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TURBOMOLECULAR PUMPS

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ABSTRACT:

After a short review of the developments in the field of turbomolecular pumps, the actual technical situation is treated. The influence of the most important constructive parameters - geometry of the rotor and the rotor speed - on the essential performance characteristics of turbomolecular pumps - pumping speed and compression - is explained.

Single flow ('vertical') and dual flow ('horizontal') turbomolecular pumps are considered under the aspects of manufacturing costs, vibration levels, reliability and after sales service. Beside the 'classic' rotor bearings on the basis of oil lubricated ball bearings for the last few years there are also some types of turbomolecular pumps with so-called 'dry' bearings on the market. These turbomolecular pumps with gas or with electro-magnetic rotor bearings have, for reason of the complex design of the bearing, prices which are almost twice as high than those of turbomolecular pumps with classic bearings.

Finally the trends in the field of further developments of turbomolecular pumps with classic or dry bearings and some of their main applications are dealt with.

1. General.

Turbomolecular pumps became commercially available not earlier than 1958. Since then the turbomolecular pump has become very popular in every field of high and ultra-high vacuum technique, due to the clean vacuum created, the easy operation and the advanced degree of operating reliability.

1.1 History.

Historically the turbomolecular pump goes back to the year 1913, when Gaede, introduced a new type of mechanical vacuum pump /1/. He realized in his 'molecular drag pump' the idea, that gas molecules can be pumped by frequent collisions with a moving solid wall. A short time later Gaede was one of the inventors of the diffusion pump. In this type of pump the gas molecules are pumped by collisions with fast moving molecules of a heated vapour stream.

1.2 Principle.

A particle which collides with a moving wall, after leaving the wall again, attains in addition to its own thermal velocity a velocity component in the direction of the moving wall. The superposition of both velocities determines the effective velocity and the direction of the leaving particle. Therefore a molecular pump basically consisted of a high-speed rotor in a housing, as it had been in the Gaede pump (Figure 1).

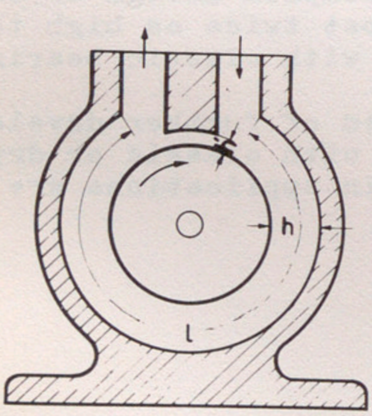


Figure 1. Principle of molecular drag pump (Gaede).

On impact with the gas or vapour particles the rotor impulse is transmitted to the particles, thus, giving them a speed component in the direction of the rotor's rotation. Provided the pump's geometry is of suitable design, the non-directive motion of the particles is changed to a directive motion - the pumping process.

In the molecular flow range, the mean free path of the particles is larger than the spacing between the rotor and the housing and the particles collide primarily with the rotor, thus, leading to an efficient pumping process. In this range there is no interacting influence of the different gases in the system and their handling is not interdependent.

In the laminar flow range, the action of the rotor is restricted by the frequent intercollisions of the particles. Thus, molecular pumps are used in combination with suitable roughing pumps to attain economical and satisfactory values.

1.3 Molecular pumps from 1913 to 1958.

In 1925 Holweck /2/ built an improved version of the Gaede pump and this pump introduced the double ended rotor, in order to increase the pumping speed by a factor of two. Siegbahn /3/ in 1940 invented another version of Gaede's pump using a disc shaped rotor.

These early molecular pumps never have been really successful, because they could not be operated safely over a longer period of time. In order to attain a high compression, which is necessary for low ultimate pressures, the distance h' in these pumps had to be between 10 and 20 μm. Thus, any change in temperature or intruding dust particles could result in a failure of the pumps, caused by the blocking rotor.

1.4 Turbomolecular pumps from 1958 to 1978.

1957 was the year of birth of the turbomolecular pump. Invented by Becker the first turbomolecular pump became available on the market in 1958 /4-6/.

The turbomolecular pump mainly consists of a high-speed rotor and a fixed stator in the housing (Figure 2). The rotor and stator disc have inclined blades and the blades are of an alternating configuration. Figure 3 shows the rotor of a modern double ended turbomolecular pump.

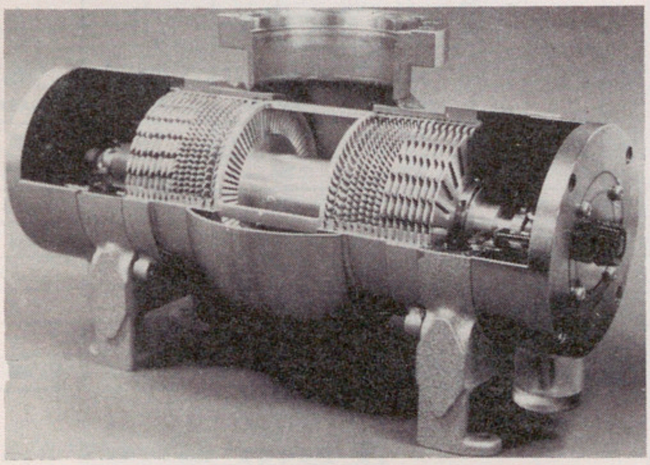


Figure 2. Cut-away model of turbomolecular pump (Becker).

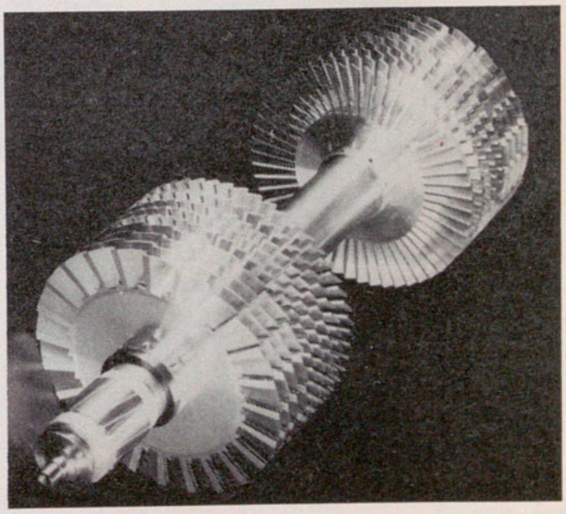


Figure 3. Rotor of turbomolecular pump (S = 500 l/s; n = 1000 Hz).

Each slot of a disc acts like an elementary molecular pump - similar to the Gaede pump. All slots of one disc work in parallel. Thus pump speeds up to several 1000 l/s have become available.

The rotor and stator discs of a pump work in series. Since several discs are used in series, approximately 10 rotor discs in modern pumps and up to 20 rotor discs in older designs, the compression of a single disc has not to be as extremely high as in the molecular pumps. Therefore in the turbomolecular pump the distance between rotating and stationary parts can be made in the order of a few hundred to a few thousand µm - depending on the size of turbomolecular pump.

With these increased distances the turbomolecular pump can be operated safely and even baking of the pumps, without the risk of blocking of the rotor, is possible.

Figure 4 demonstrates a complete series of modern turbomolecular pumps in the pumping speed range from 100 to 2000 l/s.

The improvement of turbomolecular pumps during the last 20 years is shown in Table 1. In equal scale the results of development of more and more efficient turbomolecular pumps are shown. It started with the first turbomolecular pump in 1958 and step by step pumping speeds were increased and/or the size of the pumps were reduced accordingly.

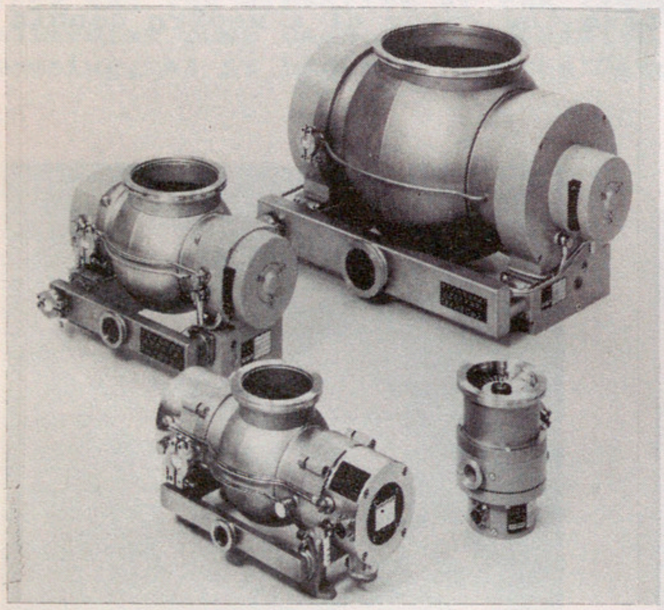
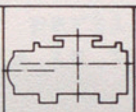


Figure 4. Line of standard turbomolecular pumps (S = 100; 200; 500; 2000 l/s).

Table 1. Comparison of turbomolecular pumps from 1958 to 1978

	 1958 TVP 500	 1972 TPH 200	 1976 TPH 100	 1978 NASA
SN_2 (L/s)	140	190	110	16
C_{H2}	700	750	500	95 000
f (Hz)	270	600	720	1450
U_C (cm/s)	14505	19792	21715	29154
G (kg)	96	20	6	1,5
Dimensions	68	28	17	8
(cm)	40	20	15	8
	37	22	20	19

The latest development is a special high compressing miniaturized turbomolecular pump, developed under a NASA contract /7/, to evacuate a mass spectrometer on board an interplanetary spacecraft.

2. Characteristics of turbomolecular pumps.

The theory of turbomolecular pumps offers two main relations irrespective of whether it deals with the particle flow as a continuum /5,6/ or with the individual fate of the particles (e.g. Monte-Carlo method) /8/.

2.1 Compression K.

In the molecular flow range the maximum compression K_{max}, i.e. the ratio of the pressure at the outlet side and the pressure at the inlet side of a turbomolecular pump at zero pumping speed, rises, with fixed circumferential speed u and geometry g, exponentially with the square root of the molecular weight M of the gas pumped

$$K_{max} \sim \exp\left(\sqrt{M}\cdot u\cdot g\right). \qquad (1)$$

Equation (1) is valid only for an ideal turbomolecular pump without losses. In reality losses occur and the resulting equation is more complex /5/. However, the exponential dependance of the compression from the geometry, speed and molecular weight remains the same.

Measured values for K as a function of the square root of M are shown in Figure 5.

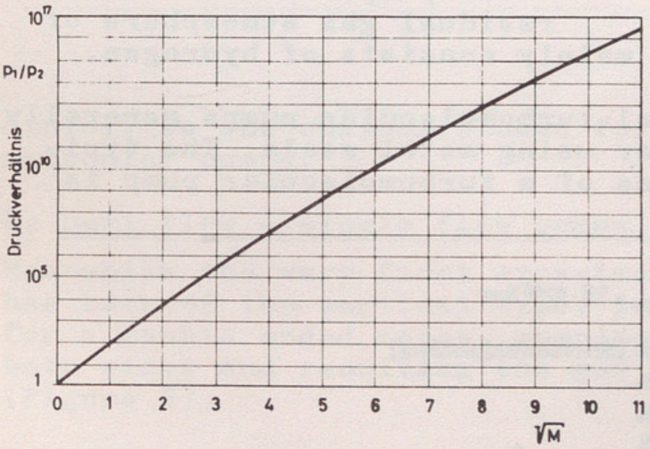


Figure 5. Compression as a function of the molecular weight.

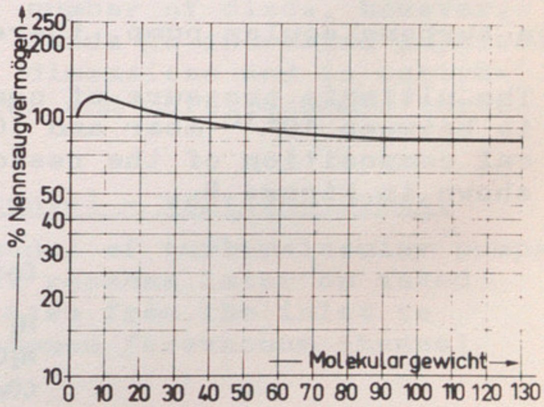


Figure 6 Pumping speed as a function of the molecular weight.

2.2 Pumping speed S.

The maximum pumping speed S_{max} in the molecular flow range is proportional to the product of a pump specific geometry factor G and the circumferential speed u. It is neither dependent on M nor on the pressure p

$$S_{max} \sim u\cdot G. \qquad (2)$$

Typical values of S as a function of M are shown in Figure 6. As demonstrated in Figure 7 the pumping speed in the molecular flow range (below 10^{-3} mbar) does not depend on the pressure p and on the size of the backing pump. At higher pressures there is a strong dependence of the pumping speed on the pressure and on the size of the backing pump.

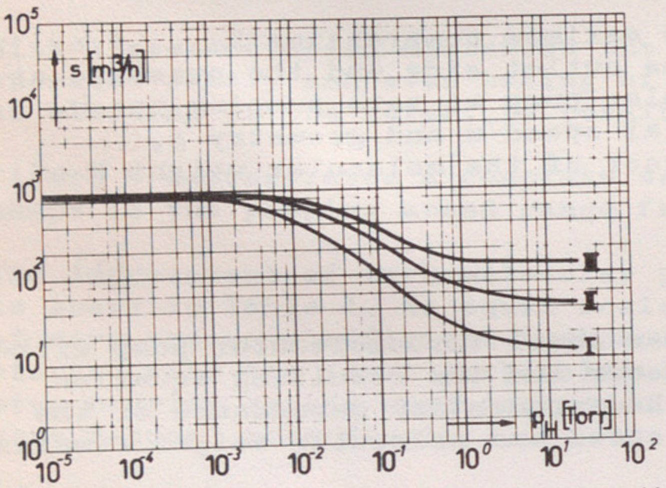


Figure 7. Pumping speed as a function of the inlet pressure with different backing pumps.

2.3 Ultimate pressure - residual gas.

The ultimate pressure p_f a vacuum pump can attain can be calculated from the pressure p_o at the pressure side of the pump by dividing it by the compression K of the pump.

$$p_f = \frac{p_o}{K} \qquad (3)$$

The increase of the value of K with the molecular weight M is the reason for the 'clean' vacuum, that is a vacuum without contamination by oil-vapours and hydro-carbons, a turbomolecular pump can create. The residual gas atmosphere of a turbomolecular pump, therefore, mainly consists of hydrogen.

The ultimate pressure of commercial turbomolecular pumps generally is between 10^{-10} mbar and 10^{-9} mbar using metal seals. The typical composition of the residual gas of a turbomolecular pump is shown in Figure 8.

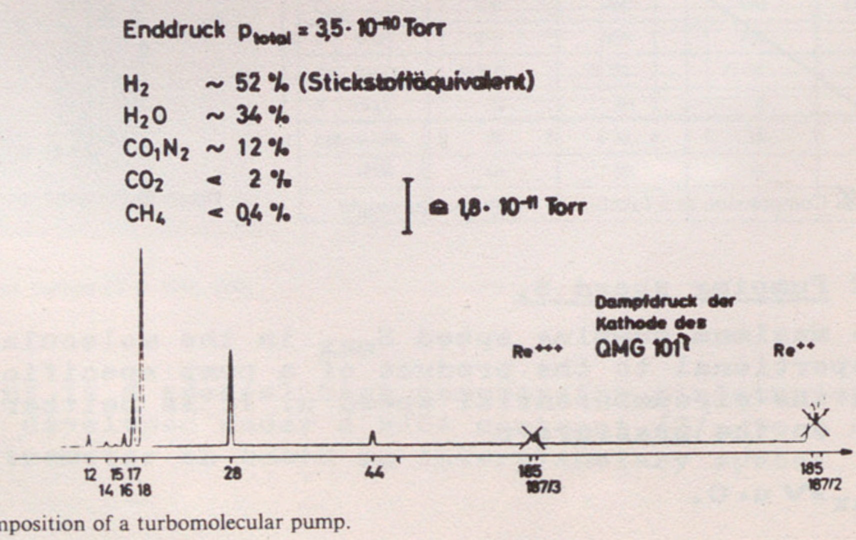


Figure 8 Residual gas composition of a turbomolecular pump.

3. Geometry.

Since, according to equation (1) and (2), the geometry of the rotor and stator blades is of decisive influence the development efforts in this field are important.

Two main groups of commercially available turbomolecular pumps can be distinguished according to the structure of the rotor and stator blades. The turbomolecular pumps after Becker have discs with a closed structure. The other group of turbomolecular pumps have discs with an open structure.

The open structure gives slightly increased pumping speed for nitrogen, but also a lower compression /9/. Catalogue values of pumping speeds of the open structure pumps for light gases show a reduced pumping speed for light gases compared to the values for nitrogen. The pumps with closed structure show a higher pumping speed for light gases (Table 2) /10/.

Table 2. Comparison of turbomolecular pumping speed for closed and open disc structures

Pumping speed	Closed (%)	Open (%)
N_2	100	100
H_2	100–132	62–83
He	100–147	62–91

Due to the lower compression the turbomolecular pumps using the open structure have to have more discs in series or discs of larger diameter (higher circumferential speeds) in order to compensate the losses in compression. An increased number of discs, however, leads to increased physical dimensions and is contradictory to the customers need for smaller and more economic turbomolecular pumps.

4. Dual flow - single flow pumps, horizontal - vertical pumps.

Meanwhile the very first experimental model of turbomolecular pumps has been of the vertical type, practical reasons later on asked for a double ended rotor, pumping the gases from the inlet to both sides and reuniting the gas in a common forevacuum channel (Figure 2).

In 1970 turbomolecular pumps of the vertical type became available using single ended rotors /11/.

In the meantime small turbomolecular pumps became available, which have a single ended rotor and can be used in either position: horizontally or vertically /12/.

Since the vertical pumps became available later than the horizontal pumps, it appears as if the trends of development would be going to vertical pumps:

- the vertical pump's housing is easier to manufacture (cylinder);
- in the horizontal pumps the particles have to be deflected, in order to see the rotor blades, thus, a loss in pumping speed occurs and a more complex housing is necessary;
- psychologically it looks more convenient to replace a vertical diffusion pump by a vertical turbomolecular pump.

On the other hand there are some important arguments in favour of the horizontal design:

- the rotor of the horizontal pumps can be balanced dynamically more efficiently and have lower vibration levels;
- the after sales service, e.g. changing rotor bearings, is much simpler and no rebalancing of the rotors is necessary after changing the bearing;
- modern horizontal turbomolecular pumps have inlet flanges, which can be directed to the top, to the side and downwards, therefore, no elbows or similar connecting elements will be necessary /13/.

Summarizing the pros and contras of single and double ended rotors in turbomolecular pumps it can be said that both designs have advantages and disadvantages. Our opinion is that the main shortcomings of the larger single ended turbomolecular pumps: vibration, after sales service, safety of operation are the reason for the fact that the development of turbomolecular pumps does not generally point to vertical pumps only. For the time being the horizontal turbomolecular pumps with double ended rotors still have some important advantages.

5. Dry turbomolecular pumps.

Besides further improvements in the field of 'classical' oil-bearing turbomolecular pumps efforts have been made also and will continue in the field of 'dry' turbomolecular pumps having dry bearings without a lubricant.

5.1 Gas bearings.

In 1974 a dry turbomolecular pump using compressed air as rotor bearings has been introduced. The pumping system of this pump consists of three parts. At the inlet is a turbomolecular pump system with discs, followed by a molecular pump similar to Holweck's molecular pump.

A very important feature of this pump is the so-called dynamic seal, which acts not only as a seal against the compressed air in the bearing area, but also as a pump having a pumping speed of a few hundredths of a l/s (at atmospheric pressure). Once the system has been roughed below 1 mbar the roughing pump is no longer necessary, since this work now can be done by the dynamic seal.

The disadvantage of this dynamic seal is the fact that the spacing between its rotating and stationary elements is only in the order of 10 μm like in the old molecular pumps. Therefore, this part of the pump is very sensitive to small particles and furthermore the production costs of this pump are so high, that its sales price is almost twice as much as the price of an oil-bearing pump of the same pumping speed, not counting the expensive ultra-clean compressed air required for the operation of the bearings.

5.2 Magnetic bearings.

In 1976 a 'magnetic' turbomolecular pump has been introduced /15/. It contains a five degree actively controlled magnetic suspension system for the rotor. For the control of the sensors and the electro magnets extensive and complicated electronics is necessary and the pump's price is in the same order as the gas bearing pump mentioned before.

The shortcoming of this pump is the fact that an emergency bearing is necessary, which supports the rotor in case of power failure and sudden air leaks. Because of its large diameter this dry ball-bearing has to be replaced after 3 to 5 full speed touch-downs.

5.3 Dry backing pump.

Still many efforts have to be done in the field of the development of dry turbomolecular pumps before these pumps will become a real alternative to the classical oil-bearing turbomolecular pump.

Since turbomolecular pumps need backing pumps for the roughing phase the same amount of skill will have to be used for the development of a dry backing pump in order to have a complete dry ultra-clean vacuum system.

As long as there is no dry backing pump available to attain fore vacuum pressures of approximately 10^{-3} mbar, the question will remain, whether the increased expense for a dry turbomolecular pump will be reasonable.

6. Application.

There are numerous application for turbomolecular pumps in all fields of high and ultra-high vacuum technique. Turbomolecular pumps are mainly used to eliminate the problem of backstreaming of oil vapour and for non-contaminating hydrocarbon-free operation.

Systems such as evaporation chambers, particle accelerators, plasmafusion installations, which require high or ultra-high vacuum, an absence of hydrocarbon contamination and large pumping capacity, are especially suited to a turbomolecular pump. Roughing ion pumps, always a troublesome problem, can be handled with turbomolecular pumps quickly and cleanly. The same is valid for cryo pumps.

Intensitivity to the chemical characteristics of the pumped gases and vapours is another quality of a turbomolecular pump that is most desirable in analytical application. Hydrocarbons can be pumped through a turbomolecular pump indefinitely without damage to the turbomolecular pump. The turbomolecular pump can pump noble gases as easily as the others. Previously pumped gases are not stored or re-ejected into the system - they are permanently removed. Also a turbomolecular pump does not decompose the pumped gases. All of these characteristics make turbomolecular pumps well suitable to mass spectrometry, gas analysis and leak detection.

The modern horizontal turbomolecular pumps have so low vibration levels, that they are used in electronmicroscopes and the main success in this operation is the cleaning of the vacuum system of the electronmicroscope during the operation of the turbomolecular pump.

The one apparent disadvantage of a turbomolecular pump is the fact, that it is a high-speed machine. Nevertheless, with long-life bearings and mechanical and electronic safeguards it can be as dependable and more 'forgiving' to operator misuse than other types of vacuum pumps.

7. Summary.

As a summary of the trends of the development of turbomolecular pumps it can be said, that in the field of oil-bearing turbomolecular pumps the trend goes to more and more compact pumps with increased l/s per money values and on the other hand to simple turbomolecular pumps with lower pumping speeds (100 l/s and lower) for as low a price as possible. The closed disc structure seems to be favourable for these trends.

The turbomolecular pumps of the future will not necessarily be of the single ended vertical type due to the important advantages the double ended rotors in horizontal turbomolecular pumps still have.

In the field of dry turbomolecular pumps the idea of the magnetic pumps seems to be favourable to further improvements, e.g. reducing the number of actively controlled degrees of freedom to one or two only, by using permanent magnets. Furthermore, the idea of using a combination of magnetic bearing and dry mechanical bearing seems to be interesting too. Together with dry turbomolecular pumps the idea of a dry backing pump will have to be followed.

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