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CFD Analysis of Variable Displacement Swash Plate Type Axial Piston Pump Flat Slipper

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Abstract

In the field of hydraulic machines, piston pumps are the only ones that can work under very high pressures and deliver the best efficiency as a result of which they have a very sophisticated design. As per surveys, most parts of these pumps have validation from the experience of designers as a result of which there isn't any mathematical tool for design optimization of different parts. Although there are now companies e.g. Oilgear Towler, who are in favor of, and themselves inserted, slots (grooves) on the slippers and in pistons as we shall in this report, there is no particular study to realize their benefits and drawbacks. Therefore, it is necessary to study the advantages and disadvantages arising due to the presence of grooves on the surface of different parts of the pump mathematically or through CFD solvers. In this project work, the aim is to analyze the effect of design parameters and working conditions on the pump behavior. This is done using a parametric study performed on a model of the slipper and simulating the physical problem on ANSYS. As major leakage occurs between slipper and swash plate clearance there-fore in this project report static and dynamic analysis of slipper is done. The Navier Stokes Equations are solved in 3-D to acquire results using Rhie and chow method and ANSYS FLUENT solver. The various design points which affect the efficiencies of a pump in a positive manner, if any, shall be discussed in the conclusion part.

Keywords

CFD, Optimization, Flat Slipper, Swash Plate, Groove, Clearance, Simulation

1. Introduction

In hydraulic machines working on liquids that are used for commercial actuation and other purposes, pumps having piston and one of their part have the most complex structure and construction. Apart from this they also have their input and output parameters tough to find. Generally, these pumps have considerable leakages that are unavoidable to some extent and are required to be controlled as the leakages in case of actuation and other concerned purpose utilization can be both expensive and disastrous. As per experiments nearly half of the total leakages occur from the clearance between slipper head and swash plate refer Figure 1. This clearance being lubricated by the same oil which is pumped to stop or avoid wearing of swash plate surface. But leakages have also to be minimized so a trade of is generally made between volumetric efficiency of pump and its mechanical efficiency.

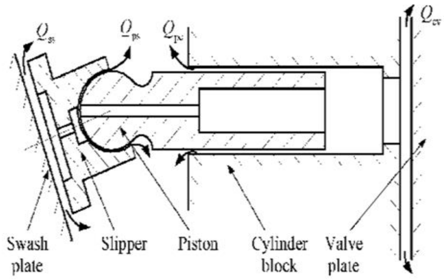


Figure 1. – Schematic diagram of slipper and swash plate [1]

2. Literature Survey

A hydraulic pump is a device that transforms the energy given in mechanical form into energy stored in fluid by changing either the angular momentum of fluid or by increasing its pressure energy. This energy is ultimately useful for works like actuation, hydraulic operated automated assembly operations etc. Mechanical energy given to a pump should be equal to that required from it + the losses which are inherent to the pump structure ex- loss due to valves present.

2.1. Axial piston pumps: As the name suggests, an axial piston pump has pistons mounted in circular fashion on a cylindrical block and provide axial discharge. They are generally bringing into application as standalone pumps. They can be also made to act as a hydraulic motor and quite often these days they are also used as air-conditioning compressors in automobiles. Mainly there are two types of axial piston pumps used commercially. Their design differs only in method opted to achieve the stroke length in the pump.

2.2. Swash plate type axial piston pump

In these pumps driving shaft, pistons and cylinder block are all aligned parallel and for stroke length creation a swash plate is provided that is in practice actuated/rotated by signals from various sensing systems and this plate is mounted inside the pump casing in transverse plane and can be rotated about the transverse axis. Slipper head follow the surface of this plate and hence the stroke is adjusted accordingly resulting in regulation discharge and pressure. As the swash plate and slipper head is permanently in contact with each other.

Therefore, lubrication is required and this is done with the help of operating fluid commonly called hydraulic fluid. They have now found application in jet aircraft's hydraulic systems being driven by gear train from turbine and are extensively used in aerospace industry. Ex- F-14 jet used a 9-piston swash plate type axial piston pump for its hydraulic systems.

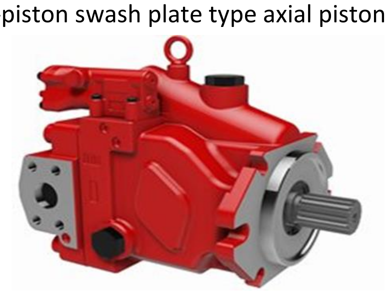


Figure 2. Swash plate type axial piston pump by Kawasaki hydraulics

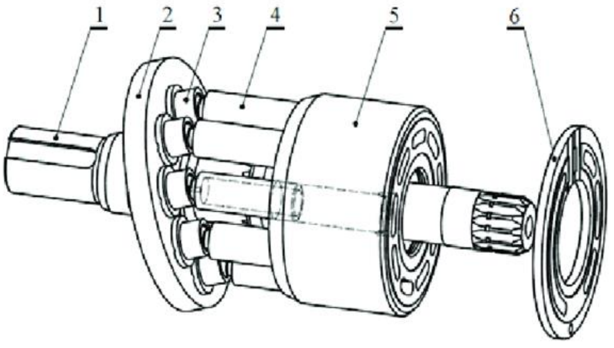


Figure 3. Anatomy of piston pump

i. Drive shaft
ii. Swash plate
iii. Slipper head
iv. Pistons
v. Cylinder block
vi. Valve plate

3. Project Motive

Some slipper heads have multiple grooves that are connected via channels. Such grooves aren't able to produce enough lift force to counterbalance the piston forces where as some grooves which are not even vented can do that. However, the study of such grooves is very less. It is needed that some analysis regarding the effect of grooves presence on slipper has to be done to analyze their effect on pump parameters. There are mainly three types of sliding surface contacts present in this pump namely gap between slipper and swash plate, gap between cylinder block and valve plate, gap between piston and piston chamber and in the last gap between piston and spherical bearing.

Out of these, the slipper swash plate gap contributes maximum to the leakages happening in the pump. Our motive in this report will be to analyze this area with different types of groove designs and configurations and relate its effect of parameters like pressure distribution, leakages, flow, torque etc.

After accessing results, analysis will be repeated for various clearances and pressure values, and then slipper with multiple grooves will be analyzed along with the one that has a scheme to reduce the lift forces. To do analysis Navier stokes equation is solved for the selected grade of oil. The motion of the slipper will create a flow field at the clearance that can't be considered symmetric/uniform in radial direction. So, 3-D computational domain is must for the analysis. [1]

4. Methodology Adopted

Parametric study is study of a model by varying its parameterized quantities to obtained considerable data points between input and output parameters to plot the graphs and study their relationship. Input parameters can be in the form of dimensions at the modelling time or initial input values at the time of setup. Output parameters can be some output quantities that are solved after the results are obtained. Generally output parameters are dependent and input parameters and independent.

In this project R3 and R4 are parameterized along with the input pressure as input parameters whereas lift force, torque, pressure distribution, mass flux will be output parameters. A step by step flow process of methodology opted is shown below for more clarity.

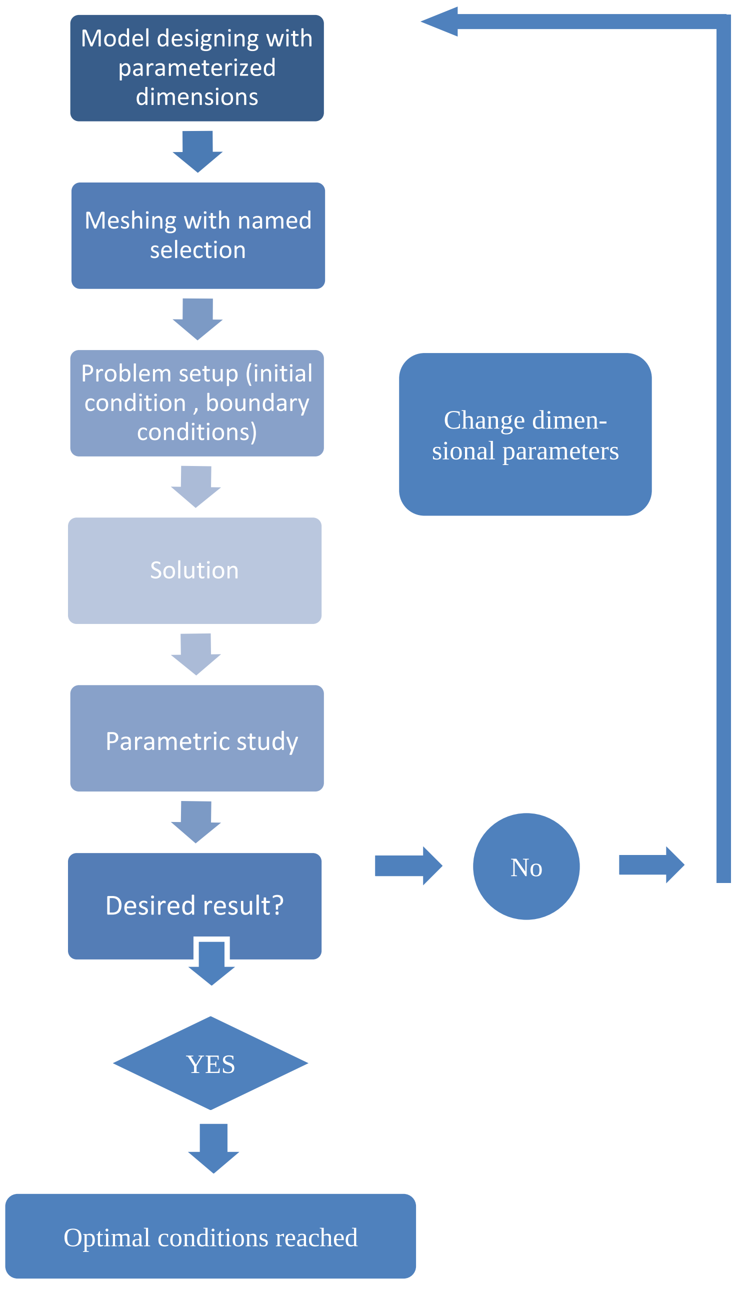


Figure 4. Methodology/flow chart for the project work process

5. Governing Equation

In this project work, unstructured meshing is done therefore to remove chequerboard oscillations as mentioned in [6] Rhie-Chow interpolation method is used as the fluent solver takes mesh as collocated grids instead of staggered grids.

To describe the solving algorithm, FVM [finite volume method] is described first which means the discretization of momentum and continuity equation.

$$\textbf{Continuity}\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \tag{1}$$

$$\textbf{X-momentum-}\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right] \tag{2}$$

$$\textbf{Y-momentum-}\ \frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right] \tag{3}$$

$$\textbf{Z-momentum-}\ \frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho wv)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right] \tag{4}$$

$$\textbf{Energy-}\ \frac{\partial E_T}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right] + \frac{1}{Re_r}\left[\frac{\partial(u\tau_{xx}+v\tau_{xy}+w\tau_{xz})}{\partial x} + \frac{\partial(u\tau_{xy}+v\tau_{yy}+w\tau_{yz})}{\partial y} + \frac{\partial(u\tau_{xz}+v\tau_{yz}+w\tau_{zz})}{\partial z}\right] \tag{5}$$

In unsteady state, for incompressible flow continuity and momentum equation in x, y, z direction is given as follows:

$$\rho\frac{\partial U_i}{\partial x_i} = 0 \tag{5}$$

$$\rho\left(\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_i}\right) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}\left(\mu\frac{\partial U_j}{\partial x_j}\right) + S_j \qquad (6), (7), (8)$$

Here as we can see there are four unknowns (U, V, W) and we also do have 4 equations. However, there is no equation for pressure (p). It should be seen that solution of velocity field obtained from equation 2, 3 and 4 is restricted to satisfy the continuity equation otherwise the field will be invalid so continuity equation basically acts as a constraint to solution from momentum equations. Here we also can't use equation of state to solve for pressure as the fluid is incompressible. Cheq-uerboard oscillations arise while discretizing the momentum equation.
If one is interested in looking at full unsteady discretization one can refer to [6]

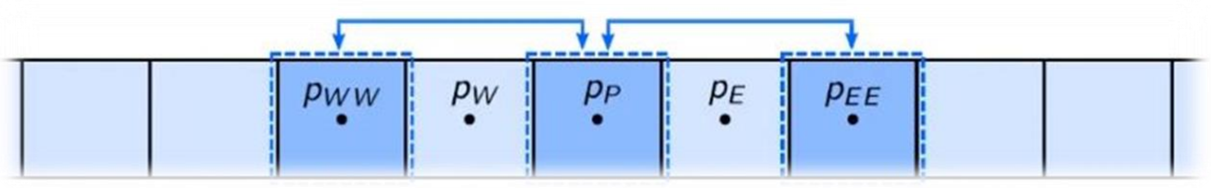


Figure 5. Dependency of pressure

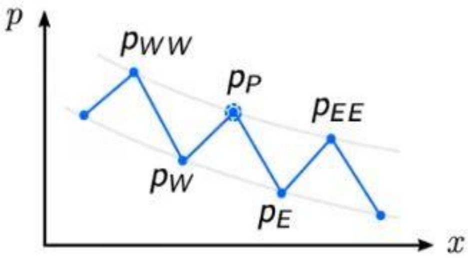
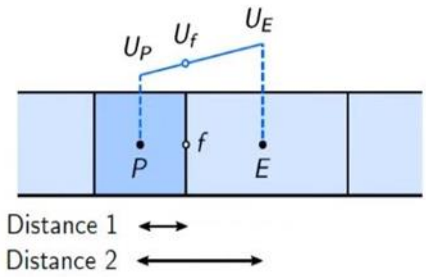


Figure 6. Graphical representation of chequerboard oscillations

This was done by interpolating flow variables linearly as



$$I_x = \frac{Distance\ 1}{Distance\ 2}$$

Figure 7. Depiction of velocity in case of collocated grids

Velocity on the face $U_f = I_x U_P + (1-x) U_E$ (9)

However, to correct the discrepancy in Rhie-Chow interpolation method a correction factor is used

$$U_f = I_x U_P + (1-x) U_E + \text{Correction} \quad (10)$$

This correction factor is equal to

$$\text{Correction factor} = -\overline{d_f}\left(\left.\frac{\partial p}{\partial x_j}\right|_f - \overline{\left.\frac{\partial p}{\partial x_j}\right|_f}\right) \quad (11)$$

This factor provides a damping effect to deviations (or oscillations) which eventually disappear as a result of iterative solution procedure.

6. Calculation

There are many hydraulic oils commercially available in market but in this report for analysis purpose ISO-GRADE-32 oil was used. ISO-GRADE-32 is a mineral-based oil that has the following properties

Calculations for dynamic viscosity μ in $\frac{kg}{m\ sec}$:

ρ= 857 kg/m^3

ν = 32.2 centistokes & 1 stoke = 10^{-4} m^2/sec

$$\text{So, } \nu = 32.2{*}10^{-6}\ \text{m}^2/\text{sec [SI unit]}$$

$$\text{Now, } \nu = \mu/\rho \Rightarrow \mu = \nu \times \rho \Rightarrow \mu = 32.2 \times 10^{-6} \times 857 = 0.027\ \frac{kg}{m\ sec}$$

Table 1. Oil Properties

Properties	Values
Density ρ @ 20 °C	857
Viscosity in cSt (centistokes) @ 40 °C	32.2
Index of viscosity	108
Flash point	202 °C

7. Model & Result

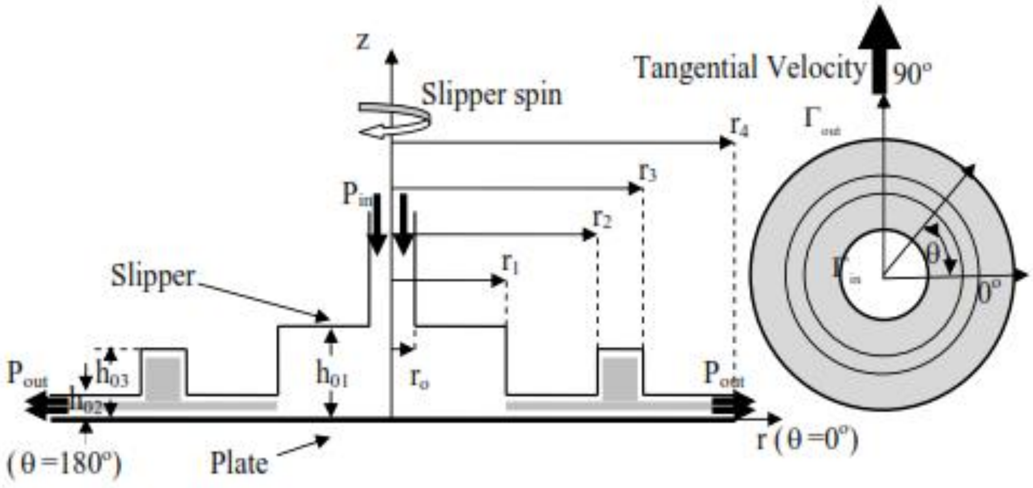


Figure 12. Computational domain with motion of slipper [1]

Table 2. Slipper Dimensions

Dimension in mm	Slipper with single groove
R1	0.5
R2	5
R3	7.43
R4	7.83
R5	10.26
D_1 [pocket depth]	H+0.6
D_2 [groove depth]	H+0.4

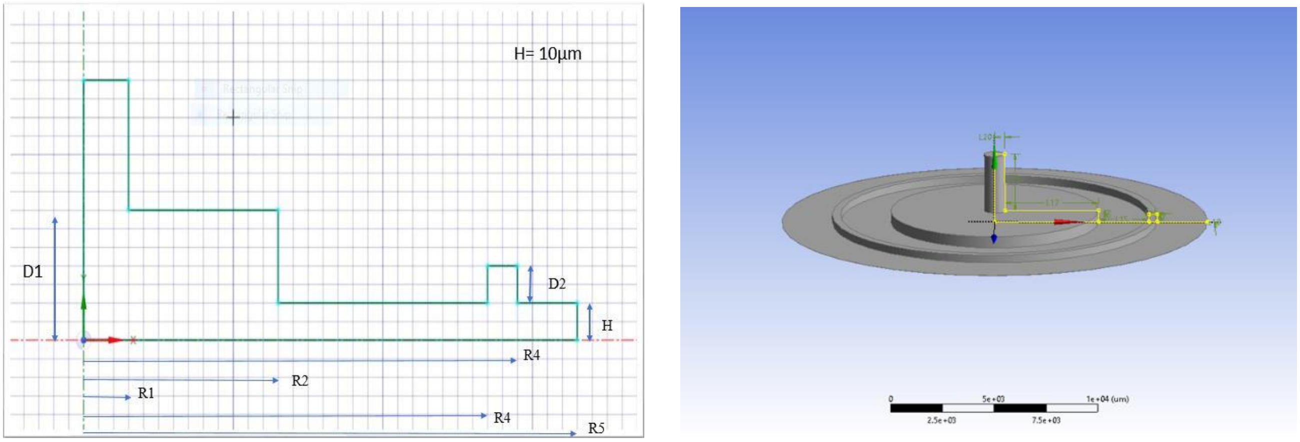


Figure 8. Dimensions of the slipper taken for design and analysis & solid model

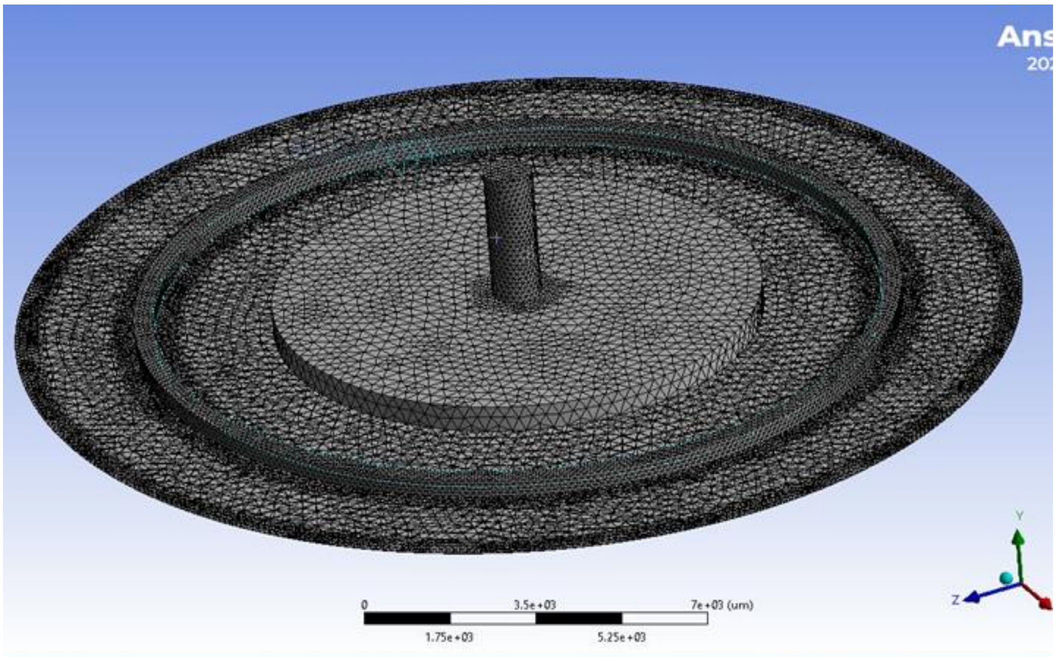


Figure 9. Meshed model

7.1 Static Analysis

The value of lift force on slipper came out to be 1644.0643 Newton.

Mass flow rate @outlet = - 0.0074081236 kg/sec negative sign at outlet shows outward flow

7.1.1 Contours at 10MPa Inlet pressure

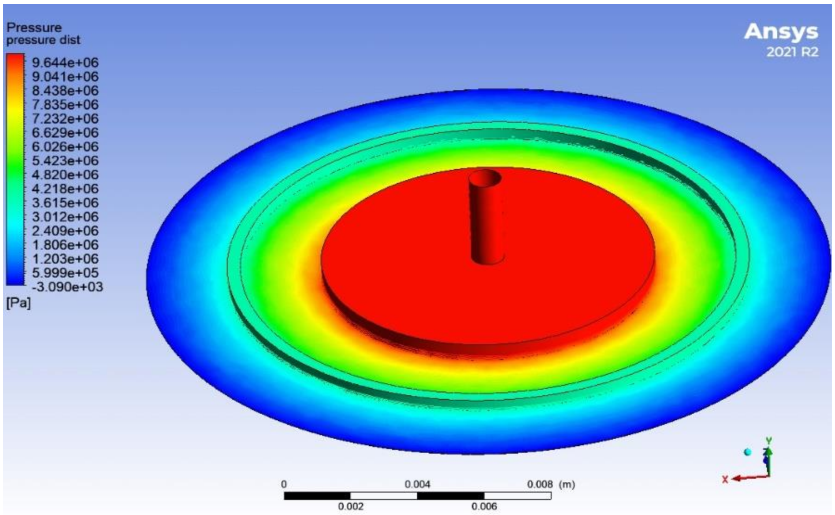


Figure 10. Pressure distribution on slipper

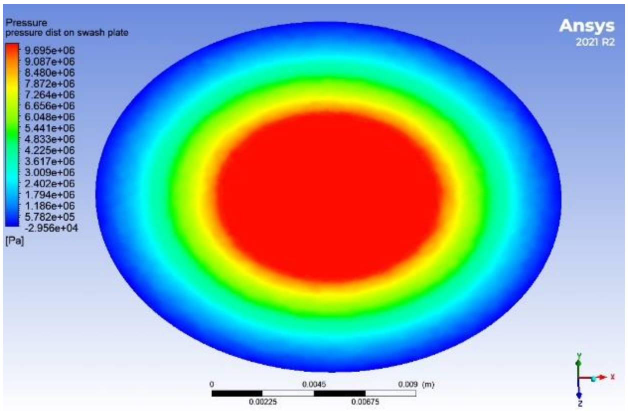


Figure 11. Pressure distribution on swash plate

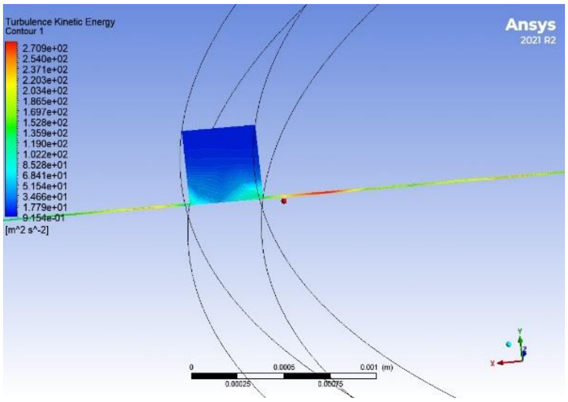


Figure 12. Turbulent kinetic energy near groove (static)

Table 3. Pressure, lift force and leakage data points

Pressure in MPa	Lift Force in Newton	Leakages in Kg/sec
6	997.0123	0.005134
10	1644.823	0.007416
13	2133.521	0.0089
14	2309.425	0.009386

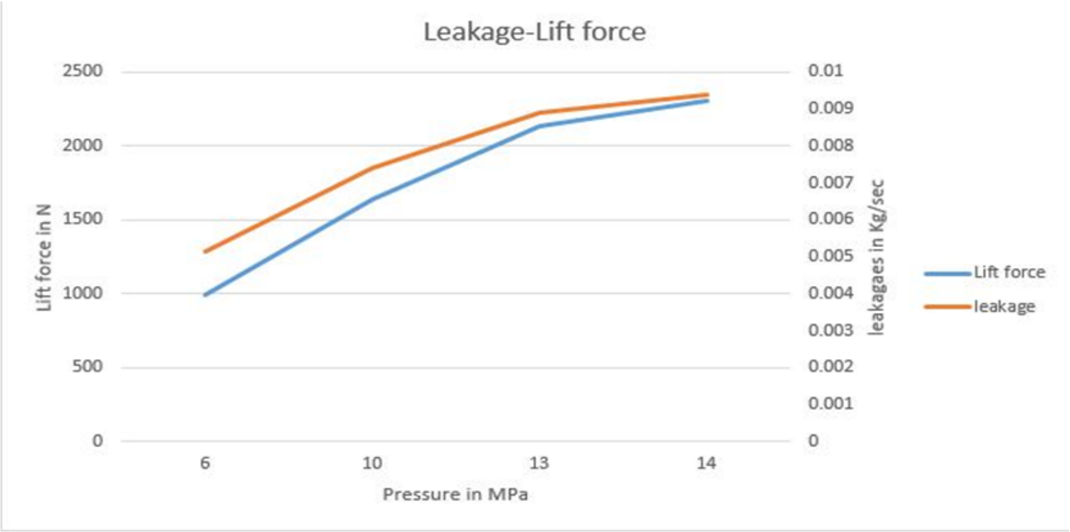


Figure 13:. Effect of pressure variation on Lift and leakage

Table 4. Data point table for surface roughness effects

Sand grain roughness	Lift force	Leakages
0	1644.823	0.007416
7.00E-06	1645.266	0.007412
6.00E-06	1661.176	0.007391
5.00E-06	1646.155	0.007394
1.00E-05	1645.763	0.007398
1.50E-05	1645.378	0.007398

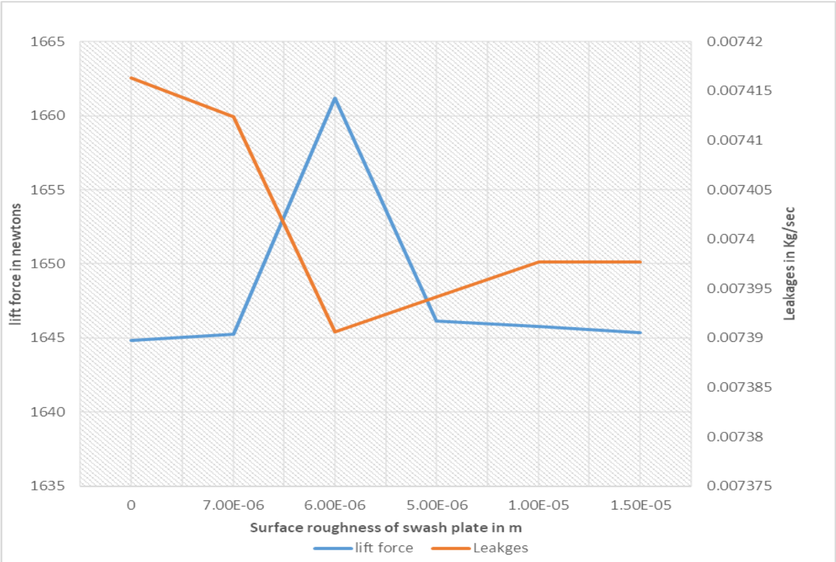


Figure 14. Surface roughness effect on Leakage and lift force

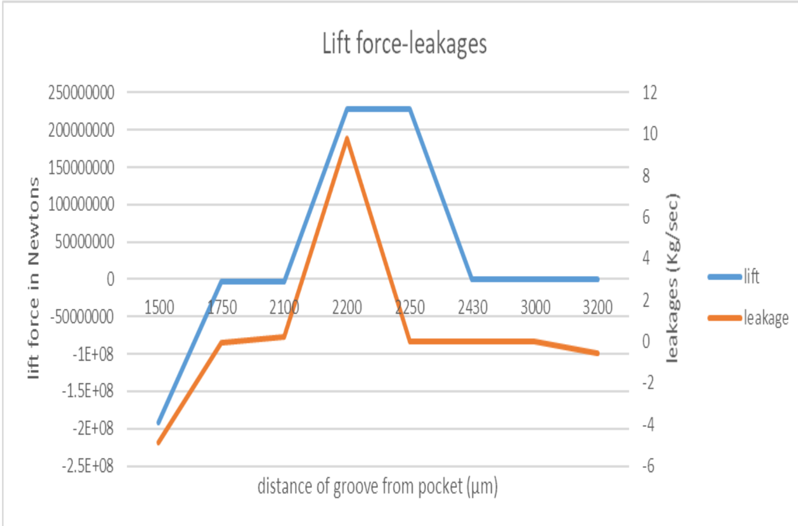


Figure 15. Effect of distance of groove from pocket end on lift and leakage

7.2. Dynamic Analysis

7.2.1 Contours of various flow variables

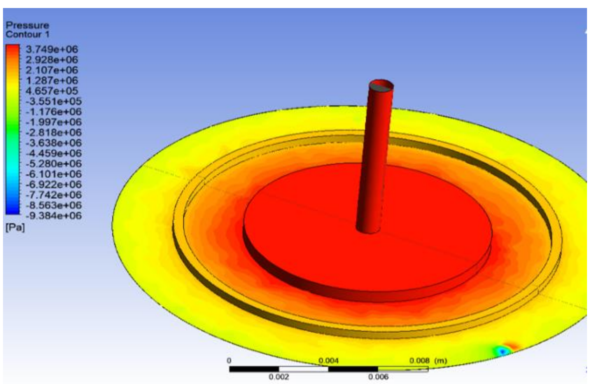


Figure 16. Pressure contour at 10MPa inlet pressure

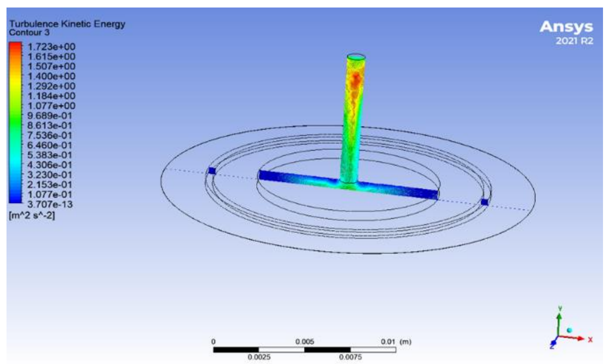


Figure 17. Turbulent Kinetic energy contour

Table 5. Data points for Rpm variation.

RPM	Mass flow rate (kg/sec)
1000	0.003933
1500	0.168649
2000	0.172489
2500	0.180473
3000	0.183587
4000	0.182577
10000	0.198797

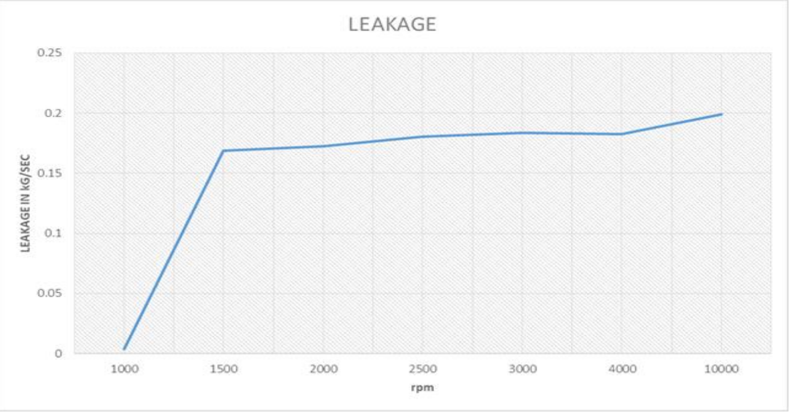


Figure 18. Variation of leakage with variation in pump speed for the given data points @10MPa

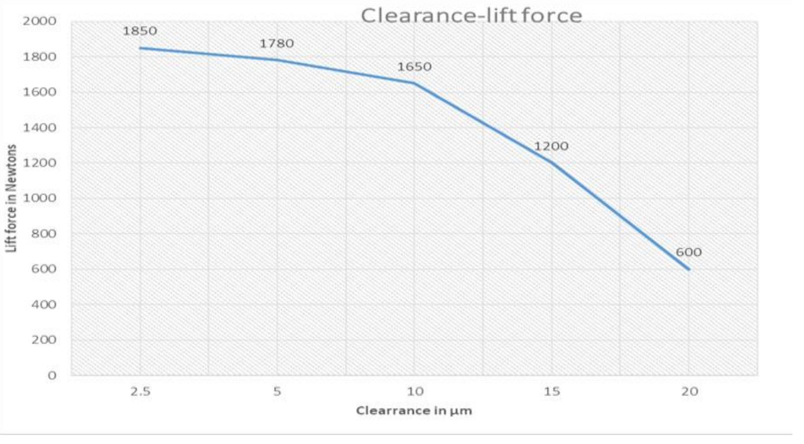


Figure 19. Variation of lift force with clearance.

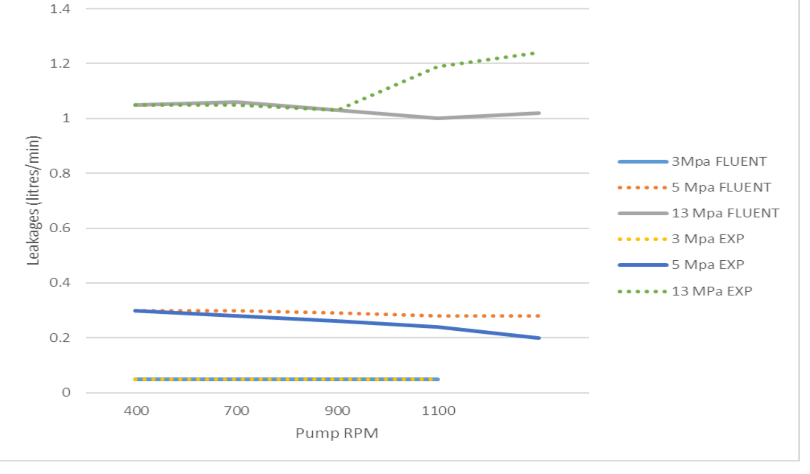


Figure 20. Experimental and CFD results of leakages on variation of turning speed.

8. Conclusion & Discussion

Pressure contours of concerned analysis show where the flow will go in the direction of negative pressure gradient, and this is required for the lubrication purpose but at the same time leakages are also coming into picture which effect the mechanical efficiency of the pump directly therefore a trade-off has to be made between lubrication (which has direct implication on pump life) and the mechanical efficiency. Every parameter that increases leakage will tend to decrease the hydraulic efficiency of the pump and every parameter that tends to decrease the lift force on slipper head will tend to decrease mechanical efficiency of the slipper. As the lift force is changing on varying the groove dimension, clearance etc. and leakages are also varying with turning speed and groove dimensions and clearances therefore a design point exists where optimum values are reached. Surface roughness can also affect the leakages and lift force as shown in Figure 17. Therefore, roughness can intentionally be provided to increase the lift force. Various studies have also shown that lift force can be increased by placing the groove near the pocket of the slipper. One of the reasons could the turbulent kinetic energy that is higher near the pocket and slowly diminishes as one moves in outward direction. There is much more to analyze for the slipper in both static and dynamic conditions. The presence of multiple grooves and how it effects the pump parameters, how the venting of groove effects the torque and output parameters and leakages. As it is now evident that on varying groove location the lift and leakages vary too. Therefore, one can find a design point where the leakages can be neglected in light of lift force acquired. The gap between swash plate and slipper is small enough to capture the effects of asperities on the swash plate that may be inherent or due to wearing therefore, if one considers the roughness of swash plate the results may be more practical and promising.

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