous gas state) |
| (2) $R > 2200$ | ($K < 0.01$) | : | turbulent | (viscous gas state) |
| (3) $1.0 > K > 0.01$ | | : | intermediate | (transition gas state) |
| (4) $K > 1.0$ | | : | molecular | (rarefied gas state). |

The exact value of R for which the flow changes from laminar to turbulent depends on the geometry of the component, its surface roughness and other experimental factors. During evacuation of a vessel, turbulent flow normally occurs only for a short period of time at the beginning. It has been found to be approximately proportional to the root of the pressure gradient.

Transport phenomena in the viscous state of a gas are characterised by its coefficient of internal friction or *viscosity* η , which is defined as the tangential force per unit area for unit rate of decrease of velocity with distance. The tangential force per unit area is given by the rate of momentum transfer between adjacent layers. From this one can derive the coefficient of viscosity (see section 6):

$$\eta = 0.499 \rho v_a \lambda ,$$

in (units of viscosity) poise (J.-L.M. Poiseuille: 1799 - 1869), $1 \text{ Pa s} = 1 \text{ kg m}^{-1} \text{ s}^{-1} = 10 \text{ poise}$.

Contrary to liquids, for which the viscosity decreases as the temperature increases, the viscosity of gases at normal pressure increases with temperature. At very high pressures, however, the intermolecular forces are important and the momentum transfer is very different. Correspondingly, at very low pressures there are almost no collisions between molecules, and momentum transfer happens only between molecules and walls. Since the viscosity in the viscous state is not a function of pressure, thermal conductivity is in this case also independent of pressure.

Like viscosity, *diffusion* of gases into each other is also determined by the mean free path λ . In the case of diffusion of molecules in the same gas at constant temperature, the coefficient of self-diffusion has been found to vary inversely as the density ρ of gas or directly with λ : $D_{11} = 1.342 \eta / \rho = v_a \lambda / 3$. Diffusion pumps function on the principle of interdiffusion (coefficient D_{12}) of a gas having a low number density of molecules $n = N/V$ into another gas that has a very high number density.

Transport phenomena in the molecular state, when λ is very large, are no longer determined by molecular collisions or viscosity of the gas. In this case, molecules condense on a surface, rest on it a given time and then reevaporate in arbitrary directions. There is a certain time required to form a monolayer on a clean surface (see section 5.2 and Table 7). If the surface is in motion it can transfer a velocity component to the molecule. This is the principle exploited by (turbo) molecular pumps. Rotating molecular gauges (like the spinning rotor gauge) also use this principle of molecular drag.

Unlike the viscous state, in the molecular state heat conductivity or so-called free molecular conduction depends upon pressure. In this range the rate of energy transferred by molecules between two surfaces is proportional to the pressure and temperature difference between the surfaces. Thermal conductivity at low pressures is used for measuring the pressure by thermal conductivity gauges. Normally, with such gauges the pressure is determined by variation of temperature, keeping the energy input for heating a filament constant.

If two chambers A and B with gases at different temperatures T_A and T_B are separated by a narrow pipe or a porous plug, the following relation holds: $p_A T_B^{1/2} = p_B T_A^{1/2}$. In this case, thermal transpiration will occur, which means gas will flow between the two chambers until an equilibrium is established.

This is important in situations where a chamber A is at low temperatures, say at liquid air temperature $T_A = 90$ K, and the pressure is measured with a gauge at room temperature $T_B = 300$ K. Then the real pressure is: $P_A = (90/300)^{1/2} P_B = 0.55 P_B$. At higher pressures (λ smaller than tube diameter) molecular collisions become predominant and the condition of equilibrium is $P_A = P_B$ instead.

7.2 Conductance and gas flow for different vacuum components and systems

7.2.1 Conductance, pumping speed and throughput

Since gases have much lower viscosities than liquids, they flow typically with velocities of tens to hundreds of meters per second at relatively small pressure differences. Under normal conditions the gas flow with the pressure difference as driving force can be compared with the flow of heat or electricity in a conductor, caused by a voltage difference. The flow rate Q or electrical current I is directly proportional to the potential difference and inversely proportional to resistance. In complete analogy to the electrical current $I = \Delta V/R$, one gets for a gas flow through a pipe with resistance, known as impedance Z :

$$Q = (p_1 - p_2)/Z = \Delta p/Z = C \Delta p .$$

The reciprocal of the impedance (resistance to the gas passage) is called conductance C of a pipe:

$$C = 1/Z \text{ (m}^3/\text{h)} .$$

For heat transfer one gets a similar expression for the thermal energy: $H = C_i (T_1 - T_2)$, with $C_i = kA/L$ (k = conductivity; A , L = cross-section, length of conductor). Flow impedance Z and flow conductance C of a vacuum component vary with gas species M and temperature T and except in molecular flow, with gas pressure. In other words, Z and C depend on the gas-flow regime and the geometry of the component. For the total impedance of several vacuum components connected in series or in parallel hold the same relations as for the resistance of conductors for the electrical current, i.e.:

$$\begin{aligned} Z_{\text{tot}} &= Z_1 + Z_2 + \dots + Z_n & \text{or} & & 1/C_{\text{tot}} &= \sum_i 1/C_i & \text{(in series)} \\ 1/Z_{\text{tot}} &= 1/Z_1 + 1/Z_2 + \dots + 1/Z_n & \text{or} & & C_{\text{tot}} &= \sum_i C_i & \text{(in parallel)} . \end{aligned}$$

The conductance of a pipe $C = Q/\Delta p$ can be written as: $C = p v A/\Delta p$, with p = pressure, v = flow velocity of the gas and A = cross-sectional area. For the energy associated with flow, namely the potential energy of pressure or the kinetic energy of motion, the principle of preservation of energy holds. This is known as the Bernoulli principle (D. Bernoulli: 1700 - 1792), which can be expressed as follows: in a fluid of negligible viscosity the sum of potential and kinetic energy, associated with p and v along a streamline, remains constant, which means acceleration (deceleration) of flow is accompanied by a drop (rise) in pressure.

Since p is associated with the density $n = N/V$, the flow of gas can be interpreted as the number of molecules N , passing with flow velocity v per unit time through a cross-section A of a pipe. This relation defines the rate of flow or the pumping speed S as follows:

$$N = A v n = S n \text{ with the pumping speed } S \equiv A v \text{ (m}^3/\text{h)} .$$

According to this definition, the rate at which gas is removed from a vacuum system by pumps is measured by the pumping speed S_p of a vacuum pump. It is generally defined as the volume of gas per unit of time dV/dt that is removed from the system at the inlet pressure p of the pump:

$$S_p = dV/dt = Q/p ,$$

where V = volume of gas flowing per unit time, p = steady pressure at the plane through which the flow or throughput Q of gas passes (not for transient pumping speeds). Therefore, the throughput Q of a pump is given as the product of pumping speed S_p and inlet pressure p :

$$Q = p S_p = p dV/dt = C\Delta p .$$

This equation holds only if p is constant, it does not apply to the transient state of flow. It describes the throughput of a pump with pumping speed S_p at the intake pressure p , if p and V are constant. Correspondingly, the throughput for a passive element can be expressed as the product of the conductance C with Δp , where Δp is the difference between the pressures at the entrance and exit of the element. By analogy with this expression, the pumping speed at any point of the vacuum system is:

$$S = Q/p .$$

This leads to the following expression for the effective pumping speed S_{eff} of a pump with nominal pumping speed S_p and the conductance of connections between the pump and the volume to be evacuated :

$$\boxed{1/S_{\text{eff}} = 1/S_p + 1/C_{\text{tot}}}$$

This is a basic formula in vacuum physics, because in most cases a pump is not connected directly to a vacuum vessel. Almost always an intermediate system of pipes and various vacuum components is necessary, which introduces a flow resistance (C_{tot} = total flow conductance) resulting in an effective pumping speed S_{eff} smaller than the pumping speed S_p of the pump. In order to ensure a definite effective pumping speed at the container, a correspondingly higher speed of the pump must be chosen. Only in the case where $C_{\text{tot}} = \infty$ (or impedance $Z_{\text{tot}} = 0$) is $S_p = S_{\text{eff}}$.

From the equation given above one sees also, that it does not make sense to increase the pump, if the conductance of the connecting components (pipes etc.) is limiting the pumping speed. One should always make sure that in a certain pressure region only the corresponding relevant conductance value is used. In general, it must be emphasised that the conductance of a vacuum component has by no means a constant value, independent of the pressure. It depends greatly on the kind of flow, viscous or molecular (see below), and therefore, on the pressure.

7.2.2 Conductance in the viscous flow and transition regime

When a gas at constant pressure p_1 escapes from a large volume through a small aperture into a region where the pressure is $p_2 < p_1$, the gas acquires a velocity and streamlines are formed in the flow direction towards the aperture. After passing to the low-pressure side p_2 , the gas jet has a minimum cross-section and then expands and contracts again approximately 10 times until finally it diffuses in the mass of gas p_2 . This is the characteristic of a *laminar* flow.

By decreasing p_2 ($p_1 = \text{constant}$), the quantity and velocity of gas are increasing up to the state where p_2/p_1 reaches a critical value, corresponding to a velocity equal to the sound velocity (*Mach number*: $\text{Ma} = 1$; E. Mach: 1838 - 1864). Further decrease of p_2 does not increase the flow or velocity further. The dimensionless Mach number is defined as $\text{Ma} = v_a/v_s$, where v_a is the average gas-flow velocity and v_s is the local acoustic velocity, which is a function of the gas species and temperature (for air at 23 °C: $v_s = 329 \text{ m s}^{-1}$).

As has been discussed already, at higher pressures, the value of the conductance depends on pressure, whereas it is independent of pressure in the region of molecular flow. Resistance to mass flow for a given pressure difference is reduced with rising pressure, because fewer molecules interact with the stationary walls and the flow rate depends on the viscosity of the gas.

The viscous flow rate of gas through a long ($L \geq 20 d$, L = length in cm, d = diameter in cm) straight pipe of uniform circular cross section is proportional to the average pressure $p_a = (p_1 + p_2)/2$ (in dyn cm^{-2}), the pressure difference at the ends of the pipe ($p_1 - p_2$) and the diameter d of the pipe to the 4th power and inversely proportional to the length L of the pipe and the gas viscosity η (in poise). This is *Poiseuille's law* (Poiseuille: see above):

$$\boxed{Q_{\text{vis}} = (\pi d^4/128 \eta L) p_a (p_1 - p_2) , \quad (\text{erg s}^{-1})}$$

For air at 23 °C this gives: $Q_{\text{vis}}(\text{air}) = 4.97 (d^4/L) p_a (p_1 - p_2) , \quad (\text{Pa m}^3 \text{ h}^{-1}) .$

The laminar conductance of straight pipes of uniform, circular cross section is :

$$C_{\text{vis}} = (\pi d^4/128 \eta L) p_a \text{ (cm}^3 \text{ s}^{-1}\text{)} \text{ and for air at } 23^\circ\text{C: } C_{\text{vis}}(\text{air}) = 4.97 (d^4/L) p_a \text{ (m}^3 \text{ h}^{-1}\text{)}.$$

The conductance for an aperture of surface area A (in cm^2) in the case of viscous laminar flow of air is given by the formula of Prandtl (L. Prandtl: 1875 - 1953) :

$$C_{\text{vis}} = 76.6 \delta^{0.712} (1 - \delta^{0.258})^{1/2} A/(1 - \delta) \text{ (l s}^{-1}\text{)}, \text{ with } \delta = p_2/p_1 < 1.$$

At the critical pressure ratio (see above): $\delta_{\text{crit}} = (p_2/p_1)_{\text{crit}} = 0.52$ the conductance for an aperture C_{vis} amounts to $40 A$ liters s^{-1} and approaches for $\delta \rightarrow 0$ the limiting value $C_{\text{vis}} = 20 A$ (l s^{-1}).

Only a few examples for conductance have been given here. Formulae for conductance values of vacuum components of different geometries and numerous nomograms for determining conductances can be found in the literature.

The steady flow of gas in the transition regime is also called Knudsen flow. This happens when the mean free path of molecules is of the same order of magnitude as the transverse dimensions of the pipe through which the gas flows. Approximate formulae for this condition have been derived for example by combining the laminar flow conductance with the molecular conductance of a long pipe.

7.2.3 Conductance in the molecular flow regime

At very low pressures, molecules will pass through an aperture from one chamber to the other in both directions without making any collisions near the aperture. In contrast with laminar flow, there is no mass motion of the molecules and the gas is practically unaffected by the presence of the aperture, the reason being that for the molecular flow regime (high vacuum) the mean free path λ is very large compared to the diameter d of the aperture ($\lambda \gg d$, aperture with length $L \approx 0$).

The molecular throughput and the molecular conductance of an **aperture** (for $p_1 > 10 p_2$) are given by:

$$Q_{\text{mol}} = (1/4) (8 k T/\pi m)^{1/2} (p_1 - p_2) A = (1/4) (8 R T/\pi M)^{1/2} (p_1 - p_2) A \text{ (erg/s)},$$

$$C_{\text{mol}} = Q_{\text{mol}}/(p_1 - p_2) =$$

$$C_{\text{mol}} = (1/4) (8 k T/\pi m)^{1/2} A = (1/4) (8 R T/\pi M)^{1/2} A \text{ (cm}^3\text{/s)} = 3.64 (T/M)^{1/2} A \text{ (l/s)},$$

with T (K), M (g/mol), A (cm^2) and $k = R/NA = 1.3806$ erg/K (see above). For air at $T = 23^\circ\text{C}$:

$$C_{\text{mol}} = 11.6 A \text{ (l/s)}.$$

One notices again that the molecular flow conductance of an aperture depends only on the kind (M) and temperature (T) of gas and not on the pressure. Accordingly, for constant temperature, C_{mol} varies with the molecular mass M only.

From these equations one can also derive the molecular pumping speed of an aperture:

$$S_{\text{mol}} = C_{\text{mol}} [(p_1 - p_2)/p_1] = 3.64 (T/M)^{1/2} (1 - p_2/p_1) A \text{ (l/s)}$$

and for air at $T = 23^\circ\text{C}$:

$$S_{\text{mol}} = 11.6 (1 - p_2/p_1) A \approx 11.6 A \text{ (l/s)}, \text{ for } p_2 \leq p_1.$$

Another example is the molecular conductance of a **long cylindrical pipe** of uniform cross-section with perimeter o , inner diameter d and length L in cm:

$$C_{\text{mol}} = (16/3) (R T/2 \pi M)^{1/2} A^2/o L = 19.4 (T/M)^{1/2} A^2/o L = 3.81 (T/M)^{1/2} d^3/L \text{ (l/s)}$$

and for air at $T = 23^\circ\text{C}$:

$$C_{\text{mol}} = 12.1 d^3/L \text{ (l/s)}.$$

From these equations for short apertures and long pipes one can also derive equations under certain assumptions for the molecular flow through short pipes and channels of various cross-sections and through vacuum components of simple and complex geometries, which all can be found in the literature.

If the vacuum system contains bends these can be considered on the basis that a greater effective length is assumed, which can be estimated in the following way:

$$L_{\text{tot}} < L_{\text{eff}} < L_{\text{tot}} + 2.66 n r ,$$

with L_{tot} , L_{eff} : total and effective length (in cm), n the number of bends and r the tube radius.

Normally, most components are constructed such that the pumping speed is not significantly throttled. As a general rule, one should always construct a vacuum line as short and wide as possible and with at least the same cross-section as the inlet port of the pump.

The values for the laminar and molecular conductance of air, given above, should be multiplied by the factors given in Table 9 for working with other gases.

Table 9
Conversion factors of conductance for air to other gases.

Gas at 23 °C	Molecular flow	Laminar flow
Air	1.00	1.00
O ₂	0.947	0.91
N ₂	1.013	1.05
He	2.64	0.92
H ₂	3.77	2.07
CO ₂	0.808	1.26
H ₂ O vapour	1.263	1.73

8 GAS LOAD AND ULTIMATE PRESSURE

In a vacuum system there are mainly three sources of gas, the so-called *gas load*, namely:

- (a) the residual gas in the system,
- (b) the vapour in equilibrium with the materials present,
- (c) the gases produced or introduced by
 - leakage (also "virtual leaks" by captured gas, without penetration through the walls)
 - outgassing (adsorption),
 - permeation (transfer of gas through a solid, through porous materials, glass etc.).

The *ultimate pressure* p_u of high-vacuum systems normally depends only on the gas load Q_G mentioned in (c) and on the effective pumping speed S_{eff} . It is given by:

$$p_u = Q_G / S_{\text{eff}} .$$

In the case of a leak, Q_G is constant and, therefore also p_u is constant, whereas p_u is a function of time when one has $Q_G = f(t)$, as it is when outgassing dominates. There exist extensive outgassing data and various tables and nomograms in the literature relating gas load and ultimate pressure and other system parameters. Table 10 presents outgassing rates K_1 for several vacuum materials.

In cases where the pumping process is dominated by residual gas, pumpdown in a high-vacuum region can be described by:

$$p = p_{t=0} \exp[-(S_{\text{eff}}/V_{\text{tot}})/t] ,$$

where p is the pressure after time t , $p_{t=0}$ is the pressure at $t = 0$, S_{eff} is the effective pumping speed and V_{tot} is the total volume of the system.

However, by far the most important uncertainty, associated with pump performances, pressure and flow measurements, and external leakage, is due to outgassing. The outgassing rates can easily vary by many orders of magnitude, depending on the history and the material of a surface, its treatment, humidity, temperature, and the period of exposure to vacuum. Since one usually approaches the ultimate pressure of a system asymptotically, even small changes in gas loads result in large differences of evacuation times.

Table 10

Approximate outgassing rate K_1 for several vacuum materials, after one hour in vacuum at room temperature.

Material	K_1 (mbar l s ⁻¹ cm ⁻²)
Aluminium (fresh)	9×10^{-9}
Aluminium (20 h at 100 °C)	5×10^{-14}
Stainless steel (304)	2×10^{-8}
Stainless steel (304, electropolished)	6×10^{-9}
Stainless steel (304, mechanically polished)	2×10^{-9}
Stainless steel (304, electropolished, 30 h at 250 °C)	4×10^{-12}
Perbunan	5×10^{-6}
Pyrex	1×10^{-8}
Teflon	8×10^{-8}
Viton A (fresh)	2×10^{-6}

9. CONCLUSION

This introduction to a special branch of classical physics attempts to cover the fundamental principles and most important phenomena of vacuum physics and technology described in much more detail in a series of textbooks. It was written with the intention of providing a short summary and useful background for the students of the CERN Accelerator School 1999 on Vacuum Technology, and to help them better understand the subsequent lectures on current areas of research in vacuum physics.

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