OPTIMIZATION OF THE TRIBOLOGICAL CONTACT OF VALVE PLATE AND CYLINDER BLOCK WITHIN AXIAL PISTON MACHINES

Stefan Geffroy^{1*}, Niklas Bauer¹, Tobias Mielke¹, Stephan Wegner², Stefan Gels³, Hubertus Murrenhoff¹, Katharina Schmitz¹

¹Institut für Fluid Power Drives and Systems, RWTH Aachen University, Campus-Boulevard 30, 52074 Aachen

²Stackpole Powertrain International GmbH, Campus-Boulevard 30, 52074 Aachen

³P&G Hydraulische Antriebstechnik GmbH, Nettestraße 39, 58762 Altena

* Corresponding author: Tel.: +49 241 80 47741; E-mail address: Stefan.Geffroy@ifas.rwth-aachen.de

ABSTRACT

In this paper, a simulation study is carried out for the development of concepts to optimize the tribological contact of valve plate and cylinder block in an axial piston machine in swash plate design. The valve plate/cylinder block contact is one of the three essential tribological contacts in axial piston machines. In a research project at the Institute for Fluid Power Drives and Systems (ifas), this contact is investigated by a specifically designed simulation tool. In addition, a test rig exists for the experimental investigation. With the results of simulation and experiment, it was shown before that the cylinder block is tilting to the high pressure side. Due to this movement, the gap height is not constant. In the area of minimum gap height, not only the fluid friction, but also the danger of solid body friction increases. Because of the higher friction losses in the area of minimum gap height, the temperature increase reduces the lifetime of the leaded coatings. In this paper, the results of the measurements as well as the simulation model are briefly summarized. It is followed by a simulation study of different possibilities to raise the gap height. Based on this pre-study, a first concept for the optimization of the tribological contact valve plate/cylinder block is presented and its applicability is discussed.

Keywords: Axial piston machine, simulation, unleaded coatings, temperatur hot-spot

1. INTRODUCTION

Axial piston machines are the most widely used type of hydraulic displacement machines and they are characterized by their high reliability and efficiency. **Figure 1** shows an axial piston machine in swash plate design and its three essential tribological contacts piston/slipper, piston/bushing and valve plate/cylinder block [1]. This paper focuses on the contact valve plate/cylinder block. To prevent leakage from the high to the low pressure side through the gap between valve plate and cylinder block, it is necessary to exert a force which presses the cylinder block against the valve plate. If this force is too low, the gap height between the components increases, causing additional leakage and thus a decrease in volumetric efficiency. If the force is too high, the gap height decreases which leads to unlubricated contact of the surface causing additional wear and decrease in mechanical/hydraulic efficiency. Therefore, it is important to design the components and

parameters in such a manner that a thin and evenly distributed oil film over the whole contact area is ensured.

Figure 1: Three essential tribological contacts in axial piston machines [2]

Currently, a hard/soft pairing is used for the contact of cylinder block and valve plate. One option to realize such pairing is that the valve plate is made of steel while the surface of the cylinder block is coated with a brass alloy. A different option is that the valve plate is coated or made out of a brass alloy. This combination allows a bedding-in process, it is insensitive to manufacturing tolerances and generally leads to low wear and acceptable friction in case of direct contact of the surfaces. However, the use of leaded alloys causes disadvantages, including the occurrence of temperature-related cracks, fluid dependent wear and adhesion behaviour as well as material incompatibilities. In the EU, the use of the toxic heavy metal lead is strongly regulated [3].

Currently there are two approaches for the substitution of leaded alloys. First, an alternative unleaded material with similar properties can be developed, as shown in [4]. A second alternative is to realize a hard/hard pairing by the use of unleaded coatings or steel to steel. A simulation based pre-study as well as a first concept for the realization of these alternatives are presented in this paper.

2. SIMULATION MODEL

For a detailed investigation of the tribological contact valve plate/cylinder block a simulation model was built up at ifas. This simulation model is further development of a simulation model for the piston/bushing contact [5]. In [6], its development is described in detail and is only shortly presented in this paper.

The simulation tool was developed with the aim to compare several geometries at different operating points with acceptable computation time and sufficient result quality. To reach this goal, the simulation tool focuses on the following physical effects [5]:

- Hydrostatic and hydrodynamic pressure build up using the Reynolds equation
- Force and torque equilibrium on the cylinder block
- Squeeze film effect, viscous friction, microscopic part movement resulting from the first two points
- Macroscopic part movement calculated in an analytic way
- Simple contact and part deformation model

The finite volume method is used to solve the Reynolds equation. To calculate the gap height and the cylinder block movement, a linear system of equations coming from mass and momentum balances is set up and linked to the Reynolds equation. With the boundary conditions from the geometry and the known high and low pressure areas, the unknown variables and the number of equations are well balanced and the system can be solved numerically.

In the simulation model a simple method is used to calculate the solid friction. The gap height is compared to the reference gap height, which comes from the surface roughness. With it, the solid friction is calculated and takes place as a contact pressure in the Reynolds equation. **Figure 2** shows the schema of the simulation model.

Figure 2: Schema of simulation model

The gap height in axial piston machines is equal to the distance between the surfaces of the cylinder block and valve plate. The movement of the cylinder block defines the distance between the surfaces when assuming a stationary valve plate. For the investigation of the gap height distribution, the full movement in all degrees of freedom has to be considered. The location of the minimum and maximum gap height are of great importance for the understanding of friction, wear and contact pressure within the contact. Both, experimental results and those from the simulation show that the cylinder block performs a sliding movement over the valve plate's surface and tilts to the high pressure side. **Figure 5** shows the simulation of pressure and gap height distribution for the two most relevant scenarios, in which five or four pistons are pressurized with high pressure. Other studies also show this effect. [9] Due to the tilt angle, the minimum gap height lies on the high pressure side between 130° and 150°. The direction of rotation (DOR) of the cylinder block is clockwise.

Figure 5: Minimum gap height position [8]

The measurement results of the experimental investigation are displayed in **Figure 6**. It shows the distribution frequency of the minimum gap height. The size of the red highlighted areas represents the occurrence frequency of the minimum gap height at the particular angular position for one revolution.

Figure 6: Frequency of minimum gap height [6]

The range 90° – 240° is much higher as those from the simulation, but on average the minimum gap height is located at 130°.

There are not only disadvantages coming from this preferred position of the cylinder block. The load situation is highly inconstant due to the

changing number of pistons on the high and the low pressure side. For the same reason the number of cylinders filled with fluid is also changing. Due to this fact, the cylinder block is very imbalanced. The first advantage of the preferred position of the cylinder block and its rapid movement towards this position is that it probably improves the smooth running of the axial piston machine by reducing the imbalance. The second advantage of the tilted cylinder block is lower leakage on the high pressure side. With the gap width b , the gap height h , the gap length l , the dynamic viscosity η and the pressure difference Δp , the volume flow Q through a small gap results from Equation 1 [2].

$$Q = \frac{b \cdot h^3}{12 \cdot \eta \cdot l} \cdot \Delta p \quad (1)$$

This equation shows the high influence of the gap height on the leakage and therefore on the volumetric efficiency of the machine. Because of the much higher pressure difference between the high pressure side and the housing pressure in comparison to the pressure difference on the low pressure side, there is a positive effect of the tilting.

These two advantages are countered by various disadvantages, which will be examined in further detail below. The tilting of the cylinder block reduces the already low gap height between valve plate and cylinder block. This increases the risk that the gap height becomes smaller than critical gap height and solid friction occurs. The resulting wear reduces the lifetime and efficiency of the axial piston machine or, in the worst case, can lead to immediate failure. In addition, the reduced gap height increases the fluid flow velocity as well as the shear rates. Due to this, the fluid load increases. The previously explained positive effect that the leakage decreases also includes a disadvantage. The reduced volume flow over the sealing gap reduces the heat dissipation. Therefore, in addition to the danger of solid friction a danger of local temperature hot-spots exists. This effect is also described in [10, 11]. Local high temperature ranges also limit the selection of possible alloys and coatings for the substitution of lead. Due to the risk of solid friction, it is not possible to use a hard/hard pairing in this tribological contact. Therefore, this paper presents a simulation study for the development of concepts to reduce the tilting of the cylinder block.

4. CONCEPT PRE-STUDY

For the reduction of the cylinder block's tilt angle the torque balance has to be influenced by additional created torques. Two basic concepts can be used for it. The first concept is to add one or more forces in z direction. The second is to add those forces in radial direction. These concepts can be extended by the possibility that these forces are stationary or synchronized with the movement of the cylinder block. This allows a static torque to be created to reduce the tilting more or less constantly. On the other hand, a dynamic torque can be created, which imposes an additional imbalance on the cylinder block. This could avoid or at least reduce a fixed temperature hotspot. In this simulation study, these four concepts are considered separately to investigate the influence on the main parameters. The parameter variation and the results of the study are presented and discussed below. The pump geometry used in this simulation is taken from the test pump. **Figure 7** shows the used cylinder block and valve plate. The geometrical data can be found in **Table 1**.

Figure 7: Cylinder block and valve plate

Table 1: Geometrical data

Parameter	Value
d_{cb}	97.2 mm
h_{cb}	80 mm
r_i	29.45 mm
r_2	44.55 mm
r_i	23 mm
r_m	37 mm
r_o	48.6 mm
γ	225°
δ	120°

4.1. Static force z-directional

The first option to create a counter torque against the tilting of the cylinder block is to add a force in positive z direction and to place this force around the area of minimum gap height. For the investigation of this concept, the three main parameters are the value of the force and the position described by the angle and radius. The force is varied in the range from 625 N to 2500 N. These values are equivalent to a pressurized surface from 25 mm² to 100 mm² at 25 MPa on high pressure side. The angle is varied around the area of the minimum gap height between 120° to 150° while radius is varied in the range from 29.45 mm to 44.55 mm due to the high pressure kidney's geometry of the valve plate. **Table 2** shows the parameter variation.

Table 2: Parameter variation

Fore [N]	Eq. surface (25 MPa) [mm ²]	Angle [°]	Radius [mm]
625	25	120	29.45
1250	50	135	37
1875	75	150	44.55
2500	100		

24 configurations have been simulated. The relative angle change of the tilting is used here as a comparative value. The tilting can be calculated with the gap height difference and the cylinder block's diameter by the following equation.

$$\alpha = \sin^{-1} \frac{\Delta h}{d_{CB}/2} \quad (2)$$

The relative angle change α_{rel} can be calculated with Equation 3. α_{new} is the tilting with the additional forces while $\alpha_{previous}$ is the tilting in the basic configuration.

$$\alpha_{rel}[\%] = \left(\frac{\alpha_{new}}{\alpha_{previous}} - 1 \right) \cdot 100\% \quad (3)$$

Figure 8 shows the relative change of the tilt angle for the parameter variations. An additional force in negative z-direction with the same value was added, so only the torque works against tilting and the cylinder block is not lifted.

Figure 8: Relative angle change for static force in z direction

The simulation results show a major effect against the tilting for this concept. Even through the greatest effect is for the forces with an angle of 150°, the minimum gap height is at angle of 130°.

4.2. Dynamic force z-directional

By synchronising one or more additional added forces with the rotation of the cylinder block an additional imbalance results. The number of the added forces determines the frequency of this imbalance. These forces can be realized by pressurized surfaces on the cylinder block, which has an additional positive effect. The value of these forces depends on the rotational angle. The high pressure results in a high force and with it a high torque against the minimum gap height and tilt angle. The added surface has nearly no influence when it is not on the high pressure side. In this concept, the value of the added forces is

varied as well as the radius. The parameter variation is included in **Table 3**.

Table 3: Parameter variation

Force [N]	Eq. surface (25 MPa) [mm ²]	Radius [mm]
250	10	29.45
500	20	37
750	30	44.55
1000	40	
1250	50	

There are 15 configurations resulting from this parameter variation. The relative change of gap height is used here as a comparative value. Because the added force is not constant, no counterforce was implemented. Due to this, the force lifts up the cylinder block while the resulting moment works against the tilting. Both effects influence the gap height. The relative change of gap height h_{rel} results from Equation 4. h_{new} is the gap height with the additional forces while $h_{previous}$ is the gap height in the basic configuration.

$$h_{rel}[\%] = \left(\frac{h_{new}}{h_{previous}} - 1 \right) \cdot 100\% \quad (4)$$

The simulation results are displayed in **Figure 9**.

Figure 9: Relative change of gap height for dynamic force in z direction

4.3. Static force radial direction

Another possibility to create a torque against the tilting is to add forces in the radial direction which means the vector of the force lies in the x-y-plane. **Figure 10** illustrates this concept idea.

Figure 10: Concept illustration for additional forces in radial direction

A counter force with the same value is added to avoid eccentricity. The value of the force and three variations of the heights are varied. The relative angle change of the tilt angle is used here as a comparative value.

Figure 11 shows the simulation results for a simulation of the forces added at V1.

Figure 11: Relative angle change for static force in radial direction

The results show a reduction of more than 80 % for forces of 750 N. It is also evident that the cylinder block is tilting in another direction for forces of 1000 N.

4.4. Dynamic force radial direction

One or more forces in radial direction can be added and synchronised to the rotational angle. The parameters are varied as it was done in the simulation of the static force in radial-direction. **Figure 12** shows the effect of this imbalance on the tilt angle.

Figure 12: Relative angle change for dynamic force in radial direction

Due to the imbalance resulting from the additional forces, the relative angle change assumes positive and negative values. This concept even leads to a temporary reduction of the minimum gap height.

4.5. Comparison

Of the concepts presented against the tilting of the cylinder block, the static force in the z-direction in particular has great potential. The effect on the tilting angle is substantial even with relatively small forces. An additional pressure pocket in the high-pressure area of the valve plate makes this concept technically feasible. This concept and its potential have been investigated under consideration of the geometric limits. The investigation is described in the next chapter.

5. STATIC PRESSURE FORCE

From the previous explained concepts the realization of concept of the static force in

z-direction is presented and discussed in this chapter.

The realization of additional power in hydraulic machines can be achieved by additional pressurized surfaces. Haug [12], for example, added additional surfaces to control the degree of relief of tribological contacts. For the concept presented here, additional surfaces would have to be implemented in the sealing gaps of the valve plate's high pressure kidney. The position of these surfaces should be in the area of 150° which is the most effective area. **Figure 13** shows the geometry of the sealing gaps for the considered area.

Figure 13: Sealing gap width

For the design of the sealing gap, it is recommended in [13] to choose the width depending on the length of cylinder block's kidney (t) in the interval of $0.125 \dots 0.175 \cdot t$. In the geometry considered here, t corresponds to the diameter of the piston bore of 25 mm. The minimum width according to this guideline is therefore 3.125 mm. This results in a potential of 0.925 mm for the sealing gap to the housing and 3.325 mm for the one to the shaft. The maximum possible surface is 145.72 mm^2 . This results in a maximum force of 3.64 kN by pressurizing it with the operating pressure of 250 bar. The surface 2 is 104.92 mm^2 and the surface 1 is 40.8 mm^2 . The point of application of the resulting pressure force is at a radius of 33.67 mm. **Figure 14** shows the optimized geometry with maximum possible surface. It also shows a surface of 101.01 mm^2 with a resulting force of 2.5 kN. This was the maximum force of the pre-study. The surface 2 is 60.21 mm^2 and the surface 1 is 40.8 mm^2 . The point of application of the resulting pressure force is at a radius of 35.44 mm. The sealing gap width is only reduced by 2 mm.

Both optimizations were implemented in the simulation model. In the first simulation runs, the value of the counter force, so that the cylinder block is not lifting, had to be found iteratively.

Figure 14: Additional pressure pockets

For the maximum surface, this additional force is 6 kN while for the surface of 101.01 mm^2 it is 5.5 kN. The simulation results show that the maximum possible surface reduces the tilt angle about 69.92 % and the contact pressure in the area of minimum gap height about 38.93 %. The surface of 101.01 mm^2 reduces the tilt angle about 56 %. In this case, the contact pressure is reduced about 37.69 %. These results show the high potential for the optimization of the tribological contact valve plate/cylinder block.

6. CONCLUSION AND OUTLOOK

The most widely used type of hydraulic displacement machines are axial piston machines. The tribological contact valve plate/cylinder block is one of three essential tribological contacts in such machines. Its optimization has a great influence on the efficiency of the whole unit. For the substitution of the commonly used leaded brass alloy to realize a hard/soft pairing in this contact the tilting of the cylinder block has to be reduced. In a research project at ifas a simulation model and a test ring has been built up. The results of simulation and experiments show that the cylinder block is tilting to the high pressure side. From this tilting a reduced gap height in the area of 130° occurs. There, wear and heat dissipation according to solid friction and higher fluid velocity increase.

This paper presents the pre-study of four concepts for the reduction of the cylinder block's

tilt angle. The reduction of the tilt angle was investigated by adding forces in z-direction and radial direction with various parameters. Dynamic forces in the same directions are added. The imbalance resulting from these forces reduces the tilting only for rotation angle range of high pressure kidney. All of these concepts have a good potential for the reduction of the cylinder block's tilting in a constant position. The realization of the static force in z-direction by additional pressure pocket at high pressure kidney of the valve plate has a very high potential. The simulation results show that a tilt angle reduction up to 69.92 % is possible by adding the maximum possible surface of 145.72 mm².

The next steps in the ongoing research project are to find the optimum geometry for this concept and its influence to leakage as well as power losses. Therefore, several simulation runs and prototype tests are needed for this iterative process. Possibilities for the realization of the other three concepts presented in this paper have to be developed.

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NOMENCLATURE

b	Gap width
C	Center point of cylinder blocks sphere
CB	Cylinder block
DOR	Direction of rotation
d_{CB}	Cylinder block's outer diameter
F	Force
h	Gap height
h_{CB}	Cylinder block's height
h_{min}	Minimum gap height
h_{new}	New minimum gap height
h_{rel}	Relative change of minimum gap height
$h_{previous}$	Previous minimum gap height
$ifas$	Institute for fluid power drives and systems
l	Gap length
Δp	Pressure difference
Q	Volume flow

r_1	Inner radius of high pressure kidney
r_2	Outer radius of high pressure kidney
r_i	Inner radius of valve plate
r_m	Medium radius of high pressure kidney
r_o	Outer radius of valve plate
t	Length of cylinder block's kidney
T	Torque
α	Tilt angle
α_{new}	New tilt angle
α_{rel}	Relative change of tilt angle
$\alpha_{previous}$	Previous tilt angle tilt angle
γ	Start angle of high pressure kidney
δ	End angle of high pressure kidney
η	Dyn. viscosity

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