Development of a Novel Mechanical Bearing Turbomolecular Pump for Research and Analytical Applications

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1 Turbomolecular pumps

The turbomolecular pump is a further development of the early molecular drag pump first introduced by Wolfgang Gaede in 1913 [1]. Nowadays, there are two designs of turbomolecular pumps which are of commercial interest:

1. The “classic turbomolecular pump” first described by Willi Becker in 1958 [4]

2. The “compound turbomolecular pump” developed and optimized in the 1980s

A “classic turbomolecular pump” is a multi-stage bladed turbine that compresses the gas to be pumped from high- and ultrahigh-vacuum to medium vacuum. The rotating part of the turbine, the so-called “rotor”, is driven at high rotational speeds so that the peripheral speed of the blades is of the same order of magnitude as the mean thermal velocity of the gas particles to be pumped. Every turbomolecular pump requires a so-called “fore-vacuum pump system” that takes over the gas flow from the turbomolecular pump and compresses the gas to atmospheric pressure. The pressure at which the gas is transferred from the turbomolecular pump to the fore-vacuum pump system is called the “fore-vacuum pressure”.

It is important to note that the maximum admissible fore-vacuum pressure of a classic turbomolecular pump is typically 0.5 mbar. That means that the fore-vacuum pump system has to hold a pressure less than 0.5 mbar permanently at the fore-vacuum port of the turbomolecular pump.

If the turbine of a classic turbomolecular pump is combined with an additional compression stage operating in medium vacuum, then the maximum admissible fore-vacuum pressure is much higher than 0.5 mbar. Such a turbomolecular pump is referred to as a “compound turbomolecular pump”. The maximum admissible fore-vacuum pressure of a compound turbomolecular pump is typically 5 mbar and hence, smaller fore-vacuum pumps can be used than in the case of a classic turbomolecular pump.

With regard to the additional compression stage the most famous designs were established by Fernand Holweck [2] and Manne Siegbahn [3]. In general linguistic usage it is said “the turbomolecular pump (TMP) is fitted with a Holweck (compression) stage or with a Siegbahn (compression) stage”.

In figure 1 on the left, the novel turbomolecular pump TURBOVAC 350i is shown in a cutaway view. Below the inlet flange (DN 100 ISO-K) the bladed turbine can be identified. Below the turbine the pump is fitted with three Holweck stages in series to achieve a high maximum admissible fore-vacuum pressure (10 mbar). In the centre below the turbine the motor can be recognized which drives the turbine and the Holweck stages at high rotational speed (1000 Hz).
Based on the principles of classic and compound turbomolecular pumps another high-vacuum pump type was developed, the so-called “multi-inlet turbomolecular pump”. Typically, such a pump is fitted with two turbines in series plus an additional Holweck or Siegbahn compression stage. Consequently, a typical multi-inlet turbomolecular pump is characterized by the fact that the pump has three inlet ports. Usually, the corresponding inlet pressures are of the order of $1 \times 10^{-6}$ mbar, $1 \times 10^{-3}$ mbar and $1 \times 10^{-1}$ mbar.

In figure 1 on the right, the novel multi-inlet turbomolecular pump TURBOVAC 350i is shown in a cutaway view. The two turbines in series plus three Holweck stages in series can be clearly recognized. The nominal rotational speed is 1000 Hz. Nowadays, the majority of the multi-inlet turbomolecular pumps are operated in high-end mass spectrometers.

Figure 1
On the left: Compound turbomolecular pump TURBOVAC 350i fitted with one turbine (①) plus three Holweck stages in series (②)
(high-vacuum flange: DN 100 ISO-K, nominal rotational speed: 1000 Hz, maximum admissible fore-vacuum pressure: 10 mbar)
On the right: Multi-inlet turbomolecular pump TURBOVAC 350i fitted with two turbines in series (① and ②) plus three Holweck stages in series (③) (nominal rotational speed: 1000 Hz, maximum admissible fore-vacuum pressure: 10 mbar)
Undoubtedly, pumping speed and compression ratio are the most important characteristics of turbomolecular pumps. Both characteristics strongly depend on gas type.

For a specific gas type, the pumping speed of a vacuum pump is defined as the ratio of net gas flow $Q$ through the inlet flange of the pump and inlet pressure. Hence, for a turbomolecular pump, the pumping speed $S_{\text{TMP}}$ is

\begin{equation}
S_{\text{TMP}}(p_{HV}) = \frac{Q}{p_{HV}}
\end{equation}

$p_{HV}$ is the inlet pressure at the high-vacuum inlet port ($HV = \text{high-vacuum}$).

It is well-known that the pumping speed of a turbomolecular pump does not depend on inlet pressure, if the inlet pressure is less than $1 \times 10^{-3}$ mbar, i.e.

\begin{equation}
S_{\text{TMP}}(p_{HV}) = S_0 = \text{const.}, \text{ if } p_{HV} < 1 \times 10^{-3} \text{ mbar}.
\end{equation}

Furthermore, it is crucial to note that the pumping speed $S_0$ shows a significant dependence on gas type.

From figure 2, it becomes evident that the dependence of $S_0$ on $\xi = \frac{v}{c_{av}}$ can be described analytically by the formula

\begin{equation}
S_0(\xi) = \left[ \frac{(AR \cdot v)}{4} \right] \left[ \frac{(a \xi^{0.9})}{(1 + b \xi^2)} \right]
\end{equation}

$AR$ is the effective cross-sectional area of the rotor, $v$ is the peripheral speed of the blades and $c_{av} = \left[ \frac{(8/\pi) \cdot (RT/M)}{1/2} \right]$ is the mean thermal velocity of the gas particles to be pumped ($R = \text{Molar gas constant}$, $T = \text{Absolute temperature}$, $M = \text{Molar mass}$). $a$ and $b$ are constants of the order of one.

For a specific gas type, the compression ratio of a gas transfer vacuum pump is defined as the ratio of fore-vacuum pressure and inlet pressure. Hence, for a turbomolecular pump, the compression ratio $K$ is

\begin{equation}
K = \frac{p_{FV}}{p_{HV}}
\end{equation}

$p_{FV}$ is the pressure at the fore-vacuum port of the pump ($FV = \text{fore-vacuum}$).

In the limit $Q \to 0$ the compression ratio $K$ tends to its maximum attainable value $K_0$. This so-called “zero-throughput compression ratio” shows a significant dependence on gas type which can be described analytically by the formula

\begin{equation}
K_0(\xi) = \exp(g \cdot \xi)
\end{equation}

with the pump-specific geometrical constant $g$ and $\xi = \frac{v}{c_{av}}$ as given above.
The main result of these considerations is that the pumping speeds $S_0$ of different gas types are not independent of each other, but they are correlated [see formula (3)]. The same statement is valid for the zero-throughput compression ratios $K_0$ [see formula (5)].

**Figure 2**
TURBOVAC 350i: Dependence of pumping speed on gas type

The solid line represents the function $(a \xi^{0.8})/(1 + b \xi^2)$ introduced in formula (3). The squares represent the experimental data for Hydrogen ($S_0 = 335$ l/s), Helium ($S_0 = 360$ l/s), Nitrogen ($S_0 = 290$ l/s) and Argon ($S_0 = 260$ l/s) (from left to right).

Inlet flange: DN 100 ISO-K, Nominal rotational speed: 1000 Hz, $A_R = 132$ cm$^2$, $v = 418$ m/s, $a = 1.10$, $b = 4.65$
2 Design of the novel turbomolecular pump TURBOVAC 350i

The rich variety of high-vacuum applications requires a rich variety of high-vacuum pump designs. In particular, high-vacuum pumps have to handle gases with significantly different thermodynamic properties, they have to perform in the wide pressure regime between \(1 \times 10^{-10}\) mbar and \(1 \times 10^{-2}\) mbar, and they have to perform at tremendously different gas throughputs.

Before the development of a turbomolecular pump starts it is imperative to decide whether the pump design should be optimized for high compression ratios or for high pumping speeds.

Analytical applications like mass spectrometers, electron microscopes and surface analysis require turbomolecular pumps with high compression ratios. On the other hand, coating applications require turbomolecular pumps with high pumping speeds. Note that turbomolecular pumps need a sophisticated temperature management, if they are operated at high inlet pressures (\(p > 5 \times 10^{-3}\) mbar), i.e. with high gas throughputs.

First and foremost, the requirements with regard to ultimate total pressure (= compression ratios) and gas type-specific pumping speeds at certain inlet pressures determine
- the design of the inlet flange and hence, the dimensions of the pump
- the design of the rotor
- the design and the power of the electric motor
- the bearing concept

The difficulty is to achieve the required performance of the pump with a limited number of reliable parts which are not too sophisticated and reasonably priced.

Nowadays, software tools reduce the verification tests to a minimum. In our development process the prediction of the performance was so precise, that there was no need for further optimization after the first verification test.

2.1 Rotor design

To make a decision in favour of a certain rotor diameter is one of the most important decisions in the development process, because the rotor diameter determines pump size and performance.

As indicated above, the ratio \(\frac{\xi}{c_{av}}\) = \(\frac{v}{c_{av}}\), i.e. the ratio peripheral speed of the rotor blades to mean thermal velocity, is the significant factor for pumping speed and compression ratio. As shown in figure 2, the peripheral speed of the rotor blades must be high to achieve a high pumping speed for light gases. However, the rotational speed of the driving motor is limited due to the reliability aspects of its own and the reliability of the ball bearings. Furthermore, the maximum admissible rotational speed is determined by the stability of the rotor material which experiences high centrifugal forces.

Finally, a pump housing diameter of 165 mm was chosen. This diameter results from the outer diameter of the DN 100 ISO-K flange at the inlet of the pump plus the size of the clamping elements (see figure 3). Consequently, the pump housing diameter of 165 mm leads to a rotor diameter of 133 mm.
2.2 Bearing concept

There are three basic bearing concepts to suspend the rotor in the housing of a turbomolecular pump:

1. Active magnetic bearing
2. Passive magnetic bearing
3. Mechanical bearing

In the absence of magnetic bearings two mechanical ball bearings are necessary to suspend the rotor. According to Earnshaw’s theorem [5], it is not possible to realize a stable, fully passive suspension of the rotor. Hence, passive magnetic bearings always require a so-called “hybrid-combination” with either a mechanical ball bearing or an active magnetic bearing on either side of the shaft. However, it is also possible to suspend the rotor by a fully (five-axis) active magnetic bearing system, a widely used and proven technology particularly for turbomolecular pumps with large inlet flange diameters.

From the technical point of view, a fully magnetic bearing concept offers several significant advantages over the use of mechanical ball bearings or hybrid-combination:

- no wear parts
- no hydrocarbons from any lubricant potentially entering the vacuum chamber
- extremely low mechanical vibrations

However, on the downside there are significantly higher costs due to the active magnetic bearing system and, in addition, there is a larger footprint of the pump. Therefore, fully magnetically suspended turbomolecular pumps are less attractive in those applications which require small and compact high-vacuum pumps (i.e. diameter of the inlet flange is smaller than 160 mm).
For the TURBOVAC 350i turbomolecular pump with inlet flange diameters 100 mm or 160 mm a hybrid bearing system was chosen consisting of a grease-lubricated mechanical ball bearing on the fore-vacuum side and a passive magnetic bearing on the high-vacuum side.

Firstly, this concept offers the advantage that the bearings can be positioned at the very end of either side of the shaft. This design is favourable for the rotor dynamics particularly for longer shafts found in multi-inlet turbomolecular pumps.

Secondly, the passive magnetic bearing does not require any kind of lubrication. Thus, a position directly at the high-vacuum end of the shaft is possible without having the severe risk that hydrocarbons are migrating into the vacuum chamber.

The mechanical ball bearing of the TURBOVAC 350i is lubricated with grease suitable for high-vacuum applications. One advantage of grease over oil is the approximately 100 times lower vapour pressure. This feature is of particular importance, if a failure occurs in the vacuum system, e.g. a mains break. Provided, the non-spinning turbomolecular pump is connected to the vacuum chamber, then hydrocarbons start to migrate into the vacuum chamber.

A potential problem of grease lubrication can be the accumulation of process particles within the grease. This feature can be strongly suppressed by using fully encapsulated mechanical ball bearings.

Due to the properties of the grease and its encapsulation in the bearing containment the turbomolecular pump can be operated in any orientation, whereas an oil lubrication usually requires dedicated design efforts to retain the oil in the lubrication cycle.

Furthermore, the grease chosen for the TURBOVAC 350i platform does not need to be exchanged during the lifetime of the bearing. On the other hand, oil-lubricated bearings usually require an exchange of oil in certain time intervals. The length of the time interval depends on the application. However, the lifetime of the bearing itself does not depend on the kind of lubrication.
Table 1 summarizes the pros and cons of grease and oil lubrication in turbomolecular pumps:

<table>
<thead>
<tr>
<th>Grease lubrication</th>
<th>Oil lubrication</th>
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<tbody>
<tr>
<td><strong>Pro</strong></td>
<td><strong>Con</strong></td>
</tr>
<tr>
<td>Very low vapour pressure (~ 100 times lower than a comparable oil)</td>
<td>Bearing requires “conditioning” during initial assembly and after exchange (special run-in procedure)</td>
</tr>
<tr>
<td>Operation in any orientation</td>
<td>Proven technology</td>
</tr>
<tr>
<td>Lifetime lubrication – no need of a lubricant exchange</td>
<td>Oil migration into the vacuum chamber</td>
</tr>
<tr>
<td>Proven technology</td>
<td></td>
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Table 1
Pros and cons of grease lubrication and oil lubrication for mechanical ball bearings used in turbomolecular pumps

As there is only one mechanical ball bearing inside the TURBOVAC 350i, which is accessible from the bottom plate, a bearing exchange is easy to carry out – also by the user of the pump. Due to the design of the shaft support there is no need to rebalance the rotor after the bearing has been replaced.

Figure 4 shows the residual gas analysis spectrum of a TURBOVAC 350i with inlet flange DN 100 CF after 48 hours of baking and subsequent cool-down and pumping for another period of 48 hours. Note that hydrocarbons are not visible in the spectrum proving that no parts of the grease were able to migrate into the vacuum chamber.

An ultimate pressure of \( p_{ult} = 2 \cdot 10^{-10} \) mbar was attained. This feature demonstrates that the rotor-stator-design of the pump allows very high compression ratios for light gases and hence, the reproducible generation of UHV conditions.
Figure 4
Residual gas analysis spectrum of a TURBOVAC 350i with inlet flange DN 100 CF after 48 hours of baking and subsequent cool-down and pumping for another period of 48 hours, ultimate pressure: $2 \times 10^{-10}$ mbar

3 Applications in R&D and analytics
3.1 Mass spectroscopy

The new TURBOVAC 350i platform is suitable for a broad range of high-vacuum and ultrahigh-vacuum applications. Two examples of the field of R&D and analytical instruments will be discussed below.

As mentioned above, the majority of the multi-inlet turbomolecular pumps are operated in high-end mass spectrometers. For instance, these spectrometers are commonly used in many applications of analytical chemistry like GC-MS or LC-MS (GC-MS: Gas-chromatography mass spectrometry, LC-MS: Liquid-chromatography mass spectrometry).

The huge advantage of the multi-inlet concept is that nowadays the high-vacuum pump system is much more compact and more customer-specific than in the past using discrete standard turbomolecular pumps.

Figure 5 shows how a typical mass spectrometer section is realized using multi-inlet turbomolecular pumps. The molecules to be analysed enter the mass spectrometer vacuum system after having been separated in the liquid chromatograph (LC) at position 1. They need to travel through several vacuum chambers (2a, 2b, 2c) where they undergo different processes such as ionization. Finally, they enter the detector chamber (position 2d). Different vacuum levels are required in the individual chambers which are connected by apertures of varying diameter (3a to 3d).
The chambers 2b, 2c and 2d are pumped via one multi-inlet turbomolecular pump (red frame, position 4) which is backed by a single-stage rotary vane pump (SOGEVAC 28 BI, position 5) which evacuates the entry chamber (position 2a) as well.

Due to the flexible rotor design of the TURBOVAC 350i platform the pumping speeds at the different inlet ports can be exactly adapted to the pressure requirements of the mass spectrometer system. The high pumping speeds and the very high compression ratios for light gases are imperative as Helium or Hydrogen are often used as carrier gases.

3.2 Beam lines

The Ruhr University in Bochum, Germany, operates in its Central Unit for IonBeams and RadioNuclides (www.rubion.rub.de) a Dynamitron tandem accelerator which is one of the biggest among the “small” tandem accelerators in the world. It provides ion currents up to several 100 µA and energies ranging from 300 keV to approx. 50 MeV depending on the charge states of the ions.

As the research facility in Bochum required a new set of high-vacuum pumps, the Ruhr University came to the decision to install 18 TURBOVAC 350i units plus diaphragm backing pumps (DIVAC 3.8HV3). This pump system shown in figure 6 ensures reliable and stable high-vacuum conditions at the accelerator today.
Figure 6
Installation of TURBOVAC 350i turbomolecular pumps at the Dynamitron tandem accelerator at the Ruhr University in Bochum, Germany
On the left: Overview of different beamlines, position of 6 turbomolecular pumps marked by red arrows
On the right: Close-up view of an upside down mounted TURBOVAC 350i / DIVAC 3.8HV3 on one of the beam lines

Acknowledgement

The authors would like to thank the Central Unit for IonBeams and RadioNuclides (RUBION) of the University of Bochum for their active support of chapter 3.2.
References


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Zusammenfassung


Das Konzept konnte sich bereits erfolgreich in Anwendungen der Analysen-Technik und Forschung bewähren.

Summary

Turbomolecular pumps are high-vacuum pumps which are used both for attaining very low ultimate pressures down to $10^{-10}$ mbar and for handling of high process gas flows up to inlet pressures of $10^{-3}$ mbar. Pumping speed and compression of these pumps essentially depend on the diameter of the inlet flange, on the design and rotational speed of the rotor and the Holweck stage respectively, and on gas type of the gases to be pumped.

The development of the novel TURBOVAC iiX turbomolecular pump by Oerlikon Leybold Vacuum aimed at the realization of high pumping speeds and high compression ratios, especially for light gases. Both the rotor design and the bearing concept were particularly adapted to these requirements, also by using modern computer simulation tools.

This design concept has already proven its functionality in R&D and analytical applications.