



Study of the scavenge pump performance for two-phase flow in an aircraft engine lubrication system

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Abstract

The proper functioning of the scavenge pump is a crucial foundation for maintaining the normal circulation of the lubrication system, with its performance and reliability directly impacting the safety of aero engines. This paper focuses on studying the two-stage scavenge pump, establishes the scavenge pump flow performance test system under oil-air two-phase medium, and conducts experimental research on the flow rate performance under relative pressure at high altitude based on ground tests. The high-altitude state takes the local atmospheric pressure at different flight altitudes of the aircraft as a reference, adjusts the inlet pressure of the pumps at all levels to the reference value, and measures the flow rate after reaching stability. This article obtains the effect of inlet pressure, outlet pressure, oil-air ratio and rotational speed on the flow characteristics and volumetric efficiency of the oil pump through experiments.

Keywords: scavenge pump; oil-air two-phase flow; high altitude pressure; volumetric efficiency

1. Introduction

The lubrication system of aircraft engines supplies lubricating oil to the bearings and gears for lubrication, which mixes with the sealed air in the cavity to form an oil-air mixture in the bearing cavity and accessory gearbox. The oil pump suctions the oil-air mixture for transport to components such as the oil-gas separator for the recovery of lubricating oil, and ultimately returns to the sliding oil tank for cyclic use. Therefore, the proper functioning of the scavenge pump is essential to ensure the smooth circulation of the lubrication system. Besides the standard mechanical operation, it is crucial to ensure that the suction capacity of the pump is sufficient to prevent oil accumulation in the cavity. Filling loss is an important factor in the reduction of volumetric efficiency of the aero-engine lubrication oil pump. Especially at high altitude, the filling loss will be especially prominent, leading to the reduction of the volumetric efficiency of the aero-engine oil pump, and the accumulation of sliding oil in the cavity will cause the leakage of sliding oil, and even cause the fire.

In the lubrication system of aircraft engines, internal mesh cycloidal gear pumps are often used as sliding oil pumps. Compared with external meshed gear pumps, internal meshed cycloidal gear pumps have a compact structure, fewer gear teeth, higher rotation speed, absence of idler shaft, high volumetric efficiency, low noise and other advantages. Early research on oil pump volumetric design primarily focused on structural design and flow characteristics. Matsunaga et al [1] proposed a variable operational mode structure for a cycloidal fuel pump, which can switch to a series operation mode at high altitudes. Biernacki et al [2-5] designed a polyoxymethylene plastic rotor cycloidal pump. Frosina and Senatore et al [6-7] analyzed the flow characteristics and pressure pulsations of internal combustion engine oil pumps using a one-dimensional method. Srinivasan et al [8] indicated that reducing rotor thickness and axial clearances can enhance the performance of the lubricating pump. Rundo et al [9] introduced a lumped parameter model for a variable displacement vane pump based on dissolution kinetics to analyze the impact of dissolved air in the lubricating oil on pump performance. The studies mentioned above are primarily conducted through ground experiments.

Considering the high-altitude operating environment of aircraft engines, researchers have investigated the high-altitude performance of oil pumps. Hussain et al [10] conducted numerical simulations and experimental studies on the high-altitude characteristics of the lubricating pump of the aircraft engine, exploring their operational performance. Li et al [11] researched the high-altitude characteristics of oil pumps, deriving relationship equations among various influencing factors. Guan et al [12] analyzed the speed-flow characteristics and high-altitude properties of multistage oil pumps

for aviation engines. Research conducted by Li [13] indicates that as the flight altitude increases, the cavitation phenomenon inside the pump intensifies, resulting in a decrease in oil supply flow.

The vast majority of the aforementioned publicly published literature pertains to the oil supply pump in aircraft engines. However, there are relatively few studies related to the scavenge pump operating under oil-air two-phase medium. Particularly, when the scavenge pump operates at high altitudes, it is more prone to causing filling loss, exacerbating the issue of cavitation. Currently, the volume of the scavenge pump in engineering is generally 3 to 5 times that of the supply pump. The specific values mainly refer to the design of the old model engine or blindly increase the volume of the scavenge pump without experimental or rigorous theoretical support. The complexity of the capacity design of the scavenge pump is attributed to the challenging experimental environment where the pump operates within a mixture of oil and air, coupled with the difficulty in conducting quantitative testing of the flowing medium at the inlet. However, engineering practice has proved that even under the above volume, there is often a phenomenon of insufficient oil return capacity in the lubrication system. This phenomenon is closely related to experimental methods and working characteristic analysis of the scavenge pump.

Up to the present, there is a scarcity of published research papers on the characteristics of oil pumps in oil-air two-phase flow, both domestically and internationally, with the variations in flow under different conditions remaining unclear. Singh [14] showed that the filling speed of oil pumps decreases with increasing air content in the lubricating oil. Ippoliti [15] took aero-engine oil supply pump as the project and found that the performance of the pump is primarily affected by gas content and cavitation in the lubricating oil, while the cavitation number was introduced to analyze the effect of cavitation on the volumetric efficiency. Furthermore, Ippoliti [16-17] conducted tests in pure oil and oil-air mixtures, highlighting significant differences in performance impacts between pure oil and oil-air mediums on oil pumps. This discrepancy emphasizes the need for separate performance testing for the scavenge pumps. The disconnection between the design and testing phases of the scavenge pumps and practical application environments poses significant challenges.

In summary, the current research progress on oil pumps, both domestically and internationally, primarily focuses on geometrical design and performance parameter evaluations of pumps under single-phase medium. There is a scarcity of systematic and comprehensive research on the operational characteristics of the scavenge pump in multiphase working environments. Therefore, it is crucial to investigate the flow characteristics of the scavenge pump in oil-air two-phase flow to provide insights for related studies of cycloidal pump performance under multiphase flow conditions and to optimize the lubrication system.

In this paper, through experimental research of a two-stage scavenge pump, the flow rate performance of the pump under the ground pressure and high-altitude pressure conditions, including suction oil flow and volumetric efficiency, is compared under the oil-air two-phase medium.

2. Experimental research

2.1 Introduction to the test system

This paper takes the two-stage scavenge pump as the object. The main geometric model structure includes the internal and external meshing gear pairs and the lubricating oil pump casing. The number of internal gear teeth is 4, and the number of external gear teeth is 5. The eccentricity is 4.5mm, and the tooth thickness is 10mm. The two-stage scavenge pump, as illustrated in Figure 1, consists of two inlet ports designated as the stage 1 and stage 2, along with a single oil outlet.

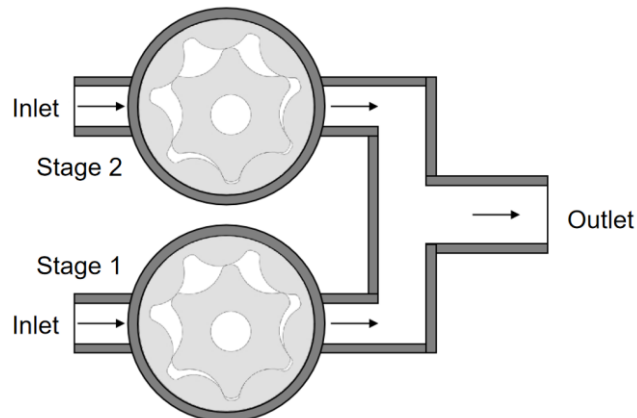


Figure 1–Schematic diagram of the two-stage scavenge pump

In consideration of the experiment being conducted under oil-air two-phase medium, the installation of an oil-air mixing device is necessary. The structure of this mixing device is depicted in Figure 2. It comprises an air inlet where an air tube extends into the interior of the mixing device and connects to the mixing device chamber through air outlets. There are 64 evenly distributed 1mm diameter air outlets on the air tube. To achieve more uniform mixing, the mixing device is equipped with two oil inlets.

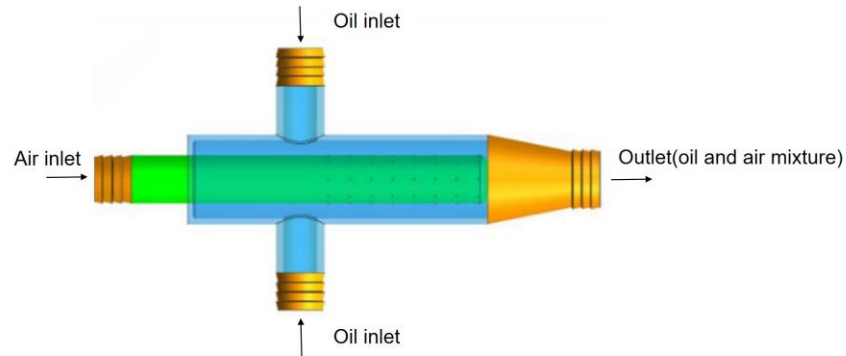


Figure 2–Schematic diagram of static oil and gas mixing device.

The test system as shown in Figure 3, air enters the oil-gas mixer after pressure reduction by the pressure reducing valve in the air supply system and measurement by the mass flow meter; the lubricating oil is pressurized by the booster pump and measured by the mass flow meter in the lubricating oil tank, and then uniformly mixed with the air in the oil-gas mixer. The oil-gas mixture flowing out of the oil-gas mixer enters the test pump for testing. After passing through the test pump, the oil-gas mixture is sent to the oil-gas separator for separation. The lubricating oil is returned to the lubricating oil tank for recycling, while the separated gas is processed and discharged into the atmosphere through the pipeline.

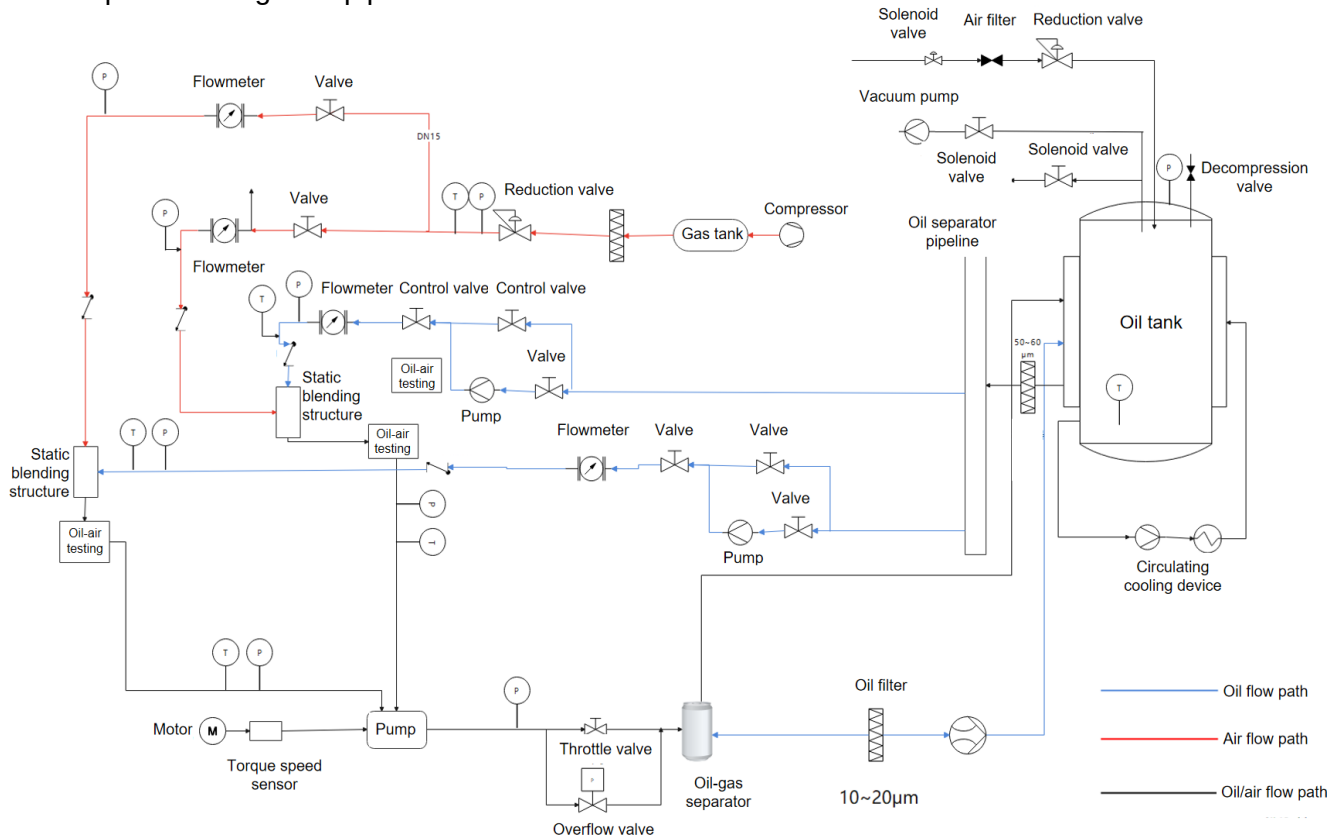


Figure 3–Schematic diagram of aero-engine oil pump test system

During the ground experiment, the inlet pressure of the scavenge pump is initially adjusted to a range of 100 ± 3 kPa under the pure oil medium, and the opening of the throttle valve behind the pump is set to 100%. The experiment commenced after the flow rate of each stage stabilized. During the experiment, the rotational speed of the booster pump is adjusted to gradually reduce the lubricant flow rate, while introducing air and adjusting the gas pressure to maintain the inlet pressure of each stage within the specified range. Measurements are taken after the flow rate of each stage

stabilized. Moreover, the state of the throttle valve behind the pump and other components remains constant throughout the entire experimental process.

To study the effect of inlet pressure at high altitude on the working characteristics of the scavenge pump, it is necessary to control the inlet pressure in the experiment. The oil supply route utilizes a vacuum pump to depressurize the lubricant tank, combined with the pressure loss along the route from the oil tank to the pump inlet, ultimately reducing the inlet pressure of the pump to the specified value. Air is supplied by the air compressor and air tank, with a minimum air source pressure of 100 kPa. If the inlet pressure cannot be decreased to the specified value, air is directly extracted from the laboratory environment through the suction capability of the pump, and the gas pressure is further reduced by throttling to achieve the specified pressure of the oil and gas mixture at the pump inlet. Measurements are conducted after the flow rate stabilizes. Additionally, the opening of the throttle valve behind the pump is set to 100% throughout the entire test process, and all components behind the pump are kept in a constant state.

2.2 The performance parameter of the scavenge pump

The purpose of the scavenge pump test is to measure the lubricating oil flow rate under different working conditions. Under the oil-air two-phase medium, the main factors affecting the flow rate of the oil pump are the inlet pressure(P_{in}), outlet pressure(P_{out}) and rotational speed(n), where the different inlet pressures simulate the pressure of the bearing chamber at different heights, and the different outlet pressures simulate the loads of the oil return system under different working conditions of the engine.

In engineering, the inlet gas content and oil-air ratio are commonly utilized as parameters to describe the oil-air two-phase flow. Inlet gas content φ is defined as the ratio of air volume flow rate to the total flow rate of the oil-air mixture, while the oil-air ratio α is defined as the ratio of the oil volume flow rate to the air volume flow rate, as shown in Eq (1) and Eq (2) .

$$\varphi = \frac{Q_{air}}{Q_{air} + Q_{oil}} \quad (1)$$

$$\alpha = \frac{Q_{oil}}{Q_{air}} \quad (2)$$

Where Q_{oil} is the lubricating oil flow rate, Q_{air} is the air flow rate.

During the test under oil-air two-phase medium, the lubricating oil volumetric efficiency is utilized as the performance evaluation index of the oil pump. This efficiency is calculated as the ratio of the actual lubricating oil flow rate to the theoretical flow rate[18], with the expression provided below:

$$\eta_{oil} = \frac{Q_{oil}}{Q_t} \quad (3)$$

Where Q_{oil} is the lubricating oil flow rate, Q_t is the theoretical flow rate.

Furthermore, the utilization of the two-phase volumetric efficiency η_{mix} is employed to characterize the performance parameters of the oil pump pumping oil-air mixture. This efficiency metric is determined as the ratio of the actual flow rate of the oil-air mixture to the theoretical flow rate and is expressed by the formula:

$$\eta_{mix} = \frac{Q_{oil} + Q_{air}}{Q_t} \quad (4)$$

Where Q_{oil} is the lubricating oil flow rate, Q_{air} is the air flow rate, Q_t is the theoretical flow rate.

3. Results and Analysis

3.1 Ground experiment under oil-air two-phase medium

3.1.1 Impact of inlet pressure on pump performance

In this section, the impact of inlet pressure on the two-phase volumetric efficiency is discussed, with the inlet pressure ranging from 90 to 110 kPa and the oil flow rate varying between 2 and 35 L/min. Figure 4 shows the variation law of inlet gas content with the change of inlet pressure under different lubricating oil flow rates under oil-air two-phase medium. The graph indicates that the impact of inlet pressure on the gas content at the inlet is minimal, with a larger lubricating oil flow rate corresponding to a lower inlet gas content. For instance, at lubricating oil flow rates of 3 L/min and 30 L/min for the stage 1, the difference between the highest and lowest inlet gas content is 3% and 1% respectively. It is approximated that the influence of inlet pressure on the inlet gas content can be disregarded, allowing for the control of a single variable during the experimental process to meet the requirements of the scavenge pump experiment.

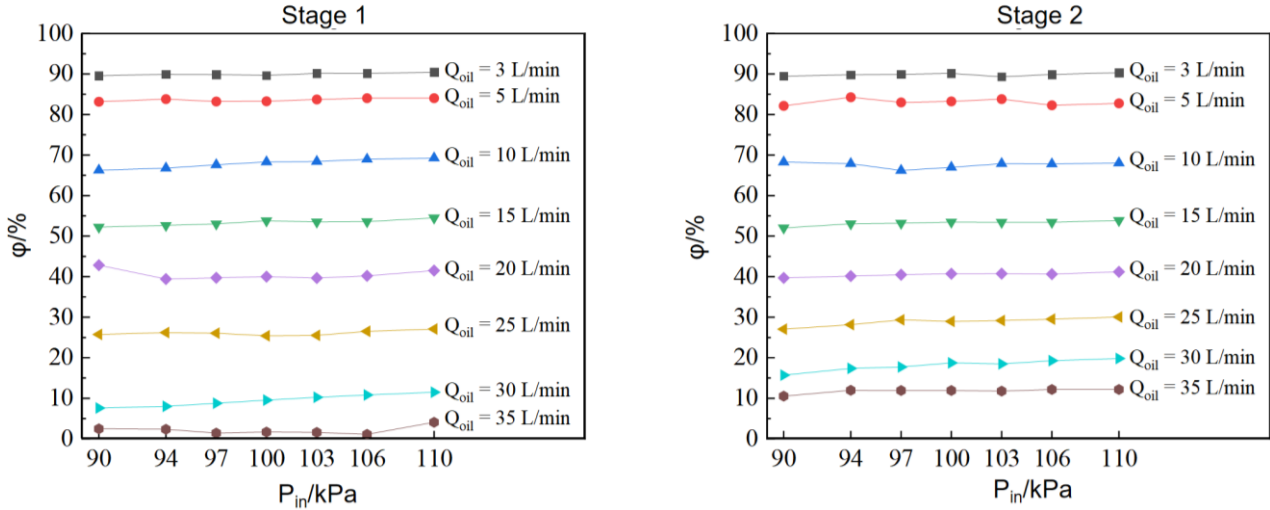


Figure 4—Impact of inlet pressure on inlet gas content at different oil flow rates

Figure 5 illustrates the variations in the inlet gas content and the two-phase volumetric efficiency of the stage 2 at different oil flow rates. The graph demonstrates a linear relationship between oil flow rate and both the inlet gas content and the two-phase volumetric efficiency. With constant inlet pressure, higher oil flow rates correspond to increased two-phase volumetric efficiency. When maintaining a constant oil flow rate, the two-phase volumetric efficiency decreases as the inlet pressure declines. The decrease is relatively small, approximately within 5%.

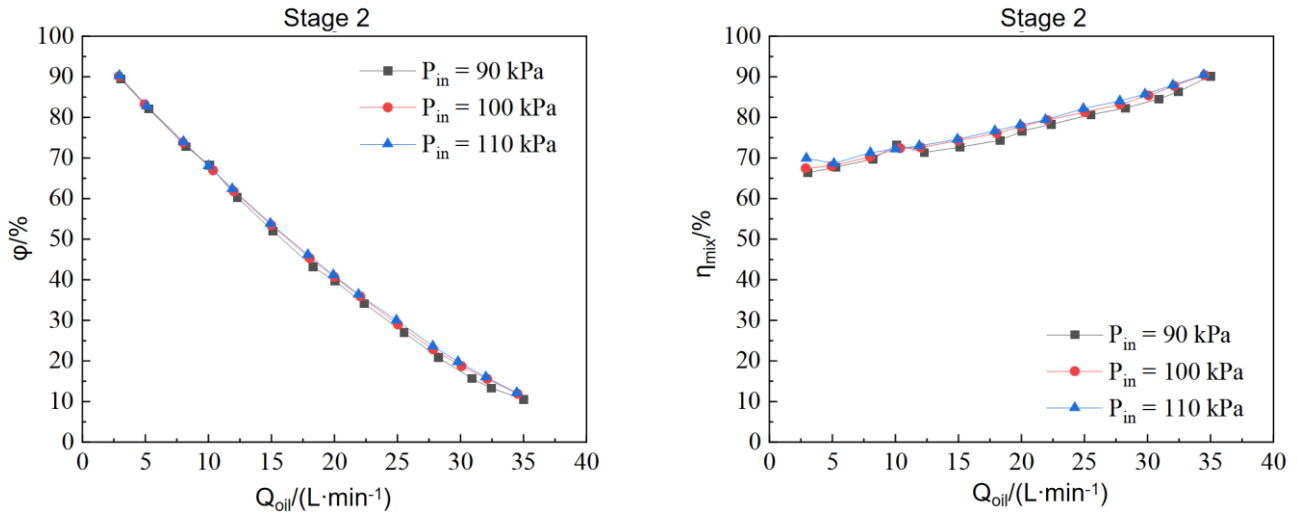
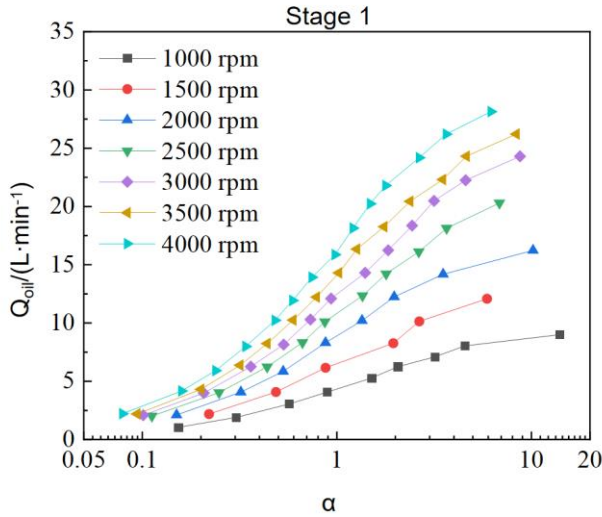


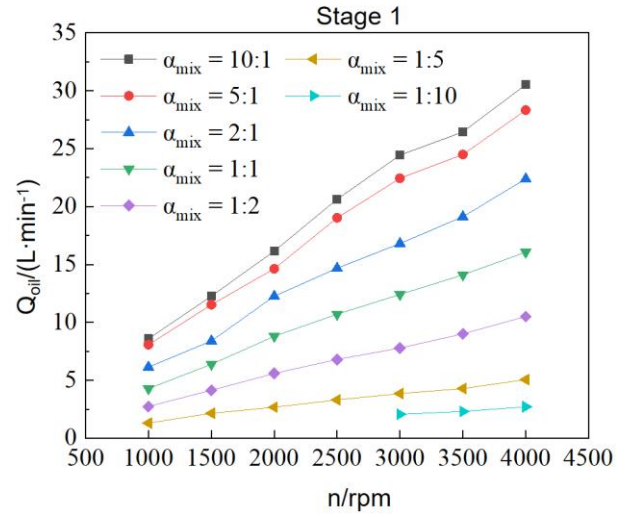
Figure 5—Impact of oil flow rate on the two-phase volumetric efficiency at different inlet pressure in the stage 2.

3.1.2 Impact of rotational speed and oil-air ratio on pump performance

This section takes the pump performance of the stage 1 as an example. Figure 6 shows the lubricating oil flow rate at different inlet oil-air ratios and rotational speeds. It is evident from the Figure 6(a) that the oil flow rate pumped is correlated with both the rotational speed and the inlet oil-air ratio. At the same rotational speed, the relationship between the oil flow rate and the inlet oil-air ratio is non-linear. Furthermore, with an increase in the oil-air ratio to a certain threshold, the pumped oil flow rate reaches a specific limit, ultimately converging towards the oil flow rate under pure oil medium. In Figure 6(b), it is shown that the oil flow rate has a roughly linear relationship with the rotational speed when the inlet oil-air ratio is below 2. This is consistent with the variation of oil volumetric efficiency with oil-air ratio when the oil-air ratio is less than 2 as shown in Figure 7. The slope of this linear relationship directly correlates with the oil-air ratio. As the inlet oil-air ratio increases, the slope also increases, indicating that a higher inlet oil-air ratio results in higher volumetric efficiency.



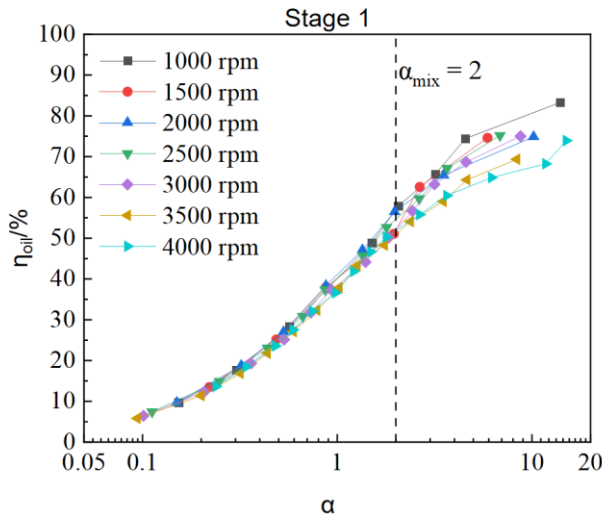
(a) Oil-air ratio- oil flow rate



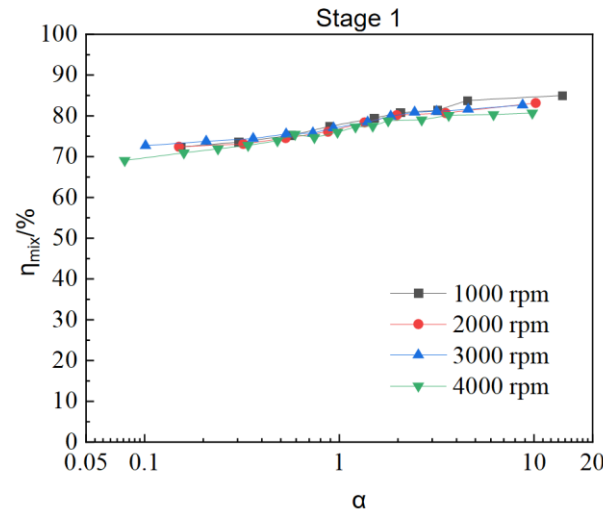
(b) Rotational speed- oil flow rate

Figure 6–Impact of the inlet oil-air ratio and rotational speed on the lubricating oil flow rate

Figure 7 demonstrates the influence of the inlet oil-air ratio on the oil volumetric efficiency and the two-phase volumetric efficiency at various rotational speeds. It is evident that both the oil volumetric efficiency and the two-phase volumetric efficiency increase as the inlet oil-air ratio increases. According to Figure 7(a), in instances where the inlet oil-air ratio does not exceed 2, the oil volumetric efficiency remains constant with the rotational speed. However, as the oil-air ratio surpasses 2, the corresponding oil volumetric efficiency decreases with increasing rotational speed. In the experimental setup, a higher oil-air ratio leads to the oil volumetric efficiency approaching that of pure oil. The results indicate that when the inlet oil-air ratio is less than 2, the oil volumetric efficiency is solely dependent on the inlet oil-air ratio. In Figure 7(b), the variation of the two-phase volumetric efficiency at different rotational speeds with changes in the inlet oil-air ratio is displayed. It is evident that, at the same inlet oil-air ratio, the difference in the two-phase volumetric efficiency between different rotational speeds is minimal. It is commonly assumed that the two-phase volumetric efficiency does not vary with rotational speed and is solely associated with the inlet oil-air ratio.



(a) Oil-air ratio- oil volumetric efficiency



(b) Oil-air ratio- two-phase volumetric efficiency

Figure 7–Impact of the inlet oil-air ratio on the oil volumetric efficiency and the two-phase volumetric efficiency at different rotational speeds

Figure 8 illustrates the variations in the outlet pressure and torque at different inlet oil-air ratios and rotational speeds. It is evident that the trends in the torque and outlet pressure changes are similar, both increasing with an increase in the oil-air ratio. The impact of the oil-air ratio on the torque and outlet pressure becomes more pronounced with higher rotational speeds.

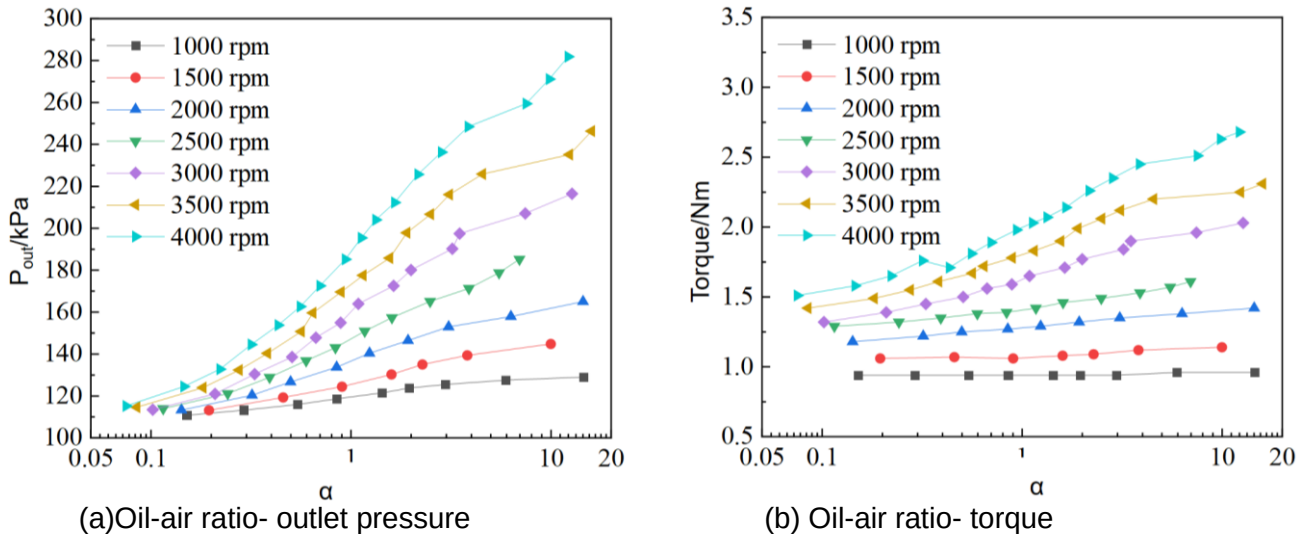


Figure 8—Impact of the inlet oil-air ratio on the outlet pressure and torque at different rotational speeds

This section examines the impact of different rotational speeds and oil-air ratios on pump performance. The analysis reveals a correlation between the volume of oil suctioned, rotational speed and oil-air ratio. When the oil-air ratio is relatively low, the rotational speed has a minimal effect on oil volumetric efficiency. Higher oil-air ratios correspond to higher oil volumetric efficiency. Once the minimum amount of suction oil is determined, the corresponding minimum oil-air ratio for various rotational speeds is also established. If the ratio falls below this critical threshold, the suction capacity of the pump becomes inadequate.

3.1.3 Impact of outlet pressure on pump performance

Under constant temperature conditions with pure oil as the working medium, the factors affecting the outlet pressure of the pump are the opening of the throttling valve behind the pump and the rotational speed. When the working medium consists of an oil-air mixture, the outlet pressure is influenced not only by the opening of the throttle valve and rotational speed but also by the oil-air ratio. Hence, it is essential to explore the influence of outlet pressure on the pump performance under oil-air two-phase medium.

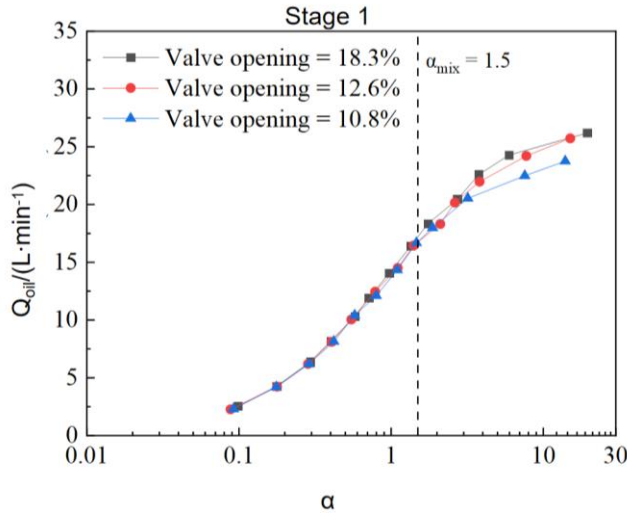
Tailoring the pump outlet pressure to specific values for each operating condition in the experiment is a time-consuming process that could potentially impact the pump inlet pressure. Therefore, in this section of the experiment, the status of the scavenging pump is adjusted to the specified outlet pressure under pure oil medium, to determine the corresponding opening of the throttle valve behind the pump, with adjustments made to the oil-air ratio at each opening. The corresponding openings of the throttling valve behind the pump for various outlet pressures and rotational speeds are provided in Table 1.

Table 1-Opening of the throttling valve behind the pump at different outlet pressures and rotational speeds

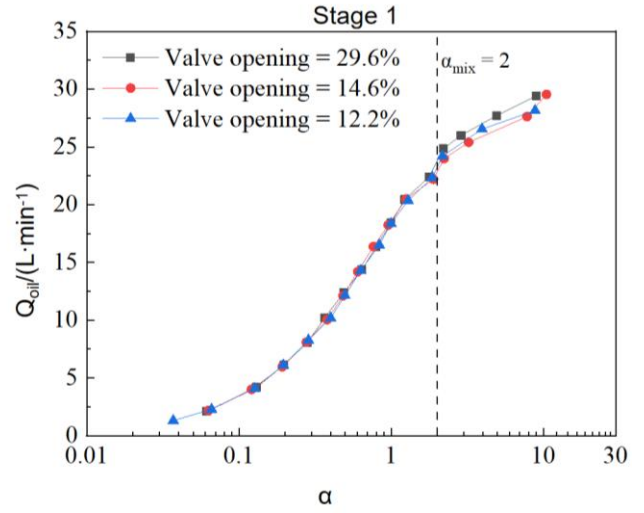
Outlet pressure under pure oil medium(kPa)	Opening of the throttling valve behind the pump (%)	
	3000rpm	4000rpm
300	18.3	29.6
450	12.6	14.6
600	10.8	12.2

Figure 9 illustrates the relationship between the oil flow rate and inlet oil-air ratio across different throttle valve openings at 3000 rpm and 4000 rpm. As shown in Figure 9(a), the correlation between the oil flow rate and inlet oil-air ratio closely aligns for inlet oil-air ratios below 1.5, even across different operating conditions of the throttle valve behind the pump, showing only minor discrepancies for oil-air ratios exceeding 1.5. This indicates that the outlet pressure has a negligible effect on the oil suction capacity of the scavenge pump under oil-air two-phase medium. Figure 9(b) distinctly reveals that when the inlet oil-air ratio is below 2, the impact of the opening of the throttling valve behind the pump on the variation between the oil flow rate and inlet oil-air ratio is minimal,

similar to the experimental results at 3000 rpm.



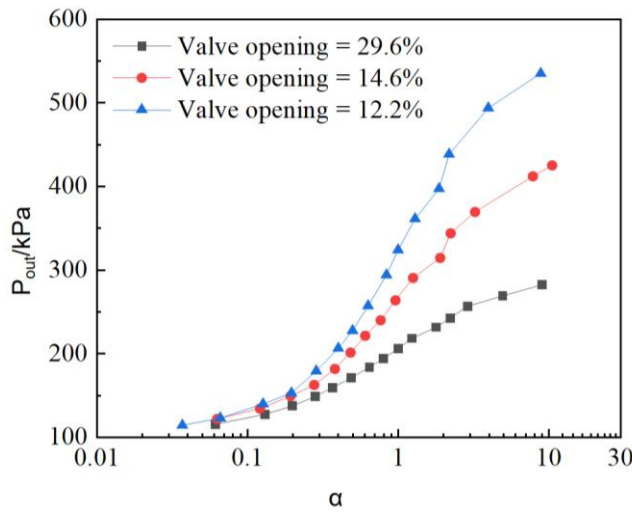
(a) Oil-air ratio- oil flow rate at 3000rpm



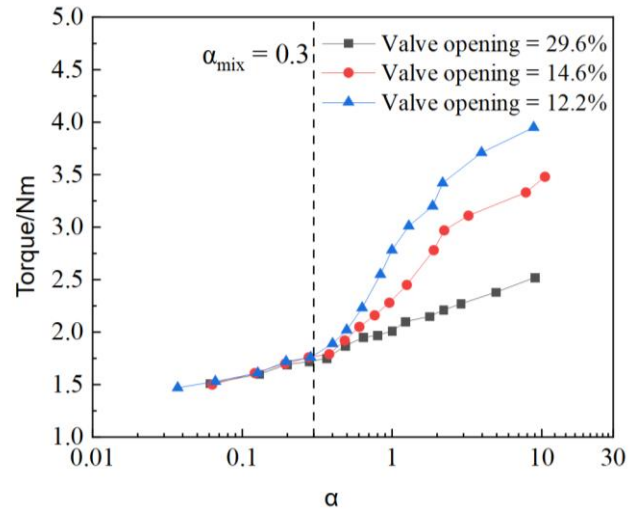
(b) Oil-air ratio- oil flow rate at 4000rpm

Figure 9–Impact of the inlet oil-air ratio on the oil flow rate at 3000rpm and 4000rpm

Figure 10 displays the variation curves of the outlet pressure and torque with the inlet oil-air ratio at different throttle valve openings. From Figure 10(a), it is evident that despite providing a specific outlet pressure value before the experiment, the actual experimental process resulted in the outlet pressure being lower than the specified value. The outlet pressure varies with changes in the inlet oil-air ratio, particularly, as the oil-air ratio increases, the oil flow rate also increases, resulting in a larger disparity in resistance. The relationship between the torque and inlet oil-air ratio is not affected by the throttle valve opening behind the pump when the inlet oil-air ratio is less than 0.3, as clearly demonstrated in Figure 10(b). In contrast, an inlet oil-air ratio exceeding 0.3 amplifies the effect of the throttle valve opening behind the pump.



(a) Oil-air ratio- outlet pressure



(b) Oil-air ratio- torque

Figure 10–Impact of the inlet oil-air ratio on the outlet pressure and torque at 4000rpm

Overall, within the experimental range, with fixed pump inlet pressure and rotational speed, the parameter influencing the oil suction flow rate of the pump is the inlet oil-air ratio. The inlet oil-air ratio corresponds directly to the oil flow rate, and shows minimal correlation with the outlet pressure and status of components behind the pump. And the pump outlet pressure is affected by both the inlet oil-air ratio and oil flow rate, with these parameters directly corresponding to each other.

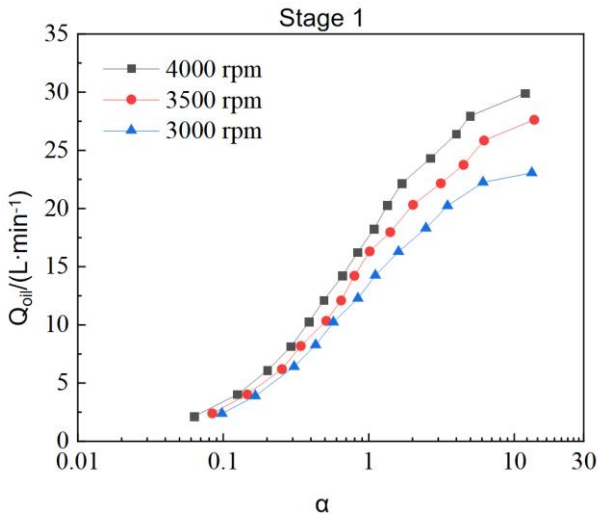
3.2 High-altitude experiment under oil-air two-phase medium

Investigating the influence of various inlet relative pressures and rotational speeds on pump performance in high-altitude conditions under oil-air two-phase medium, while regulating the pump inlet relative pressure within the range of -80 to -20 kPa. Figure 11-14 illustrates the relationship between lubricating oil flow rate, oil volume efficiency, and inlet oil-air ratio under different inlet pressures and rotational speeds. It can be seen that the suction capacity of the pump is affected by the rotational speed and the pressure before the pump.

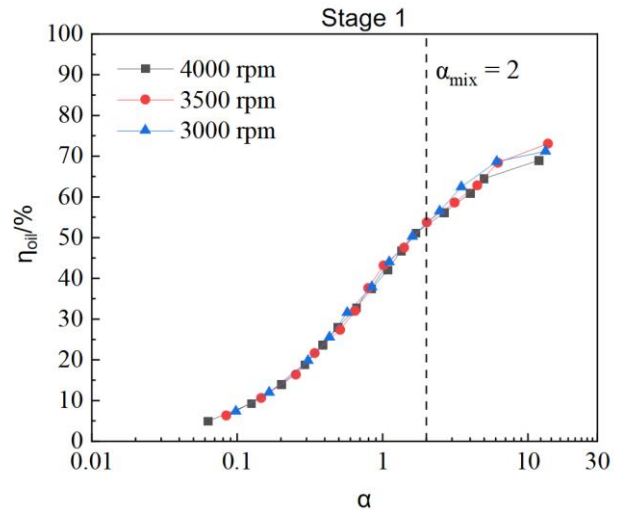
At the same rotational speed and oil-air ratio, the lower the inlet relative pressure (higher negative

pressure), the lower the oil flow rate suctioned by the pump and thus, the reduced suction capacity of the pump. With higher inlet pressure and relatively lower oil-air ratio (specific value), the difference in oil volumetric efficiency at different rotational speeds is minimal, reflecting similarities with ground experimental outcomes. However, this specific value is associated with the inlet pressure: the lower the inlet pressure, the smaller the value. For instance, at a relative pressure of -20 kPa, the oil-air ratio is less than 2; at -40 kPa, the oil-air ratio is less than 1.2. However, even at relative pressures of -60 kPa and -80 kPa, the oil volumetric efficiency of the pump differs, even at very low oil-air ratios.

Under the same rotational speed and relative pressure, the volume of oil suctioned and oil volumetric efficiency increase with an increase in the oil-air ratio. In various operating conditions, the suction oil flow rate also rises as the oil-air ratio increases, with higher ratios approaching the oil flow rate under pure oil medium. Once the oil-air ratio exceeds a certain threshold, the increase in suction oil flow rate slows down as the oil-air ratio increases, and this value changes with variations in the inlet relative pressure. For instance, at a relative pressure of -20 kPa, the oil-air ratio value is 4, whereas at -40 kPa, it is approximately 2. Additionally, at very low oil-air ratios, it may lead to issues where the pump fails to suction oil or the oil flow rate is too small for accurate measurement, especially at low rotational speeds. When the oil-air ratio is less than 1:6, the pump may fail to suction the oil, potentially leading to oil accumulation within the chamber. And with lower rotational speeds and relative pressures, the mass flow rate of air decreases, reaching approximately 0.5~5g/min, significantly lower than the flow meter range. This causes a drop in measurement accuracy, resulting in errors in calculating the oil-air ratio. For instance, at relative pressures of -60 kPa and -80 kPa with the same oil-air ratio conditions, the oil flow rate at 3000 rpm is slightly higher than at 3500 rpm.

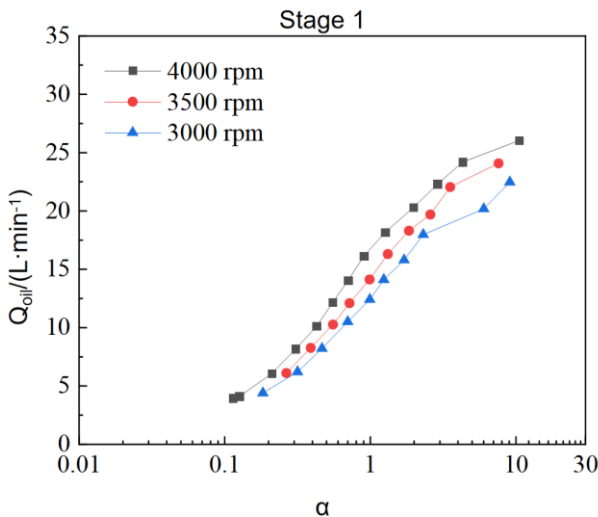


(a) Oil-air ratio- oil flow rate

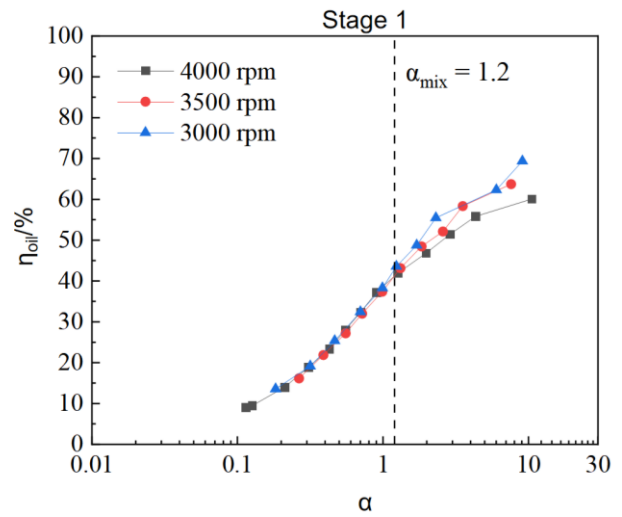


(b) Oil-air ratio- oil volumetric efficiency

Figure 11–The pump performance at the inlet relative pressure of -20kPa



(a) Oil-air ratio- oil flow rate



(b) Oil-air ratio- oil volumetric efficiency

Figure 12–The pump performance at the inlet relative pressure of -40kPa

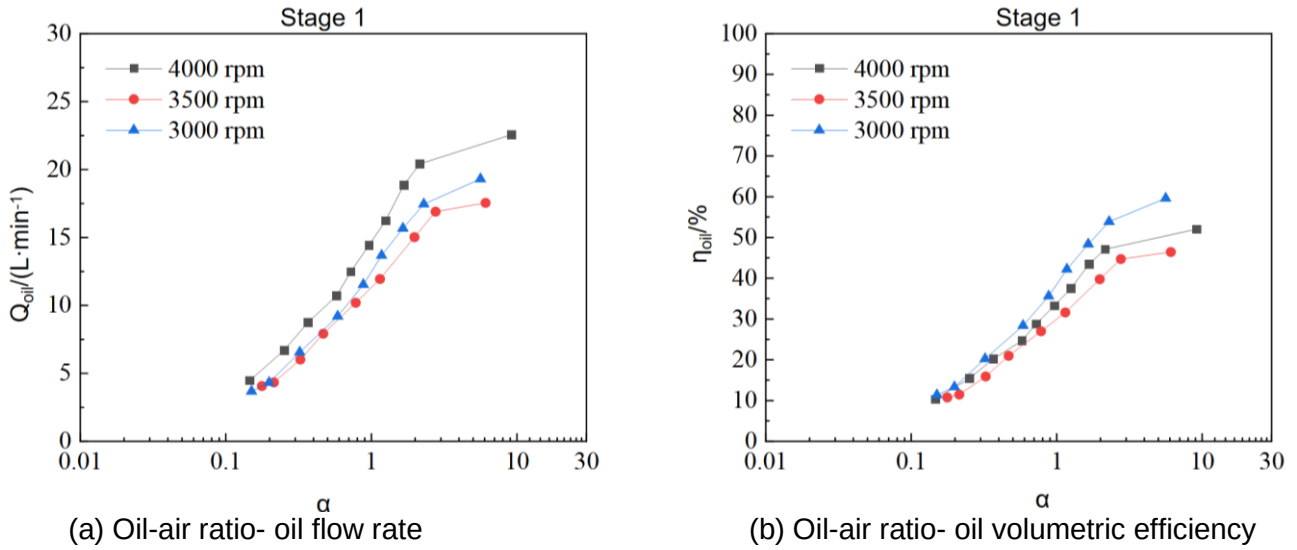


Figure 13–The pump performance at the inlet relative pressure of -60kPa

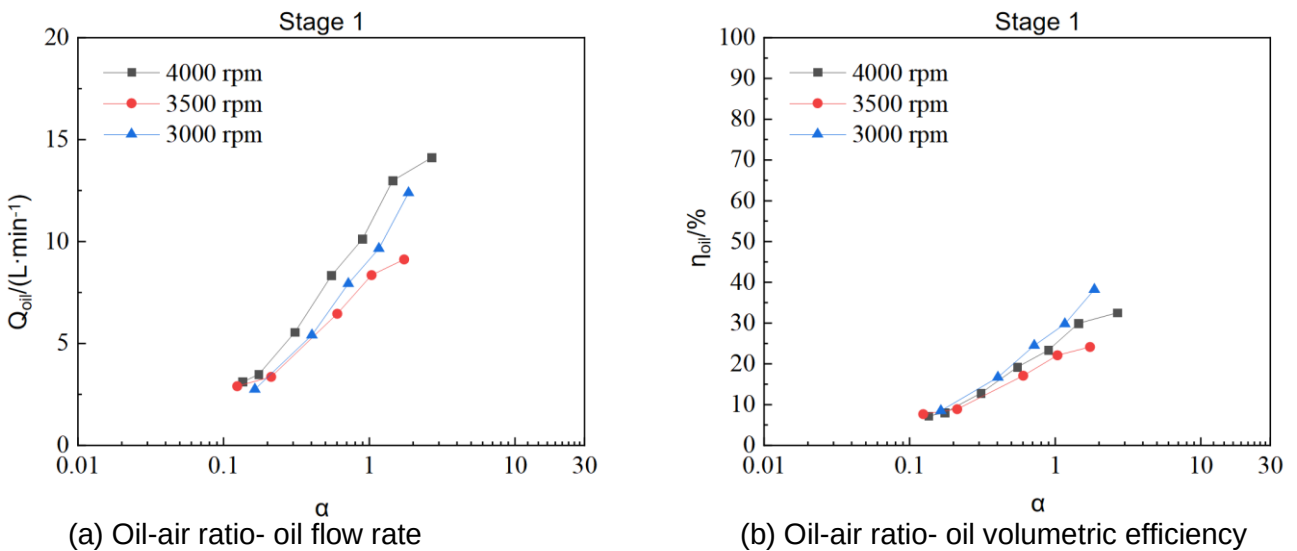


Figure 14–The pump performance at the inlet relative pressure of -80kPa

4. Discussion

This study conducted experimental research on the operational characteristics of the scavenge pump under oil-air two-phase medium, investigating the effects of inlet pressure, rotational speed, inlet oil-air ratio, and outlet pressure on the suction capacity of the pump. The following conclusions can be obtained.

- (1) Under ground pressure conditions, the main factors influencing the suction oil flow and volumetric efficiency include rotational speed and inlet oil-air ratio. When the inlet oil-air ratio is low, the relationship between volumetric efficiency and rotational speed is not significant; whereas with a high inlet oil-air ratio, there is a considerable difference in oil volumetric efficiency among different rotational speeds. When the outlet pressure is below 600 kPa, it has minimal impact on the operating characteristics of the scavenge pump.
- (2) Under high-altitude pressure conditions, the pump performance is highly sensitive to the inlet pressure. With the same rotational speed and inlet oil-air ratio, the smaller the inlet relative pressure, the lower the oil volumetric efficiency of the pump, with a significant impact. Despite the very small oil-air ratio, at lower inlet relative pressures, the oil volumetric efficiency is closely related to the rotational speed, displaying a notable distinction from pure oil medium.
- (3) For oil-air ratios below 1:6, the suction capacity of the pump may be compromised, possibly resulting in oil accumulation within the chamber.

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