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ERP Positive Displacement Pumps – Physically Based Approach Towards an Application-Related Efficiency Guideline

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Summary

There is a high probability that the Ecodesign Directive of the European Union will include positive displacement pumps in the near future. The Ecodesign Directive sets the framework of a legislative efficiency guidelines of energy-related products (ERP) to reduce their energy consumption. However, positive displacement pumps are used in various applications that affect the attainable efficiencies. Consequently, a regulation for all positive displacement pumps on the pure basis of the efficiency is not sufficient. This paper illustrates the necessity of an application-related consideration of positive displacement pumps and provides two major steps towards an application-related efficiency guideline: firstly, a concept of data acquisition and analysis is presented and discussed. The concept aims to identify the energetically relevant applications of positive displacement pumps and to determine a relationship between the various pump types, their applications and energy consumption. Secondly, a physically based, type independent and easy to apply model of the efficiency of positive displacement pumps is presented and its suitability in the context of an efficiency guideline is discussed. The model has been introduced by the authors recently and describes the efficiency as a function of four dimensionless variables. A parameter identification and model application on four different pump types and 155 different pump sizes including 2680 operating points proves its practicability to compare different pump types.

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1. Introduction

The European Union (EU) pursues ambitious objectives reducing greenhouse gas emissions in the future. Thus, energy-related products (ERP) are regulated by the European Union's Ecodesign Directive in terms of energy efficiency [1]. A large proportion of the EU's energy consumption can be assigned to energy-related products, which often have a high potential for energy savings through a better design. The goal of the Ecodesign Directive is to achieve a significant reduction of the energy consumption of the energy-related products, e.g., displacing products with a low efficiency performance form the market. Until now positive displacement pumps are not involved. However, regarding the previous strategy of the EU, the probability is high that the EU will focus on positive displacement pumps in the near future.

Positive displacement pumps are characterized by their wide operating range and diverse fields of application with all kinds of fluids. This leads to a vast variety of different pump types, e.g. piston pumps, gear pumps or spindle screw pumps, which distinguish by means of their application characteristics. In most frequent applications the pump efficiency only plays a subordinate role, but specific characteristics are necessary, e.g. low pulsation or high precision. Consequently, these application-related requirements are primary and thus, the main selection criteria for an appropriate pump type. However, the application-related requirements may have a negative effect on the efficiency. Obviously, a legislative regulation of all positive displacement pumps on the pure basis of the efficiency is not sufficient and would involve the risk of inadequate machine comparison with fatal consequences. In the worst case, process relevant pump types are displaced from the market disregarding on the one hand that the application-related requirements do not allow higher efficiencies and on the other hand that there is no alternative pump type fulfilling the primary requirements. Hence, an efficiency guideline need to be application-related. This paper presents two major steps that provide a basis for this objective:

Firstly, we present a concept of data acquisition and analysis that aims to answer the following four research questions: (i) Which characteristics of applications need to be considered in the context of an efficiency guideline of positive displacement pumps? (ii) What is the total energy consumption of positive displacement pumps? (iii) Which are the most energetically relevant applications of positive displacement pumps? (iv) Can every specific application always be assigned to one specific pump type and if not, in which applications exist a competition between different pump types? Secondly, we introduce a physically based, type independent and easy to apply model for the efficiency of positive displacement pumps. The model is applied on four different types of pumps and 155 different pump sizes including 2680 operating points. The results are presented and discussed in the second part of the paper. The paper closes with the conclusion and an outlook on future investigations.

2. Application-related study of positive displacement pumps

As a consequence of the big variety of applications of positive displacement pumps, pump manufacturers and pump users often have different perspectives and understandings of the applications. As an essential prerequisite, we characterize applications and highlight their relevant characteristics in the following section. In this way, we enable an effective discussion. Afterwards we present an approach of data acquisition and data analysis that provides a methodology to answer the above stated research questions.

Relevant characteristics of application

In the context of an application-related efficiency guideline of positive displacement pumps, it is necessary to identify those application characteristics, which influence the selection of positive displacement pumps. We divide these relevant characteristics into the following three categories. Firstly the *function*, which is described by the discharge pressure and the volume flow rate. Secondly, the *pumping medium,* which include five different medium properties. Thirdly the *application-related requirements,* which include seven different relevant requirements. A detailed itemization of the three categories with a total of 14 relevant application characteristics is given in table 1.

Table 1: Relevant application characteristics of positive displacement pump

FUNCTION	PUMPING MEDIUM	APPLICATION-RELATED REQUIREMENTS
discharge pressure	*viscosity*	*pulsation*
volume flow rate	*temperature*	*dosing accuracy*
	contamination	*controllability of volume flow rate*
	lubricity	*impermeability*
	gas content	*volume specific power density*
		sheer stress history of pumping medium
		chemical resistance

Not all of the mentioned applications characteristics influence the efficiency of a pump. The efficiency depends mainly on the discharge pressure, volume flow rate and viscosity. A model of the efficiency that considers these characteristics is introduced in the section “Type Independent Modeling of Positive Displacement Pumps”.

The physical limitations of use are another important aspect that restrict the comparability of positive displacement pumps. Specific limitations exist for the *function* and the *pumping medium* characteristics (see Tab.1). Piston pumps for example reach the highest pressures whereas spindle screw pumps are used at high volume flow rates. Figure 1 shows the operating ranges of different pump types on the basis of an acquisition of catalogue data of various pump manufacturers [2].

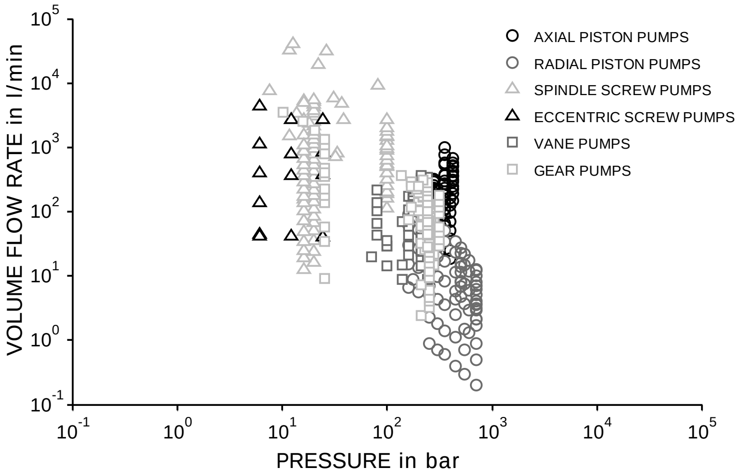

Figure 1: Rated operation points (pressure vs. volume flow rate) for different positive displacement pumps [2].

The application-related requirements are of major significance for the application and, therefore, are the main selection criteria for pump users. Concerning these requirements every pump type has strengths and weaknesses and in the end its reason for existence.

The huge number of possible combinations of the application characteristics reflect the big variety of applications of positive displacement pumps. To handle the existing complexity it is useful to set the focus on the most energetically relevant applications. This is also consistent with the aims of the Ecodesign Directive, which states that energy-related products should have a high potential for significant reduction of their energy consumption. Following this argumentation, there is a necessity for an acquisition and analysis of sales data of pump manufacturers and operating data of pump users. These data are the most reliable sources on number of sold pumps and operating conditions. On such data basis both the total energy consumption of positive displacement pumps and the most energetically relevant applications can be identified. For reasons of compliance and acceptance, the results of such a data acquisition and analysis have to be anonymized and treated trustfully. The cooperation of EUROPUMP and Chair of Fluid Systems, in the context an efficiency guideline of single-pump-units, provides a good example [3], [4].

Data acquisition and analysis

This paper focuses on the data acquisition and analysis of the sales data of pump manufacturers. Besides detailed pump data, the sales data contain necessary information of the operation point that is given by the customers, i.e., power consumption, discharge pressure, volume flow rate, viscosity of pumping medium, operating temperature, the name of the pumping medium and the name of the customer or the respective industrial sector.

The analysis method is as follows: firstly, the manufacturers name the main applications of their customers. Each application is characterized by their application-related requirements. In the next step filter criteria for the given operation points are defined. This allows us to filter the entire sales data for each application and, hence, to determine the sold power of each application. In the following step, the mean operating time of each application is estimated so that their mean energy consumption can be calculated. The analyzed data allows us to assign pump types, applications and energy consumption. Furthermore, we are able to collocate the applications according to their energetic relevance. The energetically relevant applications can be assigned to industry sectors, e.g. oil and gas industry, process industry or chemical industry. Figure 2 shows the analysis method schematically.

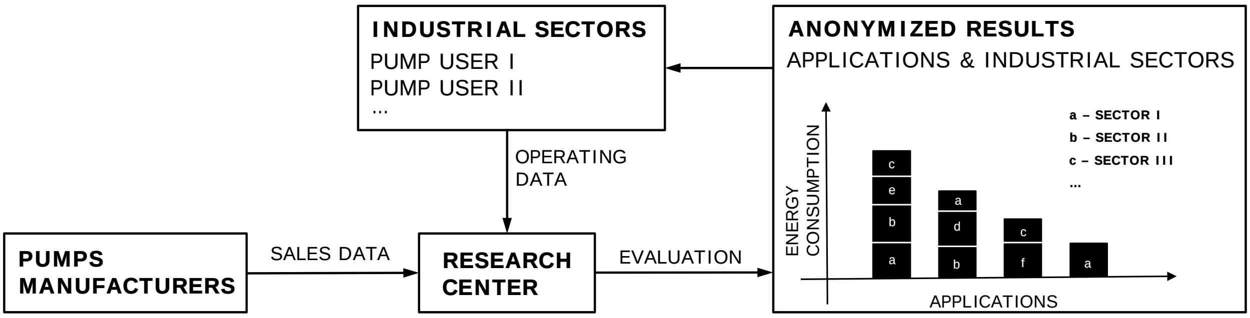

Figure 2: Schematic method of data acquisition and evaluation

The presented data acquisition and evaluation still contains major uncertainties, which, however, are normal for this kind of data driven study. Positive displacement pumps usually have an operating range and not only one single operating point. Furthermore, the operating time is closely linked to the application and the industry sector. To get more precise data for both aspects, operating range and time, pump users also need to be included in the data acquisition. On the basis of the evaluated data of the pump manufacturers, firstly, the industry sectors with the energetically relevant applications can be identified and, secondly, another data acquisition among the pump users of the identified industrial sectors allows one to estimate the energy consumption more precisely.

So far, the presented approach has been tested on a small number of pump manufacturers and has proven its practicability to identify relevant applications. For compliance reasons, these results are not presented in this paper. In the context of the Ecodesign Directive, the data acquisition needs to be extended on a higher number of manufacturers at European level. These results will indicate if positive displacement pumps make a decisive contribution to the energy consumption in Europe and which applications are energetically relevant. Furthermore, the results will reveal those applications, which are fulfilled of several different pump types. In this case an energetic comparison is useful and necessary, but requires a type independent description of the efficiency. In this context, the next section introduces a type independent efficiency model of positive displacement pumps.

3. Type independent efficiency model of positive displacement pumps

Regarding existing efficiency guidelines for energy-related products, e.g. water pumps and electric motor, one key tool to achieve a reduction of energy consumption is the prohibition of the products with low efficiency performance. For this purpose, minimum efficiency standards based on physical efficiency models have proven their practicability [5], [6], [7]. Thus, a similar approach seems useful for positive displacement pumps. As soon as different pump types are used for the same application, a consistent and energetic comparison needs a type independent efficiency model.

In general, the efficiency of positive displacement pumps is reduced by inner leakage and mechanical and hydraulic losses. Due to the various different pump types, there is a trend towards machine specific and precise loss models. On the other hand a physically based and type independent model is missing that is able to predict the efficiency as a function of the essential operating conditions and the machine size. This leads to the question, whether there exists a type independent efficiency model of positive displacement pumps, which is simply based on dimensional analysis and is independent of the machine specific design. The authors introduced a model in [8] that satisfies the above stated requirements. In the next sections, we firstly give a brief summary of the derivation of this model and, secondly, discuss the results of the parameter identification and model application on machine data in the context of an efficiency guideline of positive displacement pumps.

Type independent efficiency model of the efficiency

The isentropic efficiency η represents a measure of the energetic quality of a machine. On the basis of the first law of thermodynamics for a time averaged stationary and thermally isolated machine, the isentropic efficiency is defined as the hydraulic power, which is the product of the mass flow $\dot{m}$ and isentropic enthalpy difference $\Delta h_{t,s}$, divided by the shaft power P_S

$$\eta := \frac{\dot{m}\,\Delta h_{t,s}}{P_S}. \tag{1}$$

The model approach focus on the two essential types of pump losses: the inner leakage and the mechanical and hydraulic losses. Hence, it is necessary to divide the efficiency into a volumetric efficiency η_{vol} and a hydro-mechanical efficiency η_{mh}. For this purpose, the isentropic enthalpy $\Delta h_{t,s}$ in equation (1) is determined for liquid pumping mediums. Positive displacement pumps reach high discharge pressures and, thus, the compressibility κ also needs to be considered. The result is the efficiency as a function of the volume flow rate Q_1 at the inlet, the discharge pressure Δp, the compressibility κ and the shaft power P_S. Furthermore, the shaft power is the product of the shaft torque M_S and the rotational speed n. Extending the description of the efficiency with the displacement volume V, one obtains a representation of the total or isentropic efficiency and both the volumetric efficiency and the hydro-mechanical efficiency

$$\eta := \frac{Q_1 \Delta p}{2\pi M_S n}\left(1-\frac{\kappa\Delta p}{2}\right), \qquad \eta_{vol} := \frac{Q_1}{nV}, \qquad \eta_{mh} := \frac{\Delta p V}{2\pi M_S}\left(1-\frac{\kappa\Delta p}{2}\right). \tag{2}$$

Both η_{vol} and η_{mh} in equation (2) are a function of the losses: on the one hand the leakage Q_L and on the other hand the mechanical and hydraulic losses, which are represented by the friction torque M_{mh}. The volume flow rate is the difference of the theoretical volume flow rate $Q_{th} = nV$ and the leakage, the shaft torque is the sum of the hydraulic torque $M_{hyd} = \Delta p V(1-\kappa\Delta p/2)/2\pi$ and the friction torque. Hence, one obtains the partial efficiencies

$$\eta_{vol} := \frac{Q_1}{nV} = 1 - \frac{Q_L}{nV}, \qquad \eta_{mh} := \frac{\Delta p V}{2\pi M_S}\left(1-\frac{\kappa\Delta p}{2}\right) = \frac{1}{1+\frac{2\pi}{1-\kappa\Delta p/2}\frac{M_{mh}}{\Delta p V}}. \tag{3}$$

Equation (3) shows that a model of the leakage Q_L and of the friction torque M_{mh} will lead to a description of the volumetric, the hydro-mechanical and finally of the total efficiency.

The model approach is based on dimensional analysis. The procedure is as follows: Firstly, all major influencing variables on the losses are determined. In this case, the following seven influencing variables are considered: the operational parameters discharge pressure Δp and rotational speed n, the properties of the pumping medium density ϱ, kinematic viscosity ν and compressibility κ, and the geometric parameters displacement volume V and averaged gap size s. Secondly, the dimensional analysis reduces the number of model variables and, thus, simplifies the model while maintaining the physical significance [9]. By doing so, one obtains the following four dimensionless variables: specific pressure Δp^+, Reynolds number Re, specific compressibility κ^+, and relative gap size ψ. These dimensionless variables are defined as

$$\Delta p^+ := \frac{\Delta p}{\nu^2 \varrho V^{-2/3}} \;, \qquad Re := \frac{nV^{2/3}}{\nu}, \qquad \kappa^+ := \kappa \Delta p, \qquad \psi := \frac{s}{V^{1/3}}. \tag{4}$$

Furthermore, the leakage and the friction torque are represented by another dimensionless number, respectively: the specific leakage Q_L^+ and the specific friction torque M_{mh}^+, which are defined as

$$Q_L^+ := \frac{Q_L}{\nu V^{1/3}}, \qquad M_{mh}^+ := \frac{M_{mh}}{\Delta p V}. \tag{5}$$

Thirdly, the specific leakage $Q_L^+ = Q_L^+(\Delta p^+, \psi)$ as a function of the specific pressure and relative gap size and the specific friction torque $M_{mh}^+(\Delta p^+, Re, \psi)$ as a function of the specific pressure, Reynolds number and relative gap size need to be determined. This leads directly to descriptions of the volumetric and hydro-mechanical efficiency

$$\eta_{vol} = 1 - \frac{1}{Re} Q_L^+(\Delta p^+, \psi), \qquad \eta_{mh} := \frac{1}{1 + \frac{2\pi}{1 - \kappa \Delta p/2} M_{mh}^+(\Delta p^+, Re, \psi)} \tag{6}$$

and of the total efficiency

$$\eta = \frac{1 - \frac{1}{Re} Q_L^+(\Delta p^+, \psi)}{1 + \frac{2\pi}{1 - \kappa \Delta p/2} M_{mh}^+(\Delta p^+, Re, \psi)}. \tag{7}$$

On the basis of experimental data, the authors illustrated in [8] that the specific leakage Q_L^+ can be described by a semi empirical model in terms of a power law

$$Q_L^+ = L * (\Delta p^+ \psi^3)^m. \tag{8}$$

L and m are the only model parameters. On the other hand, Schlösser and Hilbrands [10] introduced a physically based approach for the friction torque M_{mh} that represents a linear combination of a pressure-related loss, a viscous friction-related loss and a term related to inertial losses. By means of equation (5) this approach leads to a model of the specific friction torque M_{mh}^+

$$M_{mh}^+(\Delta p^+, Re, \psi) = C + R_\mu \frac{Re}{\Delta p^+ \psi} + R_\varrho \frac{Re^2}{\Delta p^+}. \tag{9}$$

C, R_μ and R_ϱ are the three dimensionless model parameters which represent loss coefficients and are, similar to the specific leakage, determined. In summary, with equation (8) and (9) axiomatic and empirical models are found and one obtains a description of the efficiency

$$\eta = \frac{1 - \frac{L}{Re} * (\Delta p^+ \psi^3)^m}{1 + \frac{2\pi}{1 - \kappa \Delta p/2}\left(C + R_\mu \frac{Re}{\Delta p^+ \psi} + R_\varrho \frac{Re^2}{\Delta p^+}\right)}. \tag{10}$$

The result in equation (10) is a physically based efficiency model as a function of the four dimensionless variables Δp^+, Re, κ^+ and ψ. These dimensionless variables include the operating conditions, the pumping medium properties and the machine size. Furthermore, the model is type independent and, thus, can be applied on every type of positive displacement pump. For this purpose, the above named model parameters L, m, C, R_μ and R_ϱ have to be determined in the context of an empirical parameter identification.

An experimental validation of the efficiency model by means of one single positive displacement pump showed good results [8]. In the next step, a parameter identification and model application on different pump types have to prove the suitability of the presented model. The next section presents the results of the identification and application on a basis of four different pump types.

Parameter identification and model application

The data base is a result of a survey among several pump manufacturers and includes four different pump types and 155 different pump sizes including 2680 operating points. Since the uncertainty of these data is unknown an extended validation of the model is not possible. However, the data are necessary and useful for a parameter identification of both loss models, the specific leakage in equation (8) and the specific friction torque in equation (9). Table 2 specifies the data base range for both the dimensional influencing variables from the operating conditions, pumping medium properties and machine size, and the equivalent dimensionless variables from equation (4).

Table 2: Range of dimensional influencing variables and equivalent dimensionless variables.

6 DIMENSIONAL VARIABLES	RANGE	3 EQUIVALENT DIMENSIONLESS VARIABLES	RANGE
discharge pressure Δp	0.1 … 468 bar	*specific pressure Δp^+*	$4*10^6$ … $2*10^{15}$
displacement volume V	28 ml … 28 l	*Reynolds number Re*	3 … $2*10^6$
kinetic viscosity ν	1 … 10000 cSt	*specific compressibility κ^+*	0 … 0.23
density ϱ	630 … 1250 kg/m³		
compressibility κ	4.5 … $50*10^{-5}$ 1/bar		
rotational speed n	100 … 3600 1/min		

The results of the parameter identification of the specific leakage are discussed in the following. Figure 3 a) shows a double logarithmic diagram, specific leakage versus specific pressure, including all machine data. The figure reveals three essential findings: firstly, the single pump types condense and form bands. Secondly, the bands have an offset. The piston pumps, specified by the smallest leakage, can be found on the bottom side of the figure. The eccentric screw pumps, the 3-spindle screw pumps and the gear pumps follow. 2-spindle screw pumps have the highest leakage. Thirdly, all bands have approximately the same slope, i.e., the exponent $m = 0.7$.

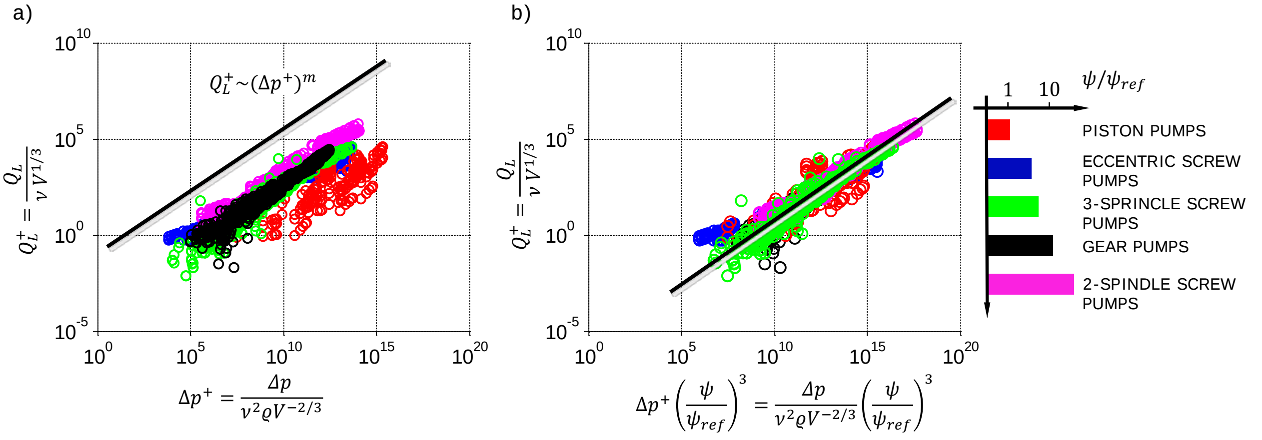

Figure 3: a) Specific leakage related to the relative gap size. b) Generalized specific leakage.

The first two findings are related to the influence of the relative gap size ψ. The relative gap size is a dimensionless design parameter that represents the pump type and the manufacturing tolerances. However, the gap sizes are part of the pump manufacturer's know-how and, thus, not included in the data base. Hence, the model of the leakage from equation (8) is used to determine the relative gap size empirically. For this reason, the pump types are considered in relation to each other. Piston pumps have the smallest relative gap sizes and, therefore, the lowest leakage. This pump type defines the reference value $\psi_{ref} := 1$. All other pump types are related to this reference measure. By doing so, one obtains a new quantity that is called class of gap ψ/ψ_{ref}. The class of gap leads to a general representation of the specific leakage so that all machine data converge to one single band. Figure 3 b) shows the general specific leakage for all pump types that can be represented by the functional relationship

$$Q_L^+ = L * \left[\Delta p^+ \left(\frac{\psi}{\psi_{ref}}\right)^3\right]^{0.7}. \qquad (11)$$

Consequently, the relative gap size or class of gap serves as characteristic quantity of the different types of positive displacement pumps. The scattering of the data in figure 3 indicates a variation of the relative gap sizes of each pump type. On the basis of the considered pump data, table 3 lists the mean, minimum and maximum values of the gap classes.

Table 3: Mean, minimum and maximum values of the gap classes.

	CLASS OF GAP ψ/ψ_{ref}	MINIMUM $(\psi/\psi_{ref})_{min}$	MAXIMUM $(\psi/\psi_{ref})_{max}$
piston pumps	1.0	0.3	2.0
eccentric screw pumps	5.0	2.9	7.2
3-spindle screw pumps	8.0	5.2	11.1
gear pumps	10.0	7.2	13.9
2-spindle screw pumps	15.0	11.2	24.0

The results of the parameter identification of the specific friction torque are represented in Figure 4. The double logarithmic diagram, specific friction torque versus specific pressure and Reynolds number, also includes all data and shows that each pump type approximated by one surface, respectively.

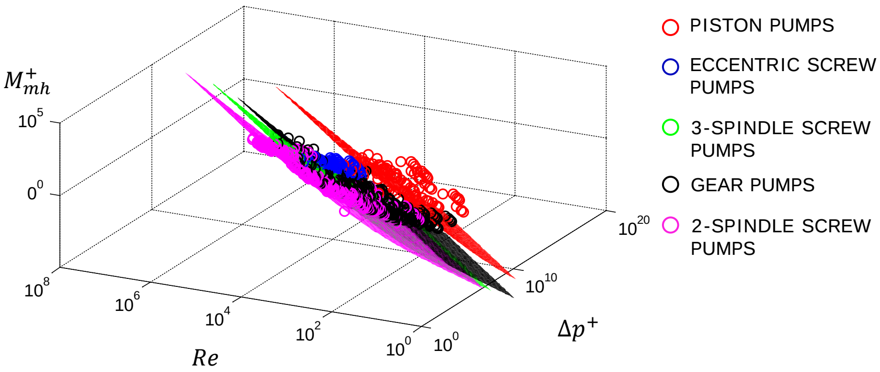

Figure 4: Representation of the specific friction torque M_{mh}^+ vs. Δp^+ and Re.

Furthermore, the pressure-related losses are negligible compared to the viscous friction and inertial losses. Hence, the model parameter C is approximately zero and the specific friction torque (see equation (9)) can be specified to

$$M_{mh}^{+} = R_{\mu}\frac{Re}{\Delta p^{+}\psi} + R_{\varrho}\frac{Re^{2}}{\Delta p^{+}}. \tag{12}$$

Figure 4 also shows, similar to the specific leakage, an offset and a scattering of the pump types which can be attributed to the relative gap size ψ and the model parameter R_{ϱ}. These model parameters differ for the various pump types. Concerning one single pump type, for increasing displacement volumes, R_{ϱ} decreases and converges to a constant value [8]. Similar to the relative gap size, R_{ϱ} also represents a characteristic quantity of the different types of positive displacement pumps.

Finally, with the equation (10), (11) and (12), one obtains a functional relationship of a type independent efficiency model

$$\eta = \eta_{vol}\eta_{mh} = \frac{1 - \frac{L}{Re} * \left[\Delta p^{+}\left(\frac{\psi}{\psi_{ref}}\right)^{3}\right]^{0.7}}{1 + \frac{2\pi}{1 - \kappa\Delta p/2}\left(R_{\mu}\frac{Re}{\Delta p^{+}\psi/\psi_{ref}} + R_{\varrho}\frac{Re^{2}}{\Delta p^{+}}\right)}. \tag{13}$$

Now, this model description can be applied to illustrate the required energetic comparison between different pump types. As stated in the first part of this paper, an energetic comparison of two pump types is only reasonable if the same applications and the operating points are considered. Figure 5 shows the efficiency as a function of the specific pressure and Reynolds number in a contour plot for a gear pump and a 2-spindle screw pump, respectively. Both pump types are determined by averaged and type specific values for ψ/ψ_{ref} and R_{ϱ}. The operating points $(\Delta p, Q, \varrho, \nu)_{i}$ are represented by the discharge pressure, the volume flow rate and the pumping medium properties, and also represent isolines. The varying parameters are the displacement volume and the rotational speed. This representation yield the following findings: firstly, for every operating point exists an optimal displacement volume V_{opt} and rotational speed n_{opt} that achieve an optimal efficiency η_{opt} in this particular operating point. Secondly, depending on the operating point, different pump types are energetically favorable. The 2-spindle screw pump reach higher efficiencies for the operating point 1, gear pumps are favorable for the operating point 2 and 3 and reach higher efficiencies.

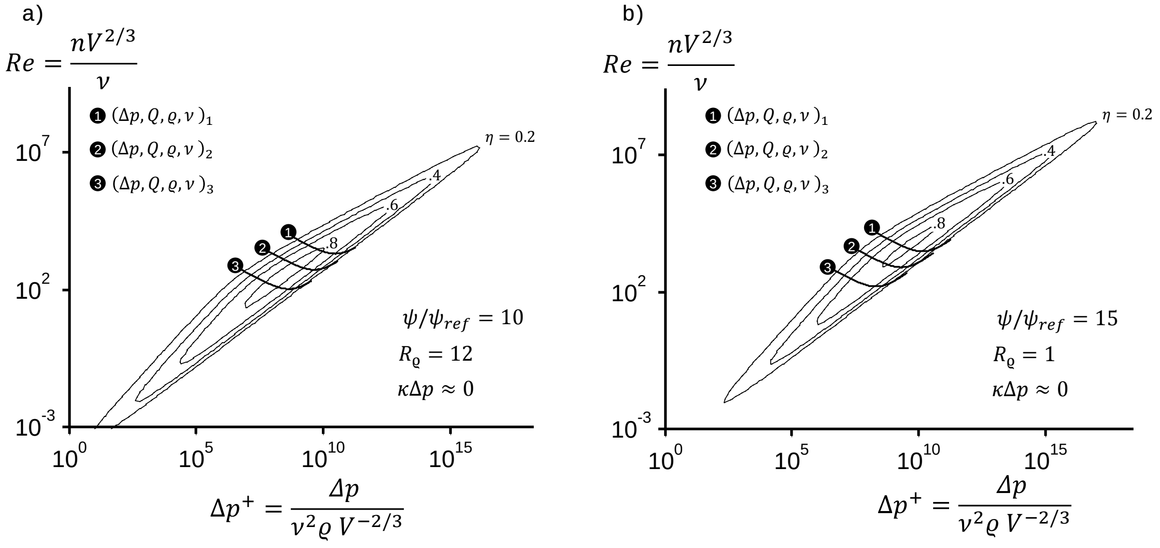

Figure 5: Contour line efficiency with isolines of three different operating points for a) a gear pump and b) a 2-spindle screw pump.

4. Conclusion & Outlook

A development of an efficiency guideline of positive displacement pumps in the context of the Ecodesign Directive is an issue of relevance and high complexity. The first part of the paper reveals the outstanding questions and, thus, motivates an application-related approach. The presented concept of data acquisition and analysis provides a methodology to identify the energetically relevant applications of positive displacement pumps on the one hand, and, on the other hand, to determine a relationship between the various pump types, their applications and energy consumption.

The second part of the paper presents a physically based, type independent and easy to apply efficiency model. This model describes the efficiency by only four dimensionless variables and proves its practicability to compare different pump types. Consequently, this paper provides a useful basis for a future efficiency guidelines of positive displacement pumps. Above this, the gained results may be useful for pump manufacturers in shorting performance tests. For pump users the results may serve for a physical based methodology for selecting pump type, size and operation.

However, only a first step has been taken and further investigations need to be done. From the scientific point of view, a validation of the presented efficiency model on a basis of precise experimental data should be carried out. A discussion, whether positive displacement pumps should be included in the Ecodesign Directive or not, requires the data acquisition and analysis of pump manufacturer and users at European level. Taking into account that positive displacement pumps already reach high efficiencies, further saving potential in the particular fluid system will play another important role.

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