Experiment of Engine Lubricating Oil Bubble Fraction in the Driving Cycles

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Abstract. Cavitation phenomenon always occurs in gerotor pumps. Bubble fraction of oil has remarkable influence in bearing lubricating characteristic. Oil mass flow rate and density is measured in a gerotor oil pump performance test, bubble fraction is analyzed based on measured oil density. Experimental results show that bubble volume fraction linearly decrease with the increasing of outlet pressure at constant pump speed. With the increasing of pump speed, influence of outlet pressure on bubble mass fraction decreases gradually. In the driving cycles, bubble mass fraction also increases with the increase of pump outlet pressure, and has a closely positive correlation with oil flow and pump speed. When the temperature of lubricating oil rises from 25°C to 100°C, the average volume fraction decreases about 72.6%, and the average mass fraction decreases about 84.3%. The changing rate of oil bubble fraction apparently lags behind the pump speed, it means that oil bubble fraction in acceleration stage is much higher than deceleration stage.

1. Introduction
In essence, the cavitation in lubricating oil is a partial cavitation phenomenon caused by the sudden drop of pressure below the vaporization pressure. During the rotating process of the gerotor oil pump, when the closed pressure cavity formed by the inner and outer rotors passes through the outlet of the pump body, there will inevitably have pressure fluctuation. When the partial lubricating oil pressure is lower than the local saturated vapor pressure, the air dissolved in the lubricating oil will be separated out or even the lubricating oil will be vaporized to form bubbles.

Lubricating oil containing a large number of bubbles will enter the gap of the sliding bearing, which will reduce the bearing capacity and cooling capacity of the bearing; the bubbles rupture on the bearing surface will cause cavitation and accelerate bearing wear. Therefore, in the design of the engine, there is a requirement for limiting the bubble fraction of the lubricating oil. Generally, the bubble fraction (volume fraction) is less than 15%.

With the increasingly strict requirements for vehicle engine emissions and fuel consumption, engine designers hope to reduce the mechanical loss of power by improving the design of the engine lubrication system. In recent years, mainstream vehicle manufacturers have reduced fuel consumption by 3-5% through technical measures for multiple vehicle engines [1-5], such as variable displacement lubricant pump design, piston-cylinder liner friction reduction design, and lubricant quantity control, which lays a technical foundation for meeting the fuel consumption target of the vehicle 4L/100km [6].

ASTM D6894 lubricating oil bubble fraction test adopts volume measurement method, that is, the lubricating oil is taken from the main oil channel, and the volume change of lubricating oil is measured just after taking out and after standing for a period of time.
Yu measured the bubble fraction of lubricating oil during the engine actual working, and to evaluate the experimental error and influencing factors. Although pressure correction and temperature correction are used in the experimental data, the rapid change of pressure in the process of lubricating oil sampling is the main factor causing the experimental error. Mattia Battarra et al. [8] used the vibration of the wall surface of the lubricating oil pump outlet and the acoustic signal of the flow in the tube to analyze the amount of cavitation bubbles, and compared the analysis results of the cavitation bubbles with the experimental results of volumetric efficiency. Hu et al. [9] used the finite element method to calculate the cavitation bubble influencing factors during the oil pump working, and proposed an optimal design. Rundo Massimo et al. [10] established a variable performance test system for automotive oil pumps to measure the power loss of oil pumps under variable working conditions. Hannibal Wilhelm et al. [11] designed an artificial gasification device for engine lubricating oil to study the effect of bubble fraction on the performance of oil pumps.

However, the experimental results of the effect of oil pump working conditions on the bubble fraction of lubricating oil are rarely reported, especially the change process of the bubble fraction of lubricating oil in driving cycles, which makes the design of engine lubrication systems lack of bubble fraction test data. In this paper, the gerotor oil pump of 1.4L displacement passenger car engine is taken as the experimental object. A test rig of passenger car engine lubricating system is established to measure the real-time density of lubricating oil, analyze the bubble volume fraction and bubble mass fraction of the lubricating oil, and evaluate the influence of oil pump speed, outlet pressure, driving cycles and other factors on the bubble fraction of the lubricant.

2. Experiential Methods

Figure 1 shows the general characteristics of vehicle engine oil pump performance test rig. This test rig can control the parameters such as lubricating oil temperature, inlet liquid level, oil pump speed, and outlet pressure, measure the results of oil pump driving torque, outlet mass flow and density. Finally, the performance indicators are analyzed, such as oil pump mechanical power, hydraulic power, volumetric efficiency, overall efficiency. Table 1 shows the main equipment parameters.

![Figure 1. Schematic of engine lubrication test rig](image)

According to the experimental results, the mechanical power $P_m$, hydraulic power $P_o$, volumetric efficiency $\eta_v$, and overall efficiency $\eta_o$ of the oil pump can be calculated. The bubble volume fraction $X_{gas}$ and mass fraction $m_{gas}$ of lubricating oil is calculated by a density method.

$$ X_{gas} = \frac{\rho_{oil}^{p,T} - \rho_{test}^{p,T}}{\rho_{oil}^{p,T} - \rho_{gas}^{p,T}} $$

(1)
$$m_{gas} = X_{gas} \frac{p \cdot T \cdot \rho_{gas}}{p_0 \cdot T \cdot \rho_{oil}}$$

where, \( \rho_{oil}^{p,T} \) is the theoretical density of lubricating oil, \( \rho_{oil}^{p,T} \) is the measured density of lubricating oil, \( \rho_{gas} \) is local air density, \( p \) is local pressure, \( T \) is local temperature, \( p_0 \) is ambient pressure, \( T_0 \) is ambient temperature.

3. Experimental Result

3.1 Steady States

In the experiment of steady-state condition, the parameters such as driving torque, outlet flow and outlet density of the oil pump are measured under the conditions of controlling the temperature of lubricating oil (20-100°C), the speed of the oil pump (1000-5000r/min) and the outlet pressure (0.2-0.7mpa). The performance characteristic curve of the gerotor oil pump is obtained.

Figure 2 and 3 shows the performance index of gerotor oil pump changing with speed and pressure under the condition of lubricating oil temperature of 30°C.

It can be seen from Figure 2 that under the same outlet pressure, the lubricating oil flow increases with the increase of oil pump speed under the same outlet pressure, the lubricating oil flow decreases with the increase of outlet pressure under the same speed. With the increase of oil pump speed, the lubricating oil outlet flow increases, and the pressure loss of relief valve increases.

In Figure 3, due to the small compression of bubbles, the density of outlet lubricating oil increases with the increase of pressure. However, as the speed of the oil pump increases, the frequency of pressure fluctuation at the outlet of the lubricating oil increases, the duration of low pressure of the lubricating oil shortens, and the amount of gasification and air separation of the lubricating oil decreases, so the density of the lubricating oil increases gradually. It can be seen from Formula 1 that the experimental results of the bubble volume fraction and density of lubricating oil show a linear relationship. With the increase of lubricant density, the bubble volume fraction decreases linearly. As can be seen in Figure 2, the bubble volume fraction of lubricating oil decreases with the increase of speed and outlet pressure.

Figure 2. Bubble volume fraction under pump speed and outlet pressure conditions

Figure 3. Bubble mass fraction under pump speed and outlet pressure conditions

Take the air bubble in the lubricating oil as the compressible gas, and consider the air density change under the pressure condition. According to Equation 2, the bubble mass fraction of lubricating oil can be calculated, as shown in Figure 3. At the same speed, with the increase of outlet pressure, the volume of bubble in lubricating oil decreases, but the air mass percentage increases with the increase of air density. Under the same outlet pressure condition, the speed of oil pump increases, the frequency of pressure fluctuation increases, and the gas quality in the lubricating oil fluctuates. This shows that the distribution of the low pressure area caused by the pressure pulsation of the oil pump in the outlet lubricating oil cavity is related to the frequency of the pressure pulsation.
3.2 Driving Cycles
In the experiment of driving cycles, NEDC, FTP75, JC08 and WLTC (high speed stage) are selected as the experimental conditions, and the lubricating oil temperature is controlled from 20°C to 100°C.

3.3 Lubricating Oil Temperature
Figure 4 and 5 show the effect of different lubricant temperature on the bubble volume fraction and bubble mass fraction of the lubricant during the suburban phase of NEDC. With the constant increase of the lubricating oil temperature, the bubble volume fraction and bubble mass fraction of the lubricating oil decrease significantly in general. When the temperature of lubricating oil is 25°C, the maximum value of bubble volume fraction is 20.02%, and the minimum value is 17.85%, which is higher than the design value. However, when the temperature rises to 100°C, the maximum value and the minimum value of bubble volume fraction decrease to 10.41% and 0.97%, which shows that the decrease is large.

In the existing lubrication analysis, the bubble mass fraction of lubricating oil is generally set to a fixed value (usually 0.05%). However, according to the test results of driving cycles, when the temperature of lubricating oil is 25°C, the maximum value of bubble mass fraction is 0.15%, and the minimum value is 0.03%. When the temperature is 100°C, the maximum value is 0.027%, and the minimum value is 0.005%. Therefore, the variation range of the bubble mass fraction of the lubricating oil is far beyond the design range during the whole vehicle driving. The experimental measurement of the bubble fraction of the lubricating oil is helpful to solve the problem which is the early wear of the engine lubricating system.

![Figure 4. Effect of temperature on bubble volume fraction in NEDC driving cycle](image)

![Figure 5. Effect of temperature on bubble mass fraction in NEDC driving cycle](image)

In order to more fully explore the influence of lubricating oil temperature on the bubble volume fraction and bubble mass fraction, the average value of bubble volume fraction and bubble mass fraction of lubricating oil at different temperatures is calculated according to formula (3) and formula (4).

$$
\bar{X}_V = \frac{\sum_j (Q_j \cdot X_{V,j} \cdot \Delta t)}{\sum_j (Q_j \cdot \Delta t)} \tag{3}
$$

$$
\bar{X}_M = \frac{\sum_j (\hat{m}_j \cdot X_{M,j} \cdot \Delta t)}{\sum_j (\hat{m}_j \cdot \Delta t)} \tag{4}
$$

where, $Q_j$ is the volume flow, $X_{V,j}$ is the bubble volume fraction, $\hat{m}_j$ is the mass flow, $X_{M,j}$ is the bubble mass fraction, $\Delta t$ is the duration of each operating point.
After calculation, the average bubble volume fraction and average bubble mass fraction of the lubricating oil in various driving cycles are obtained as shown in Figure 6 and 7. It can be seen that during the process of increasing the lubricating oil temperature from 25°C to 100°C, the average bubble volume fraction and average bubble mass fraction both have a significant decrease. Combining the average bubble volume fraction and average bubble mass fraction of each driving cycle, the former is reduced by about 72.6%, and the latter is reduced by about 84.3%. This is consistent with the test results of the lubricant bubble fraction in steady working state.

3.5 Correlation Analysis
The correlation analysis of bubble volume fraction and bubble mass fraction of lubricating oil with flow, outlet pressure, oil pump speed, angular acceleration and torque was carried out in different driving cycles. The results are shown in Table 2 and Table 3. NEDC-1 is urban driving cycle, NEDC-2 is suburban driving cycle, \( r \) is the correlation coefficient, \( X_V \) is bubble volume fraction, \( X_m \) is bubble mass fraction, \( Q \) is flow rate, \( P \) is outlet pressure, \( n \) is oil pump speed, \( \frac{dn}{dt} \) is angular acceleration, and \( T_q \) is torque.

It can be seen from Table 2 that only in NEDC-2, the bubble volume fraction of lubricating oil has a real correlation with outlet pressure, flow, oil pump speed and torque. This is because the speed of the NEDC-2 changes too little. In other driving cycles, the correlation coefficient \( r \) between bubble volume fraction and each factor is small, and the correlation degree is slightly correlated, especially with angular acceleration.

In Table 3, the correlation coefficient \( r \) of the bubble mass fraction of the lubricating oil and each factor is relatively close to 1, and the correlation degree is highly correlated. This indicates that the bubble mass fraction will change with the change of outlet pressure, flow, oil pump speed, and torque. However, it can be found that the correlation between bubble mass fraction and angular acceleration is also very low.

Table 2. Correlation coefficient of bubble volume fraction and pump working parameters

| Driving Cycles | \( r(X_V, P) \) | \( r(X_V, Q) \) | \( r(X_V, n) \) | \( r(X_V, \frac{dn}{dt}) \) | \( r(X_V, T_q) \) |
|---------------|----------------|----------------|----------------|---------------------|----------------|
| NEDC-1        | 0.1635         | 0.1035         | 0.1228         | 0.0221              | 0.1824         |
| NEDC-2        | -0.5038        | -0.5279        | -0.4544        | 0.0046              | -0.4878        |
| FTP-75        | -0.0745        | -0.2124        | -0.0607        | 0.0689              | -0.048         |
| JC08          | -0.2923        | -0.3842        | -0.3424        | 0.0686              | -0.291         |
| WLTC          | -0.1128        | -0.1189        | -0.0852        | -0.0003             | -0.1016        |
Table 3. Correlation coefficient of bubble mass fraction and pump working parameters

| Driving Cycles | \( r(X_m,P) \) | \( r(X_m,Q) \) | \( r(X_m,n) \) | \( r(X_m,\frac{dn}{dt}) \) | \( r(X_m,T_q) \) |
|----------------|----------------|----------------|----------------|----------------|----------------|
| NEDC-1         | 0.9764         | 0.7962         | 0.9552         | -0.0436        | 0.9435         |
| NEDC-2         | 0.5102         | 0.4463         | 0.5529         | -0.0139        | 0.5219         |
| FTP-75         | 0.8861         | 0.6789         | 0.8838         | -0.0145        | 0.8863         |
| JC08           | 0.9126         | 0.7994         | 0.8816         | 0.00059        | 0.9033         |
| WLTC           | 0.8032         | 0.7156         | 0.8056         | -0.0329        | 0.794          |

4. Data Analysis

According to the speed-pressure characteristic test results of the oil pump, the influence of the lubricant outlet pressure on the bubble volume fraction and mass fraction can be obtained under the same speed condition.

4.1 Bubble Volume

Figure 8 shows the change of bubble volume fraction of lubricating oil with outlet pressure. As the outlet pressure of the lubricating oil increases, the bubble volume is compressed, the bubble volume fraction of the lubricating oil decreases, and the density of the lubricating oil increases accordingly.

The bubble volume fraction of the lubricating oil decreases linearly with the pressure. This shows that the physical properties of the bubbles in the lubricating oil basically conform to the ideal gas characteristics, and there is no obvious phase change process under the outlet pressure and temperature of the lubricating oil. It can be considered as the mixture of air and lubricating oil steam.

Based on the rotation speed of 1000 r/min and the lubricant outlet pressure of 0.328 MPa, the bubble volume compression rate in the lubricant under different oil pump speed and outlet pressure is calculated, as shown in Figure 9. Compared with the isothermal compression process of ideal gas, the bubble volume compression rate of bubbles in lubricating oil is obviously slow, which shows that the outlet pressure of lubricating oil not only compresses the bubble volume, but also may affect the bubble generation rate.

4.2 Bubble Mass

Figure 10 shows the change of bubble mass fraction of lubricating oil with outlet pressure. With the increase of the outlet pressure, the gas quality in the lubricating oil increases significantly, which indicates that the outlet pressure of the lubricating oil can significantly affect the bubble generation. This also provides a basis for the bubble volume compressibility in Figure 9 to be significantly lower than that in the isothermal compression process.

It can be seen from Figure 11 that the outlet pressure of lubricating oil has a significant effect on the gas generation at oil pump low speed. When the outlet pressure increases, the amplitude of pressure fluctuation caused by the rotation of the oil pump increases, so that the amount of gas generated increases with the increase of the lubricating oil pressure.
With the increase of oil pump speed, the influence of the lubricating oil outlet pressure on the gas generation is gradually reduced. This shows that with the increase of oil pump speed, the outlet flow velocity of lubricating oil increases, the duration of low pressure area caused by pressure pulsation shortens. Finally, the increase of gas generation decreases gradually.

4.3 Bubble Hysteresis

Figure 12 shows the relationship between the bubble mass fraction of lubricating oil, outlet pressure and lubricating oil flow in NEDC suburban stage. It can be seen from the Figure 12 that the bubble mass fraction shows certain lag in varying degrees, whether with the change of outlet pressure or lubricating oil flow.

The lag of bubble mass fraction is the most obvious in the relationship diagram with flow, because the flow of lubricating oil has a large lag in the process of oil pump speed changing, as shown in Figure 13. The lag of lubricating oil flow is because the response of hydraulic system is not timely enough in the process of pump speed changing. When the pump is accelerated, the response of lubricating oil flow is not timely, and the volume of lubricating oil is unchanged, so there are more bubbles that will fill part of the volume, resulting in high mass air content. However, during deceleration, the speed of lubricating oil flow reduction cannot keep up with the decrease of pump speed, and the hydraulic system is still in the state of more flow, so there are fewer bubbles and lower bubble mass fraction.

Figure 13 shows the change of bubble mass fraction with time, which is basically consistent with the change of NEDC suburban stage. It can be concluded that the value of bubble mass fraction in the process of pump acceleration is generally greater than that in the process of deceleration. Therefore, the lag of bubble mass fraction is caused.

5. Summary

(1) In the range of working pressure and temperature of oil pump of vehicle engine, the bubble volume of the lubricating oil decreases linearly with the increase of pressure, and the compression process can
be regarded as an ideal gas isothermal compression process.

(2) Under the same outlet pressure of lubricating oil, the flow velocity of lubricating oil increases with the increase of oil pump speed. The duration of the low-pressure zone decreases correspondingly, and the increase of bubble formation decreases accordingly.

(3) With the increase of temperature, the viscosity of lubricating oil decreases rapidly, and the amount of bubble generation of lubricating oil also decreases significantly.

(4) The correlation between the bubble volume fraction of lubricating oil and the pressure, flow, speed and torque of pump outlet is low, while the bubble mass fraction is highly related to these factors. The angular acceleration of the pump has little effect on the bubble volume fraction and bubble mass fraction.

(5) Under the driving cycles, the change of the bubble mass fraction obviously lags behind the oil pump speed, which makes the bubble mass fraction of lubricating oil significantly higher in the pump acceleration stage than in the oil pump deceleration stage.

6. References

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