Gas Flow through Gaps in Vacuum Pumps

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Abstract

Dry-running positive-displacement vacuum pumps do not need any helping fluid for the compression of the working gas. However the lack of the helping fluid leads to a described viscous-circle of operation. This operation is mainly influenced by the inner leakage, which means the gas flows through the gaps in a vacuum pump. This gas flow is investigated. Therefore the real geometries of gaps are transduced into a model and categorized. The results of measurements are discussed by example for a variation of the inlet pressures, a variation of the geometry within a category and for different heights of gaps.

1 Dry-running positive displacement vacuum pumps

The trend in the market for vacuum pumps is steered by the increased technical demands on the vacuum, which are to be derived from intended areas of application. Today the fulfilment of these claims is by no means concluded /1/. The purity of the vacuum represents an indispensable presupposition for many sensitive processes and applications. For example the semiconductor manufacturing the metallurgy or the chemical process engineering, as well as the research and development. A clean vacuum demands the lowest possible contamination by auxiliary fluids. Therefore the demand for a "clean vacuum", can primarily be equated with the demand for dry-running vacuum pumps. The type of the rotational positive displacement pumps can fulfil these new demands.

Part 2 of DIN 28400 classifies vacuum pumps. One classified group is called dry-running positive displacement vacuum pumps. The screw spindle vacuum pump, the roots pump and the claw pumps are members of this group. All members have the following qualities in common:

- Two shafts and rotors.
- The working chambers are built by the two rotors and the housing
- The rotors built several working chambers, that exist at the same time

- The meshing of the two rotors and the housing gap separate the working chambers.
- The working chambers are connected by gaps.
- Relative motions can be found between the two rotors and between each rotor and the housing.

As shown in table 1, totally different designs of positive displacement pumps belong to the same group. The rotors of the screw spindle vacuum pump are threaded. The working fluid is transported in an axial direction. The rotors of the roots pump and the claw pump are not threaded. The working fluid is transported along the circumference of the rotors.

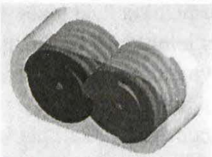	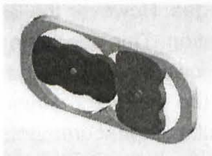	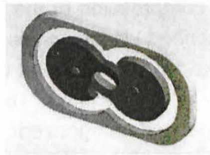
Screw spindle pump	Roots pump	Claw pump

Table 1: ***Rotor design of different types of positive displacement vacuum pumps***

2 Vicious circle

With these vacuum pumps, no auxiliary fluid is in direct contact with the working fluid in the working chamber, that is transported. A "clean vacuum" is therefore the direct consequence of this. However, with the missing auxiliary fluid there is a lack in the cooling effect and the sealing effect at the function-conditional clearances of the working chamber. This leads to the stimulation of the vicious circle of the design of dry-running rotational positive displacement pumps , figure 1

The lack of the sealing effect causes more internal leakage than with a pump using auxiliary liquids. To achieve comparable final pressure or effective suction capacity with the same rotor geometry, the dry-running pump needs comparatively higher speeds, than the one working with sealing fluids. This results in a higher thermal loading of the pump, which is strengthened by the lack of the cooling effect. The higher thermal load causes bigger rotor expansions and strains. In order to guarantee operational reliability, the dry-running pump has to be designed with bigger cold clearance heights. The effective heat-formed clearance heights are smaller in the operation of the engine on account of the thermal rotor expansion. Therefore the technical designer must be able to conclude from the cold clearance heights on the heat-formed clearance heights in the concept phase of the pump.

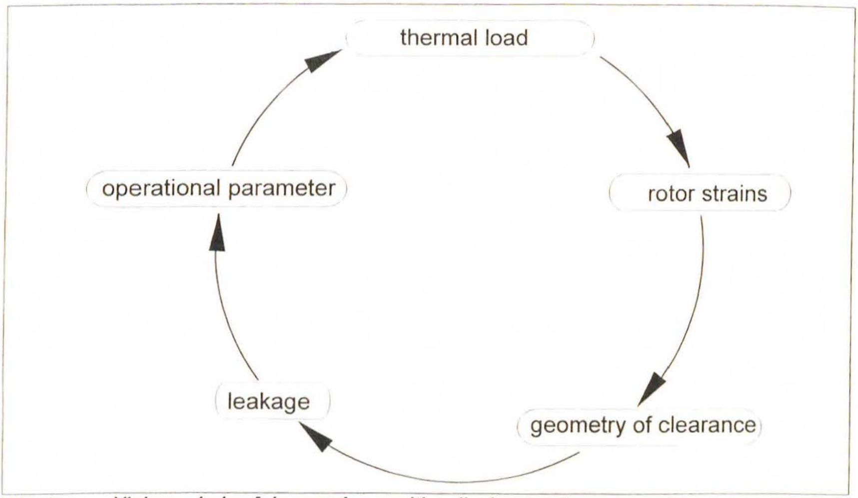

Fig. 1: ***Vicious circle of dry-running positive displacement vacuum pumps***

There follows an optimisation problem between pumps with very close clearances and low leakages and pumps with bigger clearance heights because of the need for guaranteed operational safety. At present this optimisation problem can be solved only with values of experience and the insecurity connected with it. With this insecurity the vicious circle shuts, because often too big clearance heights must be chosen or are chosen for reasons of operational reliability /2/ - /3/.

3 Modelling

The flow through the clearances of dry- running vacuum pumps represents a flow through spatial gaps in a rotating system. At the same moment the boundary walls relatively move to each other and the geometry is partly changed because of the thermal load. Therefore the flow possesses transient, adiabatic qualities.

In /4/ the deviation of the integral description by unsteady flow is examined. In a vacuum high pressure ratios and the low absolute masses are typical characteristics for the flows. Both these qualities favour the integral description of the unsteady flow by the quantification of characteristic Numbers which are determined for quasi-steady flow.

This is an important pre-supposition in order to be allowed not to examine the flow through the clearances of real pumps but in models of clearances. The usage of models is a significant advantage because of the possibility to differ geometrical and dynamic sizes of influence on the flow. The second advantage is given by the categorization and reduction of the number of parameters that have to be examined.

With the knowledge of characteristic numbers for the quantification of the steady flow the dynamic influence on the flow can be determined /5/. With it the examinations limit themselves to the geometrical parameters affecting the flow, particularly the shape of the clearances.

The number of geometrical parameters of a gap is indefinite, because a gap is finite volume with a boundary of any geometry. This volume possesses at least three dimensions. Fluidic research often is focused on the narrowest section of a geometry. This reduces the three-dimensional problem to a two-dimensional problem.

The geometrical parameters are :

- The length l of gap in direction of flow,
- the width b,
- the height of gap s (at the narrowest section),

and

- the shape of gap, compare to figure 2.

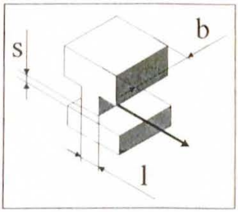

Figure 2: Geometrical parameters of a gap

In this connection, shape of gap means the series of cross sections of clearance, that supposed stream-lines pass through. If the flow rate is known for the shape of gap, the flow rate can be determined for a spatial gap /5/. Therefore the shape of gap becomes an essential parameter for the research on flows through a gap /6/ - /7/.

The whole modelling of gaps, that are experientially investigated, takes place in two steps. The first step transduces a moving spatial gap into a stationary spatial gap. The second step subdivides the spatial gap into sections of plain geometry. These sections of plain geometry are used for the experiments.

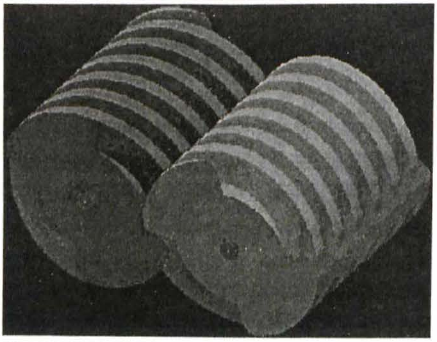

Fig. 3 ***Housing gaps between revolving rotors and the housing with moving walls***

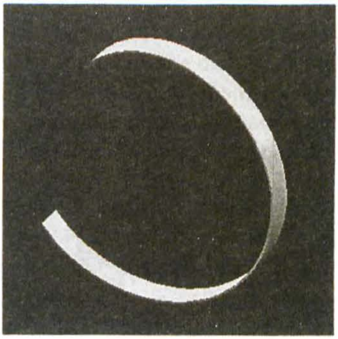

Fig. 4: ***Result of modelling Step one. Housing gap as spatial finite volume with stationary boundaries***

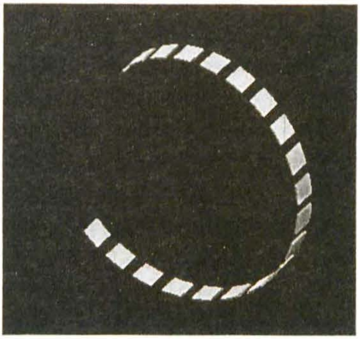

Fig. 5: ***Result of Step two. The spatial housing gap is subdivided into plain sections***

4 Categorisation

Because it is not possible to examine arbitrarily many forms of shapes of clearances, the different forms are to be reduced rather to a number capable of examination. In addition the shapes of clearances must be categorised with regard to a geometrical parameter which describes the geometry.

Category	Significant Parameter
1	Angle of shape contraction
2	Radius of convex shape
3	Radius of concave shape
4	Length in direction of flow
5	Radius of convex geometry at the outlet
6	Radius of inlet geometry
7	Height of obstacle

Table 2: ***Matrix of investigated shape of gaps***

Then within the separate categories a suitable staggering of the geometrical parameter reduces the number of the shapes to be examined, compare to table 2. Besides the described categories, two special shapes of gap are added to the group of investigated shapes of gaps. These two shapes are the geometrical limits of each category. Shape SK1 possesses the minimal length of gap in direction of flow. The shape SK2 is equal to a gap with parallel surfaces for the maximum length in direction of flow.

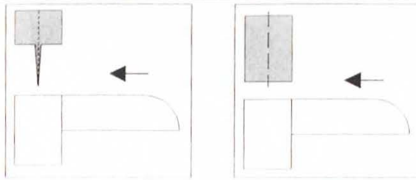

Fig. 6: ***Added shapes of gaps***

By the categorization, the expenditure decreases to the consideration of altogether forty different shapes of gaps for dry-running rotational positive displacement pumps.

5 Results of measurement

The inlet pressure p_E is used as an essential parameter for the following discussion of the measuring results. The presentation of the standardised mass-flow $\delta = f(p_E)$ as a function of the inlet pressure p_E characterises the throttle quality of a gap.

$$\delta = \frac{\dot{m}}{\dot{m}_{th,\max}} \qquad \text{eq. (1).}$$

This theoretical maximum is represented by the interlocked mass flow through an orifice for a viscous flow. In order to calculate the maximum flow rate (Eq. 2) the variables of state of the actual flow are used. The geometry is given by the minimum area A_{min} of the clearance that possesses the length $l = 0$ in direction of the flow.

$$\dot{m}_{th,\max} = \dot{m}_{th,kr} = A_{\min} \cdot \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \cdot \frac{p_E}{RT_E} \cdot \sqrt{\frac{2\kappa}{\kappa+1} \cdot RT_E} \qquad \text{eq.(2).}$$

The results are discussed for different ranges of pressure and for different types of flow. These different types of flow can be identified with the help of a characteristic number, the Knudsen number Kn.

$$Kn = \frac{\bar{l}}{l_{char}} \qquad \text{eq. (3).}$$

The throttle loss φ_{ges} of a gap is considered as a combination of a gap form resistance φ_F and a gap height resistance φ_s:

φ_F = f (Geometry, e.g. shape of gap, height s = const.) eq. (4).

φ_s = f (height of gap s, stationary geometry of gap) eq. (5).

$\varphi_{ges} = \varphi_F + \varphi_s$ eq. (6).

According to the form resistance for the flow around obstacles, we can define the gap form resistance for the throttle loss , caused by the shape of the gap. In order to characterize the flow as a function of the shape of the gap, the gap form resistance is used for every type of flow, though the form resistance is normally only used for continuous flow.

A special measuring procedure is used for the flow examination. With this measuring procedure a recipient is arranged behind the gap. At the beginning of the measurement, it is evacuated. The inlet pressure is constant during the whole measurement. The flow through the gap, floods the recipient. Therefore this measuring procedure is called "flood-curve measurement". With a sufficient size of the recipient this occurs very slowly and the different working conditions of the flow are to be considered as quasi-steady one, compare to /8/. For this constant inlet pressure the flood curve assigns the characteristic number to the combination of physical and geometrical parameters at the clearance, i.e. the flood curves describe the functional relationship between the pressure ratio Π at the clearance and the standardised mass flow $\delta = f(\Pi)$.

5.1 Variation of inlet pressure p_E (Floodcurves)

All the flood curves of a single clearance characterize the integral throttle quality of a clearance. Figure 7 shows the results of a clearance shape belonging to category 1. For a variation of the inlet pressure the different flood curves must be compared. In order to discuss the results two different inlet pressures $p_{E,1}$ and $p_{E,2}$ are considered. The qualitative analysis of the flood curves shows for high inlet pressures $p_E > p_{E,1}$ the typical characteristic for the viscous, interlocked flow. For sub critical pressure ratios $\Pi < \Pi_{kr}$ the standardised mass flow remains constant. For lower inlet pressures the value of the critical pressure ratio $\Pi_{kr} = f(p_E)$ sinks. The smaller the inlet pressure p_E the smaller the critical pressure ratio Π_{kr}. The parameter range of pressure ratios Π, that mean interlocked flows through the gap, decreases. The qualitative form of the flood curves approaches the linear characteristic of the molecular flow and shows this for inlet pressures $p_E < p_{E,2}$.

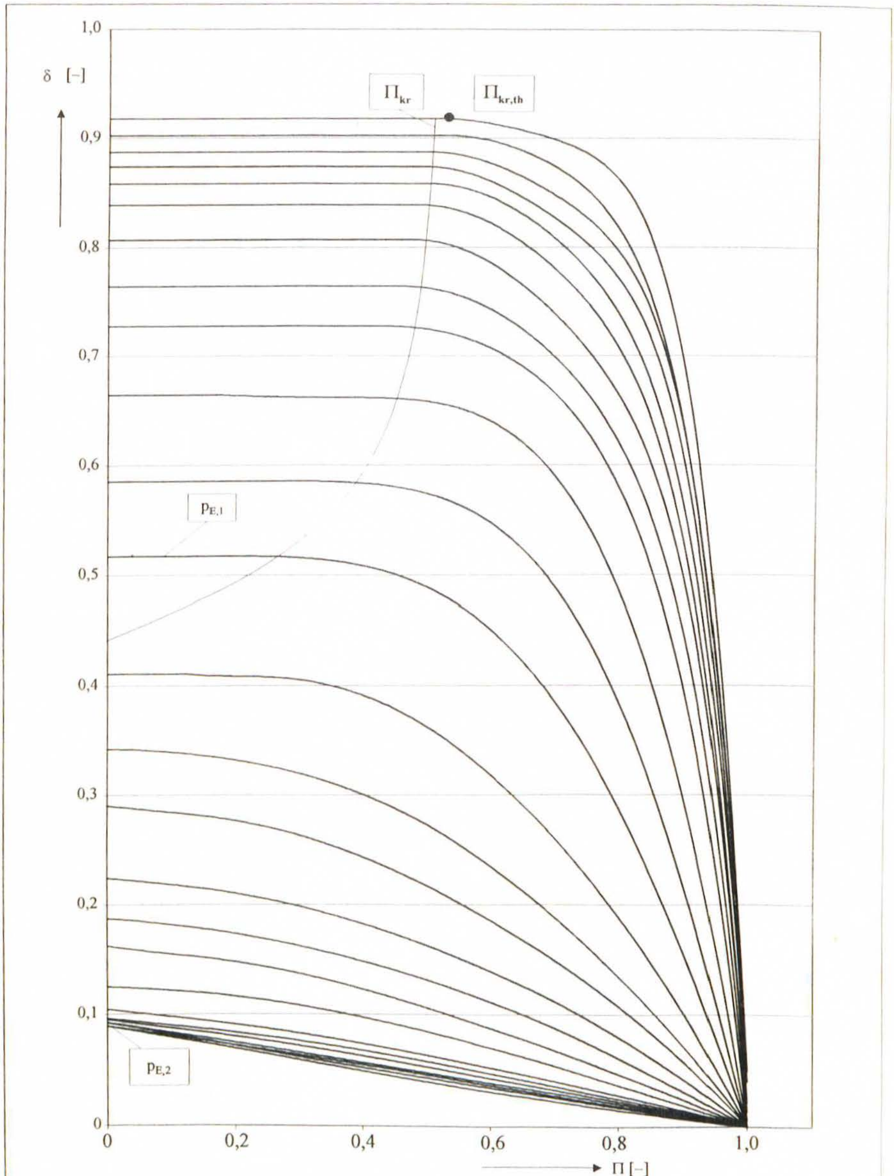

Fig. 7: ***Flood curves belonging to clearance shape W1 (category 1)***

This means, that the type of flow can be determined by the shape of the floodcurve. According to this the determination of the type of flow can be done after the measurement, while looking its results.

5.2 Quantitative characteristic pattern

The combination of the results of the separate flood curves (Π-variation) and the variation of the inlet pressure p_E, allows the representation of a quantitative characteristic-pattern of a clearance in the vacuum. Figure 8 illustrates the diagram of a clearance.

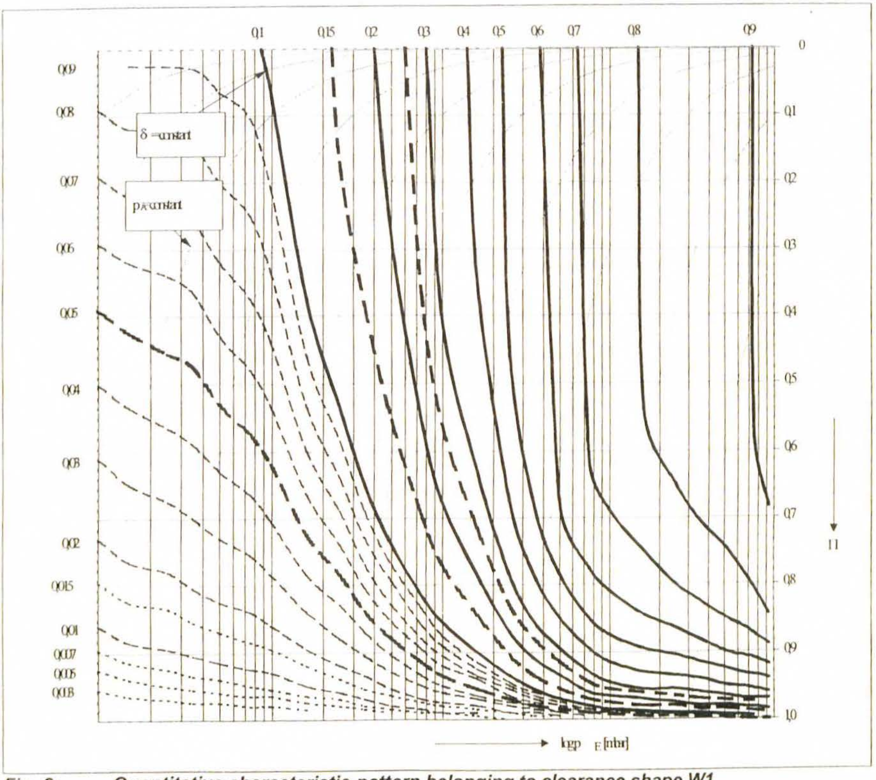

Fig. 8: ***Quantitative characteristic-pattern belonging to clearance shape W1***

The quantitative characteristic-pattern, is built by the physical parameters of the inlet pressure p_E (abscissa) and the pressure ratio Π (ordinate). Within this parameter field characteristic curves of constant standardised mass flow δ characterize the throttle quality of a clearance. In the form of the characteristic curves the typical characteristics of the different states of flow can be recognized. The interlocked flow of the viscous flow distinguishes itself by the constancy of the standardised mass flow. Accordingly, the characteristic curves run for high constant inlet pressures parallel to the ordinate. The linear characteristic of the molecular flow area can be found in the area of the low pressures. The linear relationship between the standardised mass flow δ and the pressure ratio Π causes the equidistant run of the curves representing constant values of the standardised mass flow.

However, for a comparison of different shapes of gap, that belong to the same category , the characteristic patterns are too complex.

5.3 Characteristic line for constant pressure ratio

In order to analyse the throttle loss of a gap, it is helpful to look at the standardized mass-flow $\delta_\Pi = f(p_E)$ as function of the inlet pressure p_E. But it is not possible to measure such a characteristic line directly. This type of characteristic line exists of several points (p_E ; δ_Π) . Every point quantifies the standardized mass-flow as a function of the inlet pressure for a constant pressure ratio P at the gap. That means, that every point represents a flood-curve or that every flood-curve is reduced to one point. This leads to the following figure 9.

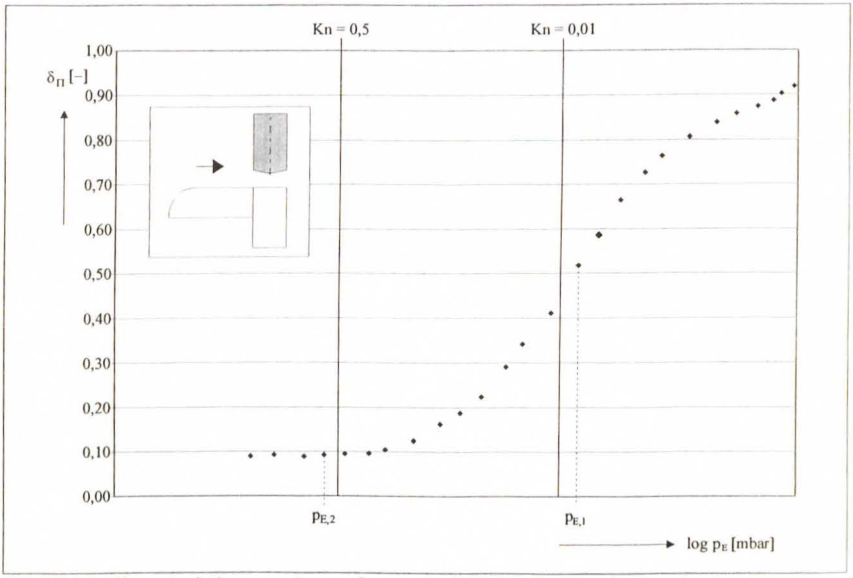

Fig. 9: ***Characteristic curve δ_Π as a function of inlet pressure p_E for constant pressure ratio Π at the gap***
Shape: Category 1 - W1
Parameter: Pressure ratio Π = const., height of gap S4

The group of flood curves of figure 7 is reduced to just one characteristic line $\delta_\Pi = f(p_E)$ for a constant pressure ratio. The standardized mass-flow δ_Π is constant for low inlet pressures $p_E < p_{E,2}$. Its value increase for higher inlet pressure monotonically. The illustrated lines, marked with Kn = 0,5 and Kn = 0,01, separate pressure ranges Δp_E . A different type of flow can be expected for each pressure range. Molecular flow is typically for the pressure range belonging to (Kn < 0,5). This is verified by the vertical course of the characteristic line. The standardized mass-flow is constant, the standardized mass-flow does not depend on the inlet pressure. (Compare to the linear characteristic of flood-curve $p_E < p_{E,2}$ in figure 7, that is also typical for molecular flow).

This vertical course of the characteristic line $\delta_\Pi = f(p_E)$ is similar to the characteristic line of a thin orifice nozzle /9/, which can be subdivided into three ranges. The standardized mass-flow is constant for the molecular flow. The values of the standardized mass-flow are rather low. For the viscous flow the standardized mass-flow is constant too, but on a comparably higher level. Between both pressure ranges of these flows, the pressure range of the Knudsen flow, the standardized mass-flow is a linear function of the inlet pressure. The course of the characteristic line is a straight line.

The comparison of the characteristic line in figure 9 with the described course of the orifice nozzle shows, that both lines are rather similar. But the strong increase of the values in figure 9 does not take place for the Knudsen flow. The standardized mass-flow increases for viscous flow too.

That means, that the standardized mass-flow depends on the inlet pressure. A gap form resistance can be established for the investigated shape of gap. This throttle behaviour is different from a thin orifice nozzle, that does not own a shape in the direction of flow.

5.4 Variation of geometry within a category

The quantitative comparison of the characteristic lines in figure 10 is done for constant inlet pressures p_E. A clear tendency can be found for molecular and Knudsen flow. The smaller the angle of shape contraction (SK2 < W1 < W2 < SK1) the smaller the standardized mass-flow. The characteristic lines can be sorted by the according parameter of the angle and they do not cross each other.

Only the already discussed characteristic line of shape W1 is rather similar to the characteristic line of an orifice nozzle. All the other characteristic lines just show two of the three described parts of the characteristic line of an orifice nozzle. It is obvious, that the shapes SK2 and W2 show a vertical course for the viscous flow. The decrease of standardized mass-flow can be assigned to the Knudsen flow. The course of the characteristic line of shape SK2 is parallel to the abscissa and increases for Knudsen flow and viscous flow.

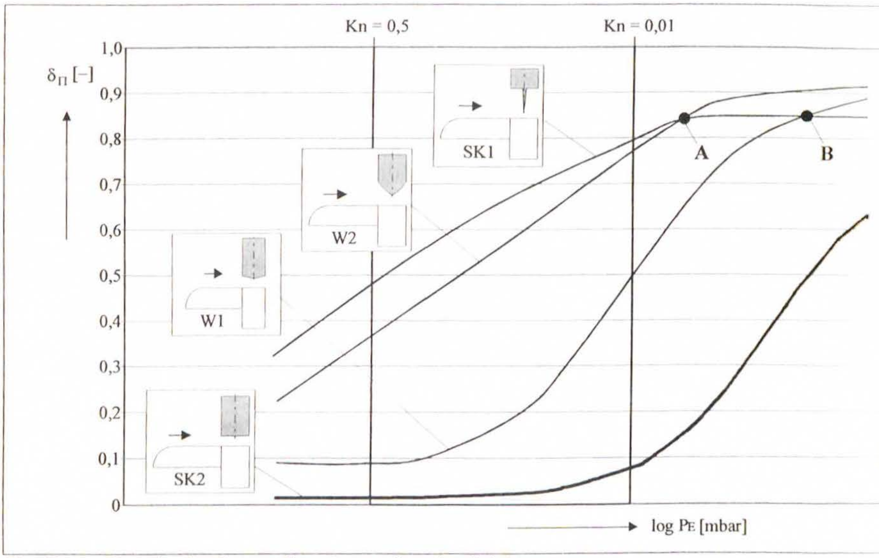

Fig. 10 : ***Standardized mass-flow δ_Π as a function inlet pressure p_E***
Varied Geometry: Category 1 – Angle of shape contraction
Shapes: Category 1 – W1, W2 / Special shapes – SK1, SK 2
Parameter: height of gap S4, pressure ratio Π = const.

This leads to the conclusion that the increase of the standardized mass-flow is not significant for the Knudsen flow. The increase of the standardized mass-flow is caused by the gap form resistance, that influences the throttle loss. With a stronger gap form resistance the increase of the standardized mass-flow is moved to higher inlet pressures.

5.5 Variation of heights of gaps

The analysis of a variation of the height of gap as effect on the throttle loss is rather complicated in comparison to the variation of the shape. The variation of the height of gaps can not be separated from a variation of the area of the gap at the narrowest section. Even for constant physical parameters the mass-flow through the gap varies with the height of gap.

The results of the measurements are illustrated for four different heights of gaps in figure 11. A constant height of gap can be assigned to every characteristic line. The chosen heights of gaps are typically for dry-running positive displacement pumps (S1<S2<S3<S4).

The results show a clear tendency. The smaller the height of gap, the lower the standardized mass-flow. The characteristic lines do not cross each other and all curves are monotonic.

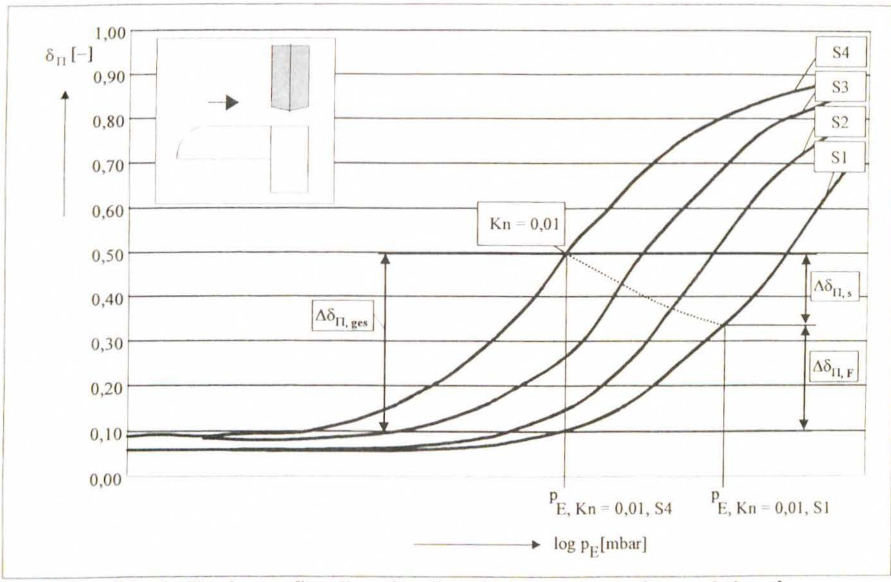

Fig. 11: ***Standardized mass-flow δ_{Π} as function of inlet pressure p_E for a variation of heights of gaps S1 $\leq$ s $\leq$ S4***
Shape: Category 1 – W1 – Angle of shape contraction
Parameter: Pressure ratio Π = const.

At first the focus is put to the characteristic line belonging to the height of gap S4. The inlet pressure $p_{E,\,Kn=0,01,\,S4}$ represents the border between viscous flow and Knudsen flow. The decrease of heights of gaps from S4 to S1 causes the decrease of the standardized mass-flow by the value of $\Delta\delta_{\Pi,ges}$. For the characteristic line of the height of gap S1 the pressure $p_{E,\,Kn=0,01,\,S4}$ does not mark any longer the change in the types of flow from Knudsen flow to viscous flow. The corresponding pressure $p_{E,\,Kn=0,01,\,S1} > p_{E,\,Kn=0,01,\,S4}$ is higher.

If the standardized mass-flow is compared for the same values of the Knudsen number Kn = 0,01; the difference in values $\Delta\delta_{\Pi,s}$ is found for the standardized mass-flow.

Thus the variation of the height of gap causes a variation of the gap height resistance for constant values of Knudsen flow Kn. The decrease of the standardized mass-flow according to the decrease of the inlet pressure from $p_{E,\,Kn=0,01,\,S1}$ to $p_{E,\,Kn=0,01,\,S4}$ for the constant height of gap S1 is caused by the pressure-depending gap form resistance.

The total change of the throttle loss $\Delta\delta_{\Pi,ges}$ is caused the combination of the gap height resistance and the gap form resistance.

6 References

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