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Master Thesis:
CFD study of leakage flow in positive displacement pumps

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Zusammenfassung

Eine Pumpe ist eine mechanische Maschine, die Fluide von einem Ort zum anderen befördert. Bei den Pumpen wird hauptsächlich zwischen dynamischen und Verdrängerpumpen unterschieden. Die Zentrifugalpumpe ist die gängigste Art der dynamischen Pumpe und die bei weitem am häufigsten verwendete. Bei den Verdrängerpumpen wird weiter zwischen rotierenden und oszillierenden Pumpen unterschieden, bei denen die Flüssigkeiten im eingeschlossenen Volumen gehalten und zur Druckseite hin verdrängt werden. Dies wird z. B. bei rotierenden Verdrängerpumpen mit Zahnrädern, Drehkolben oder Schrauben erreicht. Die Hauptfunktion von Verdrängerpumpen besteht darin, Fluide von Gebieten mit niedrigem zu Gebieten mit höherem Druck zu fördern. Dadurch entsteht jedoch ein Druckunterschied zwischen der Druckseite und der Saugseite der Pumpe, wodurch ein Teil der Fluide zur Saugseite zurückfließt. Dieses Phänomen wird als Schlupf oder Leckagemassenstrom bezeichnet. Bei rotierenden Verdrängerpumpen kann dies an der radialen Position zwischen dem Gehäuse und dem Rotorkopf, an der axialen Position zwischen der Gehäuseebene und der Rotoroberfläche und zwischen den Rotorzahnradern geschehen. Im Rahmen dieses Projekts werden jedoch nur die Leckagen an der radialen Position betrachtet und dafür vereinfachte Leckagegeometrien für Drehkolben- und Außenzahnradpumpen entwickelt. Diese Leckagegeometrien werden dann einer CFD-Untersuchung (Computational Fluid Dynamics) unterzogen, um die Auswirkungen der Geometrie- und Betriebsparameter auf den Leckagemassenstrom zu ermitteln. Der geometrische Parameter Spalthöhe hat einen signifikanten Einfluss auf den Leckagemassenstrom, während die anderen geometrischen Parameter wie Spaltlänge, Flanklänge und Radius einen geringen Einfluss auf den Leckagemassenstrom haben. In ähnlicher Weise spielt der Betriebsparameter Druckdifferenz gegenüber der Drehzahl eine entscheidende Rolle bei der Bestimmung des Leckagemassenstroms. Die in diesem Projekt entwickelten Leckagemodelle basieren auf vereinfachten Leckagegeometrien von Drehkolben- und Außenzahnradpumpen, mit denen bei grobem Netz der gleiche Massendurchsatz wie bei feinem Netz erreicht werden kann. Dies wird beispielsweise durch die Einschränkung der Fluide im engsten Querschnitt der vereinfachten Leckagegeometrien durch die I) Manipulation der Spalthöhe, II) lokale Erhöhung des Strömungswiderstandes und III) Aufbringen einer äußeren Kraft, erreicht. Bei der Bewertung der oben beschriebenen Leckagemodelle hinsichtlich ihrer Umsetzung in Vollpumpen zeigt sich, dass das Leckagemodell Spalthöhe leichter zu implementieren ist, aber keine Flexibilität bietet, um die Fluide in jedem Leckagespalt auf andere Weise zu beschränken. Diese Flexibilität kann mit dem Viskositäts- und dem Volumenkraft-Leckagemodell erreicht werden, aber diese Modelle sind in einer Vollpumpe nur schwer zu implementieren. Durch die Anwendung des Leckagemodells in Verdrängerpumpen kann der Rechenaufwand deutlich reduziert werden, ohne die numerische Genauigkeit des Massendurchsatzes zu beeinträchtigen.

Abstract

A pump is a mechanical machine that moves fluids from one place to another. Pumps are mainly classified between dynamic and positive displacement (PD) pumps. The centrifugal pump is a common type of dynamic pump and by far the most popular pump in operation. PD pumps can be further distinguished into rotary and reciprocating pumps, where the fluids are trapped within the enclosed volume and displaced into the discharge side. This is achieved, for instance, in rotary pumps with gears, lobes or screws. The primary function of PD pumps is to pump fluid at higher discharge pressure. However, this creates a pressure differential between the pump's discharge and the suction side, causing some fluid to flow back to the suction side. This phenomenon is called slip or leakage flow. In rotary PD pumps, this can occur at the radial position between the casing and the rotor head, at the axial position between the housing plane and the rotor surface and between the rotor gears. This project, however, considers only the leakages at the radial position and develops simplified leakage geometries for rotary lobe and external gear pumps. These leakage geometries are then subjected to a computational fluid dynamics (CFD) investigation to analyze the effects of geometrical and operational parameters on leakage massflow. The geometrical parameter gap height significantly affects the leakage massflow, while the other geometrical parameters, such as gap length, flank length and radius, have a mild effect on leakage massflow. Similarly, the operational parameter differential pressure plays a crucial role in determining leakage massflow compared to the rotational speed. The leakage models developed in this project are based on simplified leakage geometries of rotary lobe and external gear pumps, allowing the same massflow to be achieved with coarse mesh as with fine mesh. This is accomplished, for instance, by restricting the fluid in the narrowest cross-section of the simplified leakage geometries by manipulating I) the gap height, II) increasing the flow resistance locally, and III) applying an external force. Upon assessment of these leakage models with regard to their implementation on full scale pumps, the gap height leakage model is easier to implement but does not provide flexibility to restrict the fluid in each leakage passage in a different manner. This flexibility can be achieved with leakage model viscosity and volumetric force; however, these models are hard to implement in full scale pumps. With the application of the leakage model in full scale PD pumps, the computation cost can be reduced without sacrificing the numerical accuracy of discharge massflow.

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6 Conclusion

Centrifugal pumps are the most popular pumps used in operation. However, its uses are limited when, for instance, high head is required or when the fluid is highly viscous. In such cases, PD pumps are considered as an alternative. Reciprocating PD pumps are an absolute choice when, for instance, a high head with a low flow rate is required. Likewise, rotary PD pumps, i.e., lobe pumps are suitable when the integrity of the solids is a significant factor.

PD pumps generate a high discharge pressure, which results in a pressure differential between the discharge and suction sides of the pump. As a result, the fluid flows back towards the inlet side, which is often called leakage massflow. This project investigates the leakage massflow due to gaps between the casing and the rotor head by developing simplified leakage geometries for the rotary lobe and external gear pump. The leakage massflow in these simplified geometries depend primarily on two factors, namely geometrical and operational parameters. On the geometrical parameter side, the leakage height, i.e., the gap height, affects the leakage massflow by 80% when the leakage height varies from 50 to 200 micrometers. The other geometric parameters, such as gap length, radius and flank length, have a mild effect on leakage massflow, i.e., 10 - 20% when the respective dimensions are doubled. On the operational parameter side, the differential pressure Δp is crucial in determining the leakage massflow compared to the rotational speed, which affects leakage massflow significantly less, i.e., for instance, 10 - 20% when the rotational speed varies from 0 to 5000 rpm.

The grid element size at the narrowest cross-section of the simplified leakage geometries corresponds to the element size at the leakage channels of the full scale pump. These elements were refined by a factor of 2 in the radial direction. For instance, the base element size h was 8, which was then refined to 4, 2, and 1. After then, the Richardson extrapolation was carried out on the simulated massflows to determine the massflow at infinitely fine grid (at zero grid spacing $h \rightarrow 0$). During this grid refinement, the massflows were reduced in the simplified leakage geometries, and the average decrement lies around 18% for $\Delta p = 0.5$ to 1.5 bar for the lobe pump. This decrement is almost double, around 34%, for the simplified leakage geometry of the external gear pump. In the full scale pumps, the discharge massflows increase with the grid refinement, corresponding to decreasing leakage massflows. And the maximum increment lies around 3 and 7% for the lobe and external gear pump.

During this project, three leakage models, i.e., gap height, viscosity and volumetric force, are developed to achieve the same massflows with coarse mesh as with fine mesh. These leakage models are derived from simplified leakage geometries of the lobe and external gear pump. The leakage models are developed by restricting the fluid flow at the narrowest cross-section of simplified leakage geometries, reducing the gap height, increasing flow resistance locally, or applying external force against the flow direction. Upon assessment of these leakage models, the leakage model gap height

is very easy to implement in a full scale pump. However, it does not provide the flexibility to restrict the fluid in each leakage passage with different magnitudes. The leakage models viscosity and volumetric force are flexible but harder to implement in full scale pumps. Since the full scale pumps have more than one leakage passages where different differential pressure Δp prevail, it is necessary to develop leakage models that cover different Δp . The developed leakage models with simplified leakage geometries provide the opportunity to reduce computational costs by allowing the simulation of a full scale pump with coarse mesh without compromising numerical accuracy associated with finer grid.

With the leakage model gap height, the maximum deviation between the target massflow and massflow after implementing the leakage model gap height lies under 3%. This is achieved by reducing the gap height from 0.1 mm of full scale pump between 2 – 22%. The leakage model gap height that best suits reaching the target massflow is represented by a linear function of a gap height and a grid size. Along the path of this linear function, the deviation between target massflow and massflow after implementing the leakage model gap height is minimal. For instance, the deviation lies under 1% for both full scale pumps. With the leakage model gap height, the computational time is reduced by a factor of ~ 3 for both full scale pumps.

In this project, the full scale pump was strictly 2D to avoid leakage massflows in the axial direction. In the next step, the applicability of the leakage model should be evaluated, taking into account the axial leakage massflows and the leakage massflows between the rotor gears. Also, the implementation of the leakage models viscosity and volumetric force in full scale pumps should be analyzed to determine if they offer any advantages over the leakage model gap height. Since the leakage model was developed with water as the fluid material for one particular leakage geometry, the applicability of this model to other fluid materials and other leakage geometry should be determined.