A survey is given on the gas transfer high vacuum pumps (diffusion and turbomolecular pumps) and entrapment pumps (cryopumps and getter pumps) used in industry and research, and on some important applications in the high vacuum range.

1. GENERAL INFORMATION

High vacuum conventionally means the pressure range between 10^-3 and 10^-7 mbar (1 mbar = 100 Pa = 0.75 Torr). Typical vacuum processes for this pressure range are: Evaporative coating, crystal pulling, tube production, mass spectrometers, electron microscopes, electron beam plants and particle accelerators.

The ultra high vacuum (UHV) range is the pressure range below 10^-7 mbar down to the lowest pressures which can nowadays be reached and measured, i.e. around or below 10^-12 mbar. Typical applications are: Nuclear fusion, space research, storage rings for particle accelerators, heavy ion accelerators, surface physics and molecular beam epitaxy (MBE).

Usually, a basic pressure is produced before the actual working process begins at a higher pressure. This happens, for example, in plants for evaporative coating, electron beam welding, particle accelerators and storage rings or for sputtering with Ar gas (basic pressure 10^-7 mbar, working pressure 10^-3 - 10^-2 mbar). For dry processes in which a non-condensable gas mixture is to be pumped, the pump to be used is characterized by the required basic and working pressure and by the quantity of gas to be pumped off.

Pumping larger amounts of vapors, the vapor partial pressure is an important factor in addition to these two quantities. It determines the pumping arrangement to a high extent. In this connection, condensers are important. These can be cooled by cooling machines, water or sometimes with LN₂.

Materials preferred for HV and UHV components are stainless steel but also aluminium and copper. When using the materials mentioned and avoiding external leaks in the equipment, pressures down to 10^-10 mbar are relatively easy to reach.

For pressure ranges below 10^-10 mbar, it is not enough to use just any vacuum pump suitable for this pressure range. Lowest pressures like these can only be reached and maintained if the following requirements are met:

- The total leak rate of the system must be extremely small.
- Degassing of the walls and the installations must be very low.
- The effects the pumps themselves have on the vacuum must be virtually nil. This comprises the oil back-streaming from diffusion and turbomolecular pumps as well as the desorption of gases already pumped off for sorption pumps.

2. HIGH VACUUM PUMPS

Vacuum pumps may be divided into two major types:

- Gas transfer vacuum pumps

These are transporting pumps which remove the gases and vapors pumped from the vessel to the atmosphere in one or more stages of compression. For the HV and UHV range, the most important types are diffusion pumps and turbomolecular pumps. During operation, these pumps require the support of a backing pump.

- Entrapment vacuum pumps

These are sorption pumps which do not remove the gases from the vessel but rather collect them at surfaces by means of physical or chemical mechanisms. Pumps of this type are cryopumps, sputter ion pumps, titanium sublimation pumps, and bulk getter pumps (NEG's).
This category also comprises adsorption pumps used as oil-free forevacuum pumps. Cryopumps and getter pumps require forevacuum pumps to get started yet do not need them in continuous operation.

2.1. DIFFUSION PUMPS

For a long period of time, oil diffusion pumps backed by a rotary vane pump were by far the most common combination for pumping systems down to pressures of 10⁻⁶ to 10⁻⁷mbar. The ultimate pressure, however, can be improved to 10⁻⁹ to 10⁻¹⁰mbar by using baffles and cold traps between pump and vacuum chamber.

Diffusion pumps with pumping speeds of approximately 40 up to 50,000 l/s with flanges DN 40 – DN 1000 are commercially available. Their main disadvantage is the generation of oil vapors and hydrocarbons.

Typical applications of diffusion pumps are: HV systems, evaporative coolers, furnaces, welding systems, production of TV tubes.

2.2. TURBOMOLECULAR PUMPS (TMPs)

Turbomolecular pumps are gas-transporting, mechanical vacuum pumps. They are based on the molecular drag pump designed by Gaede in 1913. From about 1957 on, technically usable pumps were designed after Becker had applied a rotor with turbine features for the gas transport from the high vacuum to the forevacuum side.

Thus, the TMP is a multi-stage, bladed, axial flow turbine that compresses gas by momentum transfer from the high-speed rotating blades to the gas particles. Under this condition, the blade rows act as barriers allowing selective permeation of gas particles from the low- to the high-pressure side.

Turbomolecular pumps may be provided with different types of bearings: Oil or grease lubricated bearings or magnetic bearings.

Turbomolecular pumps are usually equipped with frequency-controlled, asynchronous motors placed directly on the rotor shaft. These motors are supplied by an external frequency converter. Either electronic or motor converters can be used.

In the molecular flow range, the pumping speed is not dependent on the pressure. For different gases, it varies for just a few percent.

The compression ratio K, i.e. the ratio of the partial pressures on the forevacuum to the high vacuum side, depends on the gas type to a great extent and is for heavy gases essentially higher than for light ones. For all gases, K is independent of the pressure in the molecular flow range.

Pumps with pumping speeds of approximately 40 – 7000 l/s with flanges DN 35 to DN 500 are commercially available.

Typical applications of turbomolecular pumps are in the field of:

- production: semiconductors, TV and image converter tubes, optical coating, sputtering and crystal growing,
- instruments and systems: electron microscopes, mass spectrometers, surface analysis, ion sources, leak detectors, and others,
- research: accelerators and storage rings, fusion experiments, space simulation chambers, spectrometers.

Four examples shall be picked up:

(a) Fusion experiments

For the application in large plasma fusion experiments (ASDEX, JET, TEXTOR, FFHR, JT 60), special TMPs are used which meet the safety requirements concerning tritium tightness as well as the remote handling. These pumps are metal-sealed to the outside, laid-out for an automatic oil change and equipped with vibration detectors.

(b) Radiation-proof design

An equipment for use in areas exposed to radiation as in particle accelerators is often required to withstand a radiation load up to 10⁸ rad. TMPs are made suitable by the use of radiation-resistant material for their construction, i.e. motor coated with epoxy resin, oil pump chamber made of stainless steel, ceramic insulators, elastomer gaskets of high radiation resistance.

(c) Aluminium coating of TV tubes

Some modern Al vaporization systems for TV tubes utilize TMPs instead of diffusion pumps. Thus, the processing time is drastically reduced and hence the throughput is significantly increased. Other advantages such as no cooling water requirements, no frequent oil changes after tube implosions, minimized down time, less power consumption, and improved film quality are achieved at the same time.

(d) Semiconductor processing

Due to increased requirements regarding cleanliness, base pressure and process pressure in certain semiconductor applications, high vacuum and ultrahigh vacuum pumping systems have been used for some years now. In most cases, turbomolecular and cryopumps are used. However, for these pumps, semiconductor processing is nowadays the most important application.

In several cases, corrosive gases or reaction products have to be pumped. Mainly the bearings have to be protected against these. In order to meet such requirements, special types of corrosion-resistant turbomolecular pumps have been developed.
The use of toxic, corrosive and abrasive gases and the generation of remarkable amounts of solid byproducts create various problems for the vacuum pumps. In most cases, satisfactory results are only achieved by using suitable forevacuum pumps and accessories which are adapted to the specific process. Important is the choice of suitable oils and materials.

2.3 CRYOPUMPS

Cryopumps represent one of the most direct ways to produce a vacuum: gas molecules arriving at a cold surface are fixed to it and are thus removed from the gas (or the vapor) containing volume. At very low temperatures, practically any gas can be pumped down to pressures in the HV and UHV range. In practical work, however, temperatures of 4 - 20 K are used which are also sufficient.

There are three physical mechanisms of cryo pumping:

- Cryosorption
  Cryosorption is the physical adsorption of gases on cold surfaces.

- Cryocondensation
  Cryocondensation means the bonding of gas molecules to already bonded molecules of the same species.

- Cryotrapping
  This effect may be described as the sorption of noncondensable gases by an increasing layer of gases easy to condense.

After 1970, refrigerator-cooled cryopumps were available on the market which can be operated without He and without N₂. These pumps are usually equipped with a two-stage refrigerator, operating on the Gifford-McMahon principle. The cold head is separated from the compressor unit. Both are connected to each other by flexible pressure lines. Operating medium is helium gas. Depending on the refrigerator type, refrigerating capacities of 10 - 80 W at 80 K can be obtained with a lowest temperature of 30 K at the first stage. At the second stage, refrigerating capacities of 2 - 20 W at 20 K with a lowest temperature below 10 K can be obtained.

Radiation shield and baffle are contacted mechanically and thermally to the first stage. Here, for example, hydrocarbons and water vapor are condensed.

The second stage has a mechanical contact to the cryopannels which are partly covered by charcoal. Nitrogen, oxygen, argon and other gases are condensed at temperatures between 10 and 20 K. Neon, hydrogen and helium are adsorbed by the charcoal surfaces.

These are some important characteristics:

- Standard cryopumps are available for pumping speeds from 400 - 60,000 l/s for nitrogen and hydrogen for flange nominal widths DN 100-DN 1250.

- Cryopumps have an extremely high pumping speed for water vapor.

- A typical starting pressure is approximately 100 mbar.

- Final pressure down to 10 - 12 mbar can be obtained if a premature covering of the charcoal is prevented by a starting pressure of 10 - 5 - 10 - 6 mbar and if the system (except for the cryopump) is baked.

- Cryopumps can be operated in any position.

Typical applications of cryopumps are: sputtering, evaporative coating, space simulation, HV- and UHV systems, molecular beam technique, injectors and beam lines, collection of gases.

Two examples shall be given in more detail:

a) Sputter processes

In semiconductor processes, refrigerator-cooled cryopumps are used for sputtering applications as well as for ion implantation, MBE and plasma etching. They are mainly used because they offer extremely high water vapor pumping speed and hydrocarbon-free vacuum.

b) Space simulation chambers

In several space simulation chambers, IN₃-cooled shrouds are integrated to simulate the radiation background of the space and to act as cryocondensation surface for water.

In some cases, these shrouds are completed by large-area cryopannels cooled down to 10 - 20 K by using large stationary helium refrigerators. In the largest existing chambers, pumping speeds exceeding 10⁷ l/s are thus obtained.

In medium-size space simulation chambers, standard refrigerator-cooled cryopumps with pumping speeds between 5,000 l/s for air and hydrogen (flange DN 400) and up to 60,000 l/s (flange 1,25 m or 48") are attached.

2.4. GETTER PUMPS

Gettering is the binding of gases to solid surfaces. Suitable gettering materials are titanium, tantalum, zirconium, barium and strontium.

The binding of the gases is effected by

- adsorption; i.e. accumulation at the surface
- absorption; i.e. penetration into and sticking in the solid body
- chemisorption; i.e. by forming chemical compounds such as nitrides, oxides, carbides.

Hydrogen is dissolved physically to a great extent in the getter material. The chemically inactive noble gases are the most difficult to bind.
In general, the getter effect depends on the type of gas, the gettering material, the condition of the surface and on the temperature of the material.

Getter pumps are differentiated as follows:
- Sputter ion pumps
- Titanium sublimation pumps
- Volume getter pumps or NEG pumps (NEG = Non-Evaporable Getter).

2.4.1. SPUTTER ION PUMPS

In a gas discharge, ionized gas particles are produced with which a cathode made of getter material (normally titanium) is sputtered. The getter material reaches neighbouring surfaces and causes the pumping effect for gas molecules arriving there.

Diode pumps have an electrode system similar to the configuration given by Penning: cylindrical anodes are enclosed at both ends by two plain cathode plates. Between the anode and the cathode, there is a voltage of 4-6 kV. Parallel to the cylindrical axis of the anode, there is a homogeneous magnetic field of approx. 120 mT. Positive ions produced in the plasma are accelerated towards the cathode by the electrical field and they sputter cathode material on colliding.

Chemically active gases such as N2, O2, CO2, O2, H2O and H2 can be pumped on this material. Diode pumps also have a certain, however much smaller pumping speed for noble gases caused by ion implantation in the crystal lattice. Very large molecules like hydrocarbons, however, are unable to enter the lattice. Only that part of molecules is pumped which is cracked to its components during the bombardment.

In order to avoid the disadvantage of diode pumps in pumping noble gases, different solutions have already been found:
- The use of cathodes made from two different materials such as titanium and tantalum increases the pumping speed for noble gases to 10% of the value for nitrogen and reduces the memory effect.
- The use of triode pumps.

In triode pumps, instead of the massive cathode plates, a lattice made of narrow titanium rods is used. Behind the cathode lattice, the pump housing (3rd electrode) acts as a target plate. By means of this design, the material erosion at the lattice and the growth of the getter layer and the implantation of ions at the collector are separated from each other. Particles that have already been bound are released less and the memory effect is reduced essentially. The pumping speed of triode pumps for noble gases lies around 25% to 30% of the pumping speed for nitrogen.

Standard sputter ion pumps are available for pumping speeds between approx. 2 to 500 l/s.

2.4.2. TITANIUM SUBLIMATION PUMPS

In order to produce a getter film, titanium is heated and evaporated. It is sufficient to use a wire made of Ti-Mo-alloy. The evaporated titanium deposits on a large-surface shield made of copper or stainless steel. This shield is cooled with water or IN2.

Titanium sublimation pumps can absorb chemisorb active gases, e.g. N2, O2, CO, CO2, H2O and H2. Noble gases, however, are not pumped. For this reason, an additional pump is necessary to remove gases that cannot be gettered. In general, these pumps require a pumping speed of only 5 to 10% of the pumping speed of the sublimation pump. Sputter ion pumps or turbomolecular pumps are very suitable for this application.

Typical pumping speeds for titanium sublimation pumps lie between approx. 500 and 20,000 l/s.

2.4.3. BULK GETTER PUMPS (NEG PUMPS)

NEG pumps are operated with a getter material, mainly zirconium alloys, that makes it easy for the gas particles adsorbed at the surface to diffuse into the material. Diffusion of N2 and O2 is improved considerably by heating the getter material to operation temperatures up to 400°C. At the same time, this reduces the formation of diffusion hindering, stable chemical compounds at the surface.

H2 (and D2), however, diffuse already at room temperatures into the material so soon that gettering is possible for a sufficiently long period of time without heating.

Typical applications of getter pumps are: HV and UHV systems, surface analysis, thin film research, electron microscopy, mass spectrometry and high energy physics. Especially in accelerators and storage rings, sputter ion pumps in combination with Titanium sublimation of NEG pumps are used down to the 10⁻⁹mbar range.

3. FINAL REMARK

From the typical applications of the different high vacuum pump types given before, it can be seen that for different experiments or production processes, there is a choice between these different pump types.

Besides pumping speed and attainable ultimate pressure, there may be a large number of selection criteria for the choice of a special vacuum pump.