A Simulation Study of Lubricating Oil Pump for an Aero Engine

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ABSTRACT

The lubrication system of an aeroengine is intended to lubricate and cool bearings, gears, and splines to ensure a high level of safety and reliability for many operating hours of an aircraft. One of the important accessories of the lubrication system of an aeroengine is the oil pump which consists of multiple pumps with tandem gerotor elements housed in a single casing. The lubrication pump consists of multi positive displacement pumps of "GEROTOR" type, driven by a single shaft. The aim of this paper is to study the influence of altitude conditions on the pump performance and develops a simulation technique for the prediction of output flow rate at various on and off-design conditions. A numerical study has been conducted using commercial CFD code ANSYS-Fluent. Volumetric efficiency is considered as the main parameter for the evaluation of pump performance at various operating conditions. Further, the experimental study has been carried out by simulating low inlet pressure conditions at the inlet of the pump. The comparison between simulation and experimental results shows that results are matching within a 6% deviation. Thus, the simulation method is appropriate for predicting the altitude performance of gerotor pump used in the lubrication system of an aero engine. The study concludes that the contribution of inlet pressure to the pump performance is significant.

Keywords: *Gerotor Pump; Trochoidal Profiles; Altitude; CFD; Lubrication*

Introduction

An aero-engine or gas turbine requires a lubrication system for the smooth functioning of rotating components of the engine. Another function of the

lubrication system is to collect worn-out matters from the gearbox and bearing housings which if left may cause failures in these rotating components. Most of the present-day aircraft gas turbine engines use a closed-loop lubrication system. The closed-loop lubrication system has three characteristic sections. The first section covers pipelines between the supply pump and the engine bearings. This is referred to as the supply line section. In this section, the oil after being filtered and cooled is then supplied to lubricate the main shaft bearings, gear drives, and gearbox. The second section is called scavenge pipeline section and that covers pipelines between bearing sumps and scavenge pumps. To safeguard positive suction of oil during the different altitudes of the engine in flight usually several scavenge pumps are installed in this section. The third section is between scavenge pumps to supply pumps through the filter, air-oil separator, and oil tank. The oil from scavenge pumps passes through the filter and goes to the air-oil separator where oil gets separated from air before falling back in the oil tank as shown in Figure 1. The pump discussed in this present work is the supply pump.

The oil pump of the lubrication system ensures a continuous and pertinent flow of lubricant. It is considered one of the most critical parts of a lubrication system since the failure of the pump will cause a rapid shut down of the engine. Oil pump delivers high-pressure oil to engine bearings, seals, gears, etc., and low-pressure oil is scavenged out from bearing housing and send back to the oil tank. The most demanding case for the oil pump corresponds to the altitude running conditions. So, the pump is usually designed for this case with some margin. For the other running conditions, the pump delivers more than the necessary flow rate.

Generally, a gerotor type oil pump is used in the aero-engine due to the number of their advantages, some being less noisy, reliable, simplicity due to fewer numbers of components, no sealing units, compactness leading to a lighter weight, and the possibility of higher speeds. The gerotor is a positive displacement pump, consisting of three elements: an inner rotor, an outer rotor, and an eccentric ring. Profile of inner is referred to as the trochoidal and the outer rotor is having a circular arc profile which is conjugate to inner rotor profile. An inner rotor is having one tooth less than the outer rotor. As the gerotor revolves, the liquid is drawn into the enlarging chamber to a maximum volume equal to that of the missing tooth on the inner element. When the chamber has reached its maximum volume, the tips and lobes seal the chamber from both the inlet side (low pressure) and the outlet side (high pressure). Further shaft rotation causes the chamber to become connected to the discharge port and, as additional rotation occurs, the chamber volume becomes smaller, forcing the fluid out until it is empty. This process occurs constantly for each chamber, providing a smooth pumping action.
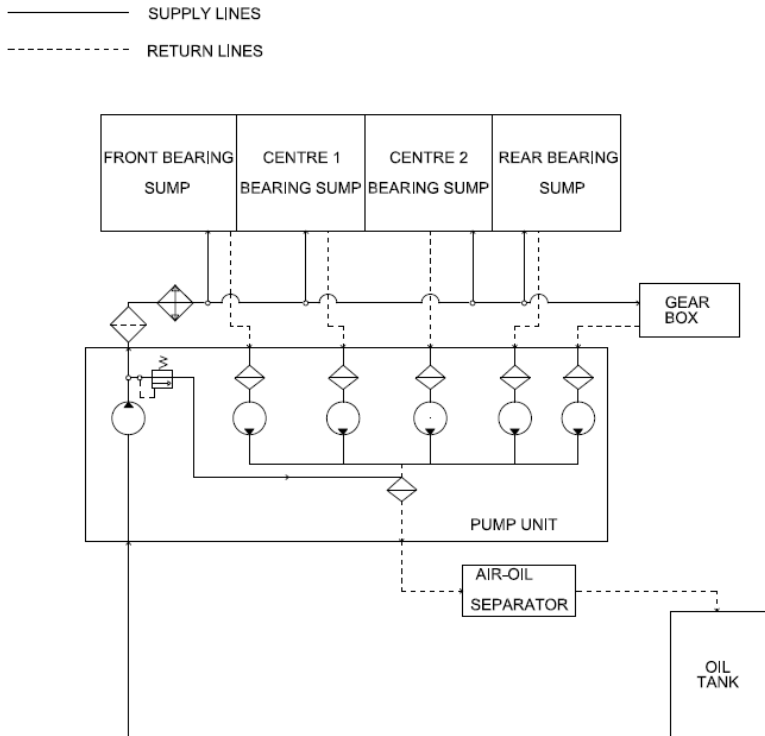
Figure 1: Schematic diagram of the lubrication system.

The outer and inner profile is described by Fabiani et al. [1] as shown in Figure 2. Figure 2 illustrates that the outer rotor is drawn by N circular arc with centers at a distance K from the center O_1. The inner rotor profile is conjugate with the outer rotor. Therefore, the inner and outer rotor rotates about their respective centers O_1 and O_2 at angular velocities ω_1 and ω_2 with a gear ratio of (N-1)/N.

The inner rotor is driven by a prime mover and the outer gear is driven by the motion of the inner rotor. This results in an increasing volume between the inner and outer rotor. This increasing volume decreases the pressure in the volume, which allows pushing the fluid into the pump. On another side, it creates a decreasing volume between the gears. This decreasing volume increases the pressure, subsequently squeezing the fluid out of the pump as shown in Figure 3. Kidney shape inlet and outlet ports are designed which facilitate entry and exit of oil.
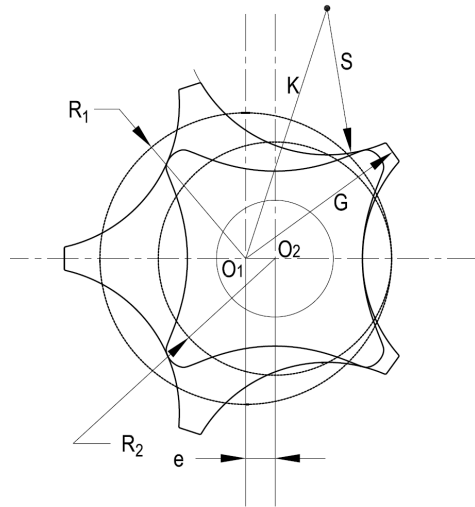
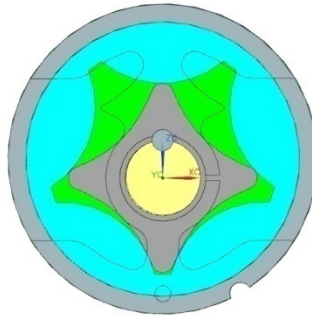Figure 2: Geometrical parameter of the gerotor pump.

Figure 3: Gerotor pump.

Aero-engine oil pump operates at various flight conditions like attitude and altitude of aircraft which affect the performance of gerotor pump. Effect of operating conditions like pump speed, outlet pressure, and design parameters like clearances was studied and discussed by Hussain et al. [2]. Generally, the oil reservoir of an aeroengine is breathed into the atmosphere, thus the oil pump inlet pressure is also close to the atmospheric pressure. Low inlet pressure reduces the pump volumetric efficiency as described by Ippoliti et al. [3]. A significant drop in efficiency was observed at lower inlet pressure when the engine is operating at high altitude conditions. Such degraded performance during high-speed rotation can cause a reduction in oil supply to engine main bearing and gears which will cause

overheating of bearing, oil cocking, oil fire, etc. Thus, it is important to design the gerotor pump in terms of its performance and the life of the pump.

In past decades, gerotors have been studied for investigation of their performance and structural integrity [4-17]. Lozica et al. [18] performed load analysis on the gerotor pump using analytical and numerical methods. A simple analytical model was developed to determine the load acting on the rotors. The contact forces and the pressure forces were taken into consideration for load calculations. Further, the FEM model of the pump was used to calculate the loads. The values of the loads obtained by analytical methods and numerical methods were compared. It was concluded that the results obtained by numerical methods are close to results obtained by analytical methods.

Kumar et al. [19] did a comprehensive study for the development of the gerotor pump inlet components for application in engine lubrication. CFD simulations results were validated with actual experiments. Adolfo et al. [20] modelled the gerotor pump using AMESim software. One dimensional model using AMESim software was developed to find out the volume variations of the chambers and to show the variation in the instantaneous flow rate. Good agreement was concluded between the model and experimental values. Altare et al. [21] rigorously studied the influence of the geometric parameters on the filling of the chamber volumes of the gerotor pump. The effect of variation in inlet port design, inlet port direction, the width of the rotor and external rotor diameter was studied using the CFD model. Karthikeyan et al. [22] studied the flow through the gerotor pump using CFD with the view of designing the pump for application in automobiles. CFD model was used to determine the mean flow, pressure, velocity vectors, and wall shear stress contours. The experimental mass flow rate is compared with the results obtained from the simulation. Jamadar et al. [23] did a complete design of Gerotor pump for application in a high-speed diesel engine. A GUI-based program was used for the profile generation of the inner rotor, outer rotor, and inlet-outlet ports. The program was also able to calculate the output parameters like the flow rate and instantaneous flow ripple.

Despite their simplicity, very few studies relevant to the development of a simulation model for altitude conditions are available in open literature due to the complexity of the geometry of the variable volume chambers and two-phase flow phenomena. In the present work, flow analysis at various operating conditions was carried out by using Commercial CFD code ANSYS-Fluent with realizable k-ε turbulence and a multiphase model [24]. A prototype pump has been manufactured and tested for its performance and compared with the simulation result. The comparison indicates that simulation results match well with the measured data. From this study, the simulation method and technique adapted are appropriate for predicting the performance of gerotor pump at high altitude conditions of an aero engine.

Pump Performance

Gerotor pumps is a positive displacement pump, the flow rate is depended on pump speed, inlet pressure, outlet pressure, and fluid temperature. In the present study, outlet pressure and fluid temperature are maintained constant to reduce the number of variables. Pump performance is decided by its volumetric efficiency. Volumetric efficiency is calculated by the ratio of the effective volume flow rate from analysis or experimental result on the theoretical flow rate computed from the pump displacement. High rotational speed and low inlet pressure induce the incomplete filling of the chamber which results in a reduction in volumetric efficiency. Low inlet pressure of fluid causes the aeration of lubricating oil which results in partly filling of chamber with air and reduction in flow rate. This phenomenon also induces a cavitation mechanism within the pump cavity.

The volume of dissolved gas in the fluid is estimated by Henry-Dalton's law [3] as mentioned in Equation (1).

$$V_{gas} = B. \ V_{liq} \ (P + P_{atm} \ ) / P_{atm} \tag{1}$$

where; V_{gas} is the dissolved volume of air under normal conditions (20 °C, 101.3 kPa), V_{liq} is the volume of liquid under normal conditions, P is relative pressure and P_{atm} is atmospheric pressure, and B is Bunsen coefficient which is 0.08-0.1 for lubricating oil.

According to this law, the amount of dissolved air/gas is directly proportional to fluid pressure. In other words, the amount of dissolved air in the fluid is reduced by decreasing inlet pressure. Consequently, the amount of free air at the inlet of the pump is increased which resides with bulk fluid in the form of small bubbles. The aeration or air content is defined by the volume of air to the total volume.

CFD Analysis

Gerotor elements like inner rotor, outer rotor, and cover plates were modelled in Unigraphics software using geometrical parameters tabulated in Table 1.

Table 1: Geometrical parameter of gerotors

Geometrical parameter	Value in mm

Outer Lobe radius (S)	17.60
Eccentricity (e)	3.50
Radius of circle to complete external gear (G)	21.80
Number of outer lobes (n)	5.00
Distance of the centers of circular arc from center O_1 (K)	31.60
Thickness of rotor	7.00
Rotor tip clearance	0.02
Radial clearance between outer rotor and housing	0.05
Axial clearance between rotor and cover plate	0.03

The commercial computational fluid dynamics (CFD) tool ANSYS-Fluent was used for the flow analysis and to predict the performance of the pump. Leakage flow through micron-scale gaps in gerotor pump was considered in the present analysis except for leakage flow through shaft is neglected due to complexity in analysis. The computational domain along with the surrounding region of the gerotor pump is as shown in Figure 4. To achieve a good quality mesh along with the best compromise between the computational time and accuracy, the computational domain (control volume) was decomposed into four smaller sub-domains, chamber volumes between the inner and outer rotor, inlet and outlet cover plate volume, radial clearance passage and extension of inlet and outlet port. The mesh pictures for chamber volumes are shown in Figure 5.
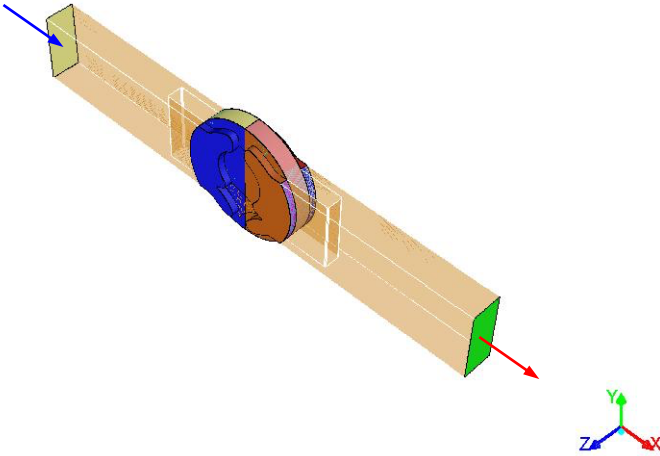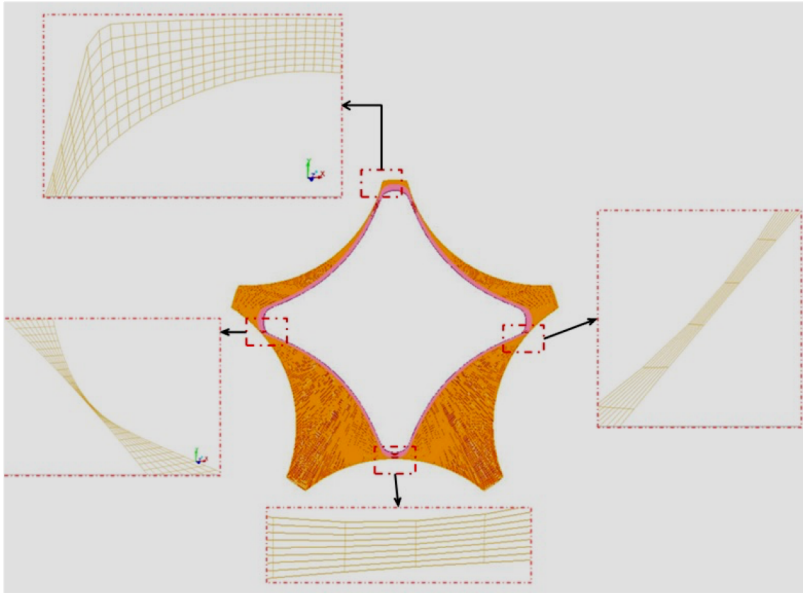

Figure 4: 3D view of CFD domain.

Figure 5: Mesh picture of chambers.

As can be seen, several elements were employed in the radial direction to achieve accurate results when resolving the radial gap fluid dynamics. In Solver, the boundary conditions and fluid properties as per lubricating oil specification MIL-PRF-23699 F were prescribed. Setting the boundary conditions mimics the operation of a real test, in that speed and pressure boundaries, are specified. A transient simulation was performed with a time step calculated based on the 0.25-degree rotation of the inner rotor. Here to perform a CFD simulation for a gerotor inside Fluent, the deforming fluid volume is identified as the region between the gerotor gears. This fluid region is known as gerotor core as shown in Figure 5 and the entire fluid volume is decomposed into moving and deforming volumes. Approximately three million elements were used after the grid-independent study. A realizable k-e turbulence model [24] was used for analysis. A multiphase model was employed to simulate the two-phase flow phenomenon inside the chamber. Four altitude conditions with four different speeds and two outlet pressures were selected for the analysis as tabulated in Table 2. Air content value is estimated from Henry-Dalton's law and mentioned in Table 2.

Table 2: Various simulation and test condition

Case Sl. No.	Altitude (km)	Pump Speed (rpm)	Inlet pressure (kPa)	Outlet pressure (kPa)	Air content (%)
1	0	3000 4500 5090 5600	100	200 400	0
2	5.0	3000 4500 5090 5600	54	200 400	4.2
3	8.0	3000 4500 5090 5600	35	200 400	5.9
4	10.0	3000 4500 5090 5600	26	200 400	6.7

Output volumetric flow along with radial and axial internal leakage flow rate were estimated at various simulation cases as mentioned in Table 2. Contour plot of static pressure, the volume fraction of air was extracted from the simulation results. A contour plot of static pressure for simulation case no. 2 is shown in Figure 6.
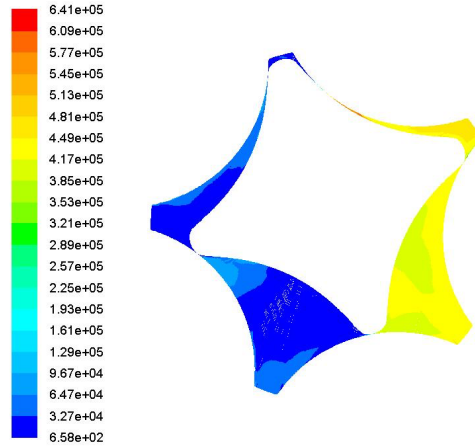

Figure 6: Static pressure contour at top surface of gerotor for case no.2.

Experimental Setup

A gerotor pump was manufactured and assembled (shown in Figure 7) in the test rig for validation of the simulation model with a set geometrical parameter as mentioned in Table 1. The layout of the rig setup is shown in Figure 8.

Test unit (oil pump) (8) draws the oil from the oil reservoir (1) and delivers it to a pressure and temperature sensors (10) turbine flow meter (11), pressure control valve (12) and then the oil is sent back to the oil reservoir (1). In the test bench, a thermocouple, and a speed sensor (not shown in Figure) were used for measuring oil temperature and rotation speed respectively. The test unit (oil pump) is driven by a variable frequency electric motor (9) which can vary the pump shaft speed; a control valve (12) is used for varying delivery line pressure. Low inlet pressure in the oil reservoir is maintained by a vacuum pump (5) and proportional valve (14). Inlet pressure and temperature are measured by pressure and temperature sensor (7). Oil is filtered by a fine filter (3) and heated by a heater (4). A Separate oil pump (2) is equipped for the filtration and heating of oil. Lubrication oil used was as per MIL-PRF-23699F. The oil temperature was maintained constant at 100 ˚C in all tests.

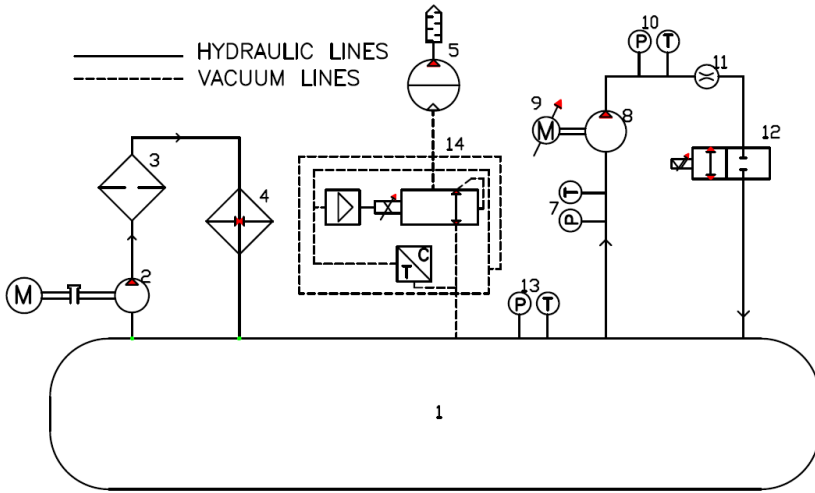Figure 7: Picture of assembled pump with test rig.

Figure 8: Schematic diagram of test setup.

Results and Discussion

Tests were performed at various speeds and inlet oil pressure as mentioned in Table 2. Tests were repeated for two outlet pressures i.e., 200 kPa and 400 kPa. Figure 9 shows the behaviour of volumetric efficiency of the pump at various inlet pressure when the pump was operating at outlet pressure 400 kPa and oil temperature 100 °C. A significant drop in volumetric efficiency was observed at maximum pump speed and low inlet pressure. Volumetric efficiency is reduced by 29% at maximum pump speed when oil inlet pressure is reduced to 26 kPa. Reduction in outlet flow rate is due to incomplete filling of the chamber by bulk oil when the pump is operating at low inlet pressure. Undissolved/free air occupies the space available in gerotor chambers at the low inlet pressure of the pump inlet.

Pump performance was presented at inlet pressures of 120 kPa to 20 kPa by Ippoliti et al. [8] which corresponds to seal level to 11.8 km altitude condition respectively. Similar kind of results was found and discussed. Volumetric efficiency was dropped to 51% and 40% at maximum pump speed when the pump was operating at an inlet pressure of 30 kPa and 20 kPa respectively. Whereas tested pump was performed with 75% and 64% volumetric efficiency when it was operating at an inlet pressure of 35 kPa and 26 kPa respectively as shown in Figure 9. The difference in pump performance results by Ippoliti et al. [8] with the tested result as shown in Figure 9 could be due to the difference in geometry of tested gerotors with the one presented by Ippoliti et al. [8].
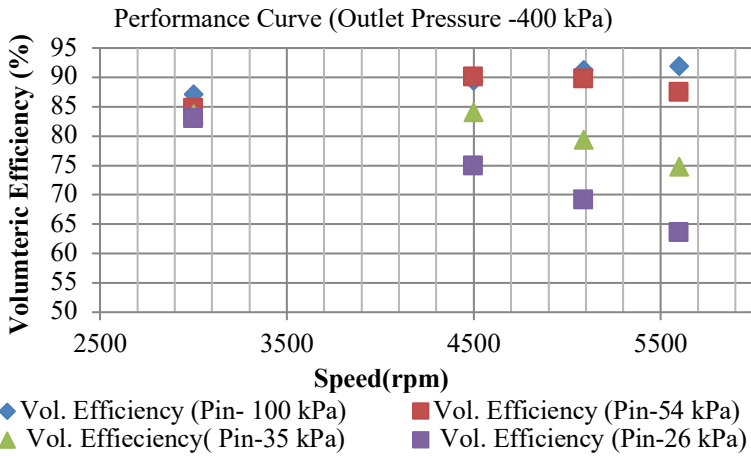
Figure 9: Pump performance curve (tested result).

Further, simulation results from CFD analysis were compared with tested results. A very close match was found between simulated values and experimental results at sea level conditions as shown in Figure 10. Simulation model prediction at maximum speed is 1.2% and 6.5% more than the experimental result when the pump was operating at outlet pressure 200 kPa and 400 kPa respectively.

Volumetric efficiency was estimated at different operating conditions and compared with experimental results. Comparison of model and test results at two different altitude conditions (8 km and 10 km) is shown in Figures 11 and 12 respectively. Good agreement is found between prediction from the simulation model and experimental results. It is also observed that simulation model results are not closely matching when the pump is operating at a lower speed compared to higher speed operation. Model is able to predict within 2-3% of volumetric efficiency at higher speed and 4-6% at lower speed. This difference is due to shaft internal leakage which is not considered in this study. As stated earlier, internal leakages are a direct function of the pressure gradient across the pump. In the present study, the pressure gradient is maintained the same during all speed operations. Therefore, the proportion of internal leakage value on the total flow rate is more at a lower speed.
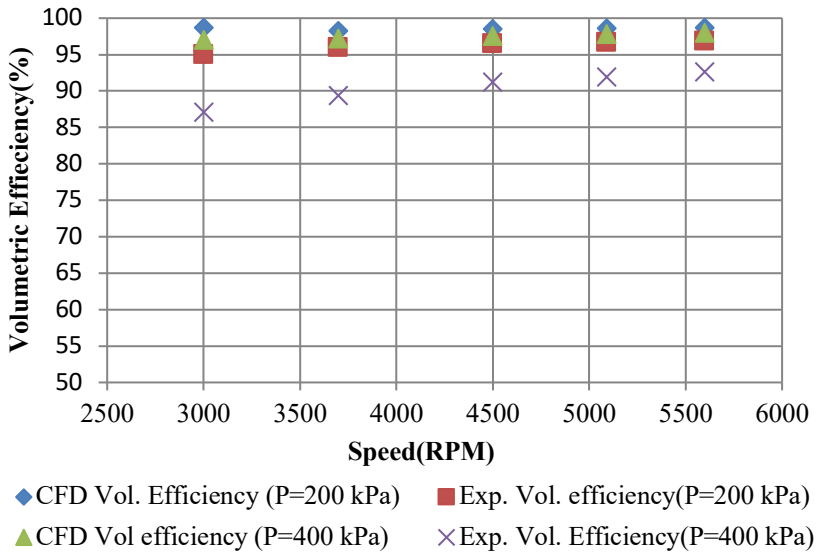
Figure 10: Comparison of volumetric efficiency between CFD results and experimental results (sea level condition).
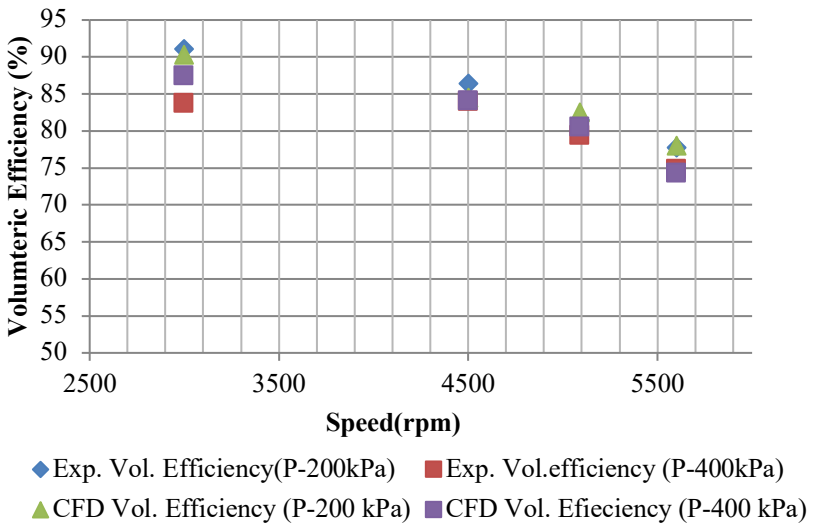

Figure 11: Comparison of volumetric efficiency between CFD results and experimental results (H=8 km).

Approximately 10-12% drop in volumetric efficiency is observed when the pump is operating at 8 km altitude condition as shown in Figure 11. Significant degradation of pump performance was observed at higher altitude conditions i.e., 10 km.

It is shown in Figure 12 that volumetric efficiency is dropped by approximately 20% at high altitude conditions. This drop inefficiency is due to an increase in free air volume in oil which causes incomplete filling of the chamber which results in the reduction of flow rate and volumetric efficiency.

◆ Exp. Vol. Effieciency (P-200 kPa)   ■ Exp. Vol. Efficiency (P-400 kPa)
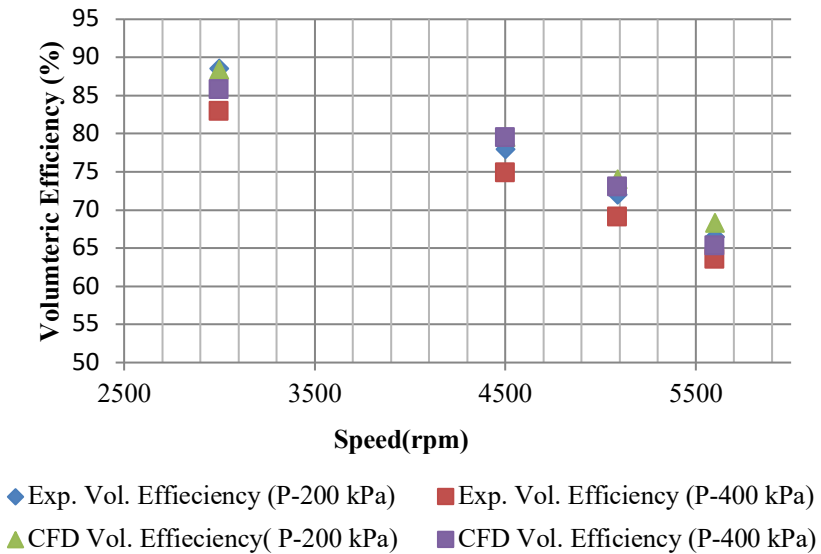▲ CFD Vol. Effieciency(P-200 kPa)   ■ CFD Vol. Efficiency (P-400 kPa)

Figure 12: Comparison of volumetric efficiency between CFD results and experimental results (H=10 km).

Conclusion

This paper presented the numerical and experimental study for investigating the performance of gerotor type lubricating oil pumps. The focus of this study is to evaluate the pump performance for high-altitude conditions. A significant drop in volumetric efficiency was observed during rig testing at simulated high-altitude conditions. Pump performance at sea level and altitude condition has been measured. Unsteady multi-phase CFD analysis of flow through a gerotor oil pump was carried out at various operating conditions. The results obtained by these analyses were compared with the

experimental values and results predicted by the simulation model have good agreement with experimental values. The simulation model is able to predict the degradation of pump performance with a maximum difference of 4-6% of volumetric efficiency. It was clearly shown that the contribution of inlet pressure to the pump flow efficiency was significant. Future studies will be focused on modelling shaft leakage flow in order to get closer results from CFD simulation. This methodology can be extended for a flow analysis of multistage gerotor pumps.

Thus, this methodology provides useful information to the lubrication system designer to design the system more easily and accurately. This proposed technique of simulation will be useful for design iteration through the fast modification of the pump design of an aero gas turbine engine.

Acknowledgment

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