FLUCOME 2009
10th International Conference on Fluid Control, Measurements, and Visualization
August 17–21, 2009, Moscow, Russia

EXPERIMENTAL INVESTIGATION IN AXIAL PISTON PUMPS BARREL DYNAMICS.

Josep M. Bergada[1] Dyfyr Ll. Davies[2] Yiqin Xue[2] Sushil Kumar[1]

ABSTRACT

It is known that an axial piston pump barrel experiences small oscillations due to forces acting over it. Cavitation also occurs in many cases, damaging the plate and barrel sliding surfaces and therefore reducing the volumetric and overall efficiency of the pump. More importantly, the resulting failure of the pump is often a critical issue in modern industrial applications. The complex fluctuation movement of the barrel while turning around the piston pump axis, has been experimentally evaluated in this paper, also the barrel plate film thickness will be experimentally studied, showing that a large amount of the piston pump leakage occurs between the barrel/plate gap. The present paper demonstrates the importance of properly designing the barrel/plate sliding surface. Some of the paper conclusions are that the film thickness between the barrel and the plate sharply decreases as oil temperature increases, mixed lubrication appears under most of the conditions studied and it is especially severe at high temperatures. With regards to the barrel dynamics two main frequencies appear, one related to the torque created when each piston enters and leaves the pressure kidney port, and a much higher frequency due to the elastic and plastic metal to metal contact.

Keywords: Axial piston pumps, barrel/plate leakage, barrel dynamics

INTRODUCTION

Piston pumps development, has a profound experimental basis, since until very recently there were no equations available to evaluate the design of each pump component. In fact, thanks to the program CASPAR, Ivantysynova et al (1999, 2002, 2004), it was possible to carefully evaluate the piston barrel relative movement, evaluating as well the pressure and temperature distribution. Also the slipper plate leakage and temporal film thickness was clarified. Pressure distribution and leakage between the barrel/plate and swash plate torque were also analytically studied, the program was based on the Reynolds equation of lubrication. Yamaguchi (1990) studied experimentally the barrel plate dynamics using four different plates; three of them having grooves to minimize the leakage resulting from barrel/plate and barrel oscillations. Kobayashi and Matsumoto (1993) conducted an analytical study of the leakage and oil film thickness fluctuation between the barrel/plate. They integrated numerically the Reynolds equation of lubrication, taking into account the pressure distribution in both the radial and tangential directions. Weidong and Zhanling (1996) studied analytically the temporal leakage flow between the barrel/plate

[1] Fluid Mechanics Department, ETSEIAT Universitat Politécnica de Catalunya. UPC e-mail bergada@mf.upc.edu

[2] Department of Mechanical Engineering, Cardiff University UK.

clearance, they considered separately the leakage from each barrel groove and the effect of the inlet groove. Barrel tilt was not taken into account. In Bergada et al (2008) explicit equations were found to evaluate leakage, pressure distribution, force and both torques, acting over an axial piston pump barrel. The dynamic torques acting on the barrel were also found, bringing a good understanding of its origins. Hong et al (2006, 2008) studied experimentally the effect of using CrZrN and TiN plasma coatings on the barrel/plate sliding surfaces, demonstrating that the friction coefficients and the rate of wear sharply decreased thanks to the use of such coatings. Despite the work done on the barrel of piston pumps, there is no direct evaluation of barrel/plate film thickness and pump leakage. In the present paper a method to experimentally evaluate the film thickness variation with pressure, temperature, and swash plate angle will be presented. The experimental rig presented here, allows carefully analysis of the barrel dynamics, allowing the origin of the barrel dynamic frequencies to be understood.

EXPERIMENTAL TEST RIG

Figure 1 presents the pump used for the experimentation; it is an axial plate nine pistons pump which gives a maximum flow of 35 l/min, being its maximum swash plate angle 20 degrees. Three Micro-Epsilon inductive position transducers, capable of measuring to an accuracy of 0.1µm were located on the pump port plate. The exact position of the transducers related to the XY axis represented in figure 1 is: Transducer 1: X_1 = 47.96 mm, Y_1 = 0.285 mm; Transducer 2: X_2 = 33.68 mm, Y_2 = 34.155 mm; Transducer 3: X_3 = -39.93 mm, Y_3 = -27.34 mm.

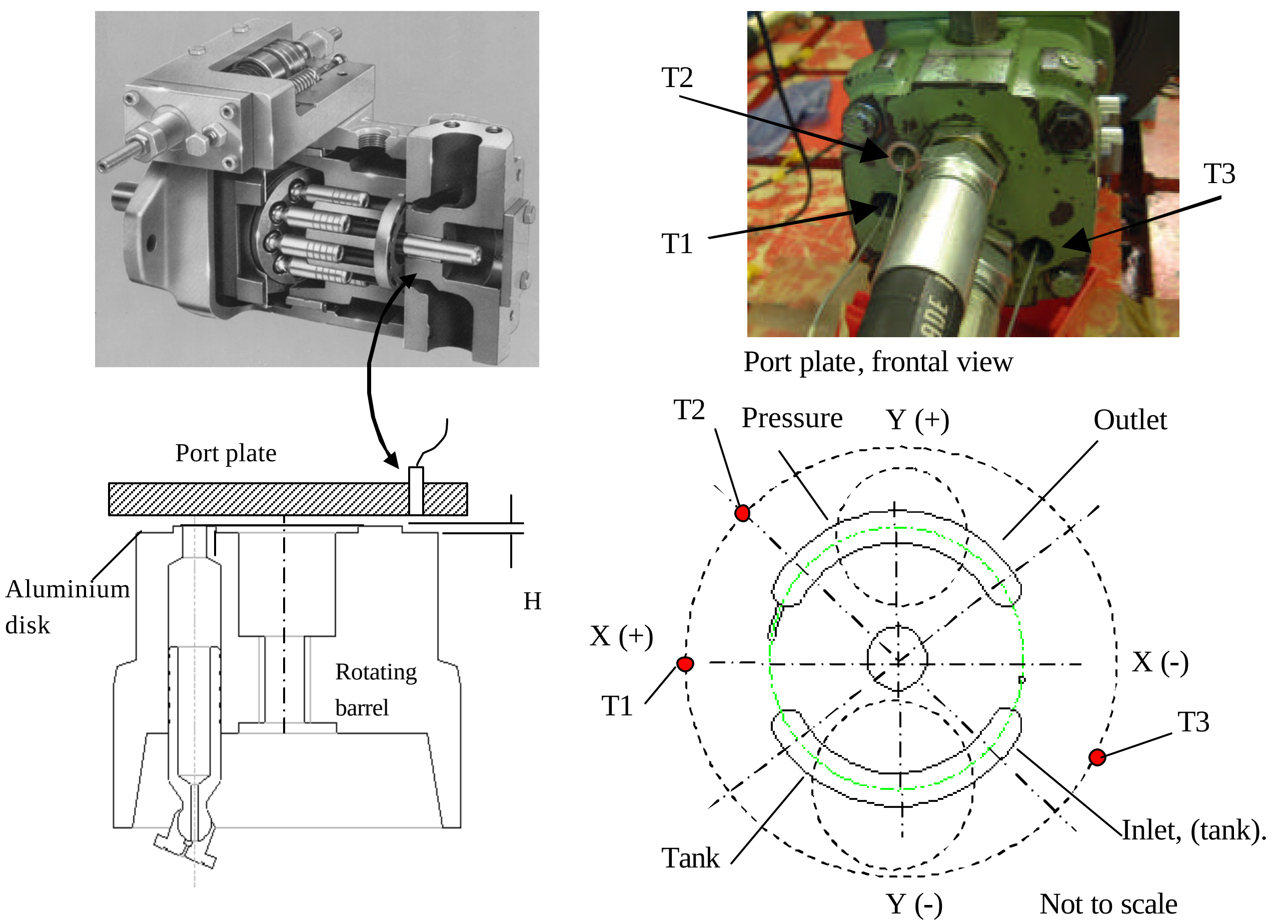

Fig. 1. Pump under study and location of the three displacement transducers used.

The transducer's calibration showed an excellent linearity, the calibration equation of each transducer was: Transducer 1; $d_1 = 0.0487399V + 0.0296410$; Transducer 2; $d_2 = 0.0452037V + 0.0328352$; Transducer 3; $d_2 = 0.0476972V + 0.0322051$, where d is measured in millimetres and V in volts. The transducer's maximum measuring range was 0.5 mm. The transducers were inserted into the port plate and facing the inner part of the pump, the barrel. Due to the transducers characteristics, which needed to point at a non magnetic material, a thin aluminium plate was inserted at the barrel end, as shown in figure 1. The run out of the aluminium plate was measured to be 7 microns, being the average distance between the barrel face and the aluminium disk of H = 0.286 mm, see figure 1.

Once the transducers were inserted into the plate, the relative position between each transducer end and the port plate internal face was recorded. The port plate with the transducers on it was attached to the pump, allowing the real distance between the transducers and the barrel aluminium disk to be measured under all conditions studied. Two sets of tests were undertaken, at both 10, 20 degrees swash plate angle, and for each case two oil temperatures 28 and 45 Celsius were studied. For each of these conditions, measurements were taken at pressures of 25, 50, 75, 100, 125, 150, 175, 195 bar. In all cases studied, the total leakage produced by the pump was measured. The pump rotational speed was constant at 1440 rpm. Samples of the results are presented in this paper.

RESULTS

Figure 2 directly presents the readings taken by the transducers. The measured barrel/plate distance, is shown to fluctuate, where the peak to peak amplitude of these fluctuations are approximately 7 µm. However, the peak to peak amplitude is not constant, varying for each transducer and with pump output pressure and oil temperature. It is necessary to consider that the aluminium plate on the barrel, has a static run-out of seven microns, therefore, the main wave amplitude is mostly due to the barrel dynamic run-out. The amplitude variation, can be seen as an indirect and approximate measurement of the barrel/plate film thickness. It is also relevant to point out that transducer 1 always gives the minimum barrel/plate distance, transducer 2 gives the maximum barrel/plate distance, and more clearly at high temperatures. Transducer 3 presents a distance smaller than that given by transducer 2, with a difference of 180 degrees phase angle between transducers 2 and 3. Since transducers 2 and 3 are respectively on the upper and lower part of the plate, and positioned at locations almost 180 degrees apart, such phase difference had to be expected. Transducers 1 and 2, have nearly the same phase, since they are located next to one another. In most of the cases studied, the wave amplitude from transducers 2 and 3 was bigger than that of transducer 1, indicating that exist a barrel oscillation around the "X" axis. As a result of the previous explanation, the barrel position and film thickness need to be studied as a temporal average.

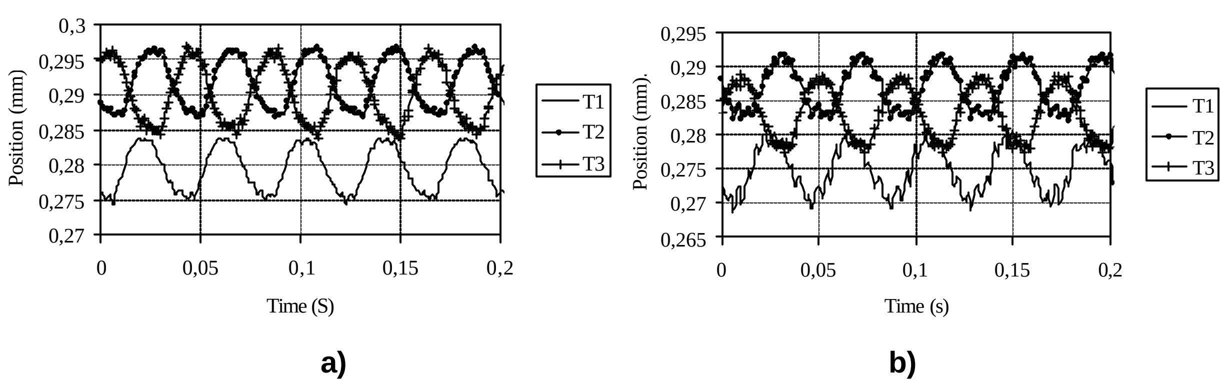

Fig. 2. Typical distance between barrel aluminum disk and port plate, given by the three transducers. Case 20 degrees swash plate, 28 Celsius. a) 25 bar; b) 175 bar.

From figure 2, it is also noticed that especially at high pressures, a second wave appears superimposed onto the first one. This second wave will be called the fluctuation wave and it is directly related to the barrel vibration frequencies. This fluctuation wave is especially relevant in transducer 1 and at high temperatures, indicating that the torque fluctuation origin has to be along the “X” axis.

Figure 3 presents the average position values given by the three transducers, clearly demonstrating that transducer 2 always gives a higher distance reading than the other two, and therefore indicates that the average maximum film thickness is to be expected around the position of transducer 2. The distance barrel/plate clearly decreases with pressure, a typical decrease being around 6 µm for transducer 1 and 2, and around 9 µm for transducer 3. In fact, the decrease of film thickness with pressure seams to be linked to the local increase of oil temperature. Figure 4 clearly demonstrates that oil film thickness is extremely dependant on oil temperature, with a second degree of dependency on the pump output pressure. The same trend shown by transducer 3 in figure 4 is followed by the other two transducers.

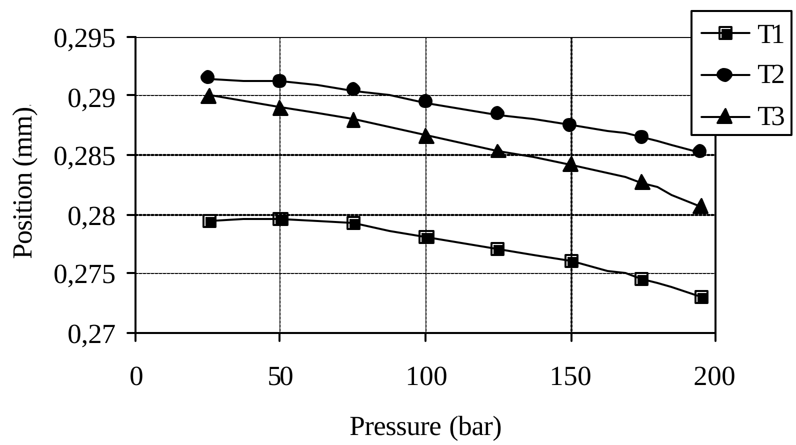

Fig. 3. Position average values as a function of the pump output pressure, given by the three transducers. Case 20 degrees swash plate, 28 Celsius.

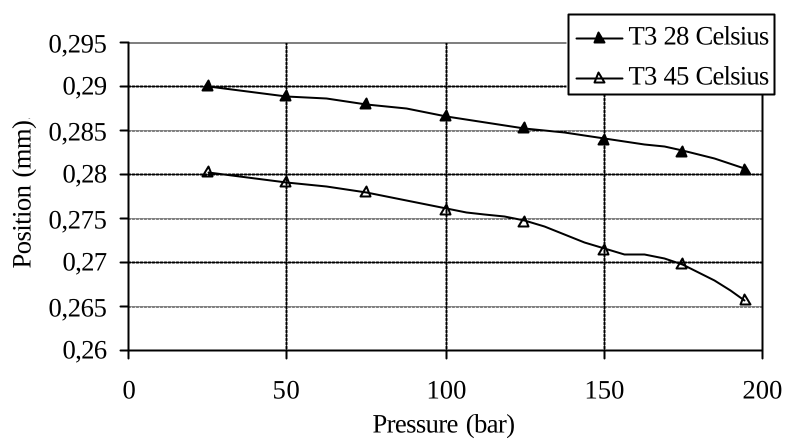

Fig. 4. Position variation from transducer 3 at different pressures and oil temperatures. Case 20 degrees swash plate.

Figure 3 and 4 clarify the kind of lubrication appearing between the barrel and plate. It can be stated that at low pressures and low temperatures the oil film thickness is bigger and a much wider part of the barrel face is turning under hydrostatic and hydrodynamic lubrication. As pressure, and especially as temperature increases, the lubrication existing between the barrel face and the plate is mixed lubrication, where elastic and plastic metal to metal contact between the two faces exists. Evidence on the plastic contact can be seen when opening the pump and looking at the port plate internal face.

When analysing the fluctuation wave, it has been found that at high pressures and high temperatures, the wave is more clearly seen. Figure 5 presents the fluctuation wave when the oil temperature is 45 Celsius and for two different outlet pressures, 25 and 175 bar. It is noticed that at low pressures and in fact regardless of the oil temperature, the fluctuation wave has a random pattern, being its peak to peak amplitude of approximately 1µm. As pressure increases, the fluctuation wave follows a clear pattern first defined in Bergada at al (2008), and consisting of a small peak and a main one, having a frequency of 216 Hz, nine times the pump frequency. These peaks are due to the torque effect of each piston, when entering and leaving the kidney port pressure groove, the peak to peak amplitude is about 3µm. At high pressure, three peaks are observed between the small and main peaks, the authors believe that such peaks, which frequency is over 1000 Hz, are related with the friction between the barrel and the plate.

a) **b)**

Fig. 5. Examples of fluctuation wave. Case 20 degrees swash plate, oil temperature 45 Celsius. a) 25 bar, b)175 bar.

Regarding the relation of the pump overall leakage and the barrel/plate leakage, an interesting experiment might be the one presented in figure 6. The overall pump leakage was measured over time and for two constant initial oil temperatures. Since the energy losses produced by the pump dissipates as heat, the oil temperature inside the pump increases over time tending to an asymptotic value, the film thickness will decrease as local oil temperature increases, and will also tend to an asymptotic value. In figure 6 it can clearly be seen that despite the initial oil temperature, the overall pump leakage trends reach an asymptotic value, indicating that the barrel/plate film thickness must decrease with time as already demonstrated and indicating as well that a large amount of the pump overall flow must be produced in the barrel/plate gap.

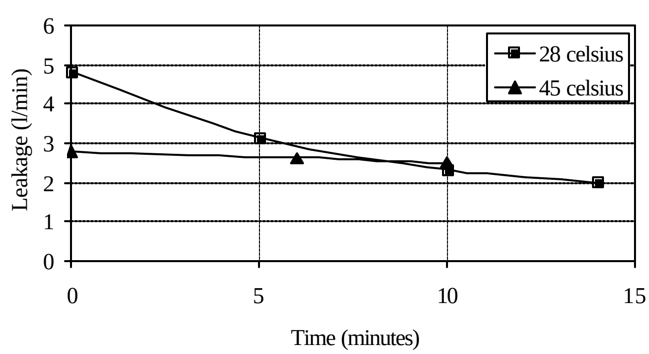

Fig. 6. Pump total leakage as a function of time and for two different oil temperatures. Case 20 degrees swash plate, 175 bar.

CONCLUSIONS

A new test rig capable of indirectly measuring the clearance barrel/plate has been presented. The experiments conclude that the average barrel/plate film thickness decreases as oil temperature increases, the average film thickness has a second order decrease with the increase of pressure.

The barrel dynamics presents two characteristic waves, a main one, with peak to peak amplitude of about 7μm and a frequency of 24 Hz, directly linked to the barrel run-out, and a fluctuation wave presenting two main peaks, a small and a large one, both of them having frequencies of 216 Hz, and related to the torques that each piston creates when entering and leaving the pressure kidney port. Peaks of much higher frequency are also appearing in the fluctuation wave, the authors believe this peaks are due to the barrel/plate metal to metal contact.

The pump total leakage clearly decreases as oil temperature increases, suggesting that a large amount of the pump overall leakage is generated in the barrel/plate gap, as previously demonstrated, the film thickness decreases with temperature, as a result, the pump overall leakage follows this trend.

ACKNOWLEDGMENTS

The authors would like to acknowledge the help of Professor John Watton, Cardiff University, UK. Then the construction of the experimental test rig was done in his lab and under his guidance.

REFERENCES

Ivantysynova M; Huang C. (2002). "Investigation of the Flow in Displacement Machines Considering Elastohydrodynamic Effect". *Proceedings of the 5th JFPS International Symposium on Fluid Power*, November 13, Nara 2002 Japan Vol. 1, 219-229.

Ivantysynova M. (1999). "A New Approach to the Design of Sealing and Bearing Gaps of Displacement Machines". *Fluid Power forth JHPS International Symposium* 1999. 45-50.

Ivantysynova M; Lasaar R. (2004). "An Investigation into Micro – and Macrogeometric Design of Piston / Cylinder Assembly of Swash plate machines". *International Journal of Fluid Power* **5** (1), 23-36.

Yamaguchi A. (1990). "Bearing/seal characteristics of the film between a valve plate and a cylinder block of axial piston pumps: Effects of fluid types and theoretical discussion". The Journal of Fluid Control. **20** (4), 7-29.

Kobayashi S and Matsumoto K. (1993). "Lubrication between the valve plate and cylinder block for low speed conditions in a swashplate-type axial piston motor". Trans of the Japan Society of Mechanical Engineers, part C. **59,** 182-187.

Weidong G and Zhanlin W. (1996). "Analysis for the real flow rate of a swash plate axial piston pump". Journal of Beijing University of Aeronautics and Astronautics. **22**, (2), 223-227.

Bergada JM, Watton J, Kumar S. (2008) "Pressure, Flow, Force and Torque Between the Barrel and port plate in an axial piston pump". ASME Journal of Dynamic Systems, Measurement and control. **130**. (1), 011011-1/16.

Hong YS, Lee SY. (2008) "A comparative study of Cr-X-N (X=Zr, Si) coatings for the improvement of the low speed torque efficiency of a hydraulic piston pump". Metals and Materials International. **14** (1), 33-40.

Hong YS, Lee SY, Kim SH, Lim HS. (2006). "Improovement of the low-speed friction characteristics of a hydraulic piston pump by PVD-coating of TiN". Journal of Mechanical Science and Technology. **20** (3) 358-365.