Analysis of flowrates as a basis for the simulation of dry-running rotational positive displacement pumps

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Abstract: New applications improve the market situation of dry-running positive displacement pumps. The mostly empirically based design of these pumps has to take into account partly competing viewpoints. These viewpoints are energetic process optimization, on the one hand, and operational reliability, on the other hand. A simulation system can be used to solve this problem. The simulation system uses an energy and a mass balance in order to simulate the operational behaviour of the vacuum pumps. Therefore knowledge of the different states of flow through clearances in a vacuum is essential. The experimental examination of the flow is done by flood curve measurements, to describe the mass flow integrally using the characteristic number of the standardized mass flow. The results for some possible plain clearance shapes are discussed.

Keywords: vacuum pumps, simulation, plain clearance, geometry of gap, standardized mass flow

1 INTRODUCTION

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, e.g. semiconductor manufacturing, metallurgy or chemical process engineering as well as research and development [**2**, **3**]. 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 rotational positive displacement pumps, the screw spindle vacuum pump particularly (Fig. 1), can fulfil these new demands.

With these vacuum pumps no auxiliary fluid that is transported is in direct contact with the working fluid in the working chamber. A 'clean vacuum' is therefore the direct consequence. 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 (Fig. 2).

The lack of the sealing effect causes more internal leakage than a pump with 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 one working with sealing fluids. This results in a higher thermal loading of the pump, which is strengthened by the lack

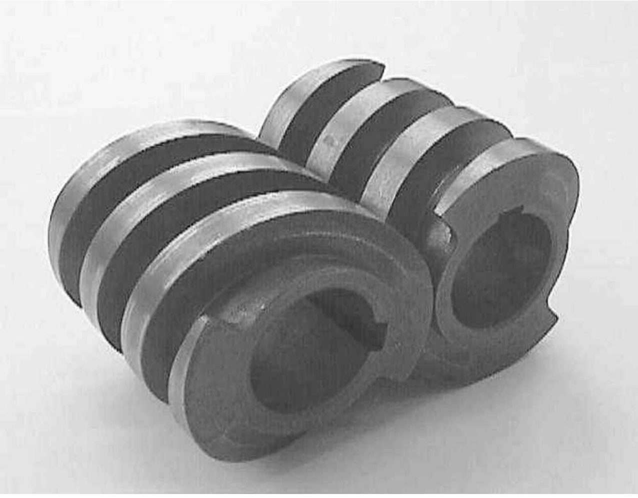

Fig. 1 Geometry of double-threaded rotors of a screw spindle vacuum pump

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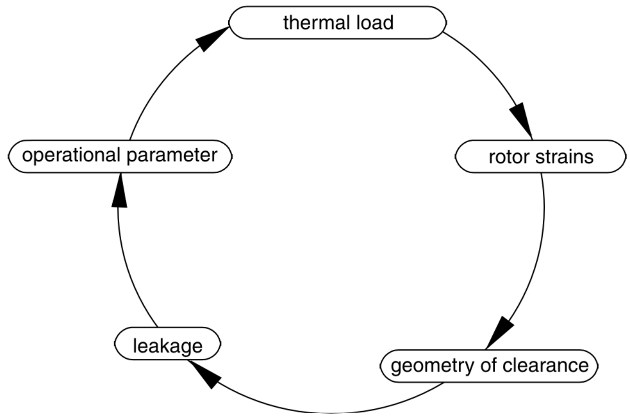

Fig. 2 Vicious circle of dry-running positive displacement vacuum pumps

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 thermal rotor expansion. Therefore the technical designer must be able to conclude from the cold clearance heights the heat-formed clearance heights in the concept phase of the pump.

There follows an optimization problem between pumps with very close clearances and low leakages, on the one hand, and pumps with bigger clearance heights because of the need for guaranteed operational safety. At present this optimization problem can only be solved with values taken from experience, producing considerable insecurity. This insecurity closes the vicious circle, because often clearance heights must be chosen that are too large or are chosen for reasons of operational reliability [**4**].

2 SIMULATION OF THE THERMODYNAMIC PROCESS

For the solution of the optimization problem a simulation system can be used. This simulation system essentially consists of a commercial finite element calculation method software and a program for simulation of the thermodynamic process. Figure 3 shows the generation of a simulation with iterative cooperation between the finite element software and the program for simulation of the thermodynamic process.

The simulation program calculates the variables of state and the boundary conditions for the finite element software in order to be able to consider all relevant influences [**5**]. The finite element software supplies the real temperature and deformation vector fields. However, the quality of the results of these finite element calculations directly depends on the boundary conditions used for calculations [**6**]. From the deformation vector fields result the rotor stretches and with it quantitative statements about the absolute changes of

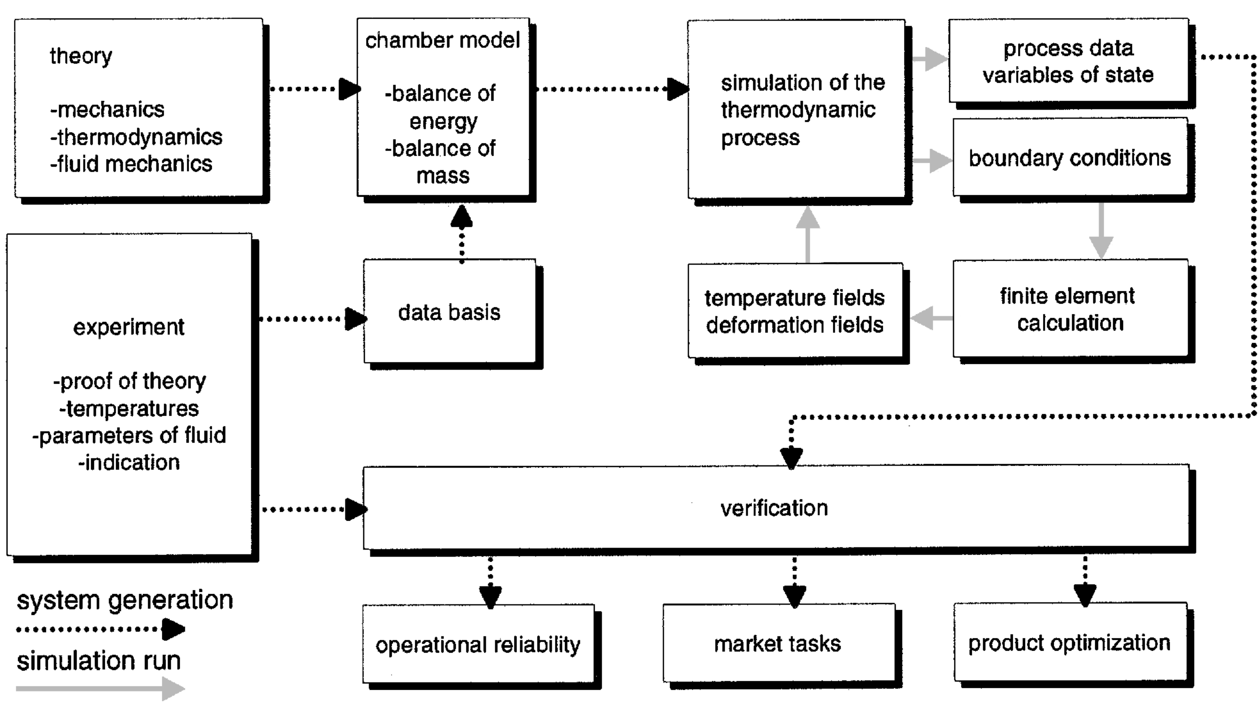

Fig. 3 Generation of a simulation system

the clearance heights between the cold clearance heights and the heat-formed clearance heights. These finite element results are fed back into the simulation program again. The number of necessary iterations between the simulation program and the finite element software depends on the convergence of the respective results. The finite element calculations allow, for example, statements about the expected operational reliability and solve the vicious circle.

3 BASIS OF THE SIMULATION

The simulation calculation of the process is intended to deliver realistic statements about the process in dry-running positive displacement pumps. For this the variables of state of the working fluid in a working chamber need to be calculated (pressure, temperature and mass). Moreover, the geometry of the real rotational positive displacement pump should be transferred in a virtual model to the so-called chamber model (Fig. 4). The form of an energy balance and a mass balance depends on the chamber model. This chamber model determines the number of terms of these balances [compare Fig. 4 and equation (2)]. If the terms of balances are quantified, the variables of state of the working fluid in the working chamber can be calculated.

Consideration of these variables of state does not take place continuously but at discrete points. These discrete points are periodically distributed throughout the whole working cycle of the positive displacement vacuum pump and reach from the formation of the working chamber on the suction side up to its disappearance on the pressure side. The balance of mass for the transition from a point n to its neighbouring point $n+1$ is as follows:

$$m_{n+1} - m_n = \Delta m \tag{1}$$

The chamber model of, for example, a screw spindle vacuum pump necessitates consideration of the mass flow through 12 clearances. Compare the following equation to the complete description in reference [7] in order to calculate a working point belonging to the transport phase:

$$\Delta m = \sum_1^2 m_{\mathrm{GSP}} + \sum_1^4 m_{\mathrm{KRO}} + \sum_1^4 m_{\mathrm{ESP}} + \sum_1^2 m_{\mathrm{RSP}} \tag{2}$$

The different types of clearances are the housing gap (GSP), the blowhole (KRO), the profile meshing gap (ESP) and the radial gap (RSP).

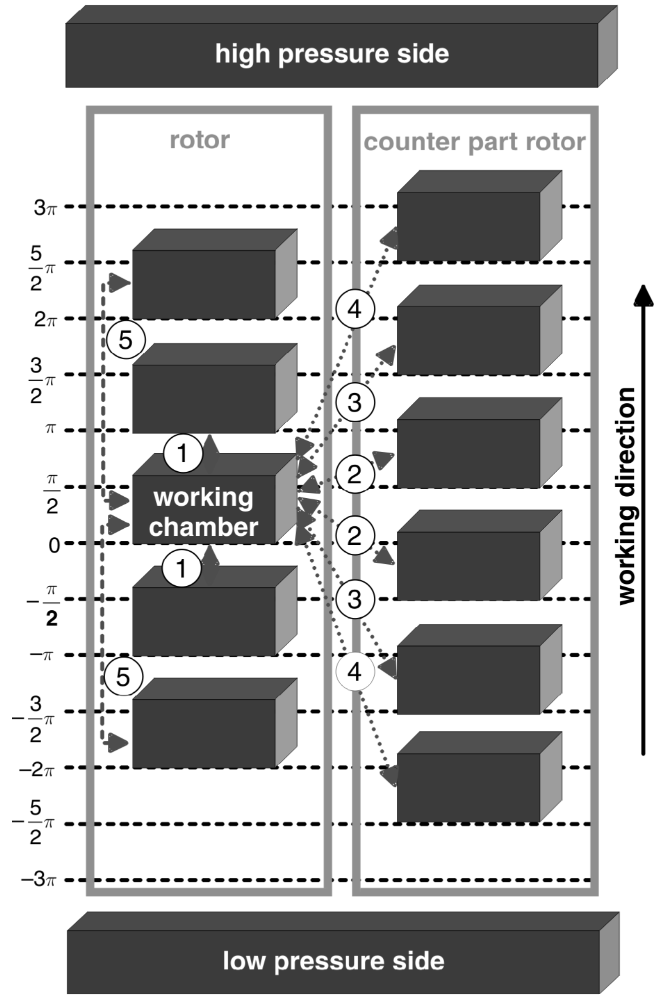

Fig. 4 Chamber model of a screw spindle vacuum pump (1, housing gap; 2, blowhole; 3 and 4, profile meshing gaps; 5, radial gap)

In analogy, the following balance is considered for the preservation of energy:

$$E_{n+1} - E_n = \Delta E \tag{3}$$

If the kinetic and geodetic energies are neglected, the energy E is equivalent to the inner energy U and from equation (3) the temperature T_{n+1} is calculated:

$$T_{n+1} = \frac{m_n}{m_{n+1}} \frac{c_{y,n}}{c_{y,n+1}} T_n + \frac{1}{m_{n+1} c_{y,n+1}} \Delta E \tag{4}$$

The change of energy ΔE contains all the relevant working principles, e.g. the energy of the compression and the heat transmission, etc. The quantities of the different terms of the balances in equations (2) and (3) are functions of the variables of state at the place from where the mass flows reach the considered working chamber. Only the quantity of the mass flow directly finds consideration in the mass balance; the quality of the mass flow is considered only indirectly via the amount of mass flow in the balance. The abstraction of the mass flow in the form of a mass balance makes it possible to calculate the mass of a fluid in a working chamber without previous comparatively difficult determination of the state of flow through the balanced clearances.

4 CHARACTERISTIC NUMBERS

The characteristic Knudsenzahl number Kn is used to qualify the states of flow:

$$Kn = \frac{\bar{l}}{d} \tag{5}$$

In this connection, the mean free path of the molecules of the working fluid is divided by the characteristic length of the construction unit through which the flow passes. For the working area of dry-running rotational positive displacement pumps the following states of flow must be expected:

(a) viscous flow ($Kn < 0.01$),
(b) Knudsen flow ($0.01 < Kn < 1$) and
(c) molecular flow ($Kn > 1$) (compare with Fig. 5).

Here the standardized mass flow δ is introduced as a characteristic number for the quantification of the flowrates through clearances. It generally finds application in reference [**8**] for the first time and in reference [**9**] concerning flowrates in the vacuum. The standardized mass flow δ is a dimensionless characteristic number for the quantitative description of flowrates through geometrical components, such as clearances. The actual flowrate is related to the theoretical maximum flowrate as follows:

$$\delta = \frac{\dot{m}}{\dot{m}_{\mathrm{th,\,max}}} \tag{6}$$

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

$$\dot{m}_{\mathrm{th,\,max}} = \dot{m}_{\mathrm{th,\,kr}} = A_{\min}\left(\frac{2}{\kappa+1}\right)^{1/\kappa-1}\frac{p_{\mathrm{E}}}{RT_{\mathrm{E}}}\sqrt{\frac{2\kappa}{\kappa+1}RT_{\mathrm{E}}} \tag{7}$$

Therefore the standardized mass flow δ describes the integral behaviour of flowrates. All possible states of flow are standardized in the parameter space [0,0]... [1,1], which is stretched by the pressure ratio Π and the standardized mass flow δ. The uniform definition of the standardized mass flow applies for all states of flow. This has a particular special advantage for the program technical conversion, because the quantification of the standardized mass does not require previous determination of the state of flow.

5 MODELLING (CATEGORIZATION)

The flow through the clearances of dry-running vacuum pumps represents a flow through double-curved clearances in a rotating system. At the same moment the boundary walls move relative to each other and the geometry is partly changed because of the thermal load. Therefore the flow possesses unsteady, diabatic qualities. On the other hand, the chamber model of a positive displacement vacuum pump requires an integral description of the flow by quantification of the flowrate. Using the introduced standardized mass flow this quantification is based on experimental examinations of quasi-steady flow. In reference [**10**] deviation of the integral description by unsteady flow is examined. In vacuum the flows distinguish themselves by the high-pressure ratios and the low absolute masses. Both of these qualities

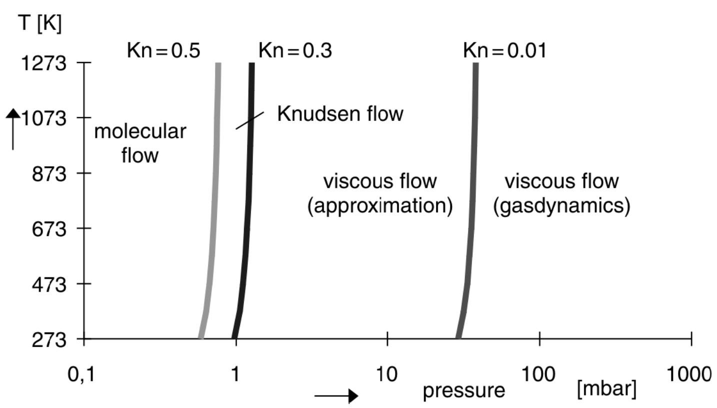

Fig. 5 States of flow in the working area of dry-running positive displacement vacuum pumps

favour an integral description of the unsteady flow by the quantification of characteristic numbers that are determined for quasi-steady flow.

This is an important presupposition in order to be allowed not to examine the flow through the clearances of real pumps but in models of clearances. Using models is a significant advantage because of the possibility of changing 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 a knowledge of characteristic numbers for quantification of the steady flow the dynamic influence on the flow can be determined [**10**]. In this way examinations are limited to the geometrical parameters affecting the flow, particularly the shape of clearances. The shape of clearances means the series of cross-sections of clearances that supposed streamlines pass through. If the flowrate is known for the shape of clearances, the flowrate can be determined for a double-curved clearance [**11**].

Because it is not possible to examine arbitrarily many forms of shapes of clearances, the different forms are reduced to a number that is capable of examination. In addition, the shapes of clearances must be categorized with regard to a geometrical parameter that describes the geometry. Then within the separate categories a suitable staggering of the geometrical parameter reduces the number of shapes to be examined (see Table 1).

As a result of categorization expenditure decreases as consideration is only given 40 different shapes of clearances for dry-running rotational positive displacement pumps.

6 RESULTS OF MEASUREMENT

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. As the flow through the gap floods the recipient, this measuring procedure is called the 'flood curve measurement'. With a sufficient size of the recipient this occurs very slowly and the different working conditions of the flow are considered to be quasi-steady (compare with reference [**12**]). For this constant inlet pressure the flood curve assigns a characteristic number to the combination of physical and geometrical parameters at the clearance, i.e. the flood curve describes the functional relationship between the pressure ratio Π at the clearance and the standardized mass flow $\delta = f(\Pi)$. All the flood curves of a single clearance characterize the integral throttle quality of a clearance. Figure 6 shows the results of a clearance shape belonging to category 1.

For 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 that for high inlet pressures $p_E > p_{E,1}$, the typical characteristic for the viscous, interlocked flow. For subcritical pressure ratios, $\Pi < \Pi_{kr}$, the standardized 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, which show 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 $p_E < p_{E,2}$.

The combination of the results of the separate flood curves (Π variation) and the variation of the inlet pressure p_E allows a representation to be made of a quantitative characteristic pattern of a clearance in the vacuum. Figure 7 illustrates such a clearance. 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 standardized 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 standardized mass flow. Accordingly, the characteristic curves run parallel to the ordinate for high constant inlet pressures. The linear characteristic of the molecular flow area can be found in the area of low pressures. The linear relationship between the standardized mass flow δ and the pressure ratio Π causes the equidistant run of the curves representing constant values of the standardized mass flow.

However, for a comparison of different shapes of clearance belonging to the same category, the characteristic patterns are too complex. For this task the standardized mass flow is shown as a function of the inlet pressure $[\delta_{\Pi} = f(p_E)]$. Figure 8 shows as an example a comparison of six clearance shapes of category 2. A radius describes the macroscopic geometry of these convex shapes. The clearances are in the direction of flow. The entry edge into all clearances is radii-formed with a

Table 1 Categories of shapes of clearances

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

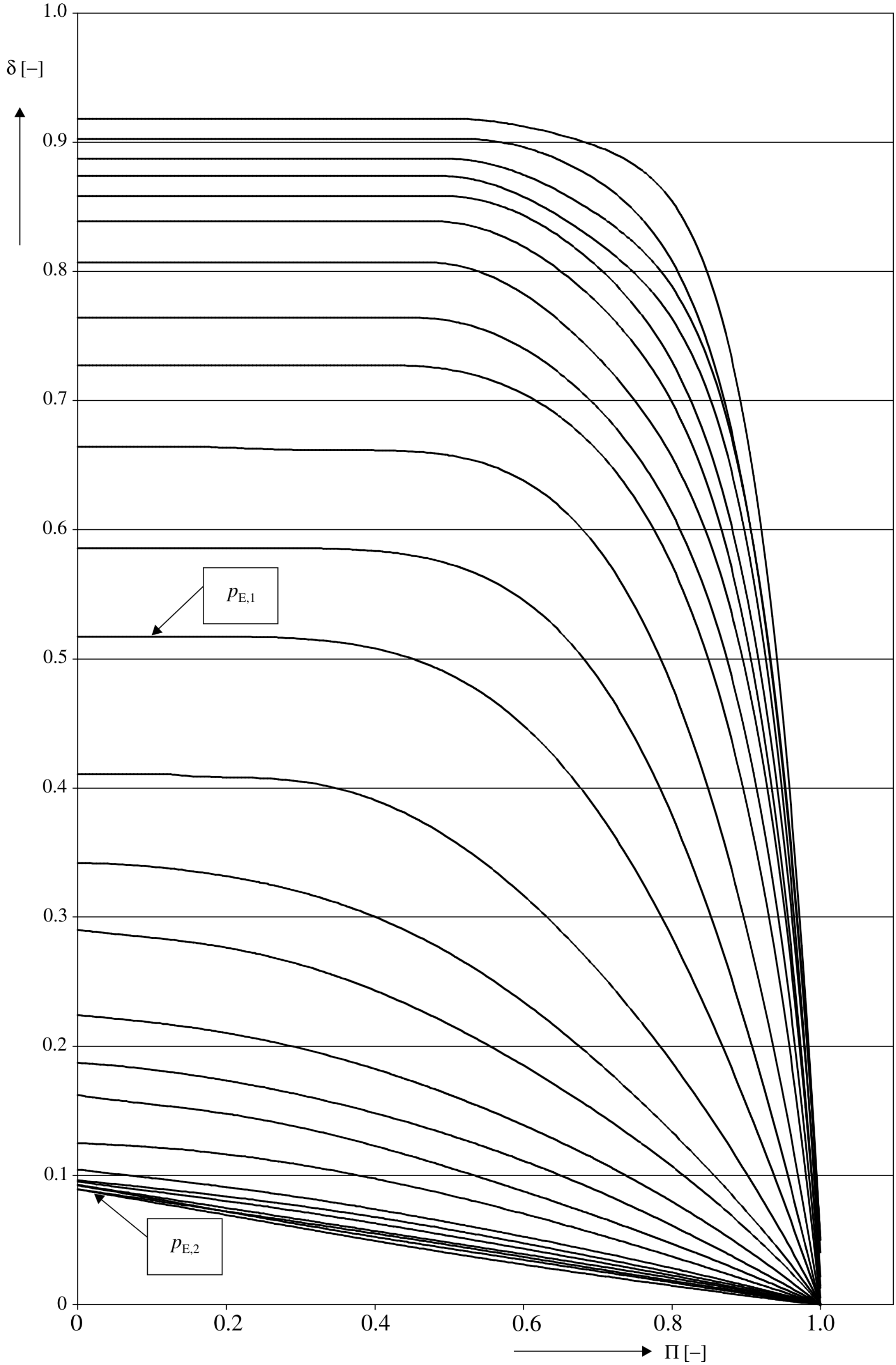

Fig. 6 Flood curves belonging to clearance shape W1 (category 2)

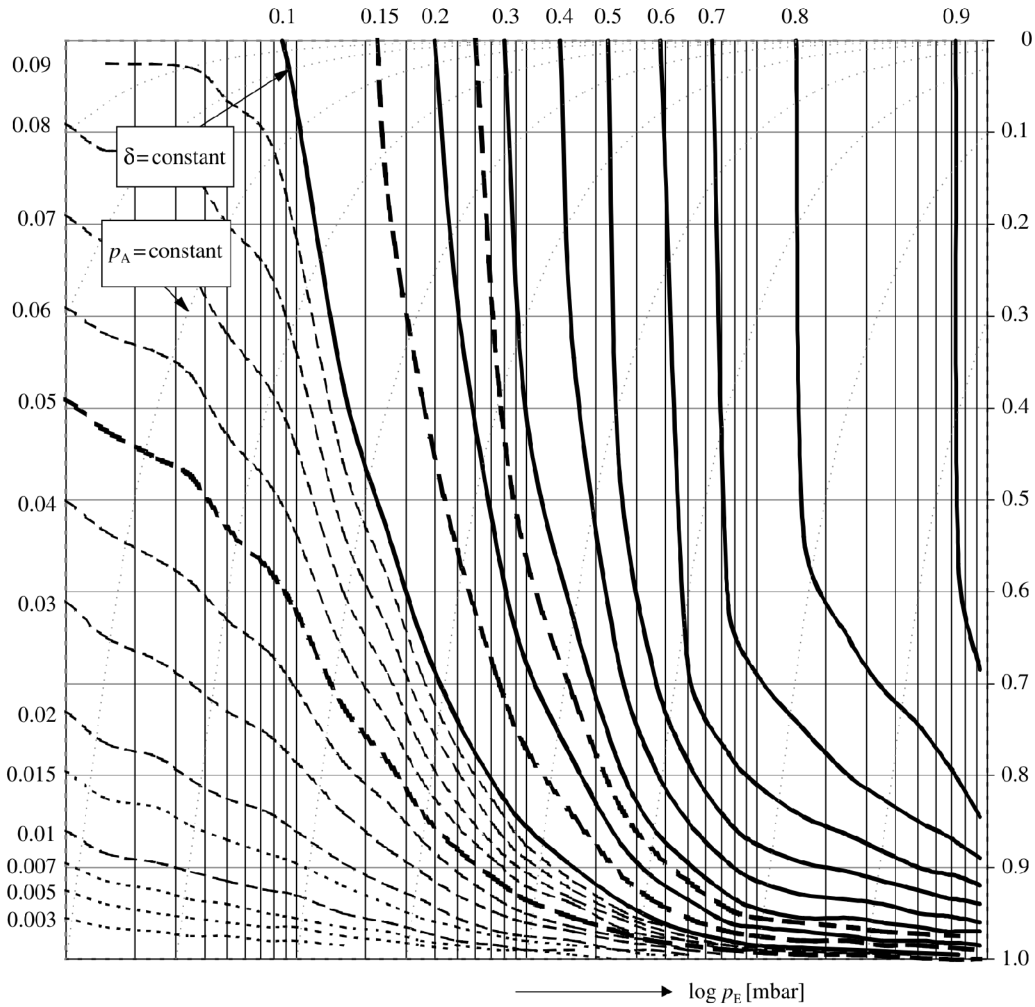

Fig. 7 Quantitative characteristic pattern belonging to clearance shape W1 (category 2)

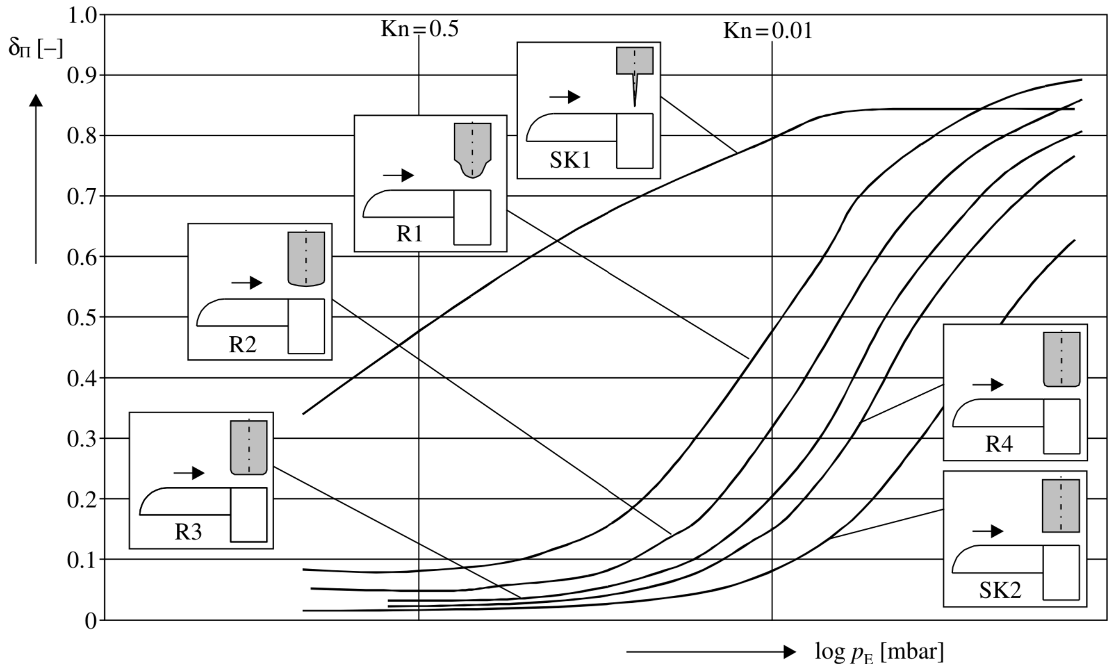

Fig. 8 Standardized mass flow as a function of inlet pressure p_E (category 2)

constant radius, which is small in comparison to the radius and describes the macroscopic geometry of each clearance shape. The geometrical cross-sections of the flow tunnel become closer up to the apex of the radius and then increase again. The clearance shape SK1 represents the limit of an infinitely small radius. Accordingly, the clearance shape SK2 corresponds to the limit of an infinitely large radius. A quantitative comparison of the characteristic curves shows that with larger radii the throttle quality of the gap also rises. Therefore the characteristic curves in Fig. 8 are ordered by the value of the radius and do not cross.

A more exact analysis of the throttle quality is performed for $Kn = 0.01$ under consideration of the characteristic curves of the clearance shapes SK1 and SK2. The shape clearance R1 possesses the smallest radius of all shapes belonging to category 2. For $Kn = 0.01$ a significant throttle quality appears for this clearance shape which is already compared to the maximum value of the standardized mass flow. The value of the standardized mass flow is halved in the first approximation. Clearance shapes with a comparatively small radius also have a significant influence on throttle quality.

However, the comparison of the characteristic curves of the outlines R3, R4 and SK2 shows that the characteristic curves R3 and R4 are not separated very far quantitatively and approximate the borderline case of the plan-parallel clearance shape. The throttle quality is less sensitive in the area of a large radius than in the area of a small radius. This is caused by the tangent to the radius, which builds a plan-parallel clearance with the plain counterpart of the clearance. With the variation of the radius greater for larger parameter values the shape adapts faster to the tangent in the area of the small radius than of the large radius. With a suitably large radius a reinforced throttle quality of the clearance can be found compared to the clearance shape SK1 in all states of flow (compare the characteristic curves of the outlines SK1, R3 and R4).

In summary, it can be stated that for category 2 the throttling quality grows with increasing radius. In the area of a small radius the variations of the parameter have a stronger effect on account of the tangent, which is parallel to the counteroutline in the area of the geometrically closest place.

7 FINAL CONSIDERATION

The results of examination of all clearance shapes, as well as of the variation of clearance heights, represent altogether a database usable for the integral description of flow. To be able to transfer the results to other clearance shapes, use has been made of similarity relations. The experimental examinations to the proof of the similarity relations suggest an incomplete similarity for geometrically similar outlines for the work area of dry-running rotational positive displacement pumps [13]. Using the similarity relations the corresponding standardized mass flow can be assigned to a clearance shape. Basis data of the clearance heights and clearance shape are needed for this.

The presented work provides data that are required to provide a simulation program for dry-running rotational positive displacement vacuum pumps.

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