An experiment of lubricating oil gas concentration in the standardized driving cycles

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Abstract. There always is cavitation in the positive displacement pump, and the bubbles in the lubricating oil have a great influence on the lubricating performance. This paper aims to measure the lubricating oil gas concentration of a passenger car gasoline engine in the standardized driving cycles. We use a passenger car engine lubricating system in the lubricating experiment, simulating the lubricating oil pump working state in the standardized driving cycles. The lubricating oil density and flow rate are measured to calculate the gas concentration in the lubricating oil, according to the engine work state in the standardized driving cycles, including NEDC Urban, NEDC Ultra Urban, WLTC High Speed. The test results show that under the steady-state conditions, the gas volume ratio decreases linearly with the increase of the outlet pressure, the air mass ratio increases with the increase of the pump speed. In the driving cycles, the air mass ratio also increases with the increase of outlet pressure, and it has a high positive correlation with lubricating oil flow and pump speed. With the increase of oil temperature from 25 to 100°C, the air volume ratio decreases by 72.6%, and the air mass ratio decreases by 84.3%. In the engine accelerating state, the rate of lubricating oil flow gain lags behind the pump speed, which makes the lubricating oil gas mass ratio in the accelerating state is significantly higher than that in the decelerating state.

1. Introduction

The bubbles in lubricating oil are local cavitating phenomenon caused by the sudden drop of pressure below the oil gasification pressure. During the rotating process of the rotor displacement pump, there is pressure fluctuation inevitably when the rotors pass through the outlet chamber. When oil pressure is lower than the saturated vapor pressure, the air dissolved in lubricating oil can be released, and even the lubricating oil can be gasified.

When the lubricating oil with a large number of bubbles enters into the clearance of engine bearings, the bubbles can reduce the bearing capacity and cooling capacity, and the bubble breakage can cause cavitation and corrode the bearing surface. Therefore, the gas volume ratio in the lubricating oil is generally limited to 15% in engine design [1], and the gas mass ratio is limited to 0.05%.

With the increasingly strict requirements of vehicle engine emission and fuel consumption, engine designers start to reduce the accessory driving power by engine lubrication system optimizing design. In recent years, the mainstream automobile enterprises have achieved 3-5% reduction in fuel consumption through variable displacement lubricating oil pump, piston-cylinder friction reduction, lubricating oil volume control and other technologies for many passenger car engines [2-6], laying a technical foundation for meeting the future fuel consumption requirement [7].

ASTM D6894 specified the limit value and test method of engine lubricating oil gas volume ratio, adopts a volume measuring method. Yu et al. [1] of Chery Automobile used this method to measure the gas volume ratio of the lubricating oil during the actual engine operation, evaluated the experimental error and influencing factors. Although using pressure correction and temperature...
correction in the experimental data analysis, the rapid change of pressure in the process of lubricating oil sampling is the main factor causing the experimental error. The pressure difference of the lubricating oil before and after sampling is 2-10 times, and the sharp pressure change causes the bubble expansion and breakage in the lubricating oil, making the measurement result smaller than the actual value. Mattia Battarra et al. [2] analyzed the number of cavitation bubbles in the lubricating oil using the wall vibration of the outlet pipe of the lubricating oil pump and the acoustic signal in the pipe, compared the analysis results of cavitation with the experimental results of volume efficiency. Hu et al. [3] used the finite element method to analyze the influencing factors of cavitation in the process of oil pump operation, put forward the optimized design scheme. Rundo Massimo et al. [4] set up the performance test system of vehicle oil pump under different working conditions to measure the driving power of lubricating pumps under different working conditions. Hannibal Wilhelm et al. [5] designed the artificial gasification device of engine lubricating oil to study the effect of oil gas ratio on the oil pump performance.

However, there are few reports about the experimental results of the influence of the oil pump dynamic working conditions on the lubricating oil gas concentration, especially its changing process in the driving cycles. In this paper, we use a rotor oil pump of 1.4L displacement passenger car engine in the experiment, measure the dynamic density of lubricating oil, analyze the gas volume and mass ratio of lubricating oil, and evaluate the influence of pump speed, outlet pressure, and oil flow on the lubricating oil gas concentration.

2. Methodology

The structure of the experimental system is shown in Figure 1, and Table 1 is the main equipment parameters. We select a rotor displacement lubricating pump used in a 1.4L displacement passenger car engine in the experiment, and Table 2 shows its parameters. A variable frequency motor drives the pump, simulates the pump working states in driving cycles, speed ranges from 100 to 7000 r/min, and a dynamic torque meter measures the driving speed and torque. A control valve is installed in the oil pipe to simulate the lubricating oil pressure loss in the real engine. A mass flowmeter measures the lubricating oil density after the pump. Moreover, the oil temperature ranges from 20 to 100°C, heated by an electric heater installed in the oil tank.

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

| Table 1. Parameters of lubricating oil pump test equipments. |
|------------------|------------------|------------------|
| Equipment        | Measuring Range  | Error            |
| Motor            | 500~6000r/min    | ±1r/min          |
| Torque           | 0~50Nm           | 0.01Nm           |
| Pressure         | 0~1MPa           | 0.25%            |
| Mass Flow        | 0~12kg/min       | 2g/min           |
| Oil Density      | 0.2~1.6kg/L      | 0.2g/L           |
| Temperature      | 20~200°C         | 0.5°C            |
| Heater           | 0~3kW            |                  |

| Table 2. Parameters of the vehicle and engine. |
|-----------------------------------------------|
| Type                                           |
| Displacement                                  |
| Leaking Pressure                              |
| Oil Pump                                      |
| Design Flow                                   |
| Test Oil                                      |
| Gerotor pump                                  |
| 12mL/r                                        |
| 400kPa                                        |
| 12L/min @1000r/min                            |
| 22L/min @2000r/min                            |
| 56L/min @5000r/min                            |
| SM 5W30                                       |
When there are bubbles in the lubricating oil, the oil density will be smaller than the theoretical value. Under stable state flow conditions (for example, the oil pipe after the pump), the bubbles are evenly distributed in the oil, then the gas volume ratio of lubricating oil can be calculated by the density method shown in Equation 1. The lubricating oil can be seen as incompressible fluid under the engine lubricating oil working states, then \( \rho_{oil} \approx \rho_{oil}^{0,T} \). The cavitation gas in lubricating oil can be regarded as an ideal gas, then \( \rho_{g,0} \cdot p_{g,0} \cdot T_{g,0} = \rho_{g,0} \cdot p_{g,0} \cdot T_{g,0} \). So that the lubricating oil mass ratio is shown as Equation 2.

\[
V_{gas} = \frac{\rho_{oil}^{p,T} - \rho_{oil}^{p,T}_{\text{test}}}{\rho_{oil}^{p,T} - \rho_{gas}^{p,T}} \quad \text{(1)}
\]

\[
m_{gas} = V_{gas} \cdot \frac{p_{0} \cdot T_{0} \cdot \rho_{gas}^{p,T}}{p_{0} \cdot T_{0} \cdot \rho_{oil}^{p,T}_{\text{test}}} \quad \text{(2)}
\]

where \( V_{gas} \) lubricating oil gas volume ratio, \( \rho_{oil}^{p,T} \) lubricating oil theoretical density; \( \rho_{oil}^{p,T}_{\text{test}} \) lubricating oil test density; \( \rho_{gas}^{p,T} \) cavitation gas theoretical density; \( p \) lubricating oil pressure; \( T \) lubricating oil temperature; \( p_{0} \) atmosphere pressure, \( T_{0} \) atmosphere temperature.

3. Experimental Results

3.1. Steady-state condition
In the steady-state experiment, the performance of a lubricating oil pump is tested, with lubricating oil temperature from 20~100°C, outlet pressure 0.2~0.7 MPa, and pump speed from 1000 to 5000r/min. Figure 2 shows the flow rate evolution with pump speed and outlet pressure conditions.

At the same outlet pressure, the lubricating oil flow rate increases with pump speed, and the hydraulic power increases too. At the same pump speed, the lubricating oil flow rate decreases with outlet pressure increase.

![Figure 2](image)

Figure 2. The oil flow rate evolution with pump speed and outlet pressure at 30°C.

![Figure 3](image)

Figure 3. Lubricating oil density evolution with pump speed and outlet pressure at 30°C.

![Figure 4](image)

Figure 4. The gas volume ratio in oil evolution with pump speed and outlet pressure at 30°C.

![Figure 5](image)

Figure 5. The gas mass ratio in oil evolution with pump speed and outlet pressure at 30°C.

In Figure 3, due to the compression of bubbles, the outlet oil density gradually increases with pressure. At the same pressure, lubricating oil density increases with pump speed, due to the frequency
of pressure fluctuation at the outlet increases with pump speed, the time of cavitation pressure pulse comes down, then the amount of oil gasification and air precipitation decreases. In Equation 1, the lubricating oil gas volume ratio is linearly related to the test oil density, and then the gas volume ratio decreases linearly with the lubricating oil density. So that the lubricating oil gas volume ratio decreases with the increase of the pump speed and outlet pressure in Figure 4.

At the same pump speed, the lubricating oil gas volume ratio decreases with pressure, but the mass ratio increases with pressure because of gas density increasing, shown in Figure 5. At the same outlet pressure, the lubricating oil gas mass ratio fluctuates with the increase of pump speed, which indicates that the cavitation pressure amplitude and time is relative not only to the pump speed but also the outlet structure.

3.2. Standardized Driving Cycles

We use four kinds of standardized driving cycles in the experiments, including NEDC (New Europe Driving Cycle), FTP-75 (US EPA), JC08 (Japan Cycle), and WLTC (World Harmonized Light Vehicles Test Cycle), shown in Figure 6. Compared with NEDC, there are more acceleration and deceleration conditions in FTP-75, DC08, and WLTC, which makes much more density fluctuation in the lubricating oil, then the gas content in the lubricating oil increases accordingly.

Figures 7 and 8 show the evolution of oil gas volume and mass ratio in the NEDC cycle. With the increase of the lubricating oil temperature, the lubricating oil gas volume and mass ratio decrease significantly in general. At 25°C, the maximum gas volume ratio is 20.02%, and the minimum value is 17.85%, which is higher than the design requirement. At 100°C, the maximum gas volume ratio reduced to 10.41%, and the minimum value is 0.97%, which shows that temperature has a great influence on the lubricating oil gas ratio.
The design requirement of the gas volume ratio in lubricating oil is less than 15% in engine design, and the mass ratio requirement is less than 0.05%. Therefore, the lubricating oil gas volume ratio cannot meet the requirement in the most working time of the NEDC cycle at 25°C, even cannot meet the requirement under high-speed and high-pressure conditions at 60°C.

The top limit of the gas mass ratio is 0.05% in engine design. Figure 8 shows that the requirement in the whole NEDC driving cycle can be met only at 100°C. The lubricating oil gas mass ratio is even larger than 0.05% under high-speed and high-pressure conditions at 80°C.

So that it is necessary to increase the lubricating oil flow rate under the low-temperature condition to improve the capacity ability of lubricating oil and avoid the engine rapid wear problem.

An average gas ratio are defined in Equations 3 and 4, analyzing the average gas ratio in the whole driving cycle.

\[
\bar{V}_{\text{gas}} = \frac{\sum_{i=1}^{n} (\dot{Q}_i \cdot V_{\text{gas},i} \cdot \Delta t)}{\sum_{i=1}^{n} (\dot{Q}_i \cdot \Delta t)} \quad (3)
\]

\[
\bar{m}_{\text{gas}} = \frac{\sum_{i=1}^{n} (\dot{m}_i \cdot m_{\text{gas},i} \cdot \Delta t)}{\sum_{i=1}^{n} (\dot{m}_i \cdot \Delta t)} \quad (4)
\]

where, \(\bar{V}_{\text{gas}}\) and \(\bar{m}_{\text{gas}}\) average gas volume and mass ratio in the driving cycle;

\(V_{\text{gas},i}\) and \(m_{\text{gas},i}\) gas volume and mass ratio at state \(i\);

\(\dot{Q}_i\) and \(\dot{m}_i\) lubricating oil volume and mass flow rate at state \(i\);

\(\Delta t\) time of a working state \(i\); \(n\) total working step number in the driving cycle.

Figures 9 shows that the lubricating oil gas volume and mass ratios both decrease with the increase of temperature, which agrees well with Figures 7 and 8.

Figure 9. The average gas volume ratio in the driving cycles.
4. Analysis

4.1. Gas Volume
Fig. 10 shows the gas volume ratio of lubricating oil changes with outlet pressure, which is similar to Figure 4. When the gas volume decreases due to the pressure increases, the lubricating oil density increases accordingly. The linear relationship between the gas volume ratio and the pressure shows that the physical properties of the gas in the lubricating oil conform to the ideal gas characteristics.

Based on the speed (1000r / min) and the outlet pressure (320kPa), the volume compression ratio of gas in lubricating oil is calculated, shown in Figure 11. Compared with the isothermal compression process of the ideal gas, the volume compression rate of gas in lubricating oil is slow, which means that the outlet pressure of lubricating oil not only compresses the gas volume but also may affect the bubble generating rate.

4.2. Gas mass
Fig. 12 shows the change of mass air content of lubricating oil with outlet pressure. With the increase of the outlet pressure of the lubricating oil, the gas quality in the lubricating oil increases significantly, which indicates that the outlet pressure condition of the lubricating oil can significantly affect the bubble generation.

Figure. 13 shows that the outlet pressure has a significant effect on the gas generation at low speed. When the outlet pressure increases, the amplitude of pressure fluctuation caused by the oil pump rotation increases, then the gas generating speed increases accordingly.

With the increase of the pump speed, the influence of the outlet pressure on the gas generation gradually reduces. With the increase of oil pump speed, the outlet velocity of lubricating oil increases, the low-pressure pulse duration is shortened, which results in the gas generating gain speed decreases gradually.
4.3. Gas generating hysteresis

Figure 14 shows the evolution of the lubricating oil gas mass ratio in the NEDC urban driving cycle. The gas mass ratio is generally linear with outlet pressure but lags behind the oil flow rate because the response of the hydraulic system is much lower than the mechanical system of the engine.

When the pump accelerates, the lubricating oil flow lags behind the pump speed, and the volume of the lubricating oil is incompressible so that more bubbles generated to fill the spare volume, resulting in the high gas mass ratio. When the pump decelerates, the lubricating oil flow cannot keep up with the decrease of the pump speed, and the lubricating pressure increases, so that there are fewer bubbles, and the gas mass ratio is lower than steady state.

Figure 15 shows the changing process of the gas mass ratio in the NEDC urban driving cycle, which is consistent with Figure. 6. Based on the analysis of Figure. 14, we can draw the following conclusion that the gas mass ratio during pump acceleration is generally greater than that of pump deceleration, which results in the hysteresis of gas generating.

5. Conclusions

(1) In the working range of vehicle engine (oil pressure and temperature), the lubricating oil gas volume decreases linearly with the increase of pressure, and it can be seen as an ideal gas;

(2) Under the same outlet pressure, the velocity of lubricating oil increases with the increase of pump speed, and the duration of low-pressure pulse decreases accordingly, and the gas generating gain decreases accordingly;

(3) With the increase of temperature, the viscosity of lubricating oil decreases rapidly, and the gas generating rate decreases significantly;

(4) In the driving cycles, the lubricating oil gas mass ratio lags behind the pump speed, which makes the gas mass ratio in the pump acceleration is significantly higher than that in the pump deceleration.

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