1. Fundamentals

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1.1 General Remarks

1.1.1 The history of vacuum technology

The first pioneering work on vacuum research was done by Torricelli, using tubes filled with mercury. These very first experiments and similar ones made by other researchers are recorded in Kaspar Schott's book „Technica Curiosa".

Independent of Torricelli, another trailblazing vacuum physicist, Otto von Guericke, was experimenting on vacuum research in Magdeburg. It was he who built the very first vacuum pump in the summer of 1657 and carried out his now famous experiments with the so-called Magdeburg hemispheres. With the help of his comprehensive work, he was able to prove that the air that surrounds us has weight and thus exerts pressure. This was the reason why 16 horses were unable to separate the sealed hemispheres evacuated by von Guericke.

With the advance of further engineering developments and improved methods of sealing with mercury and oil, lower and lower final pressures were achieved. However, it was the work of Gaede that made a major breakthrough possible. His sliding vane pump, invented in 1909, is regarded as being the forerunner of all modern rotary pumps.

The first diffusion pumps were built in 1975, opening up the path to high vacuum physics. The name of Langmuir is associated with this development.

Developments in vacuum pump technology today are centered around getter ion pumps, molecular pumps and cryogenic pumps, but mostly around important further developments in molecular pump technology.

New measuring methods and improvements in existing test systems in the field of measurement technology allow us to determine pressures down to 10^{-11} mbar. The employment of new materials open up new realms for improvement both in pump technology and in overall equipment techniques.

Despite the fact that the roots of vacuum technology reach back over 300 years, it is only over the last few decades that a rapid increase in the rate of development has taken place in this branch of technology.

Today, with the help of vacuum techniques, objects can be lifted and transported, liquids distilled and fractionated, foods and pharmaceuticals are dried and preserved. Metals and alloys melted in a vacuum often possess preferable characteristics compared with those melted with conventional processes.

Cathode ray tubes and electronic valves cannot function without vacuum.

The semiconductor industry and microelectronics are very closely involved in vacuum technology. Finest coatings created within a vacuum are used in the optical industry (mirrors, blooming). On textiles, plastics, glass and porcelain they serve as heat reflective, conductive or decorative coatings and on metals they serve as rustproof coatings. Developments in space technology, atomic physics or high energy physics are closely linked with high or very high vacuum.

As a result of the large industrial importance of vacuum techniques, leading industrial nations have a highly developed industry at hand that constructs related plant for many applications. However, commercial equipment is not available for every purpose, so that scientists and engineers are often forced to construct their own vacuum plant „made to measure", that is matched to their actual problems.

Applications

Electrics and electronics	Drying (insulating oil, coolants) Impregnation (insulating materials) Hermetic sealing (amplifiers) Evacuation and degassing (electronic valves, lamps) Evaporation and spraying (condenser production, thin-film techniques Encapsulation (tubes, semiconductor elements) Welding and surface treatment (microcircuits) Crystal growth Surface reactions (transistors, microchips)
Scientific instruments	Physical-chemical inspections, electron and ion microscopes, x-ray analyzers, microwave equipment Extremely low temperature analyzing Particle accelerators Fusion plant
Chemical industry	Distillation Filtration Drying Evaporation
Food industry	Freeze drying (fresh and cooked food) Preservation
Metallurgy and semiconductor production	Distillation Reduction Sintering Smelting and casting (alloys, high melting point and reactive metals) Drying (powder) Heat treatment
Production techniques	Impregnation (moulds) Injection molding (bubble-free alloyed parts Chucking Welding and brazing
Transport in various branches of industry	Lifting and conveying (paper, sheet metal, CRT’s, ...)
Other applications	Vaporizing (paper, plastics, textiles, ...) Thermal insulation (Dewar vessels, ...) Molding (plastic, vacuum casting) Concrete hardening

1.2.1 The definition of vacuum

Vacuum is the thermodynamic state existing in space filled with a gas and/or vapor at pressures below atmospheric pressure, as determined in DIN 28400.

Vacuum is the state of a gas in a container in which the particle number density is less than it is outside, or, when the pressure of the gas is less than 300 mbar, that is, less than the lowest atmospheric pressure existing on the earth's surface.

1.2.2 Alphabetical list of vacuum terms

Absorption
Absorption is a sorption by which the gas (absorbate) forces its way into the inner part of a solid body or fluid (absorbent)

Backing pressure (UK), fore pressure (US)
The backing pressure, or fore pressure, is the reduced pressure produced at the inlet port of a fore pump which makes it possible for another vacuum pump in a vacuum pump combination to produce the very low pressure required at its inlet port.

Capacity
The capacity of a vacuum pump S is the pV flow of the gas being pumped.
The units of capacity are
$Pa \times l \times s^{-1}$, $mbar \times l \times s^{-1}$

Compression chamber
A compression chamber is the space within the stator of some displacement vacuum pumps, the volume of which decreases and in which gas is compressed before discharge.

Compression ratio
The compression ratio is the ratio of the external pressure to the inlet pressure of a pump for a certain gas.

Condensation trap
A condensation trap works on the principle of condensation on cooled surfaces.

Conductance
In most applications, the vacuum pump is connected to the receiver via a pipe. This pipe has a conductance that is defined as the relationship of the pressure difference across the pipe (p) over the flow of gas (q). In high vacuum and very high vacuum the conductance is independent of pressure. The unit of conductance is
$s \times m^{-3}$, $s \times l^{-1}$

Degassing
Degassing is a desorption that is accelerated by a physical process.

Desorption
Desorption is the release of absorbed gases in an absorbent. The release can be either spontaneous or accelerated by physical processes.

Diffusion
Gas diffusion is the movement of a gas as a result of its gradient of concentration in another medium. The medium can be either gaseous, liquid or solid.

Final pressure
The final pressure is that value that the pressure asymptotically approaches in a blank-flanged pump under normal operating conditions and without any gas inlet.

Flow
Vacuum systems are generally evacuated from atmospheric pressure downwards. During this process - depending on the relationship of the internal size of the system components to the average length of the mean free path of the flowing gas particles - various types of flow occur. Turbulent flows with a high Reynolds' number do not generally occur. During evacuation, the flow is initially laminar, Knudsen (transition) flows occur when the pressure falls and finally molecular flows occur. The various types of flow are not sharply delineated but merge gradually with each other. The resulting phenomenon can be mathematically proven; but lead to relatively complex formulas, especially when Knudsen flows are calculated.

Gas
Gas is a material in a state of aggregation (physical condition) in which the average distances between the particles is large compared to their size and the mutual configuration of the individual particles continuously changes.
In the narrow sense of the word, gas is material in a gaseous state that cannot be changed into the liquid or solid state at the prevailing temperature.

Gas ballast
Water vapor drawn in by a rotary vane pump can condense during compression in spite of the high pump temperatures. If, for example, an air-water vapor mixture is drawn in by a pump, then during the compression phase the water vapor reaches a saturation pressure that corresponds to the pump temperature. It cannot be compressed further but continually condenses at a pressure that remains constant. The water mixes with the pump oil resulting in a reduction of the final pressure.

Gas release
Gas release is a spontaneous desorption.

Gettering
Gettering is the binding of a gas, mostly through chemical reactions. Often, getters (getter matter) have large surface areas.

Laminar flow
Laminar flow is a viscous flow at small Reynolds' numbers without any turbulent movement.

Leakage rate
The leakage rate is the pV flow of a gas through a leak. It is dependent on the type of gas, pressure differential and temperature. The unit of the leakage rate is
$1\text{Pa} \times \text{m}^3 \times \text{S}^{-1} = 1 \text{ mbar} \times \text{l} \times \text{s}^{-1}$.

Leaks
Leaks in a vacuum system occur mostly in peripheral walls or at connecting points, caused by defective materials, faulty workmanship or faulty handling of sealed elements.

Mass flow
Mass flow is the quotient of the mass of a gas flowing through a pipe cross-section over a period of time, and the period of time.

Maximum tolerable water vapor pressure P_{wo}
The maximum water vapor pressure is the highest pure water vapor pressure that a pump can continuously pump. The value is quoted in mbar.

Multiple-stage vacuum pump
A multiple-stage vacuum pump is a series of pump systems which, mostly contained in a common housing, are combined to a constructive unit.

Number density of particle
The number density of particles is the quotient of the number of particles that are contained in an element of volume and the content of the element of volume.

Oil separator on vacuum pumps
An oil separator on a vacuum pump is a separator on the outlet end of displacement pumps for capture and, if required, return of vacuum pump oil in the vacuum pump. If the oil is not separated in droplet form, the separator is called an oil mist separator or oil mist filter.

Partial pressure

The partial pressure is the pressure of a certain type of gas or a vapor in a mixture of gases and/or vapors.

Pressure

The pressure of a gas against a limiting wall is the quotient of the normal component of the force exerted on a surface element or wall by the gas, and the content of the surface element

Pumpdown time

The pumpdown times and/or pumpdown characteristics for rotary vane pumps and twin rotor pumps quoted in the pump catalogue are generally measured. Pumpdown times for pumps with a suction flow rate over a large inlet pressure range can also be calculated. This is especially applicable for sliding vane pumps between 1013 and a few tenths of a millibar. As the suction flow rate of twin rotor pumps is not constant, the calculation is made over sections of the characteristic capacity curve, taking a mean flow rate in each case.

Saturation vapor pressure

The saturation vapor pressure is that pressure that is exercised by a vapor that is in thermodynamic balance with its condensed phase at the prevailing temperature.

Sliding vane

A sliding vane is a component that divides the compression chamber between rotor and stator into different chambers in some displacement pumps.

Sorption

Sorption is the binding of a gas (sorbate) by a solid body or a liquid (absorbent). Absorbents are also called adsorption mediums.

Standard condition

The standard condition is the condition of a solid, liquid or gaseous matter as prescribed by standard temperature and standard pressure.
Standard temperature:
T_s = 273.15K δ_n = 0 °C

Standard pressure
p_s = 101325 Pa = 1013.25 mbar

Suction flow rate

The suction flow rate S is the mean volume flow through the cross-section of the inlet port of a pump
The units of suction flow rate are
$m^3 \times s^{-1}$, $1 \times s^{-1}$, $m^3 \times h^{-1}$

Total pressure

The total pressure is the sum of the partial pressures of the existing gases or vapors. This term is used if the shorter term 'pressure' does not permit a clear differentiation between the individual partial pressures and their sum in a given situation.

Trap

A trap is a device in which the partial pressure of undesired components in a mixture of gases and/or vapors is reduced by physical or chemical means.

Turbulent flow

Turbulent flow is a viscous flow with mixed flows above the critical Reynolds' number Re (Re = 2300 for cylindrical pipes).

Vacuum range

Vacuum ranges are ranges of pressure or number densities of particles into which, by agreement, vacuum is divided.

Vapor

Vapor is material in a gaseous state that is either in thermodynamic balance with its liquid or solid phase (saturated vapor) or can be brought into thermal balance (condensed) at the prevailing temperature by compression (unsaturated vapor)
Note:
In vacuum technology, if there is no need to differentiate, the word 'gas' is used in its broadest sense both for non-condensable gas as well as for water vapor.

Vapor pressure

Vapor pressure is the partial pressure of a vapor.

Volume flow rate

The volume flow rate is the quotient of the volume of a gas that flows through a pipe over a certain time interval at the prevailing pressure and prevailing temperature and the time interval itself.

Water vapor capacity C_{wo}

The water vapor capacity is the largest quantity of water in the form of water vapor that a vacuum pump can draw in and pump continuously per time unit under ambient conditions of 20 °C and 1013 mbar.

Working pressure

The working pressure is the lowest pressure that must be reached or held constant during a vacuum process. When selecting a pump, it must be taken into account that the final pressure quoted in the technical specification was measured in a vacuum circuit of good characteristics. The lowest achievable pressure in a connected receiver is not only dependent on the final pump pressure but also from the cleanliness (dirt, gas exuding from walls and fittings), from the air-tightness and from the effective pump flow rate at the suction port of the receiver.

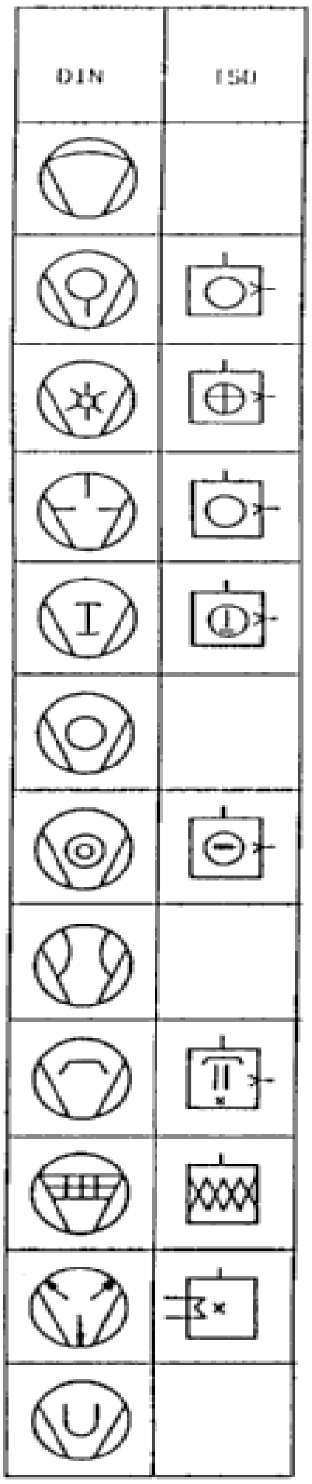
1.3 Grouping of Vacuum

Vacuum range	mbar	Particle number density	Mean free path
Low vacuum (GV)	1000-1	$2{,}5\cdot10^{25}$-$2{,}5\cdot10^{22}m^{-3}$	$l \ll d$
Medium vacuum (FV)	$1\text{-}10^{-3}$	$2{,}5\cdot10^{22}$-$2{,}5\cdot10^{19}m^{-3}$	$l \approx d$
High vacuum (HV)	$10^{-3}\text{-}10^{-7}$	$2{,}5\cdot10^{19}$-$2{,}5\cdot10^{15}m^{-3}$	$l > d$
Ultra high vacuum (UHV)	$<10^{-7}$	$<2{,}5\cdot10^{15}m^{-3}$	$l \gg d$

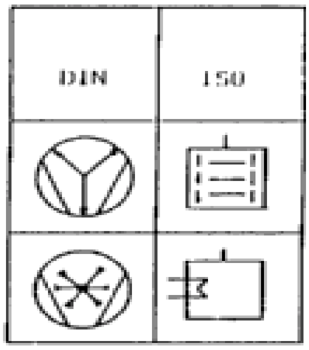
The particle number density is valid at a temperature of 20 °C

1.4 Symbols used in Vacuum Technology

1.4.1 Vacuum pumps / accessories

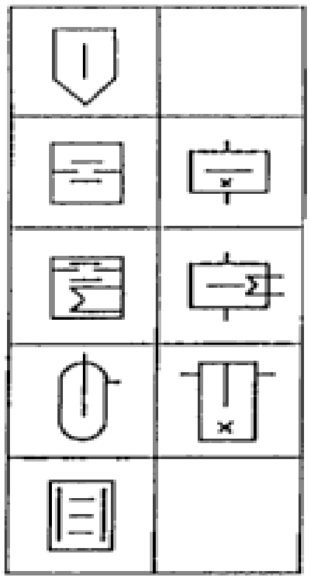


- membrane vacuum pump
- rotary plunger vacuum pump
- fluid ring vacuum pump
- sliding vane vacuum pump
- twin-rotor vacuum pump
- turbo vacuum pump (general)
- turbo-molecular vacuum pump
- fuel vacuum pump
- diffusion vacuum pump
- adsorption pump
- getter pump
- evaporation pump



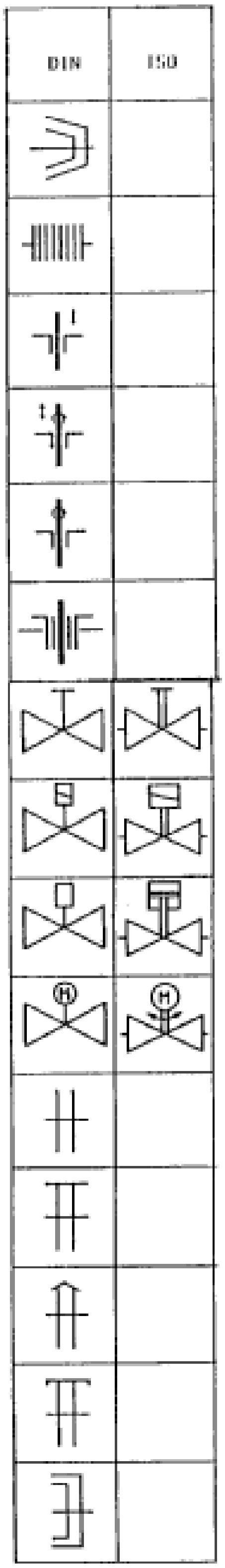
- ion transfer pump
- cryptogenic pump

Vacuum pump accessories



- separator (general)
- vapor trap (general)
- cooled vapor trap
- condensation trap (general)
- sorption trap

1.4.2 Shut-off elements



ground cone connection

flexible connecting hose

sliding lead-through

rotary sliding lead-through

rotary lead-through

electrical cable lead-through

hand operated

electro-magnet driven

fluid driven hydraulic or pneumatic)

electro-motor driven

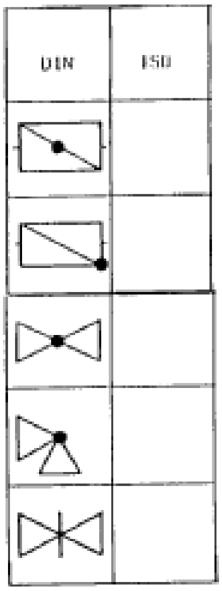
flange joint

screwed flange joint

small flange joint

clamp flange joint

threaded pipe joint



butterfly valve

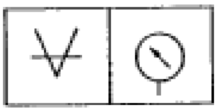
check flap

shut-off valve through valve

corner valve

shut-off slide

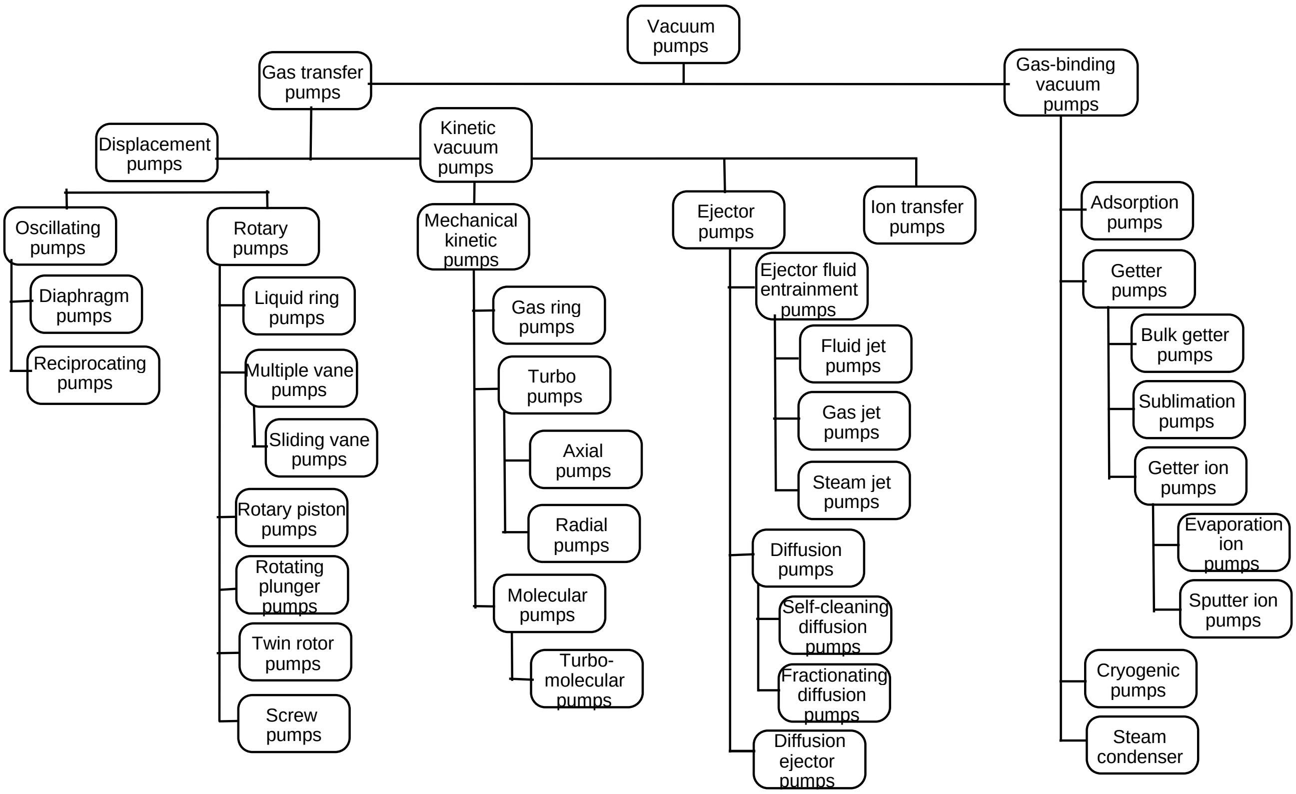
measuring devices



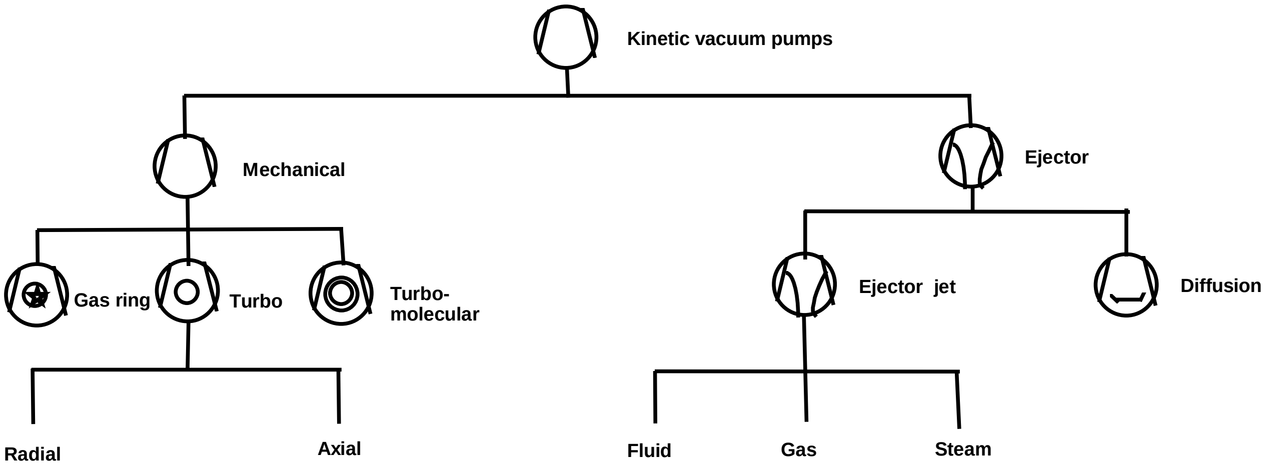
vacuum gauge

1.5 Vacuum Pumps

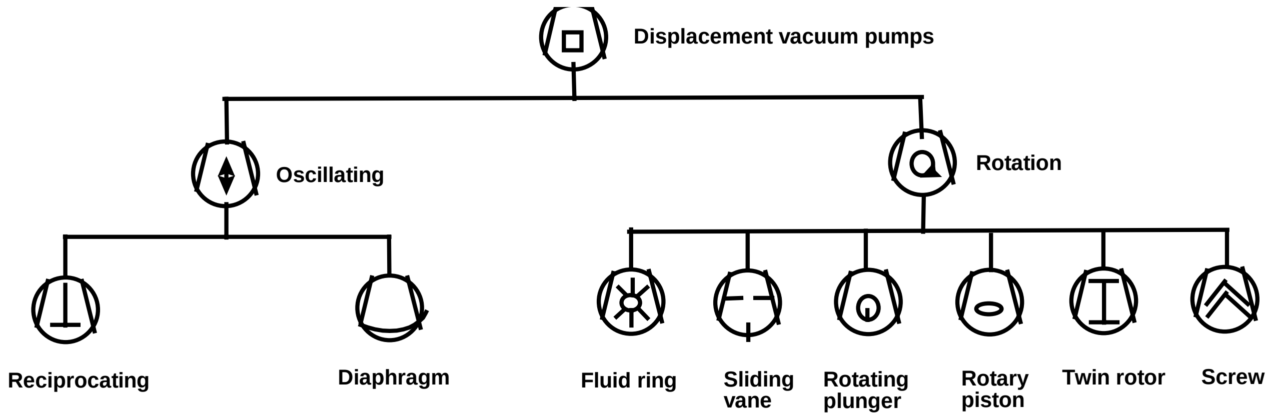
1.5.1 Classification of vacuum pumps



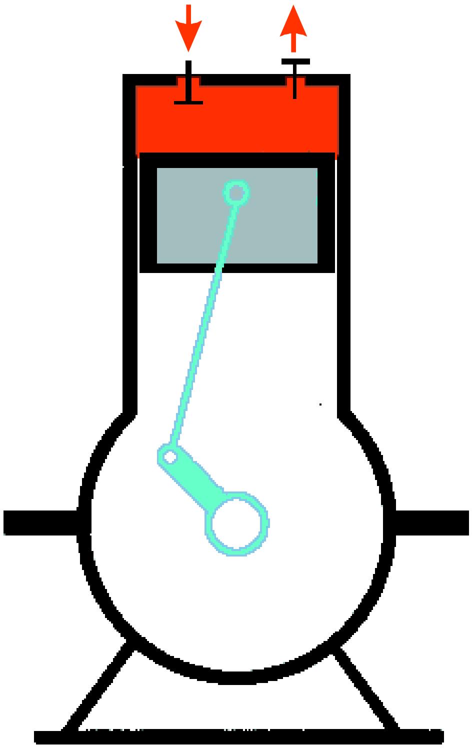
1.5.1.1 Kinetic pumps



1.5.1.2 Displacement pumps

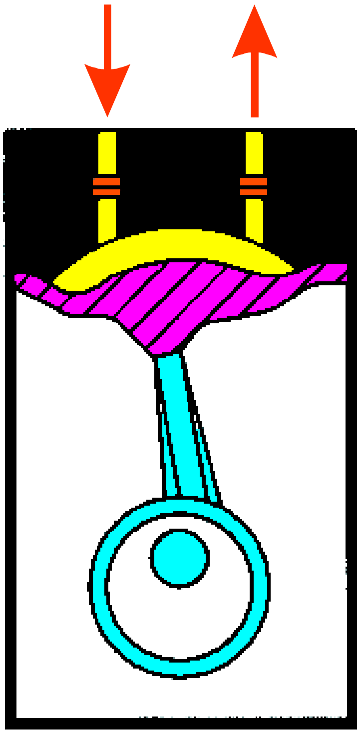


1.5.2.1 Reciprocating pumps



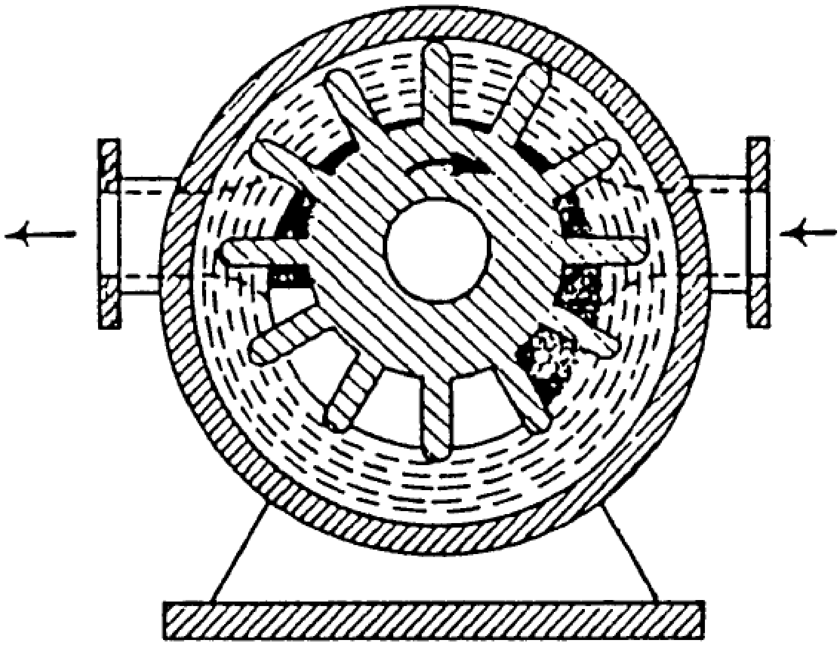
A periodically changing compression chamber is connected alternately to the inlet and discharge ports. Even with optimum design, the so-called dead space, in which gas always remains, exists at the top dead center point. It is for this reason and because of the heavy, vibrating crankshaft drive that reciprocating vacuum pumps are practically no longer used.

1.5.2.2 Diaphragm pumps



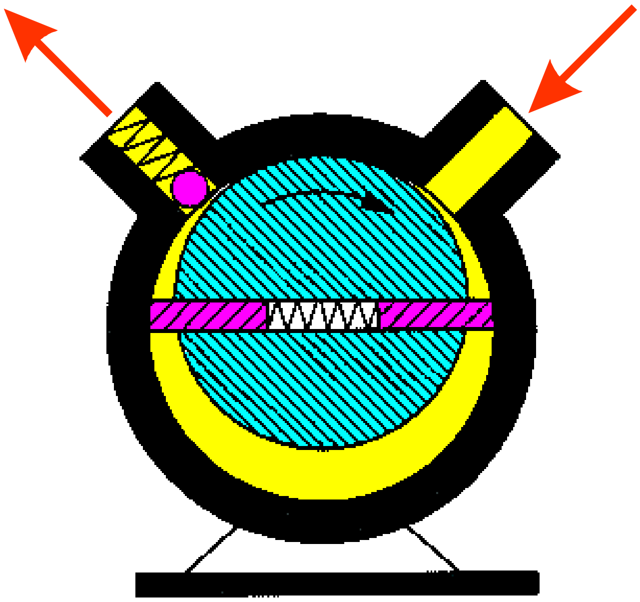
A periodically changing compression chamber is connected alternately to the inlet and discharge ports. On diaphragm pumps the piston is replaced by a flexible diaphragm. Small diaphragm pumps with low capacity ($1 m^3 h^{-1}$) are, however, used in many applications. As a single-stage unit they produce pressures down to 50 mbar, as multiple-stage units, down to 2 mbar.

1.5.2.3 Fluid ring pumps



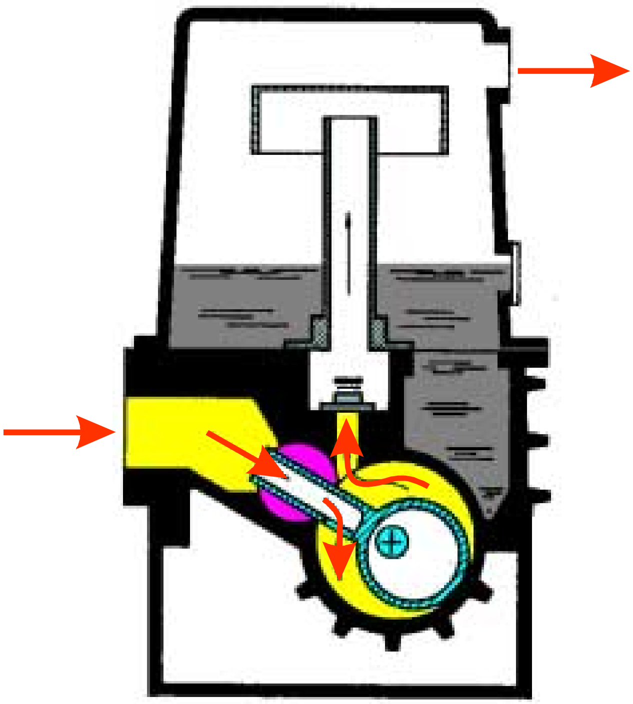
An eccentric lobe rotor generates a rotating fluid ring. Cells are built up between this ring and the hub of the rotor in which the gas is transported from the inlet to the discharge port. Fluid ring pumps work from atmospheric pressure down to the vapor pressure of the working fluid.

1.5.2.4 Sliding vane pumps



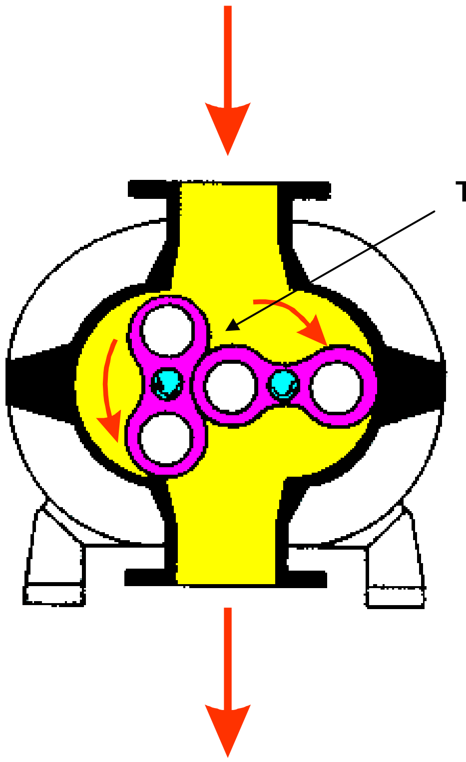
A sliding vane vacuum pump is a rotational displacement pump in which an eccentric rotor glides tangentially past the inner surface of the stator (casing). Two, or more, sliding vanes fitted in slits in the rotor (mostly radial) slide past the inner wall of the stator and divide the compression chamber into sickle shaped cells of changing volume.

1.5.2.5 Rotating plunger pumps



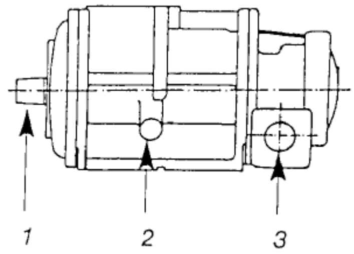
An eccentrically driven piston glides along the walls of the cylindrical casing. The gas to be pumped enters the sickle-shaped compression chamber via the rotating plunger. The piston and the plunger form a single unit. As rotation continues, the gas is compressed by the piston and is finally discharged by the discharge valve. The advantage of the rotating plunger pump is its robustness and insensitivity to contamination. Its disadvantage is the large reciprocating masses that limit its speed and cause heavy vibration.

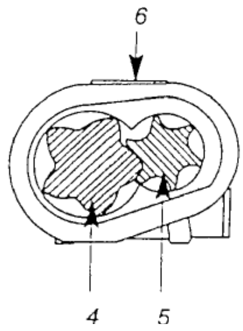
1.5.2.6 Twin rotor pumps



A twin rotor vacuum pump is a rotary displacement pump in which two figure-of-eight shaped rotors of equal cross-section rotate counter to each other in a cylindrical chamber (casing) of oval cross-section without contact with each other or the chamber walls. The two rotors are so synchronized that they move past each other with a very small clearance. No compression takes place in the actual chamber.
The task of the twin rotor pump is to increase the working range of displacement pumps to lower pressures and higher flow rates.

1.5.2.7 Screw Pumps



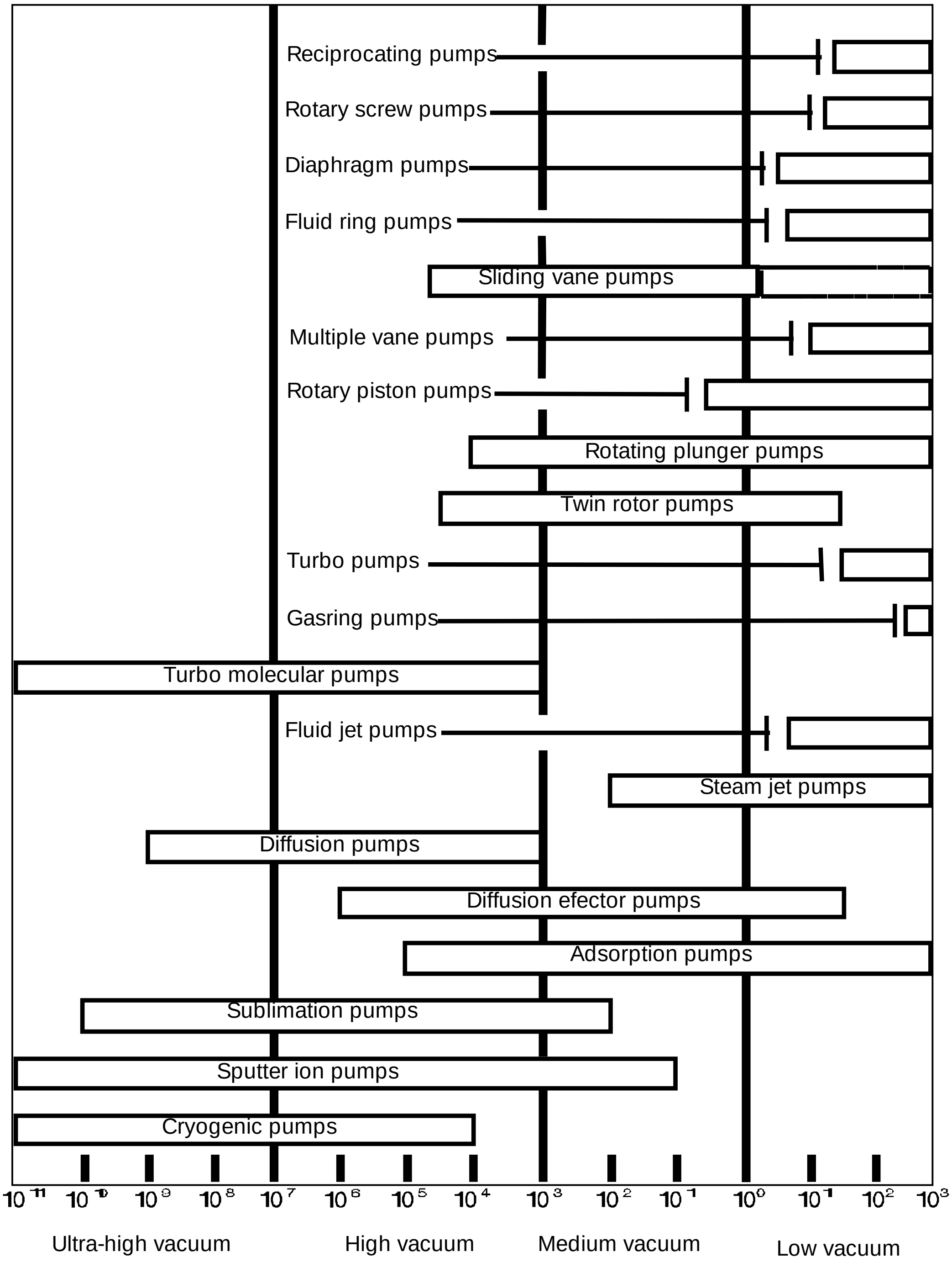


1 Drive shaft
2 Oil injector
3 Discharge port

4 Male rotor
5 Female rotor
6 Inlet port

The compressor housing contains two screw-form rotors, a mail and a female, which intermesh. As the rotors turn air is sucked into the inlet port and conveyed to the discharge, or compression port. Injected oil carries away the heat of compression as well as forming a lubricant film on the rotors to prevent direct contact, provides a seal on the rotors and between them and the housing wall, and also lubricates the rotor bearings.

1.5.3 Pressure ranges of vacuum pumps



1.5.4 Pressure ranges of Kaeser pumps