Experimental Study on Multi-attitude Oil Supply Structure

Yu Xu[1], Ya-Guo Lyu[1], Jian-Ping Hu[1], Zhenxia Liu[1]

[1] School of Power and Energy, Northwestern Polytechnical University, Xi'an 710129, China

Abstract

The high-maneuverability and multi-attitude flight of the aircraft poses new challenges to the engine lubrication system Achieving continuous oil supply and lubrication during high maneuverability flights is essential for improving engine safety. In this paper, the effects of inlet flow, working attitude angle and lubricating oil level height on the ejection capacity of the oil supply structure are analyzed. And the ventilation and oil-oil separation performance of the oil supply structure are tested. The experimental lubricating oil flow range is 10~45L/min, the air flow range is 6~37SL/min, and the attitude angle range is -35°~35°. The injection flow rate of the multi-attitude oil supply structure ranges from 0.06 to 0.12L/min, the ventilation efficiency is about 90%, and the maximum oil and gas separation efficiency is 95%.

Keywords: Lubrication system; Multi-attitude oil supply structure; Injection; Oil-gas deaerator; Ventilation.

1. Introduction

An aero engine is a high-speed rotating machine, in which high-speed rotating friction parts such as bearings and gears are subjected to huge loads. The lubricating oil system continuously supplies lubricating oil to lubricate and cool the frictional contact area, keeping these components working efficiently and continuously [1]. Due to the high maneuverability, the performance requirements for the engine oil system in multiple attitudes are gradually increasing. The existing lubricating tank structure can no longer meet the fuel supply demand under flight attitudes such as dive and flip. When the aircraft is highly maneuverable and multi-attitude flying, the roll angle or pitch angle of the aircraft is too large. At this time, the oil supply port of the oil tank will be higher than the lubricating oil level, so that the suction capacity of the oil supply pump will be reduced or even the lubricating oil will not be sucked, as shown in Figure 1. The lubricating oil system cannot supply lubricating oil normally, which greatly limits the time of high maneuverability flight of the aircraft. Therefore, the realization of the multi-attitude continuous refueling capacity of the aero engine lubricating oil system can effectively improve the current situation of small flight attitude angle range and short flight time of high maneuverability of aircraft.

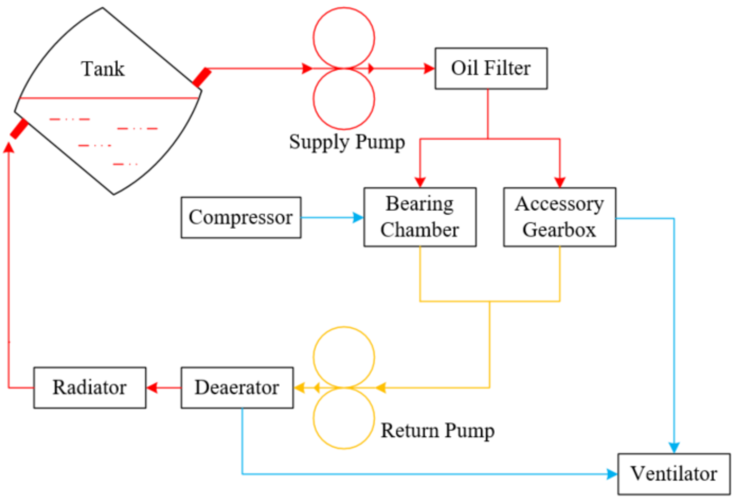


Figure 1 – Aircraft engine lubricating system at large attitude angles.

At present, in the design process of engine lubricating oil system, the oil supply within a certain range of attitude angles will be designed and realized for the special state of multi-attitude flight. Wang Min et al. [2] designed a new type of lubricating oil supply system for aero engines. By setting up an oil suction pump with a maximum load flow rate of 50%-60% of the oil supply pump in front of the oil supply pump, and designing two oil return flow paths, part of the oil return does not flow into the lubricating oil tank but directly enters the oil supply pump to participate in the circulation. The suction pump replenishes the fuel supply to the fuel supply pump and ensures the normal operation of the aero engine lubricating oil system. During the operation of the lubricating oil system, the lubricating oil will be lost due to various reasons, resulting in the continuous reduction of oil return. This greatly reduces the continuous refueling capacity of the lubricating oil system, which restricts the time of the aircraft to fly in multiple attitudes.

Gao Ming et al. [3] designed an aero-engine lubricating tank with a flexible fuel supply pipe, as shown in Figure 2. Considering the practical requirement that the engine oil failure time should be shorter than the allowable time specified in the general requirements for engine development, this aero engine lubricating oil tank with flexible fuel supply pipe was designed. The flexible oil supply pipe is composed of an oil-suction ball head, a bellows pipe and an oil supply pipe joint. It uses the oil-absorbing ball head with the flexibility of the bellows, so that the oil-absorbing ball head can move autonomously with the action of gravity and the external force provided by the aircraft when flying with high mobility. This ensures that the oil-absorbing ball head is always submerged in the lubricating surface. However, because the flexible oil supply pipe is easy to be stuck by other components, and the flexible pipe is usually made of plastic or rubber, it is easy to age after long-term use. This results in lower reliability and shorter service life for lubricating tanks with flexible supply lines. In addition, due to the length of the flexible fuel supply pipe and the size and shape of the lubricating tank, the aircraft's high maneuverability flight angle is also limited.

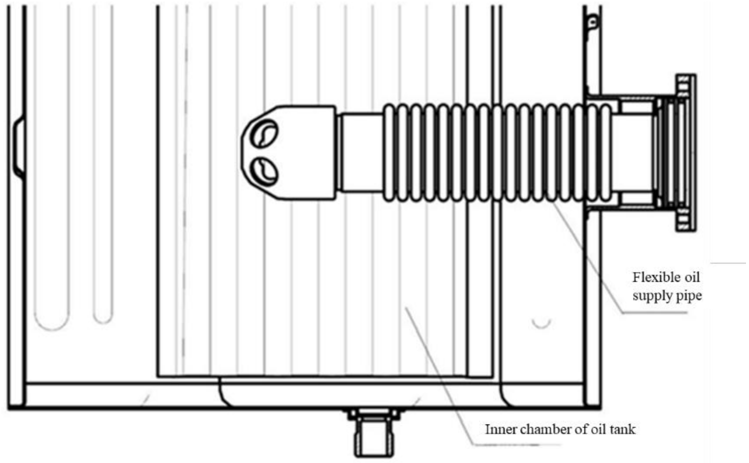


Figure 2 – Aircraft engine lucubrating oil tank with flexible oil supply pipe.

Pan Hongbin et al. [4] designed a multi-attitude aero engine lubricating tank, as shown in Figure 3. The multi-attitude lubricating tank is equipped with a partition plate and an oil pipe. The lubricating oil tank is divided into two fuel tanks, the upper and lower through the separator. The upper and lower fuel tanks are connected through the oil pipe, and a square oil chamber is arranged in the lower oil tank. The joint of the oil supply pipe is arranged in the oil chamber, so that the oil supply joint can be immersed under the lubricating oil liquid level in any situation, and the oil tank can be supplied normally in multiple attitudes. However, the fuel tank system is still limited by the constraints of the lubricating tank structure, which makes the aircraft unable to supply lubricating oil normally under the extreme flight attitude such as inverted flight, which is easy to cause potential safety hazards such as high-altitude parking.

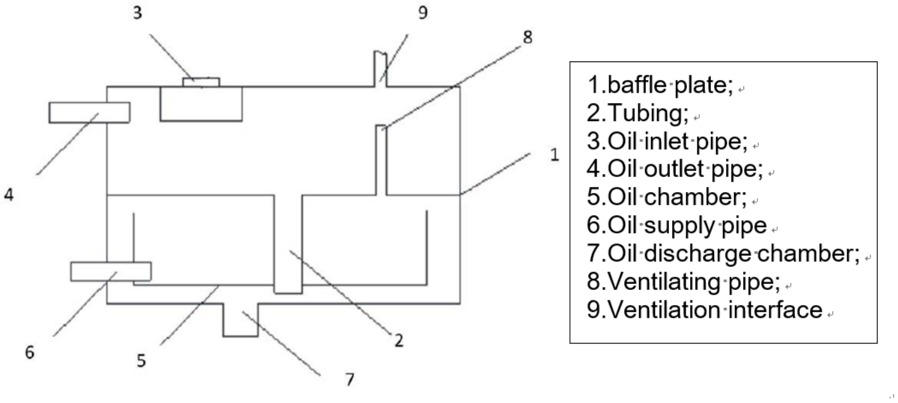


Figure 3 – Multi attitude aircraft engine lucubrating oil tank.

Aho Jr et al. [5] proposed and improved a conceptual model of a continuous fuel supply system for multi-attitude flight and a multi-attitude oil-air separator that matches the fuel tank of the system, as shown in Figure 4. This model features an oil-air separator placed inside the lubricating oil tank. The tank system works in such a way that the oil-gas mixture enters the sprue of the injection structure tangentially from the return pipe, and the return oil accelerates the flow in the injection structure while the static pressure decreases. At this time, the liquid level pressure of the tank is higher than the static pressure of the throat channel of the ejection structure. The lubricating oil in the oil tank enters the injection structure under the differential pressure and further flows into the separator along with the return oil for separation. The separated lubricating oil under centrifugal force enters the oil storage chamber and is directly supplied to the bearing chamber and other components through the oil supply pipe. The separated air is discharged through the ventilation duct to the accessory casing or ventilator. In order to ensure the fuel supply under multi-attitude flight conditions, a plurality of ejection tubes are configured in the ejection structure, which are distributed at different heights of the fuel tank to ensure that the lubricating oil can be sucked through the ejection tubes in different flight attitudes. In addition, the separated lubricating oil in the separation chamber can enter the oil storage chamber when flying in different attitudes, ensuring continuous oil supply in multiple attitudes. The model is equipped with an ejection structure on the oil-gas separator, which is distributed at different heights of the fuel tank to ensure that the lubricating oil can be sucked through the ejection tube under different flight attitudes.

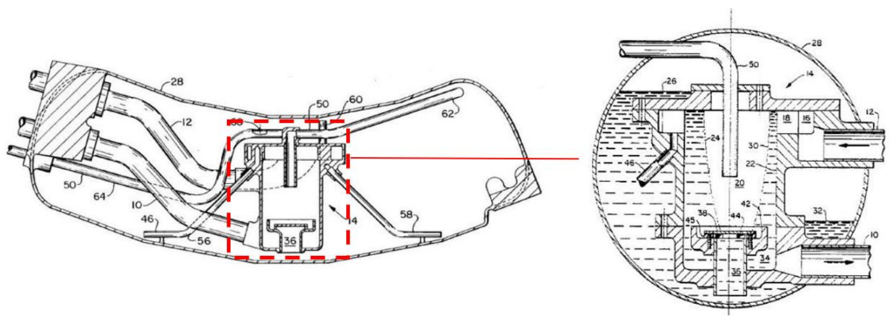


Figure 4 – Concept of multi attitude lucubrating oil tank system.

Based on the above analysis, based on the concept of the multi-attitude fuel tank system proposed by Aho Jr et al. [5], this paper theoretically analyzes the ejection capacity of the refueling structure, and optimizes the design of the structure according to the needs of the ejection performance. Through experimental research, the ejection capacity of the oil supply structure under different working conditions and working attitudes was analyzed, and its ventilation and oil-gas separation capacity were evaluated.

2. Working principle and structural design

Fig. 5 is the cross-sectional view of the ejection structure. The oil-gas mixture enters the oil-gas separator from the return pipe in the tangential direction. The sprue is of the Archimedes spiral type, and then the lubricating oil flows into the larynx of the eight single-channel injection structures. Due to the small cross-sectional area of the throat, the air-gas mixture accelerates the flow through. This results in a decrease in the fluid pressure in the channel and a pressure differential with the inlet of the inlet of the ejector tube that is below the liquid level. Under the action of this pressure difference, the ejection pipe draws the oil inside the oil tank into the oil-air separator. The mixture is then expanded in the diffuser section and enters the separation chamber of the oil-gas separator at a certain tangential velocity. The oil-gas mixture rotates around the center of the separation chamber in the separation chamber, and the denser lubricating oil collects on the wall surface of the separation chamber and enters the oil storage tank. The separated oil is supplied directly from the oil reservoir to the bearing chamber and the accessory casing for lubrication and cooling of the rotating parts. The separated air enters the ventilation duct and is discharged into the atmosphere.

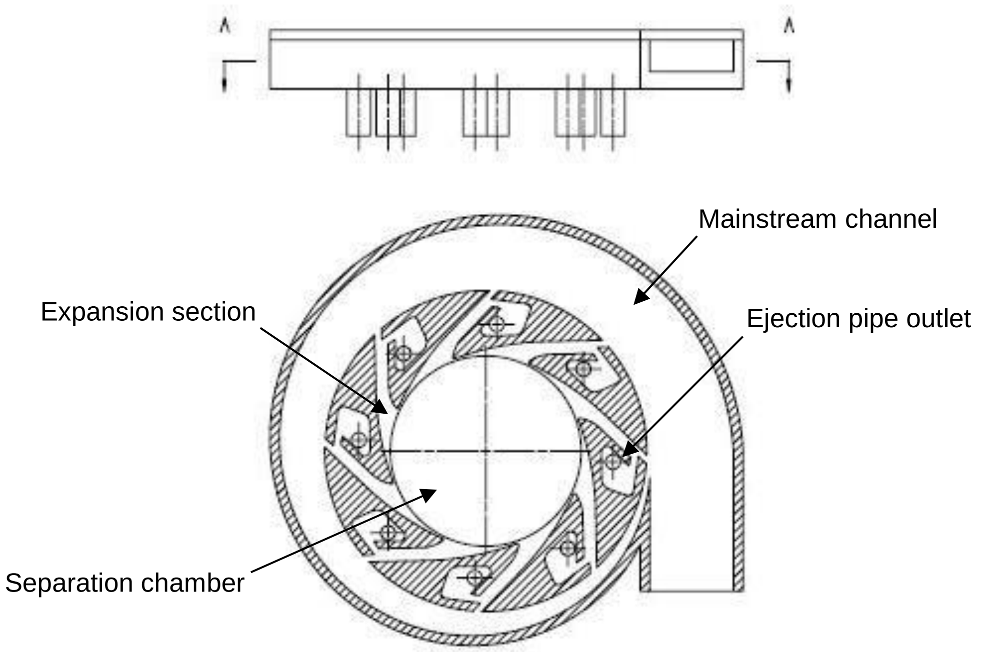


Fig 5 – Sectional view of ejection structure.

2.1 Analysis of the principle of ejection

In this paper, the injection performance test of the oil supply structure is carried out, and the injection function is observed by supplying lubricating oil with a flow rate in the range of 10~45L/min to injection structures. The test phenomenon showed that the lubricating oil formed a liquid column in the ejection tube. As the flow rate of the supplied oil increases, so does the height of the liquid column. It can reach a height of up to 8mm, but it does not form a stable ejection, and the ejection structure cannot suck the lubricating oil into the main stream, which indicates that the pressure value of the ejection structure in the low-pressure section is too high, and its design ability cannot be reached. In order to analyze the reasons for this, the following will first analyze the principle of ejection. Figure 6 shows a simplified schematic diagram of the ejection structure.

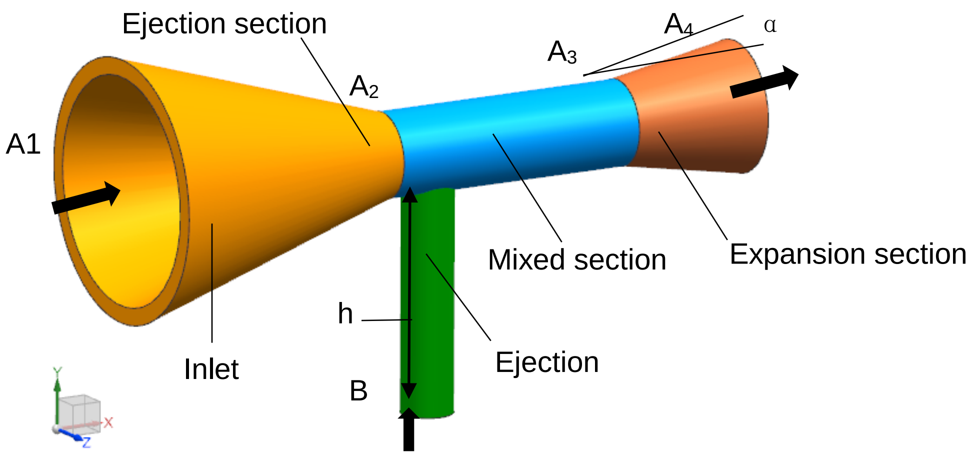


Figure 6 – Schematic diagram of ejection structure.

The principle of ejection of structures is analyzed by using Bernoulli's equation [6], which is essentially the energy conservation equation, which is applicable to incompressible, inviscible fluids. This ideal fluid does not exist in nature, so Bernoulli's equation is generalized to be applied to real fluids.

Bernoulli's equation Eq.1 is used for the inlet section, where the corresponding mixture density is calculated by Eq.2 and Eq.3 is obtained by synatomy.

$$\frac{P_1}{\rho_1}+\frac{V_1^2}{2}+z_1 g-W_f=\frac{P_2}{\rho_2}+\frac{V_2^2}{2}+z_2 g \tag{1}$$

$$\rho_m=\frac{\rho_{oil}Q_{oil}+\rho_{air}Q_{air}}{Q} \tag{2}$$

$$P_2=P_1-\rho_m(\frac{V_2^2}{2}-\frac{V_1^2}{2})+\rho_m W_f \tag{3}$$

Where P_1 is the static pressure of the A_1 plane; V_1 and V_2 are the mixture velocities of A_1 and A_2 planes, respectively. ρ_1 and ρ_2 are the density of the mixture at the A_1 and A_2 planes, respectively. The z_1 and z_2 are the mixture positions of the A_1 and A_2 planes, respectively, and due to the small size of the ejection structure, the z_1 and z_2 can be approximated to be equal under different working attitudes. W_f the work done by a unit mass of fluid to overcome frictional force, also known as flow loss.

Regardless of viscosity, Bernoulli's equation is applied to the pilot tube.

$$P_B-P_2=\rho_B gh+\rho_B\frac{V_2^2}{2}+\rho_B W_d \tag{4}$$

where P_B is the static pressure of the B plane at the inlet of the ejection tube; P_2 is the static pressure of the A_2 plane; ρ_B is the density of lubricating oil at plane B; V is the velocity of the lubricating oil; h is the height difference between the center of the A_2 where the throat is located and plane B; Wd is the flow loss of lubricating oil as it flows through the pilot tube.

If the velocity of the fluid being ejected from A_2 plane position is zero, and the static pressure is determined. The Bernoulli equation at the inlet section and the pilot tube is comprehensively analyzed, that is, the simultaneous Eq.3 and Eq.4 can obtain that the static pressure P_B of the B plane at the inlet of the pilot tube satisfies Eq.5, and the Eq.6 is further derived.

$$P_B=P_1-\rho_m(\frac{V_2^2}{2}-\frac{V_1^2}{2})+\rho_m W_f+\rho_B gh+\rho_B\frac{V_2^2}{2}+\rho_B W_d \tag{5}$$

$$\rho_B gh+\rho_B\frac{V^2}{2}=P_B-P_1+\rho_m(\frac{V_2^2}{2}-\frac{V_1^2}{2})-(\rho_m W_f+\rho_B W_d) \tag{6}$$

According to Eq.6, it can be seen that the injection oil can reach a greater height h and a faster velocity V only if the velocity of the mixture at the A_2 of the nozzle plane is V_2 large enough or the density ρ_m of the inlet mixture ρ is large enough. That is, the greater the density ρ_m of the inlet mixture, the greater the velocity V_2, the more conducive to the occurrence of ejection. It can be seen that under the condition that the lubricating oil and air are mixed evenly, the greater the density of the oil-gas mixture in the inlet section of the ejection structure, that is, the smaller the gas content, and the greater the velocity of the oil-gas mixture at the position of the induction throat, the more gravity can be overcome by the lubricating oil to be ejected, and the flow rate of the lubricating oil will be larger.

The test conditions used in this commissioning test are pure oil conditions, and the lubricating oil flow rate is gradually increased from the lower flow rate to the maximum flow rate of the variable frequency motor and the oil supply pump, and the oil supply structure can never complete the injection function, so it is necessary to use Bernoulli's Eq.7 for the diffuser section. The inlet velocity of the diffuser section is V_3 and the pressure is P_3; The outlet speed is V_4 and the pressure is P_4; The area ratio of the diffuser section is k, and the ambient pressure is P_0.

$$P_4-P_3=\rho(\frac{V_3^2}{2}-\frac{V_4^2}{2}) \tag{7}$$

From the continuous equation, it can be seen that:

$$\frac{V_3}{V_4}=k \tag{8}$$

Simultaneous Eq.7 and Eq.8 yield:

$$P_4 - P_3 = (k^2 - 1)\rho \frac{V_4^2}{2} \tag{9}$$

From the surface pressure relationship, it can be seen that:

$$P_4 = P_0 + \rho \frac{V_4^2}{2} \tag{10}$$

Assuming that the density of the diffuser section of the effluent flow of the oil-gas mixture is constant, the simultaneous Eq.9 and Eq.10 can be obtained:

$$P_0 - P_3 = (k^2 - 2)\rho \frac{V_4^2}{2} \tag{11}$$

In order to form a pressure difference, i.e., $P_0>P_3$, $k>1.414$ is required. Assuming that the circumferential velocity of the lubricating oil in the separation chamber is 5m/s and $k=1.5$, if the oil supply structure can form a stable emission, there are:

$$P_0 - P_3 = (k^2 - 2)\rho \frac{V_4^2}{2} > \rho g h \tag{12}$$

It can be obtained that $h<0.3125$m, and then considering the flow loss of lubricating oil, it can be estimated that the ejection effect of the oil supply structure will be worse, so if the oil supply structure is to form an effective ejection, it is necessary to increase the k value, that is, to increase the area ratio of the expansion section in the ejection structure. The angle of the diffuser section should not be too large, and the optimal angle of diffuser α be between 8° and 10°, so the *k* value should not be too large [7].

In this paper, the definition of effective ejection is that when the ejection tube is immersed below the liquid level of the lubricating oil tank, the lubricating oil can be induced into the oil supply structure. When the lubricating tube is not immersed below the liquid level of the lubricating oil tank, that is, it is completely exposed to air, the lubricating oil in the lubricating structure will not flow out of the lubricating structure through the lubricating pipe and enter the lubricating oil tank.

2.2 Structural optimization

According to the conclusion of the analysis in Section 2.1, the local optimization of the oil supply structure model is carried out, and the main adjustments are as follows:

(1) Reduce the diameter of the ejection tube to facilitate the occurrence of ejection.

(2) The area ratio of the diffuser section of the ejection structure is increased to 1.75.

(3) In order to ensure that a stable lubricating oil level can be formed inside the separation chamber, adjust the height of the bottom center boss so that the upper end face is higher than the oil supply pipe.

(4) In order to avoid excessive pressure inside the oil supply structure caused by excessive flow resistance of the ventilation pipe, thereby hindering the occurrence of ejection, the diameter of the inner ring of the oil baffle ring in the ventilator is increased, that is, the size of the oil baffle ring is reduced.

3. Experimental systems and methods

In order to study the ejection capacity of the oil supply structure under different working conditions, an experimental system as shown in Fig. 7 was designed and constructed. The test system includes lubricating oil circulation system, air system, oil-air mixer, test piece and attitude angle adjustment device.

In the experiment, the lubricating oil is pumped out of the oil tank by the oil supply pump, and enters the oil-gas mixer after passing through the heater, gear flowmeter and check valve. After the air is pressurized by the air compressor, the impurities and moisture in the air are removed through the filter, and then enters the oil-gas mixer through the regulating valve, flowmeter and check valve; Air and lubricating oil are mixed in the oil-gas mixer to form a two-phase mixture of oil and gas, and then pass through the development section and the stabilization section in turn to enter the test piece; After that, the oil-air mixture is separated in the oil-air separator, and the oil that excludes the air is returned to the tank to complete the system circulation.

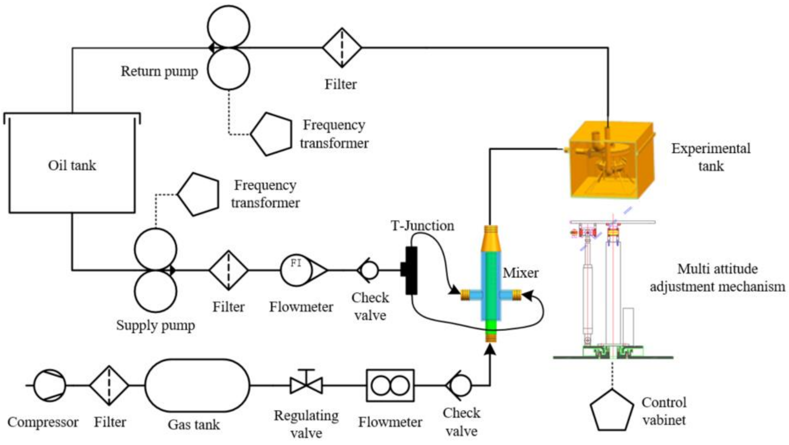


Fig 7 – Schematic diagram of experimental system.

The attitude angle adjustment device is composed of four parts: the pitching platform, the universal head support column, the lifting electric cylinder in the X/Y axis direction, and the disc fixed base. In the working process, by adjusting two lifting electric cylinders to drive the telescopic of two support shafts, the pitching platform can carry out the corresponding pitching action with the universal head of the center point of the platform as the support fixed point, so as to achieve the purpose of multi-attitude adjustment of the pitching platform, so that the test can be carried out in various attitudes required.

According to the designed experimental system and the performance of the experimental piece, the experimental medium was selected as 4106 aviation lubricating oil. Oil density 972.2kg/m3, oil viscosity 58.37mPa·s, Oil flow rate: 10~45L/min; air density: 1.205kg/m3, air viscosity: 0.018mPa·s, air flow rate: 5~25L/min. Sidewards inclination: -35°~35°, pitch angle: -30°~30°. The test was carried out at room temperature of 20 °C.

4. Results and discussions

4.1 The variation of the injection flow with the inlet oil/gas flow

In this section, experiments are carried out to analyze the influence of inlet lubricating oil flow on the inflow rate of the oil supply structure. By adjusting the frequency of the pump motor and changing the flow rate of lubricating oil at the inlet, the injection test under 7 working conditions was carried out, and the experimental conditions are shown in Table 1.

Table 1 Experimental conditions

Number	Oil flow rate (L/min)	Oil temperature (mm)	Level height (mm)	Sidewards inclination (°)	Pitch angle (°)
1	12.5	20	80	0	0
2	15	20	80	0	0
3	17.5	20	80	0	0
4	20	20	80	0	0
5	22.5	20	80	0	0
6	25	20	80	0	0

Fig. 8 is a line chart of the variation of the induced flow rate of the oil supply structure with the flow rate of lubricating oil. As can be seen from the figure, as the inlet oil flow increases, so does the flow rate of the inlet lubricating oil. This is due to the fact that when the flow rate of lubricating oil at the inlet of the oil supply structure increases, the flow rate of the lubricating oil entering the injection structure will also increase. The increase of the flow rate of the lubricating oil in the injection structure and the increase of the flow rate of the working fluid can increase the pressure difference between the inlet throat and the inlet position of the injection pipe, which is conducive to the occurrence and progress of the inflow, so that the injection capacity of the oil supply structure is enhanced with the increase of the flow rate of the inlet lubricating oil.

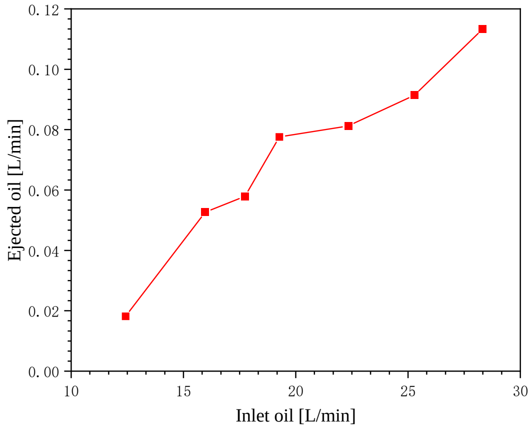


Fig 8 – The relationship between injection flow rate and oil flow rate.

Secondly, experiments are carried out in this subsection to analyze the influence of inlet air flow on the intake flow rate of the oil supply structure. During the test, the air flow rate is changed by adjusting the opening of the pressure valve on the air pipeline, and the air flow rate is measured and read by the float flow meter. The lubricating oil flow rate is adjusted by adjusting the output frequency of the inverter controller, so that the lubricating oil flow is kept at about 25L/min; The left and right inclination angles and pitch angles of the test platform are 0°, while the pilot nozzle is always immersed below the lubricating oil surface. As shown in Table 2, the size of the induced flow rate of the oil supply structure is changed in the case of changing the air flow.

Table 2 Effect of inlet air flow on injection flow

Number	Oil flow rate (L/min)	Air flow rate (L/min)	Oil-gas ratio	Injection flow rate (L/min)
1	25.24	0	\	0.0912
2	25.13	5	5.026	0.0917
3	25.02	10	2.502	0.1041
4	24.96	15	1.664	0.0981
5	24.83	20	1.242	0.0819

As can be seen from Table 2, the induced flow rate increases first and then decreases with the increase of air flow. Within the range of test conditions, the change of air flow rate on the amount of lubricating oil injection is about 10%. When the air flow rate is 10L/min, the injection flow rate of the oil supply structure is the highest. When the air flow rate gradually increases from 0 to 10L/min, the injection flow rate of the oil supply structure also increases. This is due to the increase of air flow, the flow velocity of the oil-gas mixture at the position of the priming throat increases, which enhances the ejection capacity of the ejection structure. When the air flow rate continues to increase from 10L/min to 20L/min, the injection flow rate of the oil supply structure will gradually decrease with the increase of air flow, which is due to the fact that when the flow rate of the oil-gas mixture is too large, the internal pressure of the injection structure is increased, and the pressure difference between the throat of the injection structure and the injection nozzle is reduced, which hinders the occurrence of the injection.

4.2 The variation of the injection flow with the attitude angle

In this section, experiments are carried out to explore the influence of the left and right dip angles on the ejection capacity of the oil supply structure. During the test, the working fluid of the inlet of the oil supply structure is only lubricating oil, and the output frequency of the inverter controller is kept unchanged to ensure that the lubricating oil flow rate is basically unchanged at about 25L/min. Before each test, the lifting electric cylinder is adjusted through the control cabinet to change the attitude angle of the test platform. In the experiment, the attitude angle was gradually adjusted from 35° to 35° to the left, and from 30° forward to 30° backward. Because the multi-attitude adjustment control cabinet cannot read the specific displacement angle value of the test platform, the inclination angle of the test platform is measured by the goniometer before the test and adjusted to the specified working conditions.

Fig. 9 shows the variation of the induction flow rate of the oil supply structure with the left and right inclination angles of the experimental platform when the lubricating oil flow rate is 25L/min, where the abscissa represents the inclination angle of the test platform. As shown in the figure, with the increase of the inclination angle, the injection flow rate of the oil supply structure also increases, and the maximum increase can be about 30% when the right inclination reaches 35°. This is due to the fact that when the inclination angle of the test platform increases, the pilot nozzle will be located deeper in the tank. This increases the pressure difference between the throat of the ejection structure and the nozzle of the ejection structure, making it easier for the ejection structure to draw oil from the test tank. When the inclination angle is the same, the induced flow rate when the oil supply structure is tilted to the left will be slightly smaller than that when it is tilted to the right, which is due to the deviation caused by the position of the oil supply pipe on the side of the oil storage chamber at the bottom of the oil supply structure. When the oil supply structure is tilted to the right, the oil supply pipe can more easily absorb the lubricating oil from the oil storage cavity of the oil supply structure, which reduces the accumulation of lubricating oil inside the oil supply structure, thereby reducing the additional pressure generated by the swirl at the outlet position of the oil supply structure, and enhancing the ejection capacity of the oil supply structure.

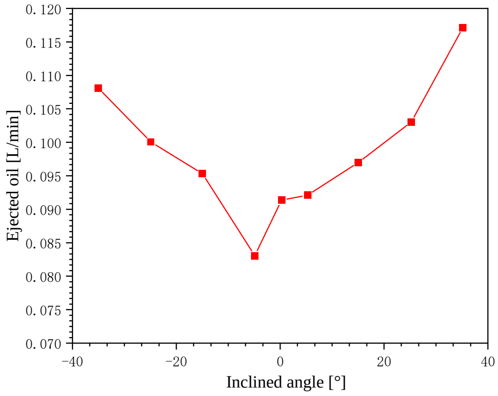


Fig 9 – The relationship between injection flow rate and sidewards inclination.

Fig. 10 shows the variation of the induced flow rate of the oil supply structure with the pitch angle of the experimental platform when the lubricating oil flow rate is 25L/min. With the increase of the pitch angle, the induction flow rate of the oil supply structure also increases. It can be seen that the variation of the intake flow rate with the pitch angle is similar to the influence of the left and right inclination angles. The reason for this effect is that the pilot nozzle is located deeper than the liquid surface when the angle changes. This increases the pressure difference between the throat of the ejection structure and the nozzle of the ejection pipe, thereby enhancing the ejection efficiency of the oil supply structure. However, from Fig. 9 and 140 it can be seen that the effects of different directions and angles are different, which may be due to the different positions of the pilot tube outlets on the main channel, as shown in Figure 5. Therefore, the cross-sectional area of the main channel is different, which leads to the difference in pressure required to inject the lubricating oil under different gravitational forces. As a result, the flow rate of the injection oil is not uniform at different attitude angles.

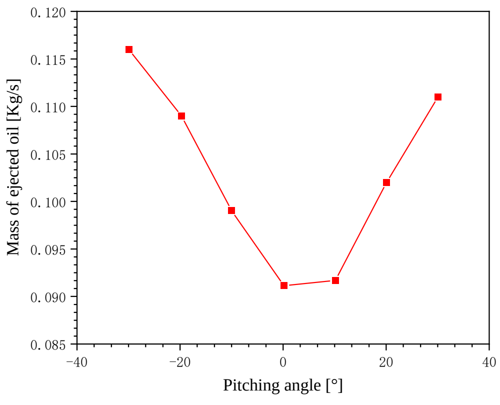


Figure 10 – The relationship between injection flow rate and pitch angle.

4.3 The variation of the injection flow with the liquid level height of the oil tank

In this subsection, a test is carried out to analyze the influence of the oil level height in the oil tank on the ejection capacity of the oil supply structure. During the test, it is ensured that the test platform remains unchanged in a horizontal position. The working fluid at the inlet of the oil supply structure is pure oil, and the flow rate of the lubricating oil is kept at about 25L/min. During the test, only the position of the liquid level height of the lubricating oil in the test tank is changed, and the specific lubricating oil level height is measured and marked by vernier calipers. The height of the liquid level gradually increases from 60mm to about 100mm, and at the same time, it ensures that the injection nozzle of the oil supply structure is always immersed in the lubricating oil of the test tank.

Fig. 11 shows the change of the lead flow rate of the oil supply structure with the liquid level height in the oil tank when the lubricating oil flow rate is 25L/min. It can be seen from the figure that when the level of lubricating oil in the test tank rises, the injection flow rate of the oil supply structure shows an upward trend. This is due to the rise of the lubricating oil level, which causes the injection nozzle of the oil supply structure to be in a deeper position of the liquid level, which increases the pressure value at the injection nozzle. As a result, the pressure difference between the throat of the injection structure and the nozzle of the injection pipe increases, and the emission capacity of the oil supply structure is improved.

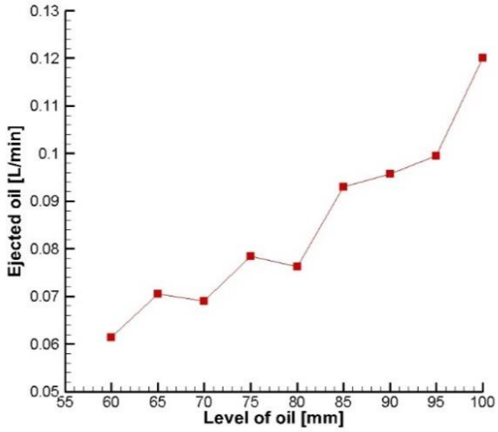


Figure 11 – Variation of intake flow rate with oil level height.

4.4 Ventilation and oil-air separation performance

For the oil supply structure, in addition to meeting the injection capacity, that is, the ability to continuously supply oil under different working conditions, the ventilation and oil-gas separation functions are also the basic functions of the oil supply structure. The ventilation and oil-oil separation performance of the oil supply structure are discussed below.

4.4.1 The ventilation capacity of the oil supply structure

The test system used for ventilation performance test is the same as that of the oil supply structure injection test system, except that a float flowmeter is installed at the outlet of the ventilation pipe to measure the ventilation flow.

During the test, it is ensured that the output frequency of the frequency conversion controller and the output speed of the speed controller remain unchanged, so as to ensure that the lubricating oil flow is about the same; The air flow is controlled and regulated by the pressure regulating valve on the air supply pipeline, and the flow rate is measured by the float flowmeter on the air supply pipeline; The ventilation flow rate of the oil supply structure is measured by a float flowmeter arranged at the end of the ventilation pipe at the top of the oil supply structure.

Table 3 shows that in the horizontal attitude, with the increase of the proportion of air flow in the inlet air-gas mixture of the oil supply structure, the ventilation flow rate of the ventilation pipe of the oil supply structure also increases, and the proportion of the ventilation flow in the inlet air flow will decrease slightly, but in the range of 5~10.3L/min, the proportion of the ventilation flow is between 89%~90%, and the increase of the inlet air flow will slightly reduce the separation efficiency of the oil supply structure. When the inlet air flow is roughly the same, the ventilation flow rate of the oil supply structure in the forward tilt attitude is slightly lower than that of the oil supply structure in the straight attitude, and the separation efficiency is also slightly reduced. The ventilation flow rate of the oil supply structure is strengthened compared with the normal working attitude of the oil supply structure when it is tilted back and left and right, and the separation efficiency is also slightly increased.

Table 3 Ventilation test results

Working posture	Oil flow rate (L/min)	Inlet air flow rate (L/min)	Ventilation flow rate (L/min)	Ventilation efficiency (%)
Horizontal	25.5	5	4.5	90.00
Horizontal	25.4	7.4	6.6	89.19
Horizontal	25.5	8.2	7.3	89.02
Horizontal	25.5	9.5	8.5	89.47
Horizontal	25.6	10.3	9.2	89.32
Tilt left 45°	25.6	8.6	7.8	90.70
Tilt right 45°	25.5	9.1	8.6	94.51
Tilt forward 45°	25.5	7.2	6.3	87.50
Tilt back 45°	25.5	8.5	7.7	90.59

4.4.2 The gas-oil separation capacity of the oil supply structure

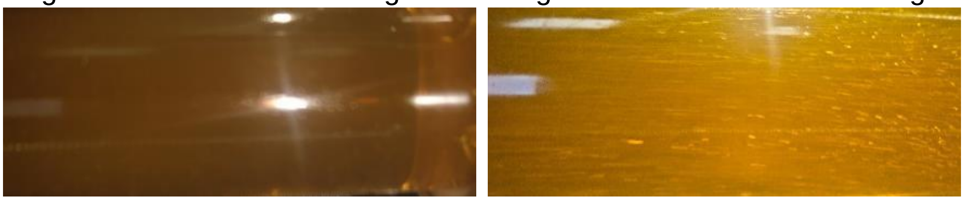
In this section, the oil-gas separation performance of the oil supply structure is analyzed experimentally, and the gas content is used to measure the separation efficiency of the oil supply structure during the analysis. The gas content is the volume fraction of the air contained in the import and export oil-gas mixture of a certain volume.

During the test, the output frequency of the inverter controller and the output speed of the speed controller are guaranteed to remain unchanged, and the lubricating oil flow at the inlet of the oil supply structure is approximately the same. The lubricating oil flow is measured by a gear flowmeter on the oil supply line. At the same time, by adjusting the multi-attitude adjustment controller, the test platform is in a constant horizontal position. By adjusting the opening of the pressure regulating valve on the air line, the air flow rate at the inlet of the oil supply structure can be changed. The air flow rate is measured by a float flowmeter installed on the air line. The outlet of the oil supply structure is connected to a multiphase flowmeter, and the gas content in the outlet mixture is measured by a multiphase flowmeter. Table 4 shows the test conditions and results of the oil-gas separation capacity of the oil supply structure.

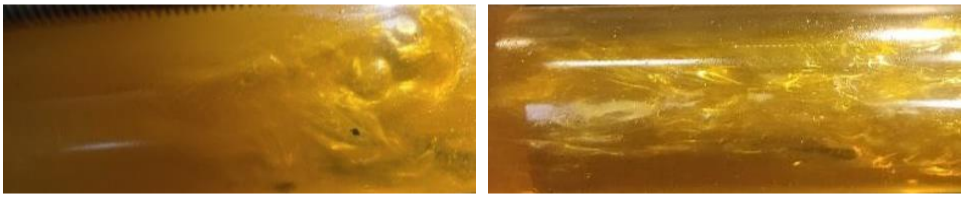
Table 4 Test conditions and results of oil-gas separation capacity of oil supply structure

Number	Oil flow rate (L/min)	Inlet air flow rate (L/min)	Oil temperature (℃)	Inlet gas voids (%)	Outlet gas voids (%)
1	25.6	0	19.1	0	0.70
2	25.6	5	20.0	16.34	3.33
3	25.6	10	21.3	28.09	4.67
4	25.5	15	21.9	37.04	3.50
5	25.5	20	22.6	43.96	3.83
6	25.5	25	22.5	49.50	4.17

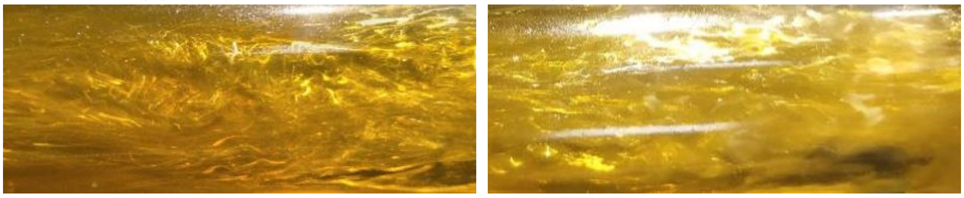
In the oil-gas separation function verification test system, two glass pipes are set up on the oil supply and return pipelines as observation ports. One of them is arranged behind the oil-gas mixer, that is, a glass pipe is arranged in front of the inlet of the oil supply structure, through which the mixing state of the oil-gas mixture entering the oil supply structure can be observed; The other is installed in front of the multiphase flow meter, that is, after the outlet of the oil supply structure, a glass tube is also arranged, through which the state of the mixture after separation through the oil supply structure can be observed. Figure 12 shows the blending of oil and gas at the inlet with different gas contents.



(a) Gas voids 0% (b) Gas voids 16.34%



(c) Gas voids 28.09% (d) Gas voids 37.04%



(e) Gas voids 43.96% (f) Gas voids 49.50%

Figure 12 – Inlet oil-gas mixtures.

Combined with Table 4 and Fig.12, it can be seen that with the increase of the gas content of the inlet working fluid of the oil supply structure, the gas content of the oil and gas mixture at the outlet of the oil supply structure will first increase, decrease and then continue to increase. This is due to the fact that when the gas content of the inlet oil and gas mixture is 0~28.09%, the air in the oil and gas mixture is mainly in the form of small bubbles, and the number of small bubbles also increases with the increase of the gas content of the inlet mixture, resulting in the increase of the gas content of the mixture at the outlet. When the gas content of the inlet working fluid rises to 37.04%, the form of air in the mixture becomes dominated by large bubbles, and the number of small bubbles decreases, which reduces the gas content of the outlet mixture of the oil supply structure. When the inlet gas content continues to increase, the number of large and small bubbles in the oil-gas mixture increases, and the increase in the number of small bubbles leads to the increase of the gas content of the outlet mixture. In summary, the performance of the oil supply structure in removing large bubbles is relatively good, and the effect of removing small bubbles is not ideal.

In order to better compare the oil-gas separation capacity of the oil supply structure, the oil-gas separation efficiency η is defined as:

$$\eta = \frac{\sigma_1 - \sigma_2}{\sigma_1 (1 - \sigma_2)} \tag{13}$$

Among them: σ_1 represents the gas content at the inlet of the oil supply structure, and σ_2 represents the gas content at the outlet of the oil supply structure.

The relationship between the separation efficiency of the oil supply structure and the gas content of the inlet mixture is calculated, as shown in Fig.13.

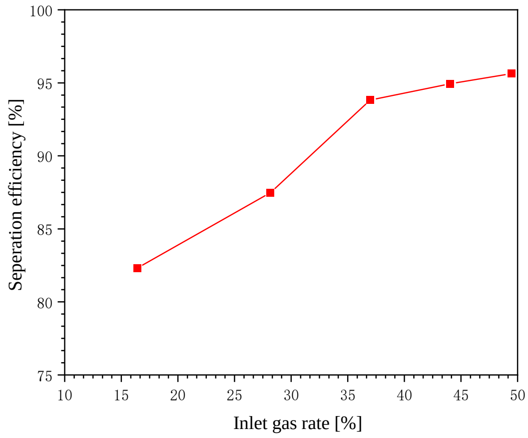


Figure 13 The relationship between separation efficiency and inlet gas voids

As shown in Figure 13, the separation efficiency of the multi attitude fuel supply structure increases with the increase of the gas content of the inlet oil gas mixture. The separation efficiency of the fuel supply structure is the lowest at an inlet gas voids of 16.34%, only 82.36%; When the gas voids of the inlet oil gas mixture exceeds 35%, the separation efficiency of the oil supply structure can reach about 95%.

5. Conclusion

In this paper, the Bernoulli equation is used to analyze the ejection structure of the multi-attitude oil supply structure, and it can be concluded that the density and velocity of the oil-gas mixture directly affect the induction flow of the ejection structure, that is, the greater the density of the oil-gas mixture, the faster the flow velocity, and the larger the ejection flow. In order to form an effective ejection without considering the flow loss, it is necessary to ensure the k value, that is, the area ratio of the diffuser section of the ejection structure should be greater than 1.414, and the *k* value considering the flow loss should be larger. When K is 1.5, the oil supply structure cannot form an effective ejection, which is due to the excessive additional pressure brought by the swirl at the outlet position of the ejection structure, which hinders the occurrence of ejection.

Through experimental research, it is verified that the final optimized multi-attitude fuel supply structure realizes the continuous ejection function within the actual working attitude range of modern fighters with high maneuverability. In the range of 12.5~27.5L/min, the inlet lubricating oil flow of the oil supply structure is proportional to the inlet lubricating oil flow of the oil supply structure, and the increase of the inlet lubricating oil flow will enhance the inlet lubricating capacity of the oil supply structure. The induction flow rate of the oil supply structure is proportional to the height of the lubricating oil level in the lubricating oil tank, and the higher the liquid level height of the lubricating oil tank, the stronger the ejection capacity of the lubricating structure. When the lubricating oil flow rate of the oil-oil mixture at the inlet of the oil supply structure remains unchanged, and the increased air flow decreases from 5:1 to 5:4, the injection flow rate of the oil supply structure will increase first and then decrease, which is because when the air flow rate increases, the velocity of the mixture will increase, and the injection capacity of the oil supply structure will be strengthened. When the air flow continues to increase, the flow pressure of the fluid inside the oil supply structure will also increase, which weakens the oil supply structure's emission capacity.

When the lubricating oil level remains unchanged, changing the working attitude of the oil supply structure will weaken the emission capacity of the oil supply structure, and the emission capacity of the oil supply structure will decrease with the increase of the deflection angle. When the total volume of lubricating oil in the lubricating oil tank remains unchanged, changing the working attitude of the oil supply structure will enhance the emission capacity of the oil supply structure, until part of the oil supply structure is completely exposed to the air, and the emission capacity of the oil supply structure is greatly weakened.

The multi-attitude oil supply structure can realize the functions of ventilation and oil-gas separation under different working conditions. The multi-attitude oil supply structure can remove the large bubbles in the oil-gas mixture well, but its separation ability for small bubbles is weak. The higher the gas content of the inlet oil and gas mixture, the better the oil and gas separation effect of the oil supply structure, the highest separation efficiency is about 95%, and the ventilation efficiency is between 89%~90%.

6. Contact Author Email Address

The contact author phone number: +86 135 7210 7833. The email address: yglu@nwpu.edu.cn

7. Copyright Statement

References

[1] Xiaobin Z. The Research on Performance of Dynamic Pressure Type Gas-Oil Separator in Aero-engine. Dissertation for the Degree of Doc, Harbin Engineering University, 2018.

[2] Min W, Qiang Z, Guangrong Y, et al. An engine oil supply system. Patent No. CN109653874A,2019-04-19.

[3] Ming G, Xinyu G, Wentao T. A oil supply method and flexible oil supply pipe for aero-engine lubricating oil tank. Patent No.CN110005528B, 2021.

[4] Hongbin P, JIaning L, Hongcui W, Zhihen C, Guihua L. Aero-engine Lubricating oil tank. Patent No.CN212535863U, 2021.

[5] Aho JR Wilho V. Oil supply reservoir[P]. US4947963, 1990-8-14

[6] Yadong H. The Application of Fluid Dynamics in Ejectors. Technology Wind, 2017(02):74.

[7] Jing W. Experimental research and numerical simulation of multiphase flow multifunctional injector. Master's thesis, Northwestern Polytechnical University, 2007.