The Influence of Clearance Flows on the Working Behaviour of Screw Compressors

Simulation results

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Abstract

The internal clearance flows in screw compressors determine the operating behaviour especially the efficiency of this machine type. The thermodynamically optimised and, at the same time, reliable design of the clearance heights is indispensable for the development of screw compressors.

The influence of the different clearances on the operating behaviour of a typical screw-type compressor is examined by means of a simulation system. A sophisticated analysis of the volumetric efficiency and the isentropic efficiency regarding the influence of the clearance heights and the operating parameters rotor speed and pressure ratio makes possible an evaluation of the individual clearance influences on the operating behaviour. The model machine is a dry-running but unsynchronized screw-type supercharger, newly designed at the University of Dortmund.

The calculation of the operating behaviour of the screw compressor was carried out using the simulation system *KaSim*, which calculates the thermodynamics inside the machine on the basis of a chamber model. A comparison of the simulation results with experimental data is imminent but too late for inclusion in this paper.

Kurzfassung

Die Ausprägung der internen Spalte in Schraubenkompressoren bestimmt maßgeblich das Betriebsverhalten und vor allem den Wirkungsgrad dieser Maschinen. Eine thermodynamisch optimale und gleichzeitig betriebssichere Auslegung dieser Spalte ist daher unabdingbar für die Weiterentwicklung und Neukonstruktion von Schraubenkompressoren.

Mit Hilfe von Simulationsrechnungen wird der Einfluss der einzelnen Spalte auf das Betriebsverhalten eines beispielhaften Schraubenkompressors transparent gemacht. Eine differenzierte Untersuchung der Betriebskenngrößen Liefergrad und isentroper Wirkungsgrad in Abhängigkeit von den Spalthöhen und von den Betriebsparametern Hauptrotordrehzahl und dem anliegenden Druckverhältnis ermöglicht eine Beurteilung der einzelnen Spalte hinsicht-

lich ihres Einflusses auf das Betriebsverhalten von Schraubenkompressoren. Die vorliegende Untersuchung wurde am Beispiel eines neu entwickelten, unsynchronisiert- und trockenlaufenden Schraubenladers durchgeführt.
Zur Simulation des Betriebsverhaltens des Laders wird das an der Universität Dortmund entwickelte Programmsystem *KaSim* verwendet, das auf Grundlage eines Kammermodells die thermodynamischen Prozesse in der Maschine berechnet. Ein Vergleich der Simulationsergebnisse mit experimentellen Kennfeldern steht direkt bevor, konnte aber bis zur Drucklegung nicht mehr eingebunden werden.

1. Introduction

The operational behaviour of screw type machines depends mainly on the internal leakage through the kinematically necessary clearances between the moving rotors and the stationary casing. Obviously larger clearances lead to increasing internal leakage, and as a consequence, to lower volumetric efficiency. Therefore most design engineers try to minimize the clearance heights, but not beyond the point where the screw-type machine is still reliable. Of course smaller gaps require more precise manufacturing and result therefore in higher production costs. It would be interesting to know the influence of each individual clearance on the efficiency of the machine to find the right compromise between operational losses and production costs.
Experimental measurements can only show the integral mass flow in different operational conditions. But by means of a simulation it is possible to identify the influence of every individual clearance on the operational behaviour of screw-type machines. The influence of individual clearance heights on volumetric efficiency and isentropic efficiency can be determined by varying the one clearance while leaving all other clearances constant or even zero. Varying clearances, especially the intermesh clearance or the casing gaps, is much easier in a simulation than in an experiment. Of course it is necessary to validate the simulation on the base of experimental data.

2. Examined screw-type supercharger

Our machine is a screw-type supercharger, developed by the FG Fluidenergiemaschinen at the University of Dortmund, Fig. 1. Although the compressor is a dry-running machine the synchronisation gearing was abandoned to keep the compressor simple and small. This is possible due to a special form of the rotor profile in combination with a tungsten carbide coating that minimizes friction in the intermesh contact. Table 1 gives an overview of the geometric properties of the compressor. A detailed description of the screw-type supercharger can be found in [1].

The estimated field of application includes not only the supercharging of Otto cycle engines but also the air supply of automotive fuel cell systems. The operating range of the supercharger covers 1 bar to 2.6 bar outlet pressure and 6000 RPM to 24000 RPM male rotor speed, Fig. 2.

Table 1: Geometric properties of the GL51

	male rotor	**female rotor**
number of lobes	3	5
rotor diameter	71.8 mm	67.5 mm
rotor profile length	101 mm	
centre distance	51 mm	
wrap angle	200°	120°
volume ratio	1.45	

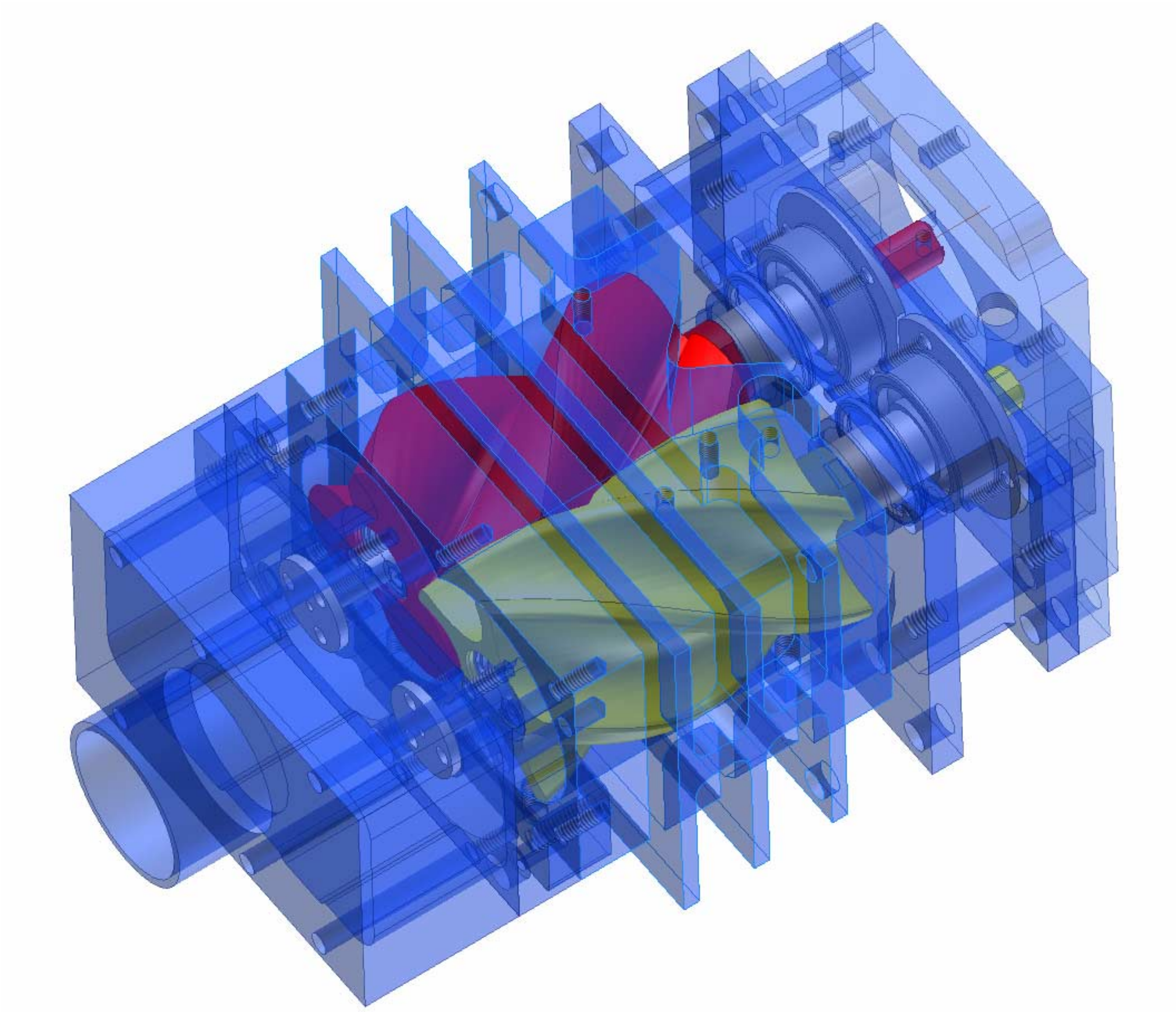

Fig. 1: Design drawing of the screw-type supercharger GL51

3. Simulation system KaSim

The simulation system *KaSim*, developed at the FG Fluidenergiemaschinen at the University of Dortmund, makes possible the thermodynamic simulation of the operating behaviour of positive displacement machines at constant and variable speeds, especially rotary displacement machines. Any gases, liquids or vapours can be used as working fluids.

KaSim calculates the state curves of the working fluid during the compression process on the basis of a chamber model. The method of simulating a positive displacement machine by means of a chamber model derives from the common characteristic of all positive displacement machines, the existence of one or more working chambers, whose volumes cycle during the working period. The state of the working fluids inside the chambers is approximately homogeneous. The basics of the simulation system *KaSim* and the associated methods for the modelling of this machine type are described in former publications, [2], [3]. The simulation system uses the Saint-Venant equations, [4], to calculate the mass flow through each clearance, depending on the actual pressure in the adjacent chambers.

Since the influence of the clearances on the operating behaviour can be expected to depend on the operating conditions, the simulations were done at five different operating points. These characterise the main operating area, varying the speed from 6000 RPM to 24000 RPM at a pressure ratio of π = 2.0, or varying the pressure ratio from π = 1.4 to π = 2.6 at a male rotor speed of 15000 RPM, Fig. 2.

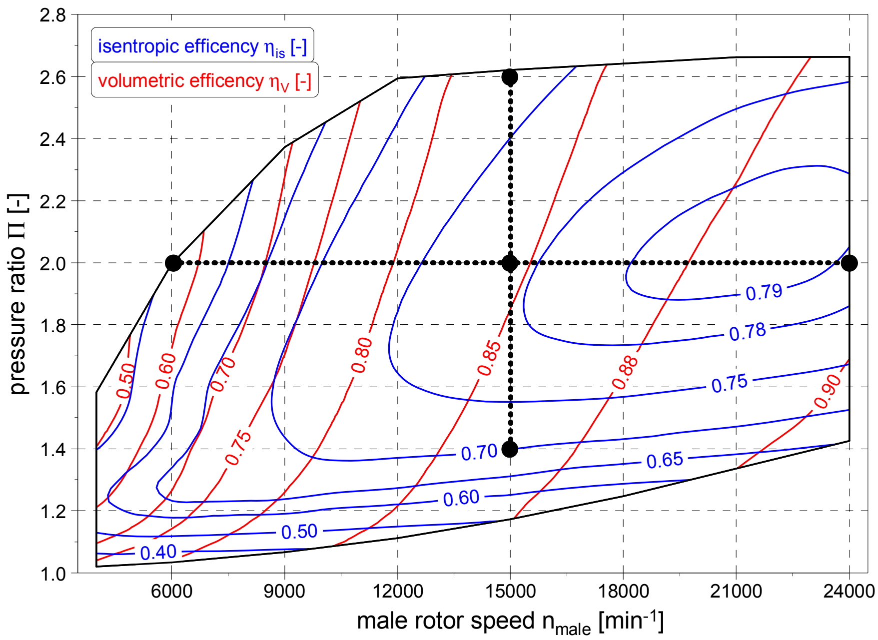

Fig. 2: Operating range of the screw-type supercharger GL51 including the simulated points of operating. The isentropic and volumetric efficiency are calculated for typical clearance heights

To analyse the influence of the different clearances on the operating behaviour, first a model of an ideally sealed screw compressor was developed. The individual clearance heights were varied while leaving all other clearances closed. All calculations were also carried out on the basis of a compressor with typical clearance heights. The qualitative effect of the clearances is the same although the quantities are slightly different. In the interests of clarity the paper generally uses the calculation results based on the ideally sealed machine.

The simulation system calculates the thermodynamic behaviour of the air mass flow delivered during the working process. Fig. 3 shows the indicator diagram of the model compressor for three different pressure ratios at a male rotor speed of 15000 RPM. The suction pressure is fixed at 900 mbar. Pressure ratios of π = 1.4, 2.0 and 2.6 result in outlet pressures of 1.26 bar, 1.8 bar and 2.34 bar.

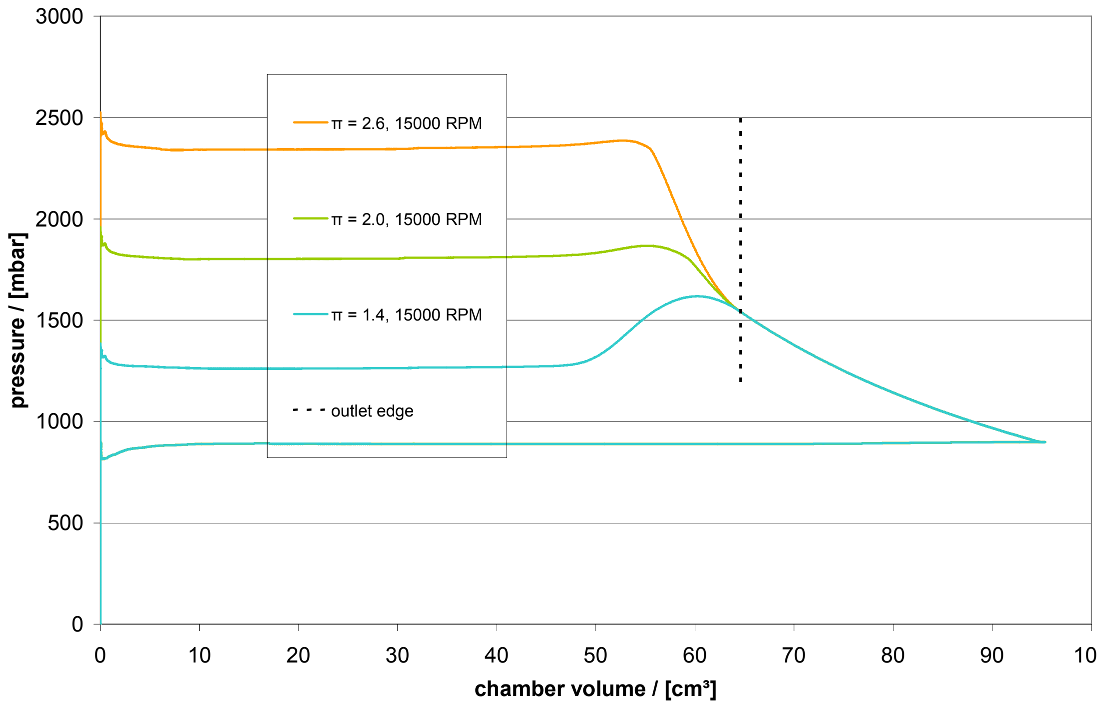

Fig. 3: Indicator diagram of the ideally sealed compressor for three different pressure ratios at 15000 RPM male rotor speed

The pressure curve of the ideally sealed compressor shows a nearly isobaric charging of the expanding chambers, followed by an adiabatic compression until the outlet aperture is reached and the compressed chamber makes contact with the discharge port. During pressure equalisation between the chamber and the discharge port the chamber volume is still decreasing and may even cause a continuing pressure rise in the chamber although the discharge pressure is lower than the actual chamber pressure, Fig. 3, (π = 1.4). The pressure equalisation gradient depends not only on the discharge pressure but also on the speed of the compressor. A slower rotor speed leads to a steeper increase or decline in the chamber pressure, which will have a noticeable effect on the power consumption of the compressor,

Fig. 4. On the other hand a higher rotor speed may lead to an overshoot of the pressure curve, because the compressor needs higher pressure in the chamber to achieve a sufficiently fast equalising mass flow through the discharge area.

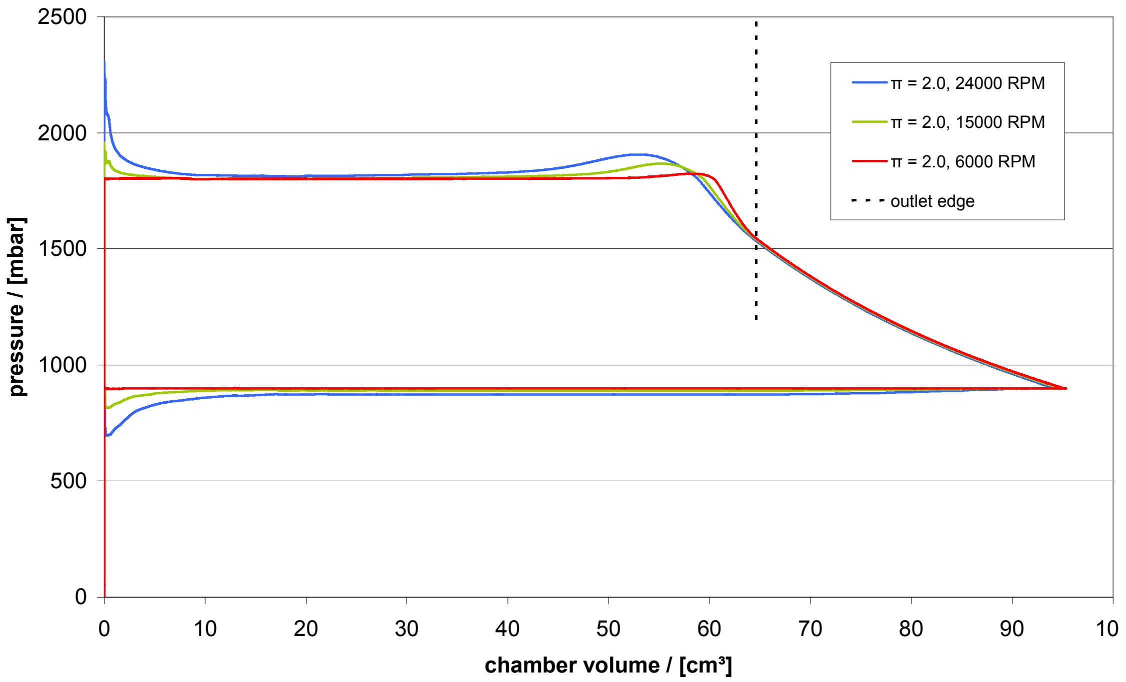

Fig. 4: Indicator diagram of the ideally sealed compressor for three different male rotor speeds at a pressure ratio of $\pi = 2.0$

4. Influence of clearance height on volumetric efficiency

Based on the in other respects ideally sealed machine, Fig. 5 shows a variation of the intermesh clearance height from 0.00 mm to 0.30 mm. The volumetric efficiency of the simulated compressor shows a linear reduction as the clearance opens. The gradient depends on the operating conditions. Higher engine speeds or lower pressure ratios lead to better volumetric efficiency and less influence of clearance gap heights on volumetric efficiency. The intermesh clearance connects chambers with already compressed fluid with chambers that are still under suction. Therefore the mass flow through the intermesh clearance is directly proportional to the clearance area, which explains the linear drop in volumetric efficiency with higher clearance heights.

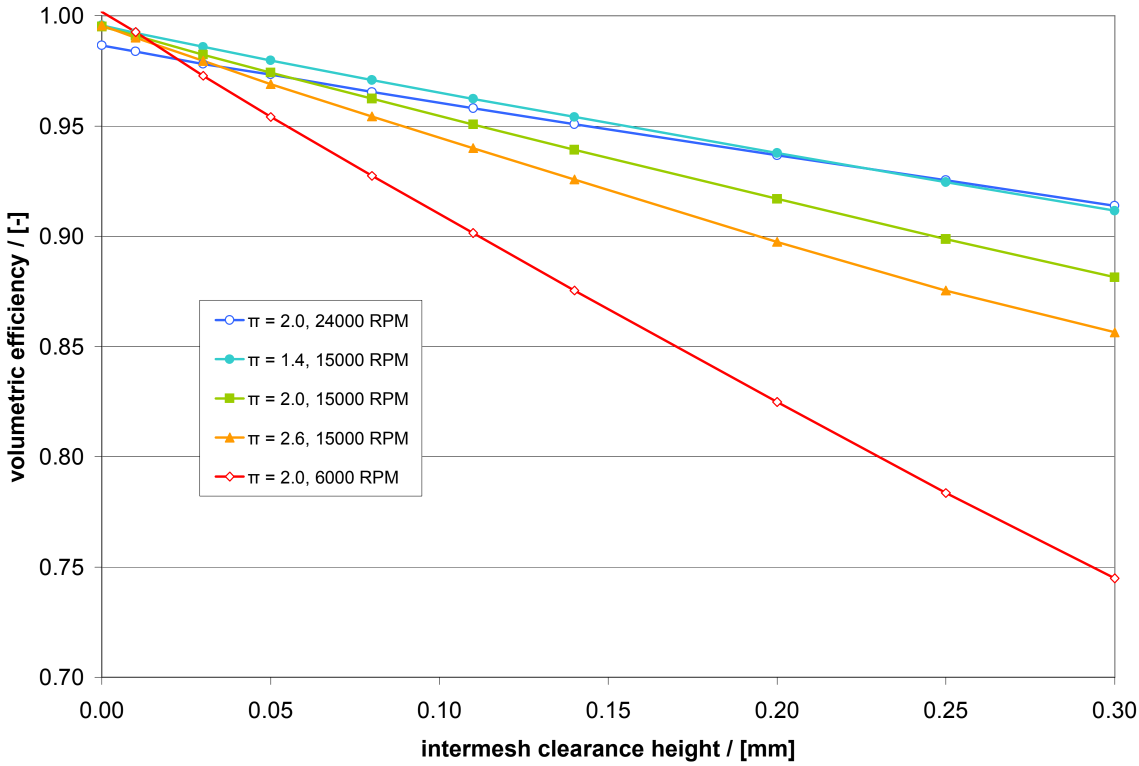

Fig. 5: Volumetric efficiency of the ideally sealed machine for different intermesh clearance heights and different operating conditions

The casing gap causes a different kind of internal leakage. It connects only adjacent chambers and consequently forms a pressure cascade from the discharge side to the suction side through multiple chambers and gaps. This results not only in a loss of volumetric efficiency but also in a change in the pressure curve during compression, Fig. 6. The leakage flow from the discharge side to the succeeding chambers causes an additional rise in pressure during the compression phase. The leakage through the intermesh clearance goes directly to the suction side chambers and, in contrast to the casing gap, causes hardly any change in the indicator diagram.

Fig. 7 shows the influence of the male rotor casing gap height on the operating behaviour of the otherwise ideally sealed compressor. The volumetric efficiency drops progressively with increasing casing gap heights. Higher rotor speeds or lower pressure ratios also lead to a better volumetric efficiency and less influence of clearance gap heights on volumetric efficiency. At low rotor speeds the influence of the casing gap is up to 50% higher than the influence of the intermesh clearance.

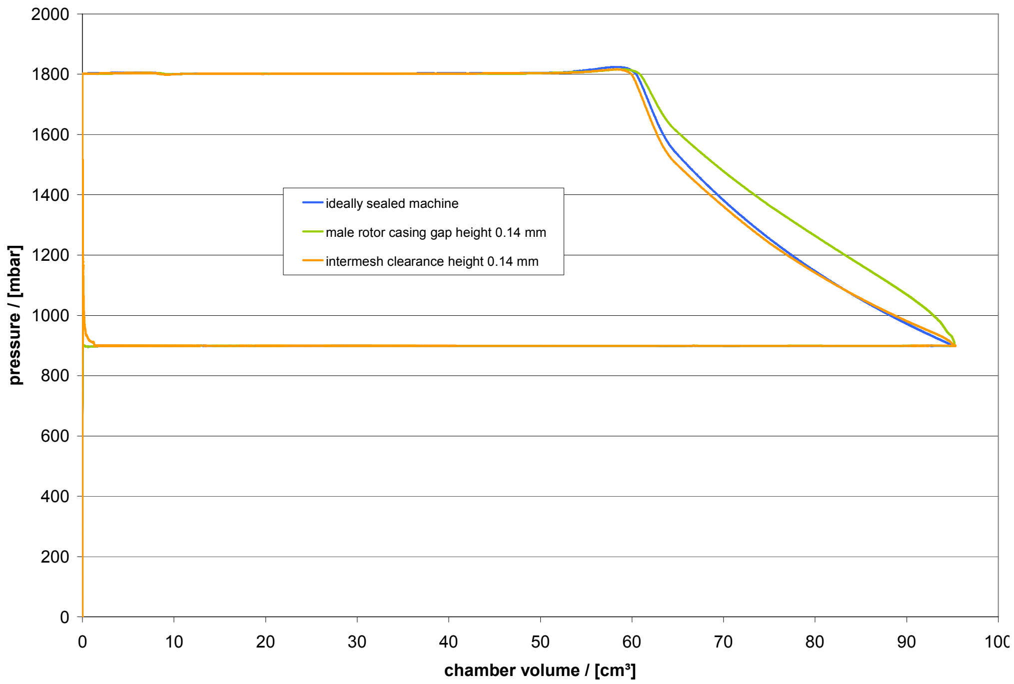

Fig. 6: Indicator diagram of the ideally sealed machine compared with variations with only the intermesh clearance open (0.14 mm) or only the male rotor casing gap open (0.14 mm) for a pressure ratio of π = 2.0 and a male rotor speed of n_{male} = 6000 RPM

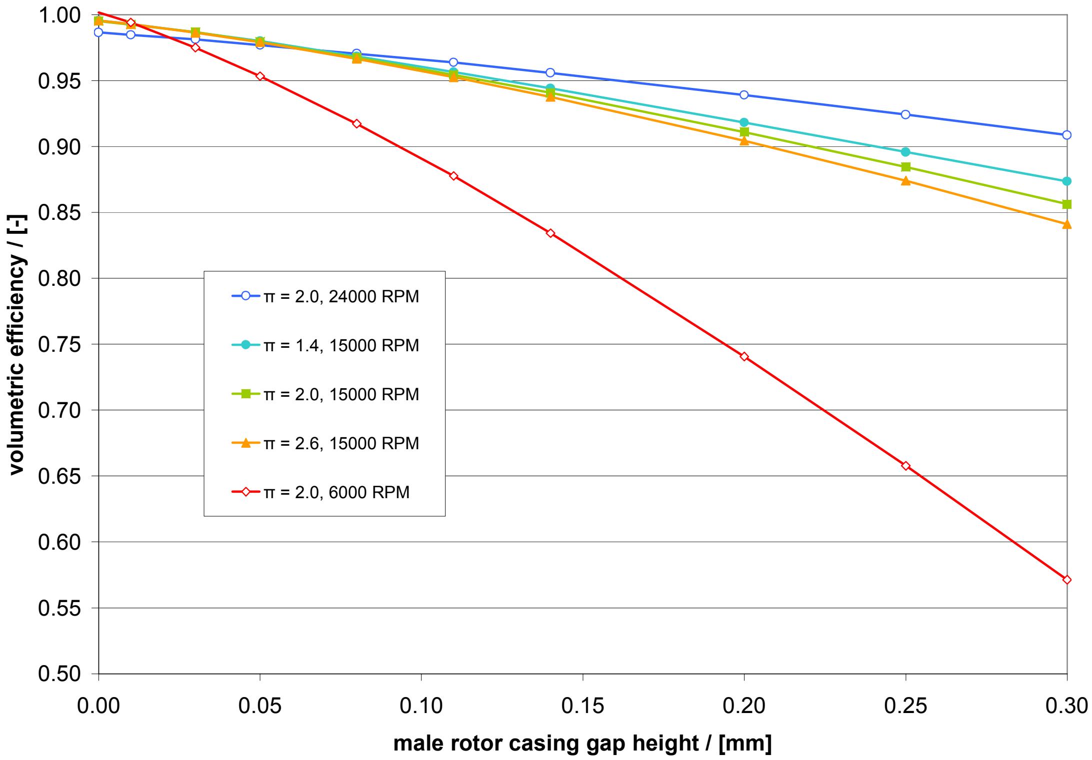

Fig. 7: Volumetric efficiency of ideally sealed machine for different male rotor casing gap heights and different operating conditions

Fig. 8 compares the effect of the different clearances on the volumetric efficiency of the model compressor at a pressure ratio of π = 2.0 and a male rotor speed of n_{male} = 6000 RPM, which is the operating point with the highest leakage rates.

The male rotor casing gap has the greatest influence on volumetric efficiency. An increase in casing gap height of 0.01 mm causes a loss in volumetric efficiency of 1.4 percentage points. The female rotor casing gap affects the volumetric efficiency in a similar way but causes only a loss of 0.8 percentage points per 0.01 mm clearance height.

At low clearance heights, the intermesh clearance has more influence on volumetric efficiency than the female rotor casing gap. But since the effect of the casing gaps rises progressively it exceeds the influence of the intermesh clearance at approximately 0.24 mm.

The impact of the front gaps on volumetric efficiency is only 10 % (suction side) to 20% (discharge side) of the male rotor casing gap.

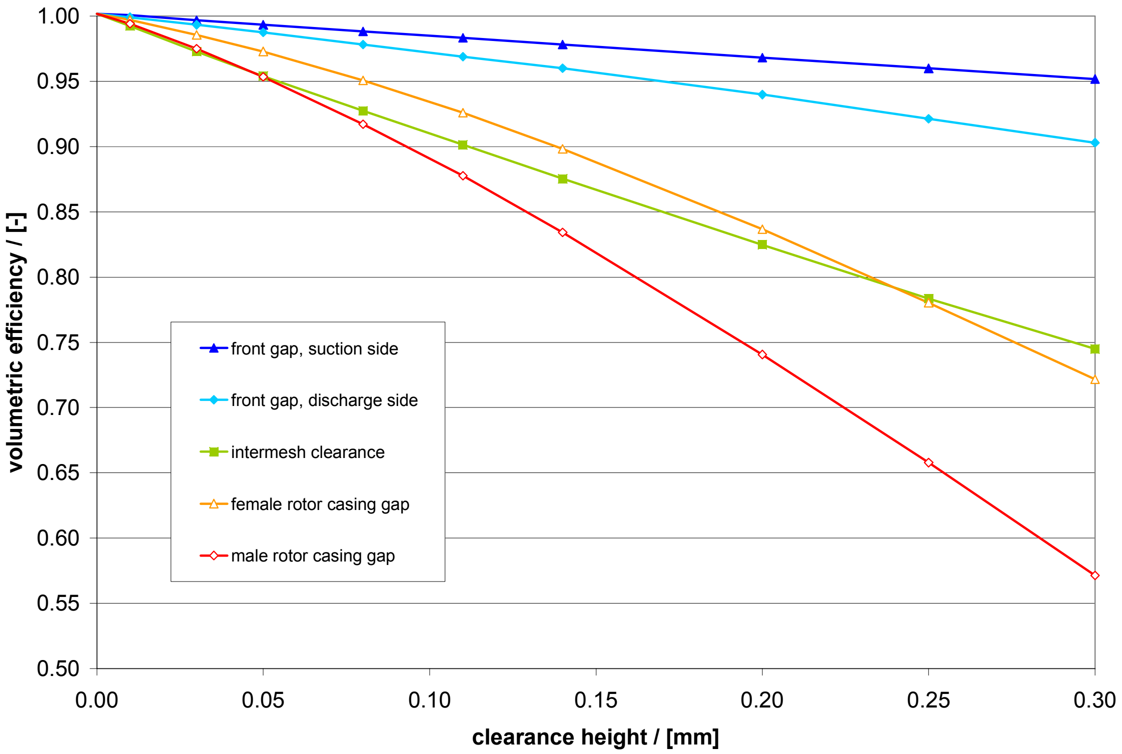

Fig. 8: Influence of the different clearances on the volumetric efficiency of the ideally sealed compressor for a pressure ratio of π = 2.0 and a male rotor speed of n_{male} = 6000 RPM

To examine the influence of the clearance heights on volumetric efficiency with respect to the operating parameters, the derivative of the volumetric efficiency with respect to the clearance heights has to be calculated. Fig. 9 and Fig. 10 display the average change in volumetric efficiency in percentage points per 0.01 mm.

The major factor affecting clearance influence is rotor speed. At low rotor speeds the influence of clearance heights rises drastically. The influence of clearance heights depends less on the pressure ratio. A variation from π = 1.4 to π = 2.6 causes only a rise in clearance influence of less than 20%, except for the intermesh clearance whose influence rises by 65%. This can be explained by the fact, that most of the intermesh clearances have the pressure ratio applied directly. On the other hand, the influence of the intermesh clearance is less sensitive regarding the rotor speed compared with the casing gaps.

The influence of the male rotor casing gap is 70% higher than the influence of the female rotor casing gap which results from an additional chamber in the compression cycle along the 5 tooth female rotor. At a low pressure ratio of π = 1.4 the influence of the intermesh clearance is between the male and female rotor casing gaps, but with an increasing pressure ratio the intermesh clearance gains more importance. At π = 2.6 the intermesh clearance has an even greater influence on volumetric efficiency than the male rotor casing gap.

The front gaps have the smallest effect on volumetric efficiency, with the suction side front gap having even only half the effect of the discharge side front gap.

A simulation based on typical clearance heights, with again varying individual clearances, shows qualitatively the same results, but the influences of the clearances are up to 60% more powerful and the volumetric efficiency is generally lower due to the open clearances.

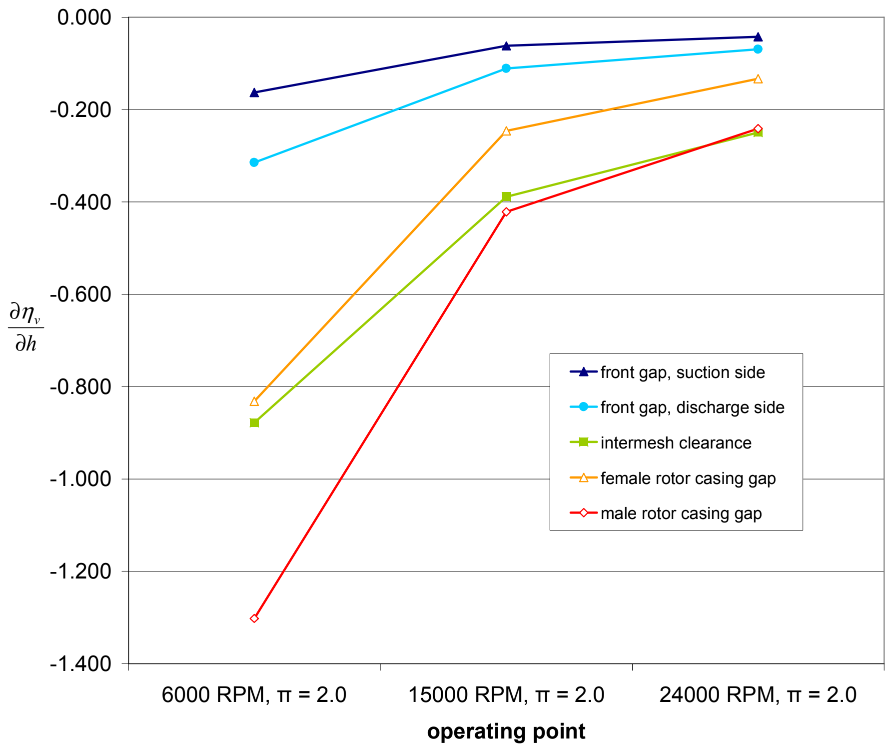

Fig. 9: Gradient of the volumetric efficiency relative to the clearance height for operating points at different rotor speeds

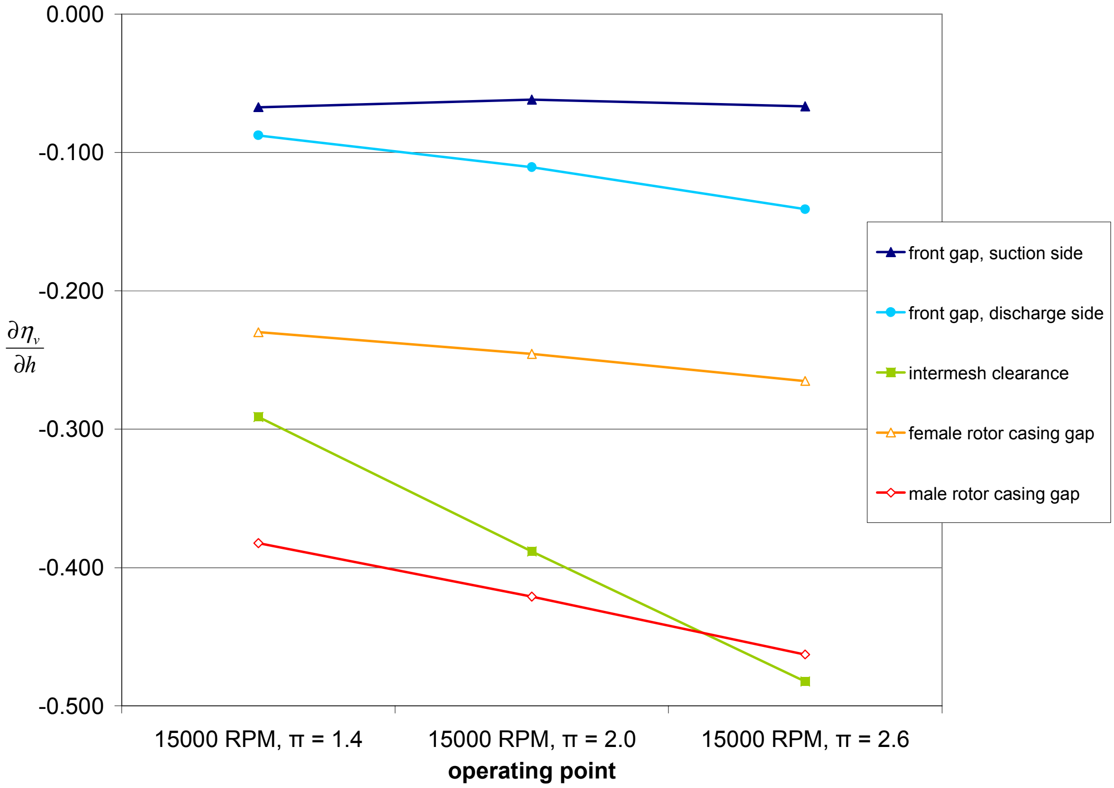

Fig. 10: Gradient of the volumetric efficiency relative to the clearance height for operating points at different pressure ratios

5. Influence of clearance height on isentropic efficiency

The isentropic efficiency of a screw-type supercharger depends not only on the clearances but also on the operating point, especially the pressure ratio. If the external pressure ratio is noticeably smaller than the internal pressure ratio defined by the position of the outlet apertures, even an ideal machine will have a low isentropic efficiency, (Fig. 11, π = 1.4, 15000 RPM). This is caused by the surplus internal compression, (cp. Fig. 3), in combination with pressure equalisation when the chamber opens to the discharge port. The required energy for the compression above the discharge pressure will be dissipated and therefore result in a higher discharge temperature.

Taking the different starting positions into account, the clearance heights have a nearly linear effect on the isentropic efficiency. The gradient depends on the operating point, Fig. 11, and on the type of clearance, Fig. 12. The male rotor casing gap shows the greatest influence on isentropic efficiency, followed by the female rotor casing gap, which has only 75% of the influence of the male rotor casing gap. The intermesh clearance has half the influence of the male rotor casing gap and the front gap on the discharge side has only 36%. The front gap height on the suction side has hardly any effect on isentropic efficiency of the compressor.

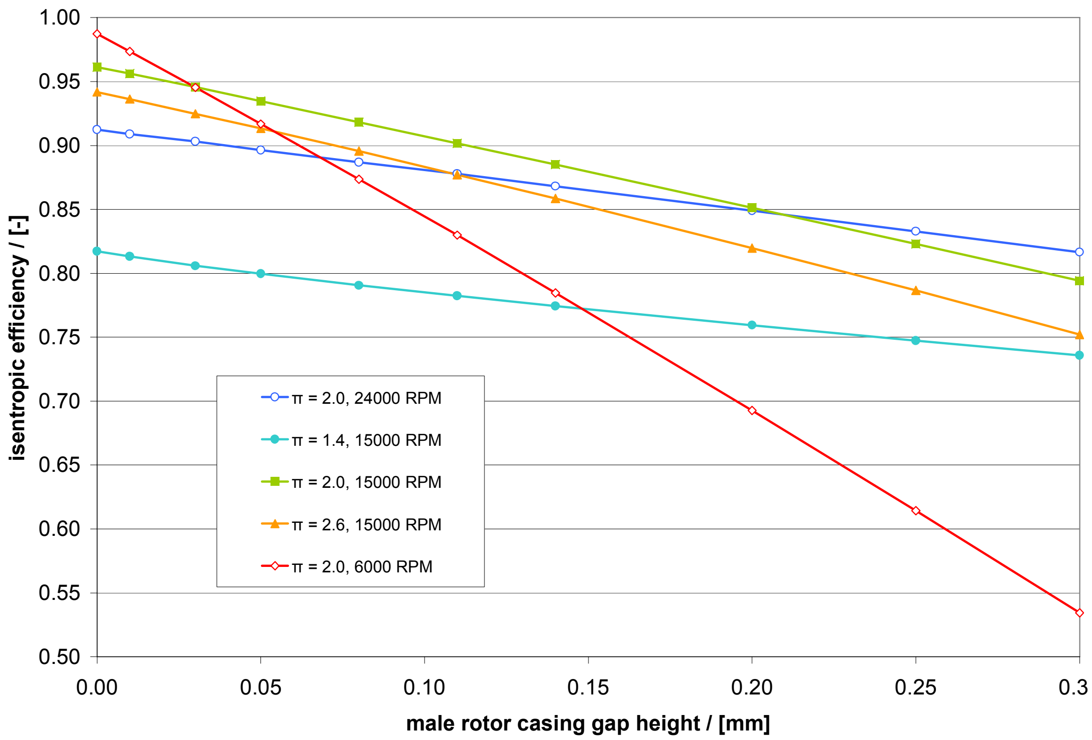

Fig. 11: Isentropic efficiency of the ideally sealed compressor with variation of the male rotor casing gap height for different operating points

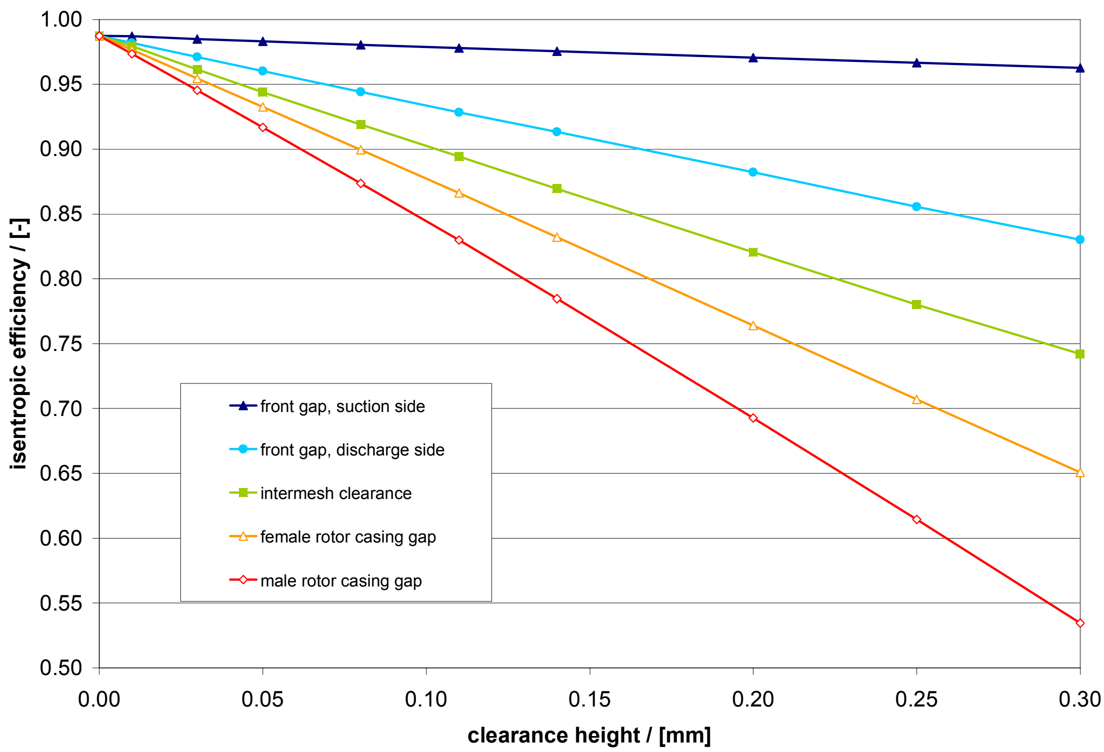

Fig. 12: Influence of the different clearance heights on the isentropic efficiency of the ideally sealed machine for π = 2.0 and a male rotor speed of 6000 RPM

It is interesting, that the intermesh clearance has less effect on isentropic efficiency than the female rotor casing gap, although its effect on volumetric efficiency is stronger. This can be put down to the differing influence of the two clearances on the pressure rise during compression, as shown in the indicator diagram (Fig. 6).

Parallel to volumetric efficiency it is of interest to examine the influence of the clearance heights on isentropic efficiency, depending on the specific operating points. Therefore the derivative of the isentropic efficiency with respect to the clearance heights also has to be calculated. Fig. 13 and Fig. 14 show the average change in isentropic efficiency in percentage points per 0.01 mm clearance height.

The casing gaps have the greatest effect on the isentropic efficiency of the compressor. At low pressure ratio the male rotor casing gap has nearly the same effect as the female rotor casing gap, but with increasing pressure the influence of the male rotor casing gap exceeds its opposite number.

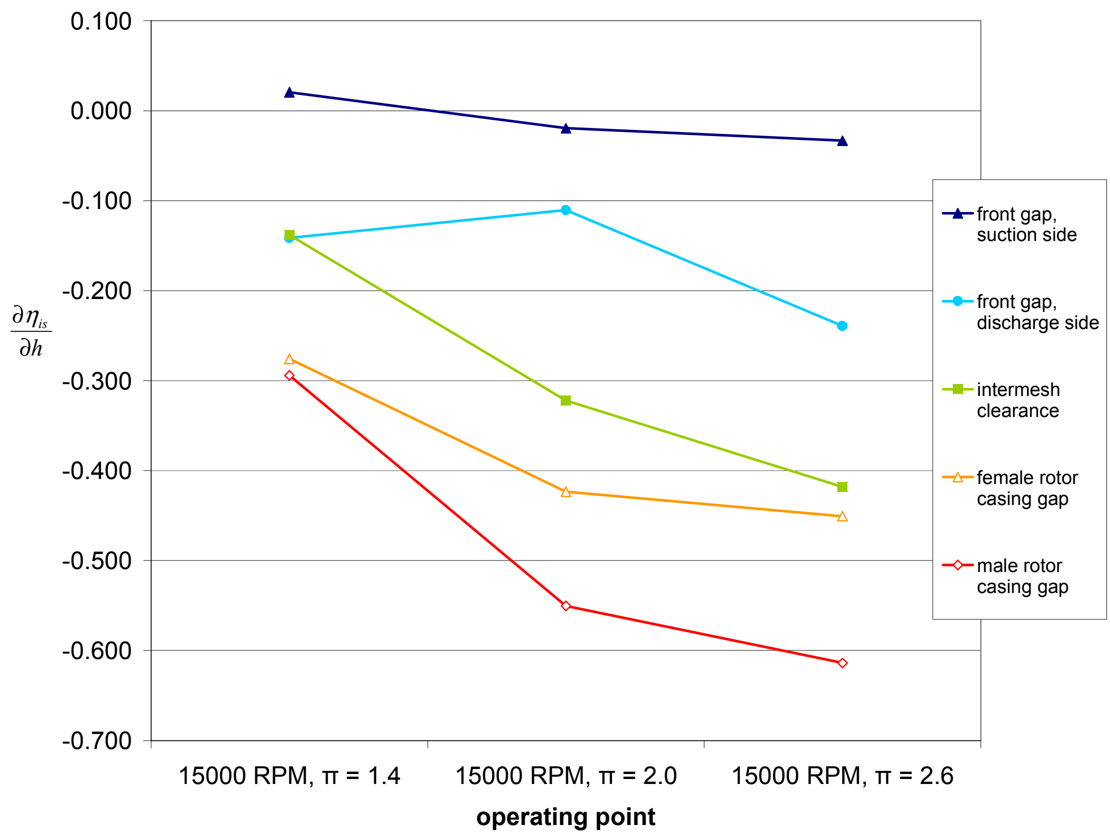

Fig. 13: Gradient for isentropic efficiency taking into account the clearance height for operating points with different pressure ratios and a male rotor speed of 15000 RPM

The front gap on the suction side has only a minor and at low pressure ratio even a positive effect on the isentropic efficiency. The influence of the front gap on the discharge side varies from 0.1 percentage points loss in isentropic efficiency to 0.5 percentage points at low rotor speeds. As with the volumetric efficiency the influence of the intermesh clearance clearly depends on the pressure ratio. At π = 1.4 the intermesh clearance matches the front gap on the discharge side as far as its influence on isentropic efficiency is concerned, but with increasing pressure ratios the influence of the intermesh clearance gains more weight.

The most important factor determining the effect of the clearance heights on the isentropic efficiency is the rotor speed, Fig. 14. With a decrease in rotor speed from 15000 RPM to 6000 RPM the negative influence of the clearance heights increases by the factor 2.6. The order of importance of the clearances stays the same.

Comparing the operating behaviour of the ideally sealed compressor with the behaviour of a compressor with standard clearance heights reveals hardly any differences in the effect of the clearance heights on isentropic efficiency. Only at the low rotor speed of 6000 RPM is an increasing influence of the clearance heights compared with the ideally sealed machine noticeable.

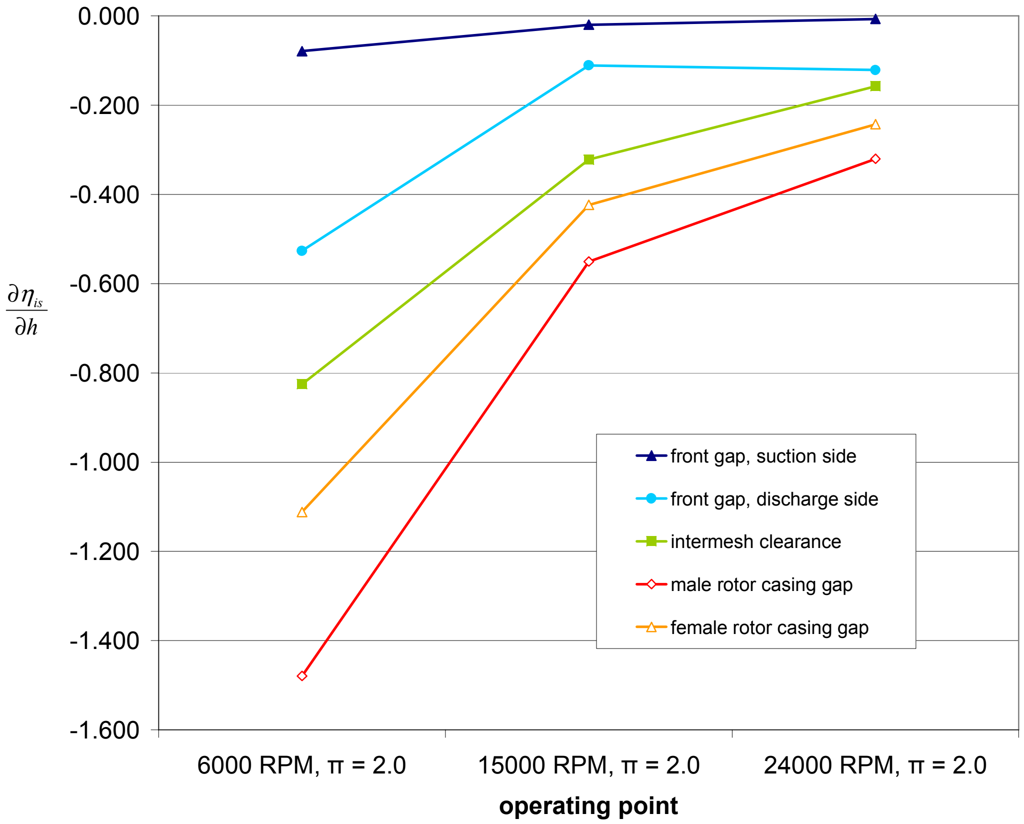

Fig. 14: Gradient of isentropic efficiency taking into account the clearance height for operating points at different rotor speeds and a pressure ratio of π = 2.0

6. Conclusion

The simulation study shows the dominant influence of the internal clearance flows on the operating behaviour of screw compressors using a screw-type supercharger as an example.
A change in clearance heights results in an almost linear change in volumetric efficiency and isentropic efficiency of the model compressor. The degree of influence depends on the type of clearance and on the operating point. The male rotor casing gap and the intermesh clearance show the strongest influence on volumetric efficiency. Isentropic efficiency depends mainly on the male and female rotor casing gap. An increasing pressure ratio or a decreasing rotor speed results in a growing influence of the clearance heights on volumetric and isentropic efficiency, with rotor speed having the larger effect on the role played by the clearances.
This paper uses simulation to make the operating behaviour of screw type machines more transparent. This method obviously requires an experimental validation of the simulation results. Therefore the next step in research will be the verification of the results presented based on an experimental variation of the clearance heights.

Literatur:

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