Serbian Tribology Society

SERBIATRIB '25

19th International Conference on Tribology

Faculty of Engineering University of Kragujevac

Kragujevac, Serbia, 14 – 16 May 2025

TRIBOLOGICAL ASPECTS OF IDENTIFICATION OF THE KEY CAUSES OF REDUCTION IN THE EFFICIENCY OF AXIAL PISTON WATER HYDRAULIC PUMPS

Nenad TODIC[1], Slobodan SAVIC[1,*], Zivojin STAMENKOVIC[2], Blaza STOJANOVIC[1]
[1]Faculty of Engineering University of Kragujevac, Kragujevac, Serbia
[2]Faculty of Mechanical Engineering University of Niš, Niš, Serbia
*Corresponding author: ssavic@kg.ac.rs

Abstract: *This paper analyzes the phenomenon of reduction in operating characteristics in the course of operation of axial piston pumps which use water as the working fluid. The focus of the paper is to identify the key causes of the decrease in pump efficiency. As part of this investigation, experimental testing was performed on an axial piston water hydraulic pump. The key operating parameters were analyzed during the simulation process as well as the condition of the components after the experiment. The results confirmed a decrease in the efficiency and identified the dominant degradation mechanisms. Various wear mechanisms relevant to water hydraulics and the influence of water as the working fluid on the wear processes were studied. A mathematical model was developed to define the tribological aspects of the pump working processes. Further research will be directed towards the development of new materials and surface coatings with improved resistance to the identified degradation mechanisms.*

Keywords: *axial piston pump, water hydraulics, efficiency, mathematical modelling, tribological pairs.*

1. INTRODUCTION

Water hydraulics, as a fundamental principle of power transmission using an incompressible fluid (water) under controlled pressure, is experiencing a significant renaissance in modern engineering. Its increasing importance stems from the global awareness of the need for sustainable technological solutions and the reduction of the negative impact of industrial processes on the environment [1-6]. Unlike traditional hydraulic systems based on mineral oils, water hydraulics offers a number of key advantages. Environmental friendliness is primary – water is non-toxic, biodegradable, and widely available, thus eliminating the risk of soil and water contamination in case of leakage. Water is an ideal working fluid in environments with a high risk of fire, such as mines or certain industrial processes. This aspect is particularly important in the context of increasingly stringent safety regulations and standards [7-9]. Furthermore, the high thermal conductivity of water can contribute to more efficient heat dissipation from the system, potentially reducing the need for additional cooling systems. These characteristics position water hydraulics as a key technology for the future, with the potential for widespread application in sectors striving for sustainability and safety [10-12].

Tribological aspects of water hydraulics represent the key area of research and development. Unlike oil hydraulic systems, water has significantly lower viscosity and weaker lubricating properties, which leads to increased friction and wear of contact surfaces in hydraulic components, including pumps. Effective lubrication in water systems is therefore critical for achieving long service life and high performance [13]. Tribological challenges in water hydraulics include different lubrication regimes, the interaction between water and materials, as well as the influence of impurities and dissolved gases in water on the formation of a lubricating film and wear. It is necessary to understand these complex interactions in order to design reliable and efficient water hydraulic systems [14-16].

Previous research in the field of water hydraulics has focused on overcoming the aforementioned tribological challenges. Significant efforts have been invested in the development of new materials with improved resistance to corrosion and wear in aqueous environments, such as special stainless steel alloys, ceramics and composite materials. Intensive work has also been done on the development of water additives that can improve its lubricating properties and reduce corrosion. Various surface treatment techniques and the application of thin films have been investigated to reduce friction and wear of contact surfaces. In addition, significant attention has been paid to the development of new design solutions for hydraulic components optimized for operation with water as the working fluid, including improved sealing systems and bearings [17-19].

In this context, axial piston pumps, as one of the most efficient and commonly used types of hydraulic pumps for generation of high pressure and controlled flow, represent the key component of water hydraulic systems. Their complex construction, which includes precisely manufactured pistons, cylinders, a rotating group and valves, makes them susceptible to gradual performance degradation during long-term operation in contact with water. This paper therefore focuses on a comprehensive analysis of the fundamental physical and chemical processes which lead to reduction of the operating characteristics of these pumps under specific conditions of water hydraulics.

The key investigated degradation mechanisms include tribological phenomena on sliding surfaces (abrasive and adhesive wear), the interaction between the working fluid and the pump materials (erosion due to hydrodynamic forces and cavitation, electrochemical and chemical corrosion), the response of the materials to dynamic loads (cumulative damage due to cyclic loading – fatigue) and losses of the working fluid due to compromised sealing element integrity [14]. The influence of the system operating parameters (pressure, flow rate, temperature), working fluid characteristics (cleanliness, chemical composition, presence of additives) and the pump construction materials on the intensity of these processes is examined in detail.

Furthermore, the paper quantifies the impact of the described degradation mechanisms on the key pump performance metrics, such as volumetric efficiency (reduction in flow rate at nominal speed), hydromechanical efficiency (increase in internal power losses) and reliability (failure rate). Correlations between the degree of the component degradation and the measurable system operating parameters are also analyzed.

The application of predictive maintenance strategies based on the analysis of historical data, modelling of degradation processes and prediction of the future state of the pump is also discussed as the crucial approach for optimizing maintenance intervals, reducing costs, and increasing the overall reliability of hydraulic systems with water as the working fluid. Understanding and addressing the problem of the reduction in the operating characteristics of axial piston pumps is therefore of vital importance for the further development and wider application of water hydraulics as a sustainable and efficient power transmission technology.

2. MATHEMATICAL MODELING

The three basic tribological pairs in a water hydraulic axial piston pump are the piston/cylinder liner, the slipper/swash plate, and the cylinder block/valve plate (Figure 1). These pairs represent the key zones of friction and potential wear [20]. The mathematical description of these interfaces requires consideration of the contact geometry, lubrication regime, friction forces, and wear mechanisms. Modelling often includes the analysis of hydrodynamic lubrication using Reynolds equation, which describes the pressure distribution within a thin film of fluid between two relatively moving surfaces [21].

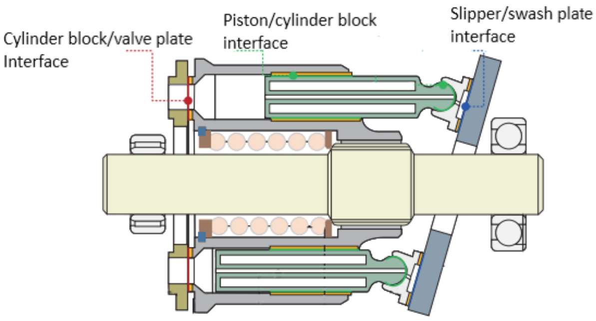

Figure 1. Configurations of the axial piston pump PPT VH10

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h^3}{\mu}\frac{\partial p}{\partial y}\right) = 6\left[\frac{\partial(v_x \rho h)}{\partial x}+\frac{\partial(v_y \rho h)}{\partial y}+2\rho\frac{\partial h}{\partial t}\right] \quad (1)$$

While in operation, a relative motion occurs between the cylinder block and the valve plate, during which a thin oil film is formed, enabling hydrodynamic lubrication. The analysis of this film is crucial for understanding the friction mechanisms, wear, and leakage in the pump. One of the fundamental equations used to describe the behaviour of the fluid in this film is Reynolds equation. In case of the axial piston pump, an extended form of Reynolds equation is used, so that it takes into account fluid compressibility, variable viscosity, variable film thickness, and temporal changes in geometry, where:

- ρ – fluid density,
- h – thickness of the lubricating film,
- μ – dynamic viscosity,
- p – pressure in the film,
- v_x, v_y – components of the relative velocity of the surface in x and y directions,
- t – time

The left side of the equation describes the distribution and change of pressure in the fluid film due to viscous effects, while the right side represents the sources of fluid in that film – either due to the movement of surfaces (fluid transport) or due to changes in the film thickness over time.

In the zone between the cylinder block and the valve plate, the oil film is of crucial importance because it prevents direct surface contact, reduces wear, and enables even load distribution. The pressure in the film needs to be determined correctly in order to design optimal geometry and achieve high performance of the pump.

Reynolds equation enables a detailed analysis of the lubrication processes in the contact zone between the rotating and the sliding elements. In axial piston pumps, the relative motion between the parts and the oscillations of the pistons lead to constant changes in the oil film thickness, velocities, and pressure. Using this equation, it is possible to:

- predict the pressure distribution in the lubricating film;
- identify potential local wear sites;
- analyse energy losses due to friction and leakage;
- optimise component design for better lubrication.

Furthermore, the equation can be used in combination with numerical methods (e.g., finite element method or finite volume method) to obtain solutions for specific operating conditions and geometries.

Reynolds equation is a fundamental tool for the analysis of hydrodynamic lubrication in axial piston pumps. Its application enables better understanding of the complex mechanisms within the contact zone, which directly contributes to increasing the efficiency, reliability, and service life of hydraulic systems. By integrating this equation into the design process, it is possible to improve performance and reduce energy losses in pumps.

3. EXPERIMENTAL INVESTIGATION

In order to confirm the accuracy of the numerical model, experimental measurements were performed on:

- the pressure and flow rate in the hydraulic circuit;
- the oil temperature and viscosity during operation;
- the surface wear using microscopy and profilometry;
- the vibration and noise – as indicators of poor lubrication.

By comparing the simulation results with the experimental data, it is possible to further calibrate the model and improve the accuracy of predictions.

To experimentally identify the key factors that led to the reduction in the efficiency of axial piston water hydraulic pumps, experimental tests were performed at the Development and Research Laboratory "PPT Namenska". As part of this experiment, a test installation was specially designed [18]. The tested pump is the model PPT VH10, manufactured by PPT NAMENSKA Trstenik (Figure 2).

The basic component of the installation was a 37 kW electric motor with regulated speed and torque. Figure 3 shows the experimental hydraulic installation used to test the characteristic parameters of the axial piston pump consisting of a drive motor, an axial piston pump (test object), a speed and torque sensor, a module for data acquisition and processing, temperature and pressure sensors, an auxiliary feed pump, and secondary hydraulic installation components. The auxiliary feed pump was installed at the inlet port of the test pump in order to ensure a safe and predetermined supply of the working fluid to the test pump.

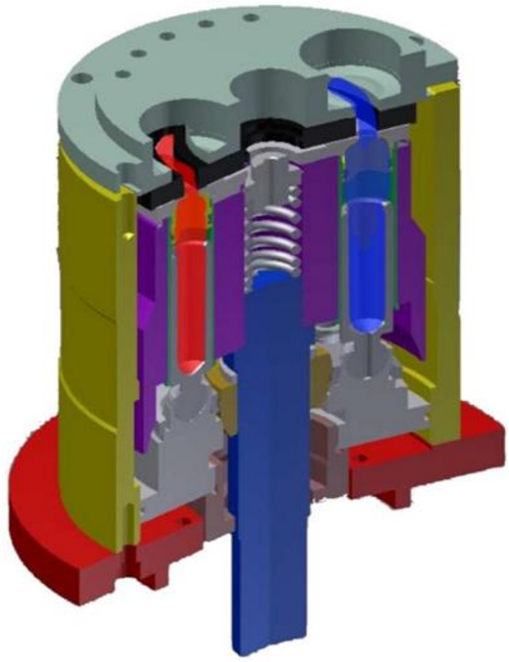

Figure 2. Axial piston pump PPT VH10

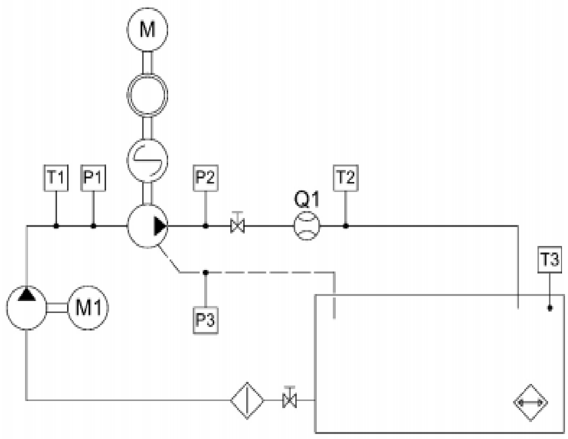

Figure 3. Test installation scheme (*P1,P2,P3-Gauge pressure, Q1-Flow meter, T-speed and torque meter,T1,T2,T3-Thermometer, M-Electro motor)*

The test stand was equipped with a water tank with a capacity of 1000 litres and a temperature control system, which would ensure stable conditions during the test. The temperature of the working fluid during the test was maintained in the range from 2 to 50°C. Figure 4 shows the test pump installed on the test stand.

Through the analysis of the collected experimental data, the focus was on determining the influence of various operating parameters (pressure, rotational speed, working fluid temperature) on the pump's efficiency, with a particular emphasis on identifying the key causes of hydraulic and mechanical losses that lead to a reduction in its efficiency.

Figure 4. The test pump installed on the test stand

4. RESULTS AND DISCUSSION

The efficiency of axial piston pumps represents a key parameter for evaluating their performance in converting the input mechanical power into useful hydraulic output power. This parameter summarizes all internal energy losses within the pump. In order to fully understand the pump performance, it is essential to analyse different components of efficiency: overall efficiency, volumetric efficiency and mechanical efficiency.

The overall efficiency (η_{uk}) of a piston axial pump is a key indicator of its effectiveness in converting the mechanical energy of the drive shaft into the hydraulic energy of the fluid. It quantifies how efficiently the input power is used to generate flow and pressure, while minimizing losses due to friction, leakage, and other non-idealities. A high overall efficiency directly contributes to the reduction of energy consumption and the operating costs of the hydraulic system. The overall efficiency directly depends on the volumetric efficiency (η_v) and mechanical efficiency (η_m). The relationship between them is given by the following equation:

$$\eta_{uk} = \eta_v \cdot \eta_m \qquad (2)$$

The volumetric efficiency η_v (3) defines losses that occur while the fluid flows through the pump.

$$\eta_v = \frac{Q}{Q_T} \cdot 100\% \qquad (3)$$

where:
η_v - volumetric efficiency of the pump in *%*,
Q - fluid flow through the pump per a unit of time *l/min*,
Q_T - theoretic fluid flow through the pump per a unit of time *l/min*.

Figure 5. shows a diagram of change in volumetric efficiency η_v as a function of time τ for different operating regimes of the pump.

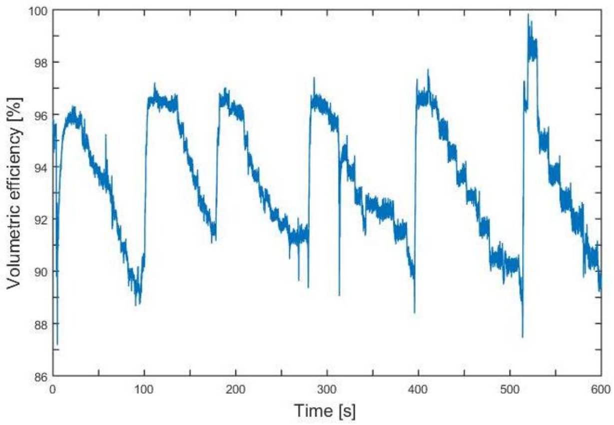

Figure 5. Volumetric efficiency of the pump

The mechanical efficiency (η_m) of an axial piston pump represents the efficiency of mechanical power transmission, specifically the ratio of the theoretical torque required for hydraulic work to the actual torque applied to the drive shaft.

$$\eta_m = \frac{T}{T_T} \cdot 100\% \quad (4)$$

where:

η_m- mechanical efficiency of the pump in %,
T- actual torque of the pump in Nm
T_T- theoretical torque of the pump in Nm

The flow through the clearances can be up to forty times higher than the flow in the axial piston oil hydraulic pump because viscosity of water is much lower compared to oil. As a consequence, the volumetric efficiency of a water hydraulic pump decreases very rapidly with the increase of the pump pressure, therefore the decrease in the volumetric efficiency is one the key problems in designing water hydraulic pumps. As seen it the diagram, when the pressure at the pump outlet drops there are sudden jumps in the volumetric efficiency values.

As shown above, the efficiency of axial piston hydraulic pumps is a complex parameter encompassing various aspects of the pump performance. To ensure optimal efficiency and longevity, it is crucial not only to understand the efficiency but also to identify the key causes of its reduction.

Factors that can lead to a decrease in the overall efficiency include:
Increased internal leakage: This directly affects the volumetric efficiency, reducing the actual delivered flow compared to the theoretical flow. Causes can include wear of pistons, cylinders, the valve plate, and seals.

- Increased mechanical losses: Friction in bearings, seals, and other moving parts increases the input torque required to drive the pump, reducing the mechanical-hydraulic efficiency. Causes can include poor lubrication, fluid contamination, and component wear.
- Increased hydraulic losses: Turbulent flow and pressure drops through the internal channels and orifices can reduce the effective power transfer to the fluid.
- Non-optimal operating conditions: Operating the pump outside the recommended pressure, flow rate, or rotational speed range can lead to a decrease in efficiency.
- Cavitation: These phenomena can damage internal components and significantly reduce it's efficiency.

Understanding and identifying the main causes of decrease in the efficiency is essential for implementing preventive maintenance strategies, optimizing operating conditions, and ultimately, for improving the overall efficiency and reliability of axial piston water hydraulic pumps. Focusing on these aspects enables more effective energy management and reduced operational costs.

Figure 6. The wear of swash plate and sliper

After conducting the experimental investigation of the performance of an axial piston pump, the next critical step in evaluation of its efficiency and reliability is a detailed inspection of the wear on vital components. This process is essential for understanding degradation mechanisms within the pump during operation and for identifying potential causes of decreases in efficiency. The inspection involves careful visual examination as well as precise measurements of the key components such as pistons, cylinders, valve plates, bearings, and seals. The aim is to detect any signs of damage, including scratches, scoring, corrosion marks, discoloration, or deformation. Figure 6 shows the wear, due to tribological aspects of friction, of the swash plate and the slipper after experimental testing.

To quantify the extent of wear, advanced measurement techniques are employed. Microscopy provides detailed insight into the surface microstructure and allows identification of minor defects not visible to the naked eye. Profilometry is used for precise measurement of surface roughness and detection of changes in geometry due to material wear. By comparing these measurements with factory specifications and pre-experiment data, it is possible to determine the extent and rate of wear for individual components. This is crucial for assessment of numerical wear models, prediction of the remaining service life of the pump, as well as for recommendations for future maintenance strategies and potential design modifications.

5. CONCLUSION

In conclusion, the analysis of efficiency of axial piston hydraulic pumps represents a fundamental step in understanding and optimizing their performance and energy efficiency. Breaking down the overall efficiency into volumetric and mechanical-hydraulic aspects provides a deeper understanding of the various sources of internal losses within the system. Experimental validation of numerical models, accompanied by detailed wear analysis of critical components, yields valuable insights into degradation mechanisms and identifies the key factors contributing to efficiency reduction during operation. These insights are essential for implementing effective maintenance strategies, extending the pump service life, and reducing operational costs.

In the context of increasing reliability and reducing maintenance demands, the application of advanced materials with superior tribological characteristics plays a significant role. High-performance polymers such as PEEK (polyether etherketone) offer exceptional wear resistance, low friction coefficients, and good chemical stability, making them potentially ideal candidates for manufacturing critical components of axial piston pumps, such as piston rings, seals, and bearing parts. The use of such materials can significantly reduce wear during operation, helping to maintain high efficiency over extended periods and minimizing the need for frequent replacement and servicing

The future development of axial piston hydraulic pumps will undoubtedly focus on the integration of advanced materials and sophisticated condition monitoring systems. Continuous monitoring of key performance parameters and component condition in real time, combined with the use of wear-resistant materials such as PEEK, paves the way for more durable, efficient, and reliable hydraulic systems with minimal maintenance requirements. This approach will not only reduce operational costs but also contribute to more sustainable use of resources by extending the service life of the equipment.

ORCID iDs

Nenad TODIC 0000-0002-6154-8112
Slobodan SAVIC 0000-0001-6609-4845
Zivojin STAMENKOVIC 0000-0001-8722-3191
Blaza STOJANOVIC 0000-0003-4790-2856

REFERENCES

[1] G.H. Lim, P.S.K. Chua and Y.B. He, “Modern water hydraulics - the new energy-transmission technology in fluid power,“ *Applied Energy*, vol. 76, no. 1–3, pp. 239-246, 2003, ISSN 0306-2619.

[2] G. W. Krutz and P. S. Chua, “Water Hydraulics -Theory and Applications 2004“, Water Hydraulics, Agricultural Equipment Technology Conference (AETC ’04), February 8-10, Louisville, Kentucky, 2004.

[3] E. Trostmann, “*Water hydraulic control technology*“, Marcel Dekker Inc., 1996, ISBN 0-8247-9680-2.

[4] F. Conrad, “Trends in design of water hydraulics motion control and open-ended solutions“, 6th JFPS International Symposium on Fluid Power, Tsukuba, 2005.
[5] H. Riipinen, “Life in the water hydraulics system“, PhD dissertation, Tampere University of Technology, 2008.
[6] E. Trostmann, B. Frolund, B. Olesen and B. Hilbrecht, *“Tap Water as Hydraulic Pressure Medium“,* Marcel Dekker, New York, 2001.
[7] F. Majdič and A. Bombač, “Piston-Type Accumulator for Water Power-Control Hydraulics,“ The 9th International Fluid Power Conference, 9. IFK, March 24-26, Aachen, Germany, 2014.
[8] F. Majdič and E. Strmčnik, “Tribological Aspects of Water Hydraulics,“ 16th International Conference on Tribology, Kragujevac, Serbia, 2019.
[9] N. Todić, S. Savić, S. Jovanović and Z. Djordjević, “Research of water hydraulic components and systems from aspects of quality of life“, 9th International Scientific Conference - IRMES 2019, Kragujevac, pp. 94-95, ISBN 978-86-6335-061-8, 2019.
[10] N. Todić, S. Savić, D. Gordić and V. Šušteršič, “Saving energy and sustainable development with water hydraulic components and systems– opportunities, challenges and objectives,“ *Energija, ekonomija, ekologija*, vol.20, no.1-2, pp. 415-420, ISSN 03540-8651, 2018.
[11] T. Bech, S. Olsen and P. Klit, “Design of Pumps for Water Hydraulic Systems“, 6th Scandinavian International Conference on Fluid Power, SICFP’99, Tampere, Finland,1999.
[12] N. Todić, S. Vulović, R. Petrović, I. Vujović and S. Savić, “Sustainable development of agriculture techniques using water hydraulic components,“ *Traktori i pogonske mašine*, vol.23, no.1/2, pp. 71-77, ISSN 0354-9496, 2018.
[13] Z. Wang, S. Hu, H. Ji, Z. Wang and X. Liu, “Analysis of lubricating characteristics of valve plate pair of a piston pump,“ *Tribol. Int.*, vol. *126*, pp. 49–64, 2018.
[14] S. Wang, M. Tomovic, M. And H. Liu, *Commercial Aircraft Hydraulic Systems: Shanghai Jiao Tong University Press Aerospace Series*, 1st ed.; Elsevier: Waltham, MA, USA, 2015.
[15] S. Wang, M. Tomovic and L. Han, „Performance degradation based on mixed wear theory of aviation hydraulic piston pump,“ 15th International Conference on Tribology – Serbiatrib ’17, Kragujevac, 2015.
[16] M. Ivantysynova and J. Baker, “Power Losses in the Lubricating Gap Between Cylinder Block and Valve Plate of Swash Plate Type Axial Piston Machines,“ *Int. J. Fluid Power,* vol. 10, pp. 29–43,2009.
[17] S. D. Leif, „Testing of Danfoss APP1.0–2.2 with APP pumps as water hydraulic motors for energy recovery“, *Desalination*, vol. 183, no. 1–3, pp. 41-54, 2005, ISSN 0011-9164.
[18] N. Todić, S. Savić, D. Gordić and R. Petrović, “Experimental Research of the Hydrodynamic Processes of an Axial Piston Water Hydraulic Pump,“ *MACHINES*, vol.10, no.9, 2022, Doi https://doi.org/10.3390/machines10090728.
[19] T. Wang, J. Fang, H. Liu, L. Chen, X. Ouyang, S. Guo, X. Zhao and Y. Lu, “Modeling and Characteristic Analysis of a Cylinder Block/Valve Plate Interface Oil Film Model for 35 MPa Aviation Piston Pumps.“ *Machines,* vol. *10*, pp. 1196, 2022, https://doi.org/10.3390/machines10121196.
[20] A. Yamaguchi, “Formation of a fluid film between a valve plate and a cylinder block of piston pumps and motors, 1st Report, A Valve Plate with Hydrodynamic Pads,“ *Bulletin of JSME*, vol.29, no.251, pp.1494-1498, 1986.
[21] J.M. Bergada, D.L. Davies, S. Kumar and J. Watton, “The effect of oil pressure and temperature on barrel film thickness and barrel dynamics of an axial piston pump,“ *Meccanica*, no.47, pp. 639-654, 2012.