Gas Flow through Gaps in Screw-type Machines

Gasspaltströmungen in Schraubenmaschinen

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1 Abstract

The reliability as well as the efficiency of screw-type machines is influenced by their internal gas flows. Statements about the reliability and the aim for progress concerning the quality of the machine's energy conversion can be achieved via a realistic model of the screw-type machine. A numerical flow simulation by means of "Computational Fluid Dynamics" (CFD) will be a fundamental part of this model. The complex flow conditions require experimental verification as a basis of this simulation. In the present paper the gas flow at the male rotor housing gap is made visible by means of Toepler's 'Schlieren-method'. A variation of the gap-height and -form is included. The Mach angle visible in the Schlieren-picture provides information about the sealing properties of the various gaps. These accounts are supported by qualitative measurements of the mass flow through the gaps.

2 Zusammenfassung

Sowohl die Betriebssicherheit als auch die Energiewandlungsgüte von Schraubenmaschinen werden von den Gasströmungen innerhalb der Maschine beeinflußt. Eine realistische Modellierung der Maschine ermöglicht Aussagen zu ihrer Betriebssicherheit und eine angestrebte Steigerung ihrer Energiewandlungsgüte. Ein wesentlicher Teil dieses Modells wird die numerische Strömungssimulation mittels "Computational Fluid Dynamics" (CFD) sein. Die komplexen Strömungsverhältnisse verlangen nach einer experimentellen Verifikation als Grundlage dieser Simulation. In der vorliegenden Arbeit wird die Strömung am Hauptrotorgehäusespalt für unterschiedliche Spaltformen und –höhen mittels des Toeplerschen Schlierenverfahrens visualisiert. Der im Strömungsbild erfassbare Machwinkel ermöglicht Aussagen über die „Dichtheit" der verschiedenen Spalte, die quantitative Spaltdurchflußmessungen ergänzen.

3 Introduction

This paper has to be seen in connection with several reports on experimental research into the gas flow in a plane screw-type machine model, [1] to [5]. The aim of this research is the characterisation of the gas flow in selected gaps inside a plane screw-type machine model. This is the first step on the way to a verified model of the gas flows in a screw-type machine in order to support statements about the reliability and the energy conversion of the machine. The experiment is based on the influence of the behaviour of the heat transfer of the gas flow in the working chamber on the reliability and the effect of the gap leakage flows on the energy conversion.

The starting point of the experimental studies is an asymmetric profile of a common screw-type compressor in order to support the transfer of the results to a real screw-type machine. A plane cut, vertical to the rotor-axles, ensures a good two dimensional approximation to the geometrical conditions inside this machine, **fig. 1**.

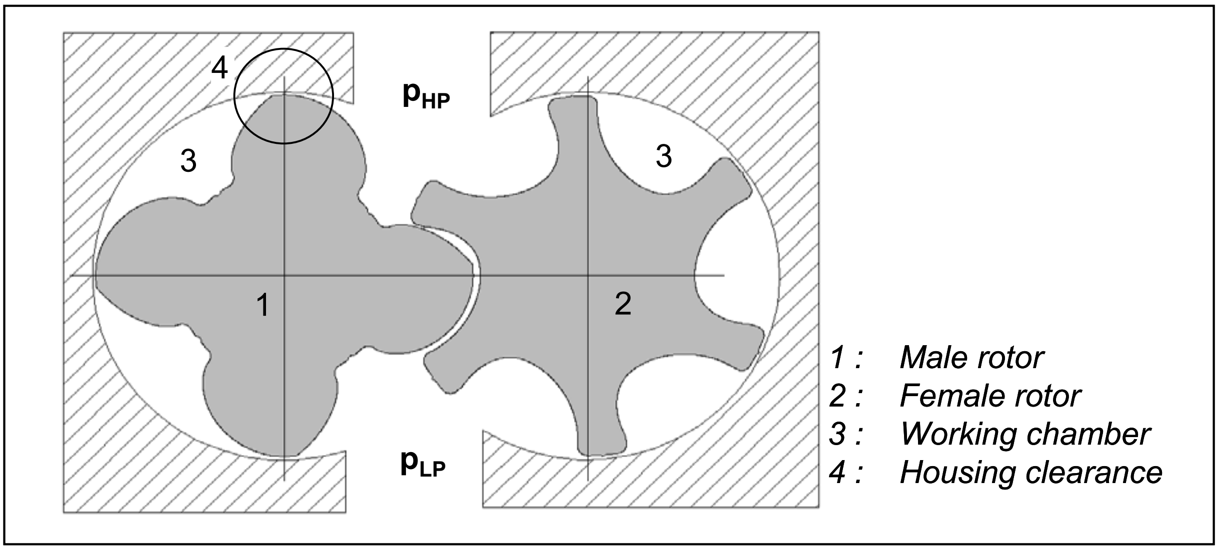

Fig. 1: Vertical cut of a plane, non-screwed 4+6 rotor pair

In the present paper the quality of the gas flow at the male rotor housing gap is examined using Toepler's 'Schlieren-method' for different gap-forms and -heights and selected pressure ratios. The paper begins by describing the gas flow qualitatively. From this follows a quantitative statement with the help of the gas flow velocity as determined by the Mach angle visible in the Schlieren-picture, [6]. By using an assumed connection between the supersonic jet elements, which are detectable in the flow-pattern after the last widening of the gap, and the ability of the gap-form and -height to hinder the gap flow, it is possible to define the function of the male rotor housing gap as a seal. This assumption is based on the fact that jet elements are a sign of a transsonic flow, which indicates a blocking of the gas flow.

Additionally, the measuring system for gas mass flows, mentioned in chap. 4.2, provides accurate information on the quantitative mass flow through the gaps and with it, a check of the evaluation on the Schlieren-pictures.

4 Test Technique

4.1 Method for gas flow visualization

For the gas flow research Toepler's 'Schlieren-method' is used, a method for visualizing a change in the density of light-transmitting media that takes advantage of the dependence of the refraction index on the density of the medium. The application of this technique can produce a complete picture of the flow field in the working section and has no influence on the gas flow itself. An explanation of the basic function of the Schlieren-method, which is required for the interpretation of Schlieren-pictures, can be found in [1] [2] [4] [5] [7].

4.2 Mass flow measuring technique

The equipment shown in **fig. 2** is used to measure the mass flow at the male rotor housing gap. For the comparatively large mass flows through the gaps with a height of 0.4 mm a volume flow meter is applied in order to count the frequency of the separation of vortices. The mass flows at gaps with a height of 0.2 and 0.1 mm and pressure ratios near to 0.5 are measurable with this technique too. If the pressure ratio decreases, mass flow meters working in parallel are used that measure temperature differences at a heating element.

The pressure ratio of the gap model

$$\Pi_{Sp} = \frac{p_{out,Sp}}{p_{in,Sp}} \qquad \text{(Eq. 1)}$$

determined with inlet pressure $p_{in,\,Sp}$ and outlet pressure $p_{out,\,Sp}$ gives no information about a critical pressure ratio of the geometries tested, because of the position of the pressure measuring points.

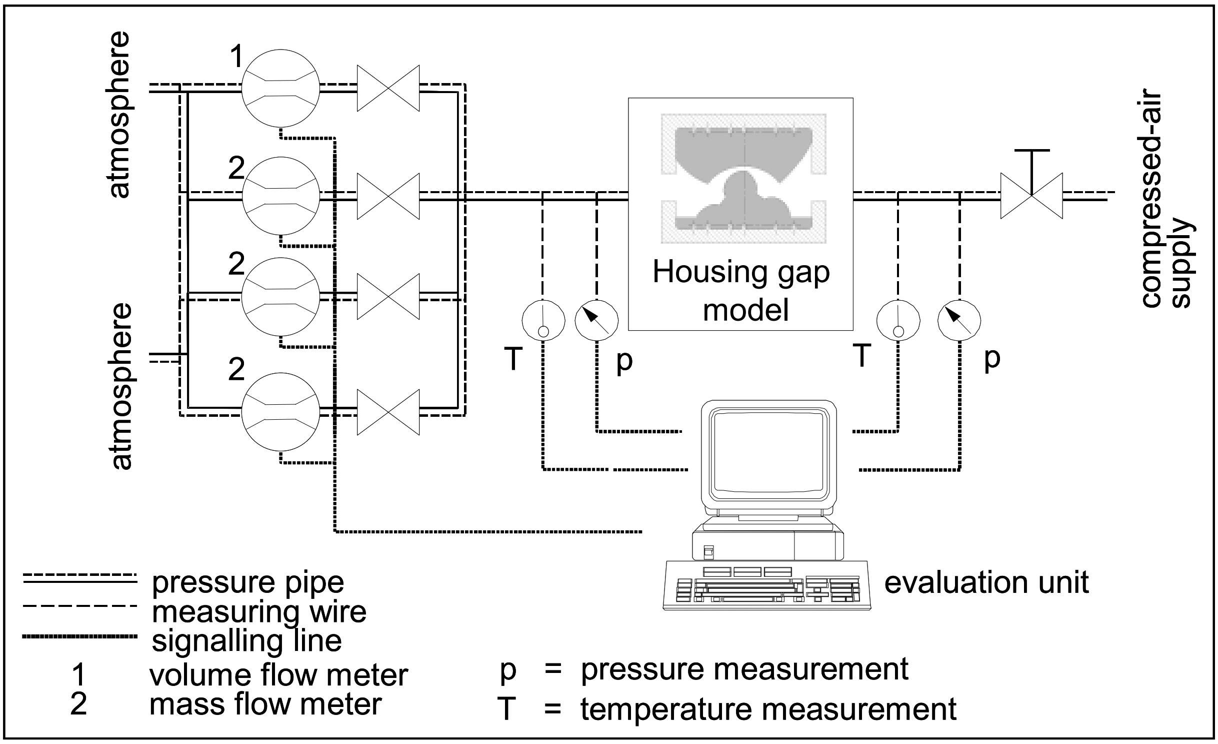

Fig. 2: System for measuring gap mass flows

5 Gas flow through the male rotor housing gap

Before a variation of the form of the male rotor tooth tip is undertaken, the original geometry with one sealing strip and a surface roughness of R_z = 10 μm is tested. The shape of this gap including its length l_{Sp} and the height h_{Sp} can be seen in **fig. 3**. The gap height h_{Sp} is the distance between the sealing strip and the housing. The gap length commences at the first bend, at the transition between the flank of the tooth and the gap, arrow 1 in fig. 3. Then the gap cross-section increases. Arrow 2 marks the point from which the cross-section decreases again. The sealing strip itself is equidistant to the housing and has a little step at the beginning and the end. A widening of the gap follows up to arrow 3, a contraction can be found up to arrow 4, then the cross-section decreases once more, arrow 5. Here the gap meets the following flank of the rotor.

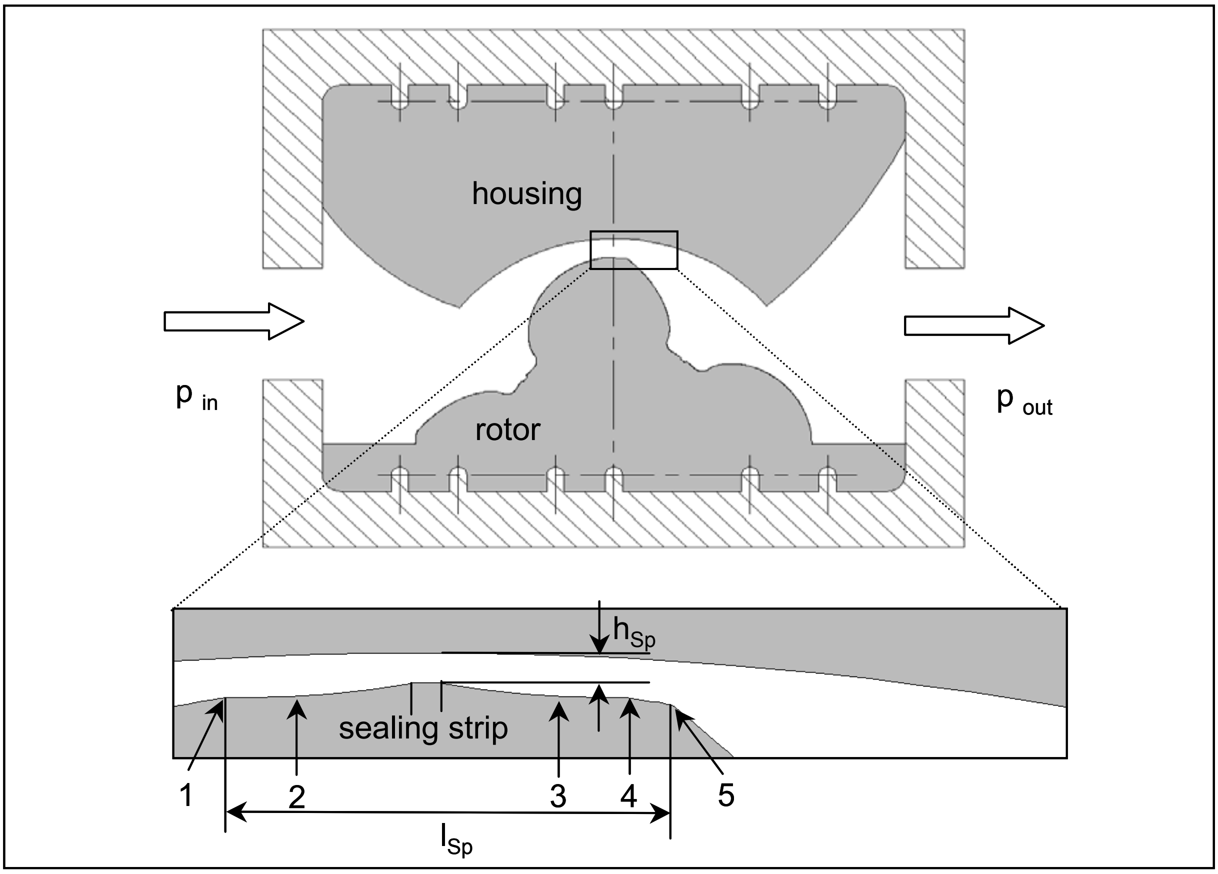

Fig. 3: Model of the housing gap of the male rotor; enlarged view of the tooth tip with one sealing strip; height of gap h_{Sp} (variable); length of gap l_{Sp} = 6 mm

5.1 Flow visualisation

5.1.1 Gas flow quality and the Mach angle at the male rotor tooth tip with one sealing strip

The picture of the male rotor housing gap without flow, i.e. a pressure ratio of $\Pi_W = 1$, can be taken as a reference image, **fig. 4 a**.

The model of the housing gap is installed in a wind tunnel. The pressure at the inlet of the wind tunnel p_{in} and the pressure at the outlet of the wind tunnel p_{out} results in the pressure ratio of the wind tunnel

$$\Pi_W = \frac{p_{out}}{p_{in}}. \qquad \text{(Eq. 2)}$$

Similar to Π_{Sp} (Eq. 1), Π_W allows no statement about a critical pressure ratio of the geometries tested.

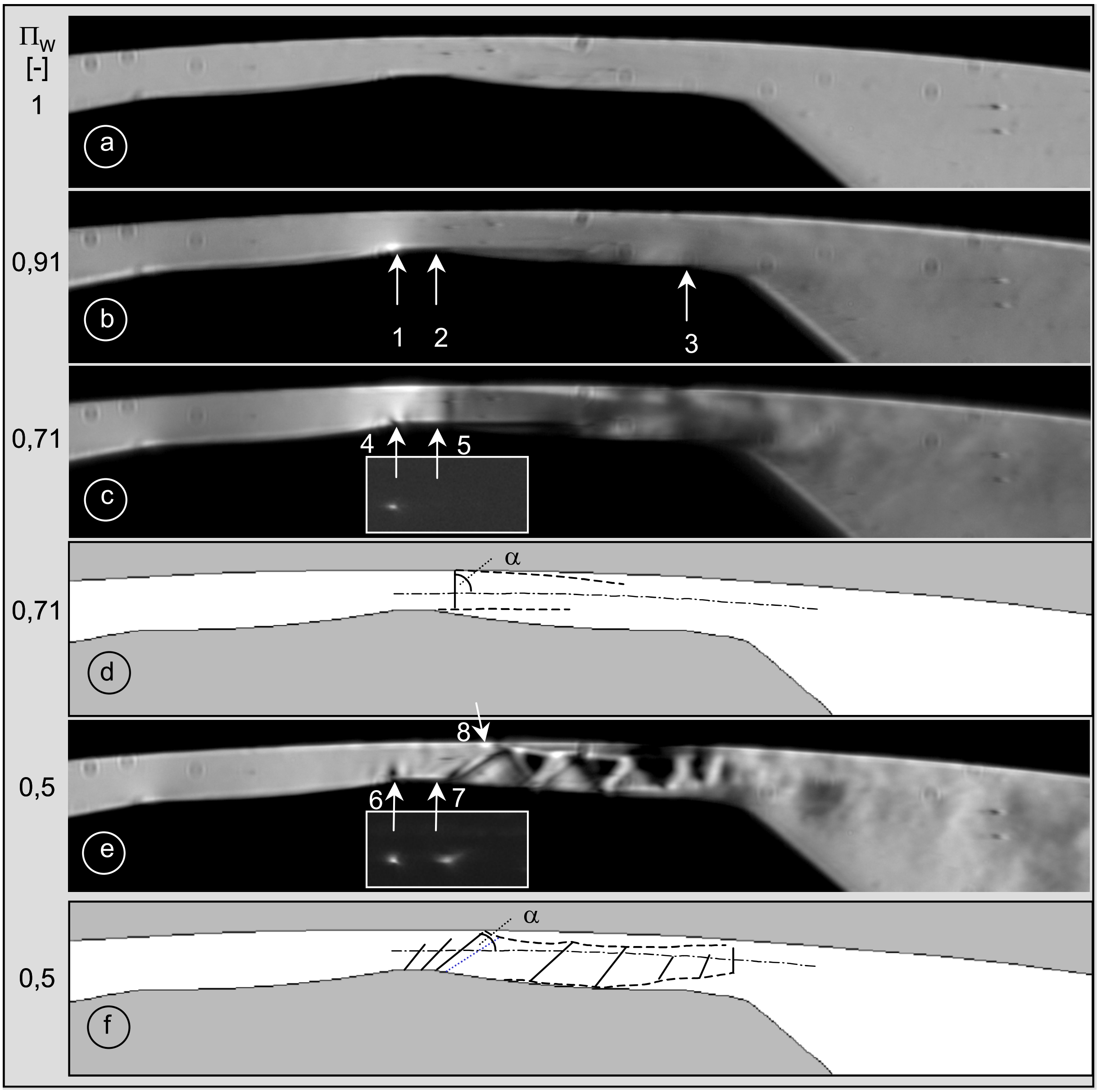

Fig. 4: ***Gas flow at the tooth tip of the male rotor housing gap with one sealing strip; variation of pressure ratio Π_W; height of gap h_{Sp} = 0.4 mm; exposure time t_{exp} = 0,5 μs; output pressure p_{out} = 1 bar***
dotted line: flow separation; solid line: pressure gradients for determination of the Mach angle

Fig. 4 b presents the changes in the Schlieren-picture, resulting from a subcritical pressure ratio. As to be expected, the gas accelerates as it flows around the sealing strip. This can be observed by the brightening at arrow 1. At the rear edge of the sealing strip a flow separation is formed, arrow 2, followed by another one at the last widening of the gap, arrow 3.

A detailed explanation of the correlation between the brightness-level in the

Schlieren-picture and the density gradient in the gas flow, derived from the path of light in the Schlieren-system, can be found in [7]. In the present Schlieren-pictures, brightening corresponds to decreasing density and darkening to increasing density, except for areas with very strong negative density gradients. In this case, brightening turns into darkening, what is caused by the special arrangement of the Schlieren-aperture, see [7]. To keep the correlation between the brightness-level and the density gradient consistent, in such cases another Schlieren-picture with correct scale is integrated into the original one. The new image shows only the places with very strong negative density gradients as bright spots against a dark background, see white framed image in fig. 4 c and e. In this way the points of maximum acceleration in the gas flow are marked.

The flow situation at a pressure gradient of Π_W = 0,71 is shown in **fig. 4 c**. Due to the geometry of the step in front of the sealing strip, the flow around it becomes fast enough i.e. the negative density gradient and thereby the diffraction of the light beams in the Schlieren-systems is sufficiently high to show the above-mentioned effect, see arrow 4 and the white framed image in fig. 4 c.

The local Mach number, the ratio of the local flow velocity and the local velocity of the sound, is calculable from the Mach angle α

$$\mathrm{Ma} = \frac{1}{\sin\alpha} \qquad \text{(Eq. 3)}$$

The Mach angle indicates the inclination of Mach lines to the main flow direction.

The positive density gradient at arrow 5 in fig. 4 c can be seen as a perpendicular shock wave. Its position at 90° to the main flow direction results in a Mach number of Ma = 1. It follows that the flow just behind the sealing strip reaches the local Mach number. The flow separation behind the sealing strip is caused by the edge at the end of the strip and is therefore geometry-induced.

At the housing on the level with the perpendicular shock wave a flow separation occurs. This can be interpreted as a shock induced separation [8]. In **fig. 4 d** the separations and the shock wave are sketched for greater clarity. The pressure ratio of Π_W = 0,5 leads to the flow situation visible in **fig. 4 e**. At the beginning, arrow 6, as well as at the end, arrow 7, of the sealing strip strong negative density gradients, i. e. flow acceleration, can be detected with the help of the small, white framed Schlieren-picture. Behind the sealing strip the accelerated gas flow hits the surface of the tooth tip and a diagonal shock wave is formed. This shock is reflected from the housing, arrow 8, and causes a flow separation at this point. The following reflections of the shock waves and expansion fans finish between two strongly developed flow separations just before the end of the gap, as **fig. 4 f** illustrates.

5.1.2 Variation of the height of the gap

Fig. 5 shows the visualized gas flow at the male rotor tooth tip with one sealing strip and gap heights h_{Sp} of 0.4 mm, 0.2 mm and 0.1 mm. To obtain a good comparison all images are displayed on the same scale. Again the small white framed Schlieren-pictures that present the areas of maximum negative density gradients are integrated into the corresponding Schlieren-pictures. Arrows 1 and 2 mark the beginning and the end of the sealing strip.

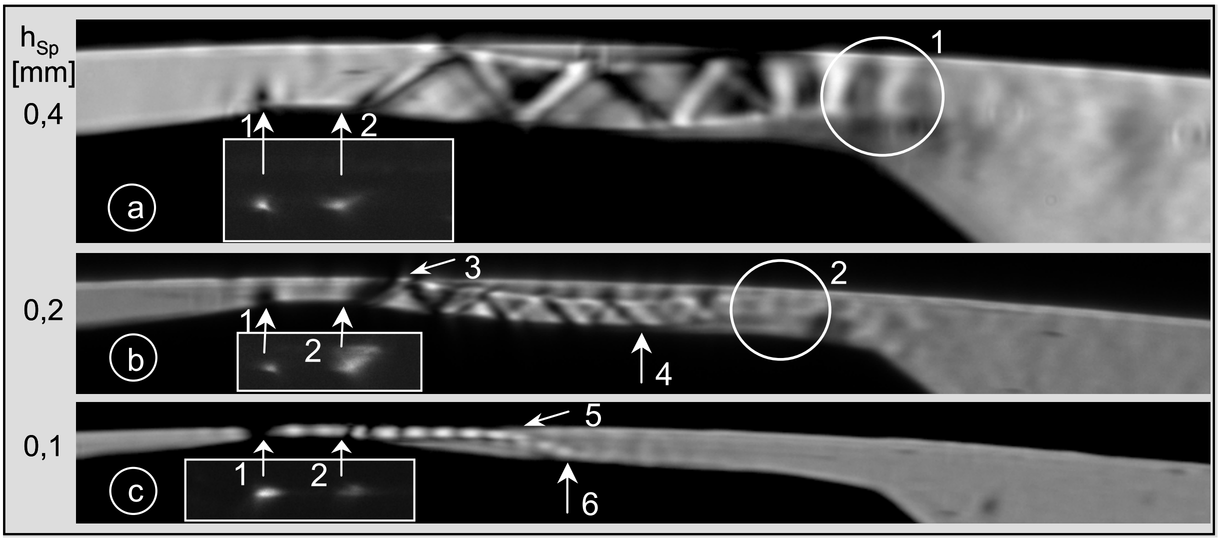

Fig 5: Schlieren-pictures of the gas flow at the male rotor tooth tip with one sealing strip; variation of height of gap h_{Sp}; pressure ratio Π_W = 0,5; exposure time t_{exp} = 0,5 μs; output pressure p_{out} = 1 bar

The area of maximum increasing density in front of the sealing strip expands when the gap height gets smaller, arrow 1 in fig. a, b and c. The flow picture behind the sealing strip at a gap height of 0.2 mm is similar to that with the gap height of 0.4 mm. A flow separation can be found at the housing, arrow 3, as well as at the rotor, arrow 4. The length of the sonic sector decreases with the length of the gap constant, circle 1 and 2. A reduction in the gap height to h_{Sp} = 0.1 mm leads to a shortening of the sonic sector, as can be seen from the structure of the jet that ends near arrow 5. The jet flow separates from the housing and hits the rotor surface, arrow 6. The boundary layer separations don't touch each other, even in this small gap.

The mean flow velocity decreases along the gap with reducing gap height, as demonstrated by further investigations. The reason for this is an increase in the throtteling character of the gap form, as a result of which the flow becomes subsonic even at small pressure ratios Π_W, [7].

5.1.3 Variation of the shape of the tooth tip

The starting point for the variations visible in **fig. 6** is the male rotor tooth tip with one sealing strip and a surface roughness of R_z = 10 μm as shown in fig. 3. The first variation changes only the roughness to R_z = 70 μm, with a constant macroscopic shape. The other variations of the tooth tip form with a constant roughness of R_z = 10 μm can be seen in fig. 6 b to e. The length of the gap l_{Sp} remains unchanged in all variations.

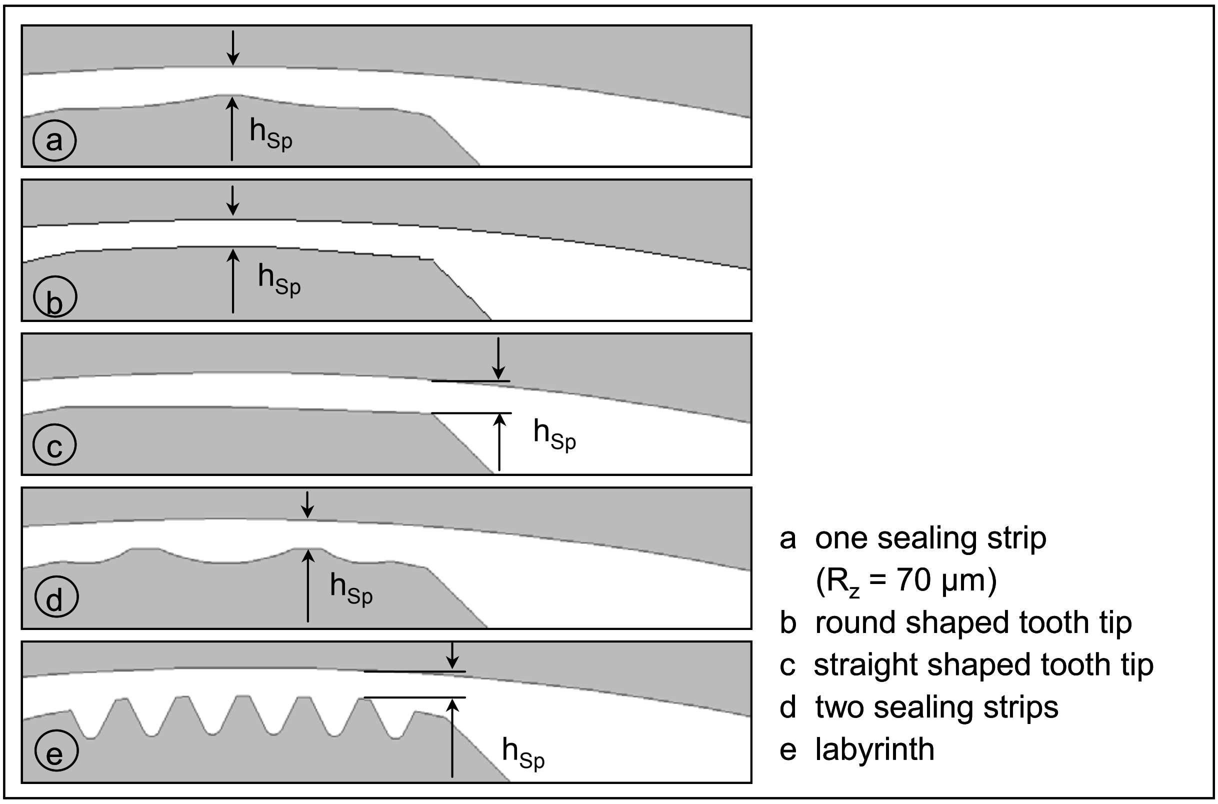

Fig. 6: ***Variation of shape and surface roughness of the male rotor tooth tip; h_{Sp} = height of gap***

The round shaped tooth tip forms a concentric circle to the housing, i.e. the height of the gap is constant. A straight connection from the beginning of the gap to the end results in a straight shaped tooth tip. The tooth tip with two sealing strips is derived from the original gap type. The shape of the labyrinth tooth tip is taken from the literature, [9].

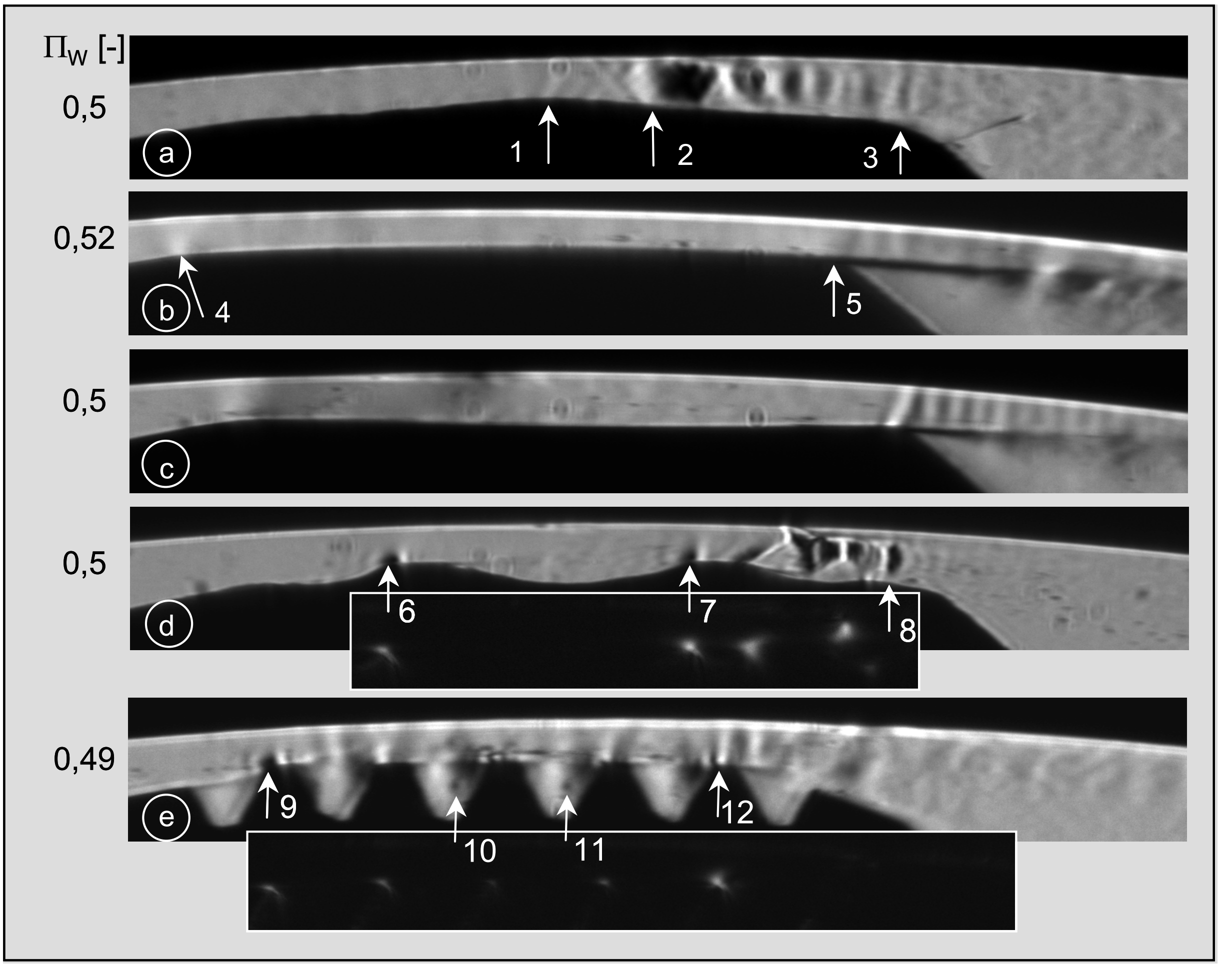

Fig. 7: ***Schlieren-pictures of the gas flow at the male rotor tooth tip; variation of shape and surface roughness of the tip; height of gap h_{Sp} =0.4 mm; exposure time t_{exp} = 0,5 μs; output pressure p_{out} = 1 bar***

In comparison to fig. 4 e **fig. 7 a** clarifies the abrasion of the sharply defined edges by the roughening of the surface to R_z = 70 μm at the sealing strip and the beginning and the end of the gap. The pressure ratio Π_W = 0,5 causes expansion fans at the beginning of the sealing strip, arrow 1. These expansions are reflected from the housing. The adjacent flow separates from the housing and the rotor at the position of arrow 2, and becomes subsonic with a perpendicular shock wave at the end of the gap, arrow 3. The visualization of the flow at the round shaped tooth tip is shown in **fig. 7 b**. The acceleration of the gas flow is made clear by the bright streak at the gap entry, arrow 4. A flow separation occurs at the end of the gap, arrow 5, and signs of a sonic flow can be recognized from a pressure ratio Π_W = 0,5. The gas flow conditions at the end of the gap with the straight shaped tooth tip, **fig. 7 c**, are similar to those at the end of the round shaped one.

The Schlieren-pictures of the gas flow at the male rotor housing gap with two sealing strips, **fig. 7 d**, support the interpretation of the oncoming flow at the first edge in the gap with one sealing strip. Immediately in front of the sealing strip an expansion occurs, arrow 6, suggesting an acceleration of the gas flow at this point. The flow separation at the end of the first sealing strip indicates that the flow velocity achieved is still subsonic. The streak in front of the second sealing strip demonstrates a negative density gradient as well, arrow 7. It is assumed that the gas flow here, analogous to the situation at the first sealing strip, is still subsonic. At the end of this sealing strip a flow acceleration follows in a sonic flow between two strongly developed flow separations. The flow velocity becomes subsonic again near arrow 8.

The Schlieren-picture of the gas flow in the labyrinth gap can be found in **fig. 7 e**. The condensed fluid on the glass plates which form the boundary of the wind tunnel in the direction of the light beams, is marked with arrows 10 and 11. This seems to be the centre of a vortex in a labyrinth chamber. An area with a negative density gradient as a sign of flow acceleration is located in front of the first bend in the gap, arrow 9. The same area, but with a lower intensity, can be seen at the following teeth of the labyrinth, too, as confirmed by the white framed additional Schlieren-picture. Near to arrow 12 the typical signs of a sonic jet are visible.

5.2 Some observations on the influence of gap-shapes and –heights on gap mass flows

Based on the condition of a direct proportional dependence between the appearance of sonic jet elements with a falling pressure ratio and the ability of the gap-form and -height to hinder the gas flow, the pressure ratio necessary for a sonic gas flow is shown in **fig. 8** as a function of the gap-height. This statement is based on Schlieren-pictures that have been published in [7].

The tooth tip with one sealing strip, i. e. the original gap form, needs the highest pressure ratio to reach the speed of sound. This form creates a relatively high number of oblique shock waves, but the dissipation is small compared to the other gap forms, as is the slowing down of the flow. The roughening of the surface to $R_z = 70\ \mu m$ introduces disturbances coming from the wall to the gas flow. The pressure difference has to be higher to reach a transonic flow velocity.

A small improvement in the restriction of the flow is possible with a gap form with two sealing strips. The two points of minimum gap height can be assumed to be the reason for this.

A distinct change comes with the round shaped tooth tip. The necessary pressure in front of the gap to form a transonic gas flow is higher. The dissipation in the long and equidistant flow canal seems to work better against the flow than the sealing strips.

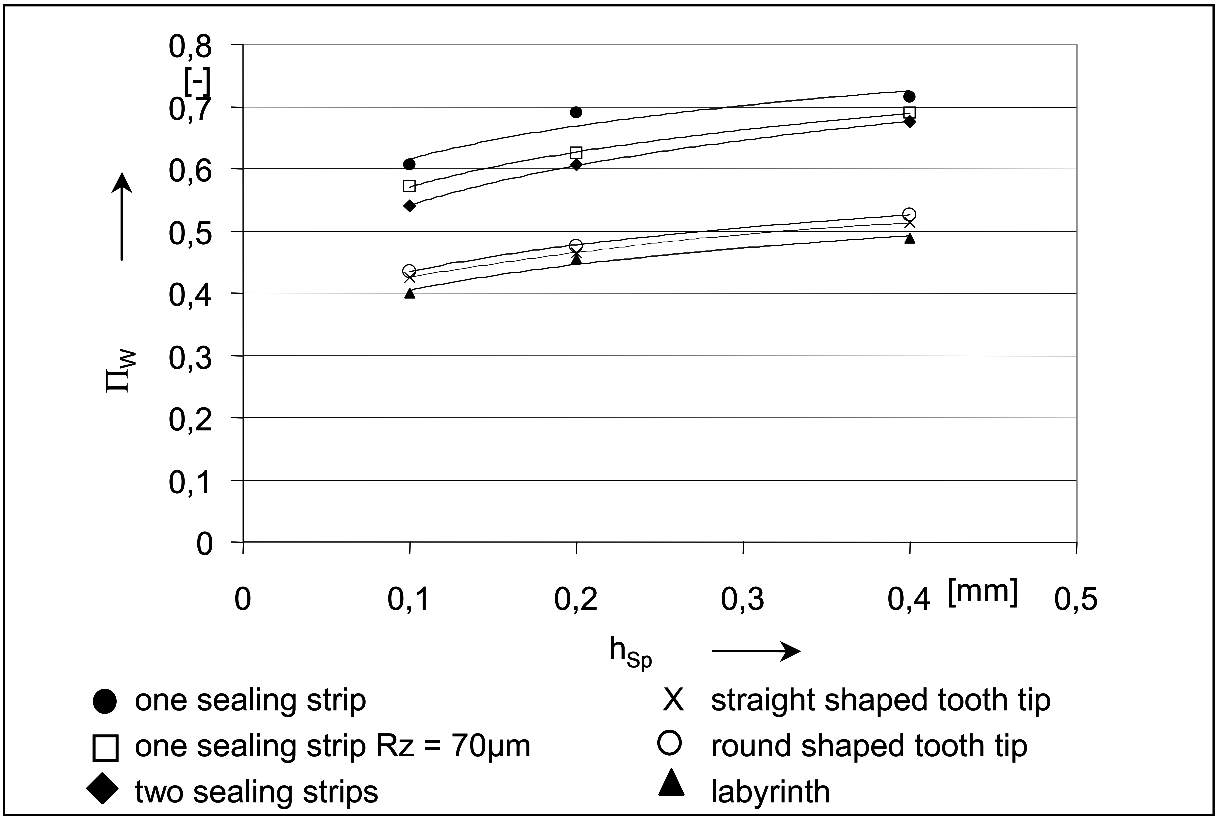

Fig. 8: Measured pressure ratio Π_W for appearing supersonic free-jet elements as a function of the height and the shape of the male rotor housing gap; output pressure p_{out} = 1 bar

The straight shaped tooth tip has a slightly lager height in the middle of the gap, compared to the round shaped one. But there is a sharp bend at the beginning and the end of the tip, which allows transonic speed to occur at a slightly lower pressure. The flow contraction at the edges leads to a reduced cross-section for the through-flow and an improved restriction of the flow.

As could be expected, the labyrinth requires the highest pressure in front of the gap to reach the transonic flow at the end of the gap. Thus the labyrinth offers the best possibility to restrict gap flow of all examined gap forms, but will possibly be the most expensive to produce.

5.3 Evaluation of the mass flow measurements

In order to prove the hypothesis that forms the basis for fig. 8 and the assessment of the different gap forms, it is necessary to measure the mass flow through these gaps. The quotient of the measured mass flow $\dot{m}$ and the theoretical mass flow $\dot{m}_{th}$, referring to the smallest cross-section of the gap, is called mass flow coefficient α:

$$\alpha = \frac{\dot{m}}{\dot{m}_{th}} \qquad \text{(Eq. 4)}$$

This mass flow coefficient covers all proceedings inside the gap in an integrated way. The mass flow $\dot{m}$ is determined with the measuring system described in chap. 3.2. The calculation of the theoretical mass flow $\dot{m}_{th}$ requires a steady and isentropic change of condition in an ideal and in viscid gas and uses the equation of de Saint Venant and Wantzel [7].

Fig. 9 shows the mass flow coefficient α as a function of the pressure ratio Π_{Sp} for a gap height h_{SP} = 0.4 mm. The mass flow coefficient of the labyrinth is near to a critical pressure ratio (Π_{krit} = 0,528 for isentropic flow of a diatomic, ideal gas), 16% less than the coefficient of the other gap forms.

In the subsonic sector a further differentiation becomes possible. A mass flow coefficient larger than one can be found at the gap forms with a slight enlargement behind the geometrically smallest cross-section of the gap. These are the forms with one sealing strip (R_z = 10 µm and R_z = 70 µm) and two sealing strips. The coefficient is larger than one due to the position of the pressure measuring points.

The calculation of the theoretical mass flow takes into account the pressure in front of the housing gap (inlet pressure) and behind it (outlet pressure) but not the pressure at the narrowest part of the gap. The enlargement of the cross-section behind the sealing strip works as a diffuser, which means that the pressure at the narrowest part of the gap becomes smaller than the outlet pressure. Thus the measured mass flow is larger than could be expected from the pressure ratio, which explains why the mass flow coefficient is larger than one.

The equidistant flow canal, i.e. the round shaped tooth tip, causes a nearly constant mass flow coefficient in respect to the pressure ratio. The mass flow coefficient of the gap with the straight shaped tooth tip is a little smaller than that of the round shaped one, corresponding to the assessment in fig. 8. The labyrinth shows the smallest mass flow coefficient in the transonic sector, too.

The progress of α allows reliable conclusions to be drawn concerning the ability of the tooth tip geometry to hinder the flow in the gap, because the minimum gap height of all measured forms and the outlet pressure p_{out} = const = p_{at} are constant.

The original tooth tip form with one sealing strip is hardly suitable to seal the housing gap. As to be expected, the labyrinth is the best form to restrict the flow.

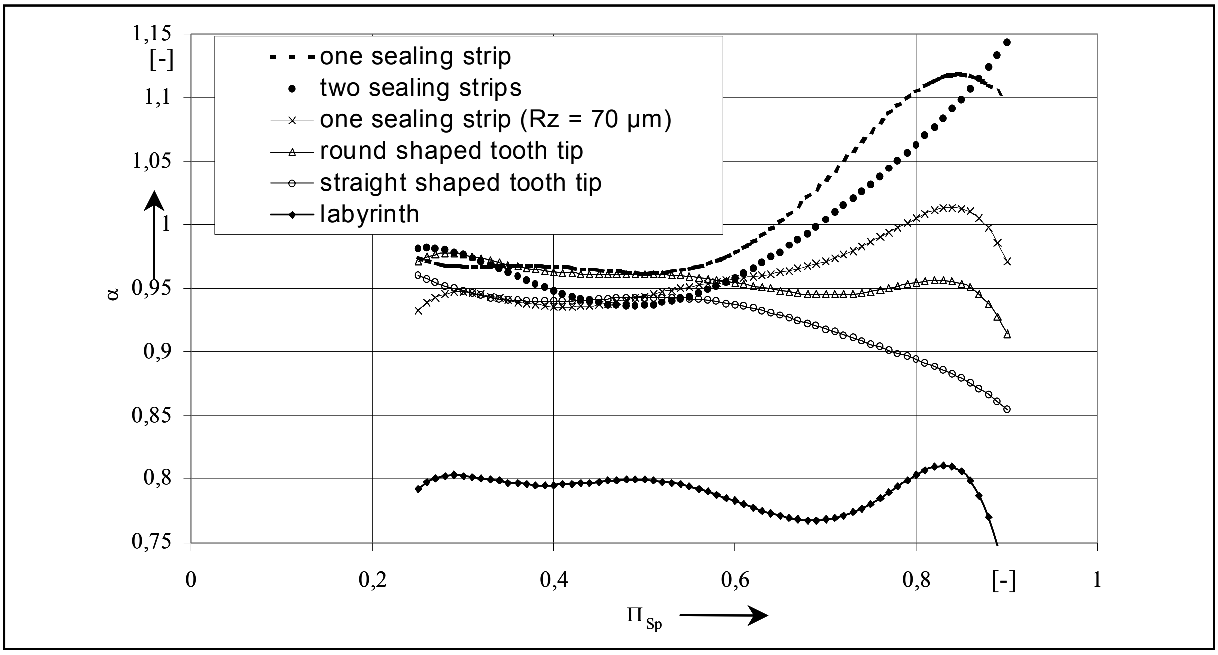

Fig. 9: ***Mass flow coefficient α as a function of the pressure ratio Π_{Sp}; variation of the shape of the male rotor tooth tip; height of gap h_{Sp} = 0.4 mm***

The sequence of the ability of the gap configuration to restrict the flow in the gap as shown in fig. 9 is comparable to the evaluation of the Schlieren-pictures, see fig. 8. Only the difference between the result concerning the labyrinth and the other gap forms is unlikely. It has to be considered that the Schlieren-pictures visualize only density gradients in the main flow direction, entailed by the type of the Schlieren-aperture [7]. Consequently the images cannot reproduce a kinetic energy dissipating vortex in the gas flow.

Information about the required gap height for a particular tooth tip form, in order to ensure a constant gap mass flow in relation to the original gap form, is of additional importance.

In order to gain this information, the labyrinth is compared with the male rotor housing gap with one sealing strip and a gap height of 0.1 mm. With the help of a linear interpolation between the measured values of the mass flow at the labyrinth gap, its gap height can be estimated approximately as a function of the pressure ratio relative to the original gap, **fig. 10**.

Using a labyrinth at high pressure ratios shows that the gap height can increase up to 60% of the original height without raising the mass flow. Effects on the reliability and safety of the screw-type machine and the necessary manufacturing precision can undoubtedly be expected.

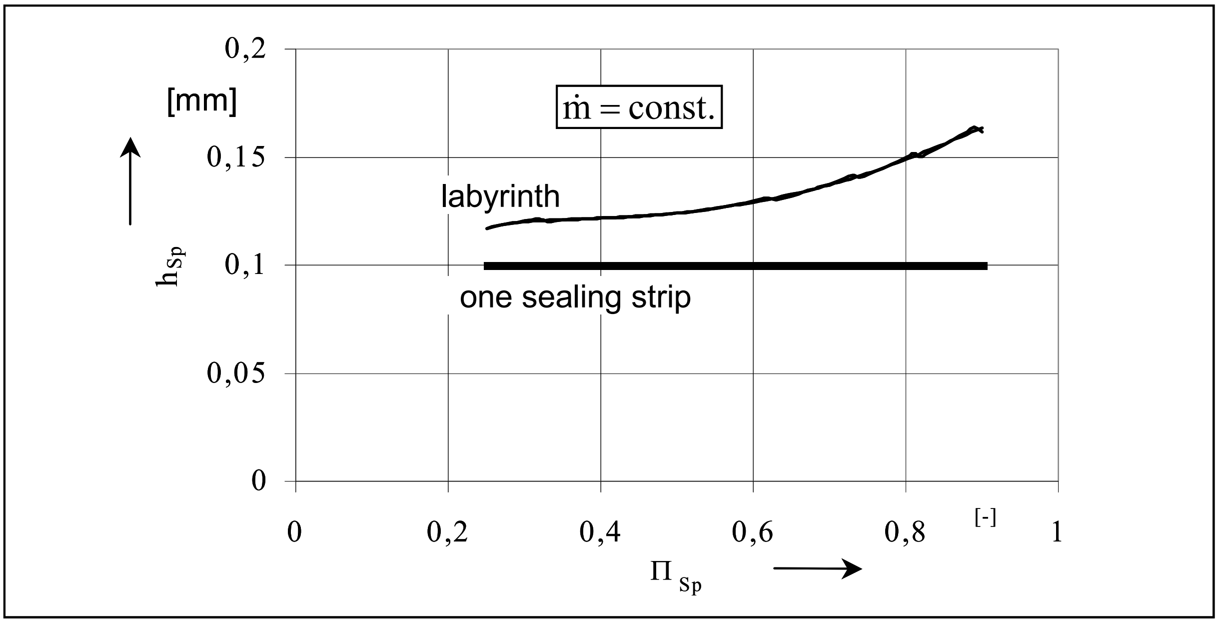

***Fig. 10:** Estimated height of the male rotor housing gap with the tooth tip in labyrinth shape in relation to the male rotor housing gap with the tooth tip with one sealing strip and a height of the gap of h_{Sp} = 0.1 mm as a function of the pressure ratio Π_{Sp}; the mass flow is constant*

6 Recommendations

A more detailed coverage of the gas flow situation in screw-type machines remains a complex task, which should be continued in long-term research projects aiming for a complete simulation of the machine.

Improvement is possible in the experimental technique, e.g. a laser light source to get better resolution of the Schlieren-pictures. Also important are measurements of quantitative data of the flow (velocity, turbulence) in the plane screw-type machine model with a Laser-two-Focus (L2F) Anemometer. Registration of the flow field in the working chamber in a real screw-type machine would be possible with a Laser-Doppler-Anemometer (LDA).

The combination of experimental investigations and computational fluid dynamics (CFD) offers the possibility of an extensive modelling of the gas flow conditions in screw-type machines. Preliminary studies have been done using the CFD-Software FLUENT® [10] [11].

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