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Vacuum pumps and pumping systems

4.1 INTRODUCTION

Vacuum pumps are instruments whose purpose is to remove gas from an enclosed volume. This can happen in two distinct ways: the gas is either removed out of the enclosed volume or somehow bonded to an internal surface. In the first case, we speak of a *transfer pump*, in the second case we are dealing with a so-called *capture pump*.

A transfer pump removes gas by means of a moving part or substance, such as the rotating vanes or claws in a mechanical pump, or the working fluid in a diffusion pump. In a capture pump, gas is retained in the pump itself either by chemisorption to a suitable material, such as a vacuum-deposited titanium layer, or by physisorption (condensation) to a low-temperature and/or porous surface. Ion pumping (= ionization of gas particles, followed by acceleration and implantation of the ions in a solid surface) also belongs to the latter category.

Within the group of transfer pumps, based on their gas transfer principle, we distinguish between *displacement pumps* and *momentum transfer pumps*.

In a displacement pump part of the gas is mechanically separated and compressed at each ‘stroke’. Examples of such pumps are diaphragm pumps, rotary-vane pumps, liquid ring pumps, claw pumps and Roots pumps. A very simple 'home-garden-and-kitchen' example of a displacement pump is the so-called ‘Vacuvin’, sketched in figure 4.1. This small pump is used to remove air out of an opened wine bottle, in order to make the wine non-perishable. By putting the pump on the bottle and moving the piston up and down a few times, a pressure of roughly 0.2 atm can be achieved above the wine in the bottle.

In a momentum transfer pump gas particles are driven in the direction of the exhaust by interaction with high-speed (supersonic) vapour jets or fast-moving rotor systems. Examples of these are diffusion pumps and (turbo)molecular pumps.

In the category of capture pumps we distinguish sorption pumps (physical adsorption in porous materials, such as zeolite, activated charcoal or alumina), cryopumps (condensation to a deep-refrigerated surface), getter pumps (chemisorption to an active surface

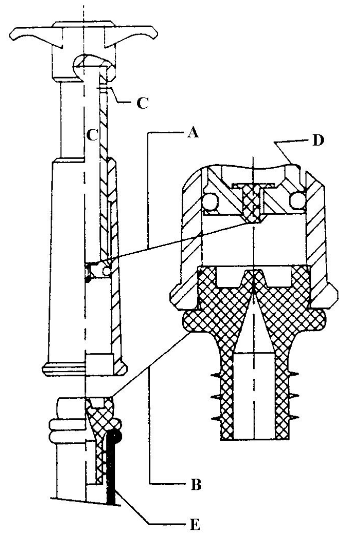

Figure 4.1
Vacuvin; A - *exhaust valve,* B - *intake valve (rubber plug),* C - *connection to atmosphere,* D - *piston,* E - *bottle neck.*

such as titanium) and sputter-ion pumps (a combination of chemisorption and ion pumping).

At the beginning of this chapter it seems useful to consider the question of what features we would like to assign to an 'ideal' vacuum pump. An ideal pump should operate at a constant pumping speed down to any desired pressure. Furthermore, any gas particle arriving at the inlet of the pump would be removed definitively from the vacuum system. The pump should not contaminate the vacuum system by unwanted gases or vapours and not affect its surroundings by electric or stray magnetic fields. Finally, the pump should be easy to use, have a compact design, inexpensive to purchase and maintain, environmentally friendly and reliable. Although no vacuum pump simultaneously unites all these ideal properties, the current offer provides plenty of useful pumps for application from coarse to ultra-high vacuum.

In case of transfer pumps as well as capture pumps, we may distinguish between pumps employable from atmosphere and pumps that require a (strongly) reduced pressure for proper operation. The first group includes the diaphragm pump, liquid ring pump, oil-sealed and dry rotary pumps, steam jet pump and sorption pump. With these pumps, depending on the type, ultimate pressures down to about 0.1 Pa can be achieved. Lower pressures are only attained by pumps of the second group, such as the diffusion pump, turbomolecular pump, cryopump and sputter-ion pump. Thus, for ultimate pressures below about 0.1 Pa, a suitable combination of pumps out of both categories must be selected. In this case, it is important to ascertain that the various pumps effectively complement each other and as few as possible disturbing effects will occur.

In addition to the specified classifications based on operating principle and working range, nowadays the quality of the vacuum supplied in terms of the residual gas composition is considered as the most relevant characteristic of a pump. An interesting distinction related to this property can be made by a classification into *wet pumps* and *dry pumps*.

We speak of wet pumps because of the presence of a liquid pump medium. Open connection with the chamber or vessel to be evacuated means that vapour particles of the pump medium can back-diffuse towards the vacuum region. Although provisions can be made to minimize this effect, in the long term, contamination of the vacuum compartment by these vapour particles cannot entirely be prevented. In various applications of vacuum in research and industry, such contamination is essentially impermissible. For example, in surface physics and thin layer manufacturing (e.g. optical coatings), the quality of the investigated surface or the deposited thin layer would be influenced in an uncontrollable way by the adsorption of water or oil molecules. In food industry, it is unacceptable that the aroma of vacuum-packed coffee would suffer from 'oil odor'. In the semiconductor industry oil or water molecules will contaminate the process chamber and cause defects in the electronic microstructures. In all these cases, dry pumps are preferred, because they are free of pump liquids. Application of dry pumps, therefore, does not lead to the described contamination problems.

There is another downside to using wet pumps, especially in the semiconductor industry. This concerns in particular the traditional oil-sealed roughing pumps, such as the rotary-vane pump. Aggressive gases and vapours, gaseous reaction products and solid particles that arise in the manufacture of semiconductor devices, all end up in the pump oil. Consequently, the oil is damaged and important properties as lubrication and sealing are lost. From the moment these problems were noted, much effort has been put into minimizing maintenance requirements. Solutions were achieved in extensive filtration, oil rinsing with inert gases and the use of very expensive 'inert' grades of oil. Nonetheless, oil-sealed pumps under these extreme circumstances are to be cleaned sometimes weekly or even daily(!). It were the lack of reliability and the costs of maintenance that gave the greatest impetus to the development of dry pumps in the 1980's.

In the 1990's the industry became faced with increasing environmental costs and stricter regulations, thus leading to a further stimulus for a much wider use of dry pumps. Especially in branches of industry such as the chemical sector, where until that time water ring pumps and steam jet pumps were widely used, mixing of the working liquid water with the process gases to be pumped led to large amounts of polluted water. A rough estimate gives that all present-day conventional wet pumps worldwide produce more than a million cubic meters of polluted water per day, leading to high costs for transport and cleaning. Transition to dry pumps in this light is considered as an economically attractive alternative. Based on the above discussion, we conclude that the difference between wet and dry pumps is not only fundamental but also topical. In the following sections, different types of pumps will therefore be discussed on the basis of this criterion. In the wet pump group we will focus on liquid ring pumps, oil-sealed rotary pumps and vapour-stream pumps. The dry pumps to be discussed are: diaphragm pump, piston pump, dry rotary pumps, molecular pumps and capture pumps (sorption pump, cryopump, sublimation pump and sputter-ion pump). We note that what we call ‘dry rotary pumps’, usually are not true 'dry' pumps, because the drive shaft in these pumps is still oil-lubricated. Thus, in case of failure of the separation mechanism between pump drive and pump interior, the vacuum volume may become contaminated by lubricants. Especially in the semiconductor industry, where large amounts of reactive gases are to be pumped, this risk for contamination cannot be neglected. This is why the demand for completely lubricant free vacuum pumps and/or pumps where the pump interior is rigidly separated from the drive, becomes increasingly urgent. Obviously, this is a real challenge for any manufacturer of vacuum equipment. Modern multistage versions of diaphragm pumps are so far the only real dry alternative in the pressure range from 1 atm.

4.2 DEFINITIONS

There are many types of pumps on the market, each with their own specific physical (and chemical) properties and related applications. In general, a fairly complete picture of the quality of a particular pump can be obtained by its:

- throughput
- pumping speed (or pump speed)
- ultimate pressure
- compression ratio
- gas type dependency
- working range

Usually, these properties are listed in the manufacturer's documentation. Since the usability of a pump for a specific application is primarily judged on the basis of these data, it seems appropriate to further define and explain them. More specific characteristics of a particular type of pump will be discussed in the section treating this pump.

Throughput (Pam^3/s)

The throughput of a pump is defined as the amount of gas which passes the inlet port of a pump per unit time. In § 3.9 this quantity has already been discussed in relation to the concept ‘vacuum conductance’ under the name *pV flow rate*. Although throughput can be