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Operating Performance of Screw Vacuum Pumps - Experimental and Theoretical Analysis

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Abstract

This paper presents detailed analyses of the operating performance of a dry-running screw vacuum pump. The characteristic parameters, suction speed and final attainable pressure - which primarily define the operating performance of screw vacuum pumps - are explored in experimental and theoretical investigations.
Experiment and simulation in combination are used to show the correlation between the main physical and technical characteristics and the operating performance of screw vacuum pumps. This basic knowledge is essential for understanding the specific machine physics of positive displacement vacuum pumps, especially for screw vacuum pumps, and is useful in view of further design and optimization processes.
The experiment covers measurements of the operating performance of the investigated isochoric screw vacuum pump working against ambient pressure. As operating parameters intake pressure (1000mbar to 10^{-3}mbar) and rotor speed are varied over a wide range.
The theoretical analysis of the operating performance contains simplifying models as well as simulations of the thermodynamic processing. The impact of external leakages, clearance vacuum flows and further losses on operating performance are described in detail.

Note:
The research project is supported by the German vacuum industry represented by the German Engineering Federation (VDMA). For this reason confidential data are partly given in standardized form.

The investigations are carried out for a model machine of the screw vacuum pump type.

1 Introduction

The operational and application area of vacuum pumps is specified by suction performance and final attainable pressure. There are multiple machine types for the production of vacuum, whereby positive displacement vacuum pumps are the most important and effective for lower vacuum. Applications for these machines are mostly limited to rough (1 < p [mbar] < 1000) and fine vacuum (10^{-3} < p [mbar] < 1).

Higher standards in vacuum cleanliness have led to the banning of cooling and sealing fluids inside the working chamber and an increasing demand for and intensified development of dry-running vacuum pumps [1-3]. The absence of service liquids leads to unfavourable operating behaviour in dry-running pumps, resulting in a significant reduction in suction speed and ultimate pressures [3, 4].

In spite of these problems, the advantages of their design principle have led to continuous production of dry-running screw vacuum pumps [**Fig.1**] for more than 25 years, and they are still increasingly entering industrial markets for vacuum applications. Consequently nearly every vacuum pump supplier world wide offers a screw vacuum pump in their product portfolio [5].

The significant design features and main advantages of the screw-principle in comparison to other competing pumping methods are:

- compact design and construction concept with few moving parts,
- dry-running gap-sealed operation for oil-free vacuum applications,
- high rotor speed potential - due to pure rotational motion,
- high suction performance - due to high rotor speeds,
- low final attainable pressures in fine vacuum regions and below, and
- ability to achieve internal compression in order to reduce power consumption.

Fig.1: Dry-running screw-type vacuum pump of the type investigated (model test machine)

The operating performance of positive displacement vacuum pumps results from the main physical and technical machine characteristics. The term 'physical-technical' refers to the direct interrelation between constructional features, operational characteristics and actual performance. There are various machine-specific physical-technical mechanisms at work, which affect and determine the thermodynamic processes inside the pump.

Focussing on the complex interaction between geometry and thermodynamics, the mechanical and operating parameters represent the input-factors. These establish and influence the basic operating conditions, **Fig.2**. The rotor design - with or without internal compression, plus the design of the axial and radial inlet and outlet areas, the presence or absence of pre-inlets and in particular the clearance geometry - defines the main mechanical and geometrical parameters. The other group of input-conditions is the operating parameters. Here the rotor speed, inlet pressures and temperatures, outlet pressures and also the medium to be pumped are the main considerations.

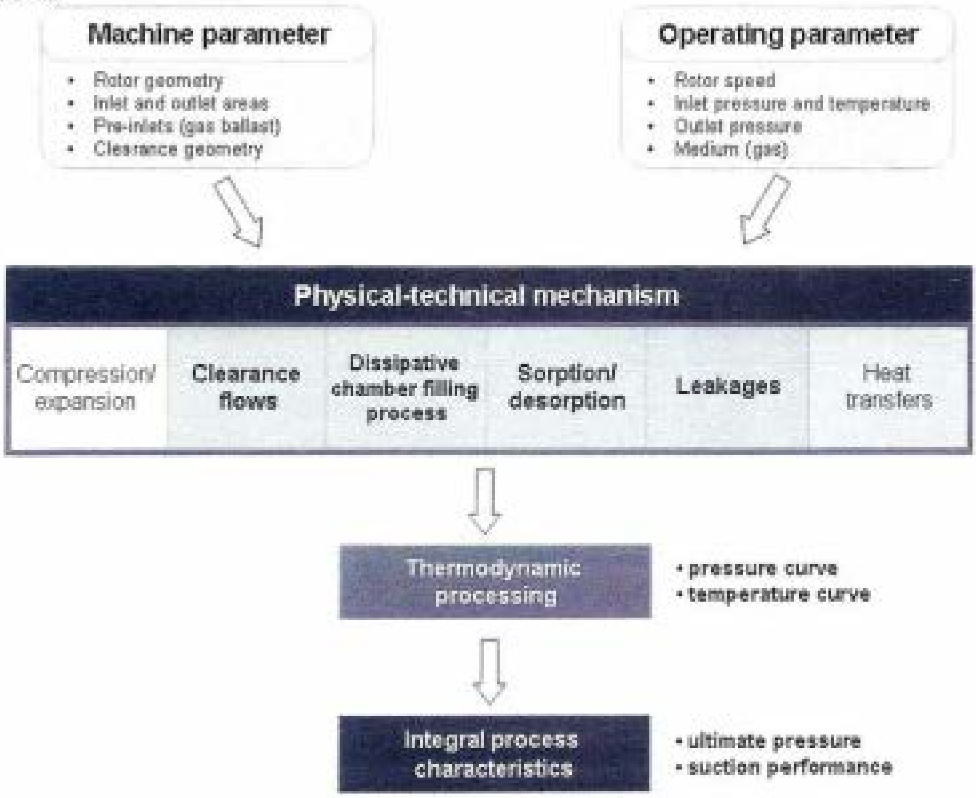

Fig.2: Physical-technical mechanisms affecting the integral process characteristics and performance of positive displacement vacuum pumps

Both the groups described above determine and influence fundamentally the main physical-technical mechanism. Compression and expansion is achieved in the first instance by the rotor geometry and the volume curve for the working cycle. Clearance flows such as internal leakage losses - the predominant physical-technical effect, especially for screw vacuum pumps working in rough vacuum conditions – are a major influence on machine performance and operating conditions. Moreover external leakages can, in the worst case, have an undesirable effect on the process parameters. The effects of sorption and desorption, as well as losses during the chamber filling process, must also be taken into account at lower vacuum pressures and higher rotor speeds. Furthermore, heat transfer between gas and mechanical components can affect performance, increasing with the thermal loading of dry-running vacuum pumps working against ambient pressure.

As a result of the complex interaction of physical-technical factors, operating behaviour will take the form of pressure and temperature curves describing the thermodynamic processing. The overall integrated machine characteristics are derived from the correlation of all boundary and operating conditions, and are specified in the process parameters giving ultimate attainable intake pressure and suction performance.

The following combined experimental and theoretical investigations were carried out in order to analyse and point out the correlation between the main physical and technical characteristics and the operating performance of screw vacuum pumps.

2 Experiment

The experimental investigations were carried out for an air-sucking, dry-running, isochoric screw-type vacuum pump working against ambient pressure and consisting of two symmetrical double-threaded rotors with rather low constant pitch and consequently a large wrap angle [Fig.1]. In contrast to series machines of this type the test pump does not incorporate inner compression. The drive concept allows variation of the rotor speed over a wide range.

In order to identify the operating behaviour and the overall machine performance, measurements cover the parameters: intake (final) pressure, volume flow, and rotor speed **[Fig.3]**.

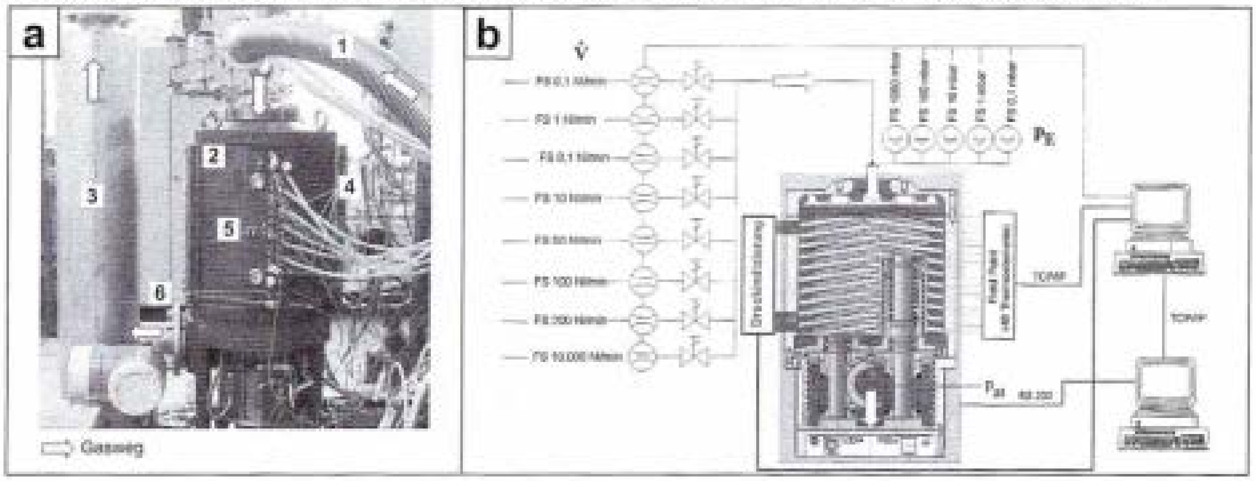

Fig. 3: Test rig dry-running screw vacuum pump (a) and schematic set-up (b)

1	*suction pipe*	*4*	*pressure lines*	$\dot{V}$	*volume flow*
2	*casing*	*5*	*pre-inlet (gas ballast)*	p_E	*inlet pressure*
3	*silencer*	*6*	*thermocouples*		

The known thermal loading of components in this type of machine, which increases at higher rotor speeds and lower gas densities, is directly associated with modified clearance geometries and changing leakage mass flows. To gain directly comparable results for known and stable boundary conditions – especially constant clearance heights and the temperatures of machine components, data were acquired for 'cold' operating machine conditions. To ensure cold machine conditions any operating point determined by revolution speed n and inlet pressure p_{in}

was selected after a short period of time (less than 1 minute), while long cooling-down intervals between two measurements were retained

The external leakage of the machine casing comprising all measurement positions was calculated via $L = 10^{-4}$mbar*l/s according to the pressure rise method.

3 Simulation

In order to understand the complex interaction of the physical-technical mechanism simulations on the operating performance of the screw vacuum pump under examination, the theoretical investigations which were carried out in the first instance included models and calculation algorithms for clearance and external leakage flows . The influence of external leakages on the ultimate attainable pressure of positive displacement pumps can be estimated initially in relation to the theoretical suction performance by a radically simplified approach based on mass continuity, eq. (1). Here a worst case estimation is given assuming that all leakage is on the suction port side. The complete leakage mass flow, which actually consists of several leaks distributed over the whole casing, is assumed to be on the suction side. Leakages which are not on the low-pressure side within the transportation phase disrupt and influence the suction performance and the attainable final pressure insignificantly, as in the case of gas ballast operation.

$$\dot{m}_{th} = V_{AK,max} \cdot z \cdot i \cdot n = \dot{m}_{Leackage} \quad \rightarrow \quad p_{in,min} = \frac{(p \cdot V)_{Leakage}}{S_{th}} \qquad \text{eq. (1)}$$

Simulation Software *KaSim*

The main objective of the software *KaSim* is the simulation of the thermodynamic behaviour of positive displacement vacuum pumps within the design and development process [6, 7]. The simulation program calculates the thermodynamic behaviour of positive displacement machines generally - not only one particular machine type - based on a chamber model of the machine being investigated. The implementation of an enhanced algorithm for the calculation of vacuum clearance flows is based on experimental data [8], and also on a Monte-Carlo-simulation of particle transmission probabilities for molecular flow regimes. This takes into account the influence of moving clearance boundaries on the flow rate for the intermediate and molecular flow regime [9]. This calculation module for vacuum clearance flows, as well as the modelling of external leakages, enables the program *KaSim* to simulate the thermodynamic processing of positive displacement vacuum pumps. The verification of the program has already been carried out successfully for rough and fine vacuum conditions [9, 10].

Modelling the Test Machine

The machine under investigation is described by the chamber model as an input parameter for the simulation program. The chamber model contains basic specifications concerning the existing working chambers, and the connections between them and the high and low pressure port.

4 Operating Performance

The principal physical-technical influences on the characteristic machine performance of the examined screw vacuum pump are established by comparing experimental and simulated machine characteristics, focussing on the final pressure and suction performance at varying rotation speeds and intake pressures.

Ultimate pressure

The final attainable pressure of the screw vacuum pump measured with closed suction pipe, shows significant rotor speed dependence, **Fig. 4**. With low rotor speeds as a starting point, an increase leads at first to a moderate drop in attainable final pressure (rotation speeds $n^*<0{,}375$). With a standardized rotation speed of $n^*=0.375$ a final pressure of 160mbar is achieved. A further increase in rotation speed then causes a continuous significant drop in final pressure. Over a relatively small, crucial speed range ($0.375<n^*<0.50$) the final pressure reacts to speed regulations very sensitively, so that the final pressure can be reduced by more than three decades. Further increases in revolutions ($n^*>0.50$) do not achieve any further reduction in the final pressure, which seems to be almost independent of rotation speed. The absolute minimum final pressure is $4.9*10^{-3}$mbar and is defined for a standardized rotation speed by $n^*=0.625$.

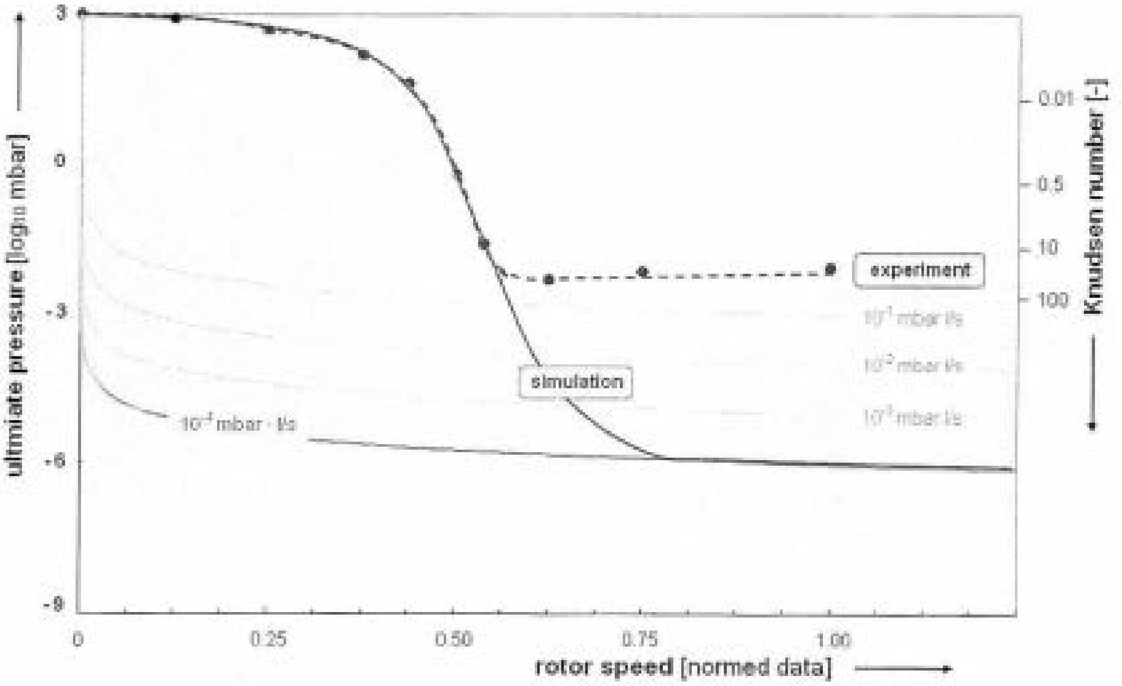

Fig. 4: Ultimate inlet pressure related to rotor speed compared with simulation results and influence of external leakage

Knudsen numbers Kn, which characterise the flow regime in machine clearances, are given for a exemplary clearance height s = 0.30mm, a gas temperature T_{Gas} = 293K and defined at ultimate pressure.

As a function of the machine revolution speed and with it the theoretical suction speed, Fig. 4 also illustrates a simplifying approach for the calculated final pressure described above, applicable for a number of exclusively low pressure side leakages. As rotation speed increases, there is a consequent continuous drop in final pressure. Doubling the rotor speeds results in halving the final pressure. This means that at lower rotor speeds there is a comparatively steep gradient, which decreases as rotor speed rises. A reduction in the external leakage of around a decade causes a relative decrease in final pressure of 90% at constant rotor speed. For the experimentally measured leak rate of 10^{-4}mbar*l/s and rotation speeds of n*>0.5, final pressures are defined in the field: 10^{-6}mbar*l/s. This relatively low rotor speed dependence corresponds with the experimental results. Obvious deviations of more than 10^{-3}mbar indicate that besides external leakages, additional physical-technical effects determine final pressure behaviour. This is even more the case for rotation speeds of n*<0.5.

In the simulation, as well as the influence of vacuum specific clearance flows on attainable final pressure, external leakage is also represented. The degree of rotation speed dependence for the field n*<0.6 is rendered very well by the simulation. Here it becomes clear, in combination with the leakage approach, that especially in rough and fine vacuum clearance flows, leakages have far and away the greatest influence on final pressure compared with other physical-technical mechanisms. The quantification of clearance flow rates in the simulation is validated for viscous (Knudsen numbers Kn<0.01), transitional and molecular flow regimes (Kn>0.5). The mainly pressure-dependent flow conditions in machine clearances near the suction port und in the suction chambers turn out to be critical, so that a classification based on the final pressure is reasonable and practical, Fig. 4.

The significant drop in final pressure detected in the sensitive speed range can be assigned to the increased throttle effect of the machine clearances at lower gas densities. It is in particular for this important area – with focus on the dimensioning rotor speeds - that the performance of the simulation software is demonstrated as a helpful and appropriate design tool.

In the speed range 0.6<n*<0.8 a further reduction in final pressure, which was not carried out experimentally, was simulated, resulting in increased clearance areas within the molecular flow regime in the direction of the outlet port. This led to reduced backstreaming clearance flows to the inlet port. For rotation speeds n*>0.75 the influence of external leakage predominates, so that clearance influences in the simulation are practically negligible. In particular the deviations referred to above indicate that an additional physical-technical effect not modelled in the simulation so far must be considered. This effect is likely to occur with low gas densities, molecular flow conditions and higher rotor speeds, so that the chamber filling process is considered.

Suction Performance

The measured suction performance of the investigated screw vacuum pump shows variation in the suction pressure for different machine rotation speeds, **Fig. 5**. Rotor speed dependent and pressure-dependent performance, generally characteristic for screw vacuum pumps, can be observed. With atmospheric pressure as the starting point a drop in volumetric efficiency occurs at reduced intake pressures, as expected (p_{in}>100mbar). The gradient of the decrease in supply rate performance is dependent on the rotor speed and decreases with increasing speeds. This supply rate behaviour is at first decreasing with reduced intake pressures, but becomes increasing in and above the sensitive speed range and is responsible for significant expansion of the operating range (10< p_{in} [mbar] < 100). Further reducing the intake pressure leads again to a significant drop in volumetric efficiency until the attainable final pressure indicates the limit of the possible operational range (p_{in}<10mbar). In this case the clear drop in volumetric efficiency occurs at rotation speeds n*>0.56, for fine vacuum conditions (p_{in}<1mbar), and seems to be practically independent of rotation speed.

Figure 6 also shows a comparison of the suction performance measured experimentally and in the simulation as a function of the rotor speed and intake pressure for the screw vacuum pump under examination. The clear drop in the suction performance for low rotation speeds in rough vacuum can be simulated in the same way as that occurring at higher rotation speeds (n*>0.5), where the further decrease in intake pressures (p_{in}<100mbar) which was observed, led to improved intermediate range suction performance. This is due to the increased throttle influence of machine clearances at decreased operating pressure during transition from viscous, via intermediate to molecular flow. This applies especially for clearances near the intake port side working chambers. A modified pressure profile was produced during the working cycle, with reduced clearance flows and consequently reduced backflows into the current charging working chambers as well as into the inlet port.

The good match between simulation and experiment with regard to the rotation speed and pressure-dependency of the suction performance confirms the significant influence of clearance flows as the decisive physical-technical working-mechanism in the rough and fine vacuum operation of screw vacuum pumps. Vacuum-specific external leakage (L < 10^{-4}mbar*l/s) is practically negligible under these circumstances.

Deviations between experiment and simulation occur with further decreases in intake pressure at higher rotation speeds (p_{in}<0.1 and n*>0.56), as has already been observed for final pressure behaviour. A further loss mechanism should be mentioned at this point. This is the chamber filling process, which is not ideal and has not so far been modelled, because this phenomenon is more likely to occur mainly with low gas densities and molecular flow conditions for the charging process, and at higher rotation speeds.

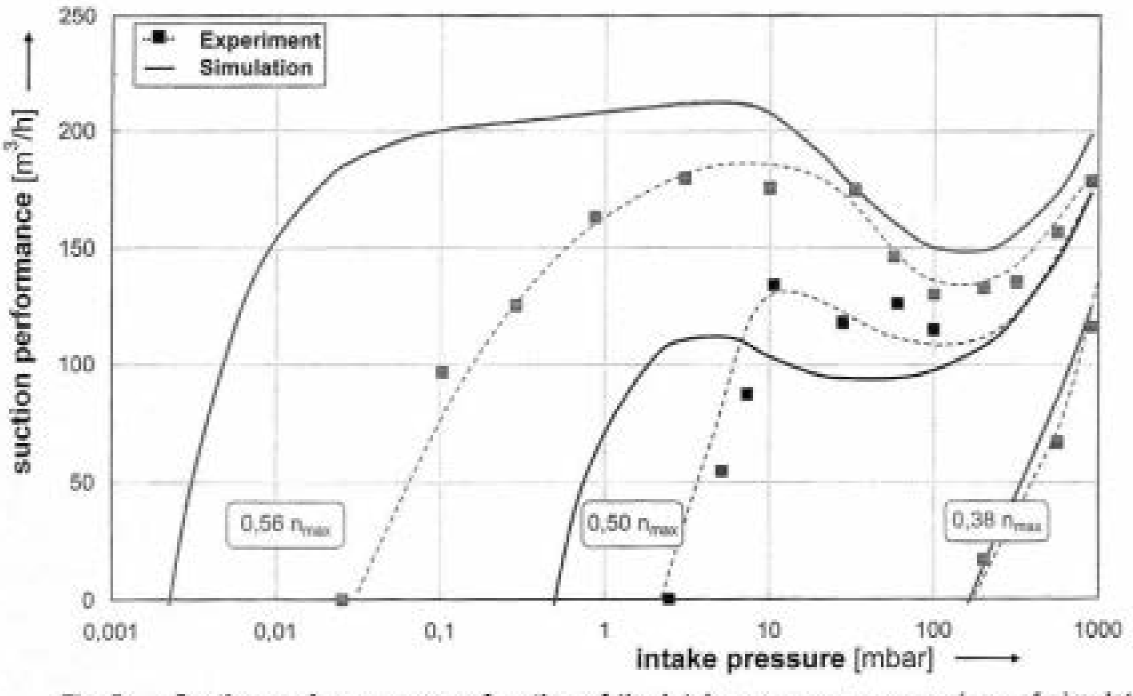

Fig. 5: Suction performance as a function of the intake pressure – comparison of simulation vs. experiment (parameter: rotor speed n)

5 Conclusions

The characteristic machine performance and thermodynamic behaviour of the screw vacuum pump under examination is represented via the parameters *ultimate attainable pressure* and *suction performance*, based on rotation speed and operating pressures, and can be considered as generally characteristic for this type of vacuum pump. Experiment and simulation in combination show the importance and interrelationships between physical-technical working-mechanisms, clearance flows and external leakage. The attainable final pressure and suction performance of the screw vacuum pump result from physical processes during chamber filling. Both experiment and simulation confirm the vital significance of internal pressure and rotation speed dependent clearance flows on the overall pumping performance in rough and fine vacuum situations.

In particular, the increased throttle function which occurs during the transition from viscous to molecular flow conditions at the low pressure side machine clearances, forms a distinctive rotor speed sensitive range. Here, even with higher pressure gradients over the whole vacuum pump, suction performance is improved, and ultimate attainable pressures can be significantly reduced. The influence of external vacuum-specific leakages on attainable pressure and suction performance can be disregarded as small to negligible. With a dimension of 10^{-4}mbar*l/s external leakages only exert a significant influence on suction performance at high vacuum pressures ($p<10^{-3}$mbar).

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Symbols and Indices

Symbol	Meaning	Dimension
m_{th}	Theoretical mass flow	kg/s
P_{in}	Intake / inlet pressure	mbar
p_{at}	Ambient pressure	mbar
$p_{in,min}$	Ultimate (final) pressure	mbar
L	Leakage	mbar*l/s
$V_{AK,max}$	max. chamber volume	m^3
Kn	Knudsen number	-
T_{Gas}	Gas temperature	K

Symbol	Meaning	Dimension
s	Clearance height	mm
S_{th}	Theoretical suction speed	m^3/h
m_L	Leakage mass flow	kg/s
z	Tooth number of rotor	-
i	Number of rotors	-
n	Rotor speed	1/min
n*	Normed rotor speed	1/min

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