Bubble Behavior in Engine Lubricant

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ABSTRACT: Air bubbles in engine oil cause the serious issues, while high flow rate of the oil is circulated in resent engines lubrication system. In this study, the authors developed the bubble measurement technique based on image processing and analysis. This technique enables bubble diameter distribution and oil aeration rate to be measured without oil sampling. This measurement technique was applied to the operating engine and the bubble behavior in each lubrication passage was observed.

KEY WORDS: (Standardized) heat engine, lubricating oil/engine oil, measurement/diagnosis/evaluation
(Free) bubble, visualization [A1]

1. Introduction

Oil supply in engines is tending to increase, because demand for engine cooling capacity and the number of oil pressure actuated parts is increasing in order to improve engine performance. On the other hand, oil capacity has decreased due to the engine downsizing. Therefore, the oil recirculation rate is increasing, and oil is pumped again before entrained air bubbles disappear sufficiently in the oil pan. The problems associated with these bubbles are a source of concern (1). For this reason, there is an increasing demand for engine designs that minimize oil aeration rate, and it is necessary to grasp where and how much bubbles are entrained in order to improve engine design in the earliest stage of development. In the past, some studies have measured the aeration rate of oil at main gallery or oil pan (2)(3). However, there is no study which has measured at lubrication parts separately. We developed a method for measuring bubbles in oil at lubrication parts through image analysis, and analyzed bubble behavior in an operating engine.

2. Measuring Method of Air Bubbles in Lubricant

The aeration rate of oil has been measured in order to grasp the quantity of supplied oil and the cooling characteristics. It was necessary to measure not only aeration rate but also bubble diameter distribution in order to understand the bubble generation and dissipation characteristics. We then developed a method of measuring bubbles based on image analysis in which the aeration rate and the bubble diameter distribution can be measured simultaneously. This method does not require physical contact or oil samples.

2.1. Method of taking photographs of bubbles in oil

Figure 1 shows how photographs were taken on the actual engine. Each area where bubbles were measured was fitted with a viewing window through which photographs of the oil inside the engine were taken using a light source and a CCD camera. The light source was installed in the same direction as the CCD camera, and because the photograph was taken using scattered
light, the difference in the index of refraction made the oil appear black and the bubbles appear white (Figure 2). A visual field 1.58mm wide and 1.18mm high and a visual depth of 0.2mm were obtained with the camera and lens used in this study. The image analysis described in the following sections was carried out on this image to measure the bubble diameter distribution and the aeration rate.

2.2. Method for measuring bubble diameter distribution

To measure bubble diameter distribution, we created a program that is able to recognize bubbles automatically based on the following three processes.

(a) Distinguishing the oil
   A threshold value for luminance is used to distinguish the oil from everything else (bubbles and foreign matter) in a binary fashion.

(b) Distinguishing bubbles from foreign matter
   The bubbles in lubricant are spherical in shape, because the bubbles are 1mm or less in diameter, and the surface tension of bubbles is high. To distinguish the bubbles from foreign matter, the diameter and roundness of the bubbles are determined from the image. If the roundness of an object is below a threshold value, it is regarded as foreign matter.

(c) Distinguishing bubbles in the focal point from the other bubbles
   In order to remove bubbles that are not in the measurement volume, the luminance gradient at the bubble-oil interface is determined, and any bubbles with a gradient that is below a set threshold are treated as blurred bubbles that are out of focus.

The bubbles that remain after the three processes above are regarded as bubbles in the measurement volume, allowing the bubble diameter to be measured. The average value of multiple images is determined because there is some variation in bubbles depending on the image.

2.3. Method for measuring aeration rate

The image that is obtained is regarded as a rectangular volume of Width W × Height H × Depth of field D, and based on the number and diameter of bubbles found in the previous section, the aeration rate is calculated using Equations (1) to (3) below. It is assumed that the center of the bubble exists in the center of the depth of field, and if the bubble is larger than the depth of field, the excess portions are cut away (Equation (3)).

\[ A = \sum_{i=1}^{n} A_i \]  
\[ A_i = \frac{4}{3} \pi \left( \frac{d_i \times 10^{-3}}{2} \right)^3 \] 
\[ A_i = \frac{2\pi}{3} \left( \frac{d_i \times 10^{-3}}{2} \right)^2 - x^2 \] 

\[ \frac{dx}{V} \] 

\[ A: \text{Aeration rate [%]} \] 
\[ A_i: \text{Aeration rate of bubble } i \text{ [%]} \] 
\[ d_i: \text{Bubble diameter of bubble } i \text{ [μm]} \] 
\[ V: \text{Image volume } (V=W \times H \times D) \text{ [mm}^3\text{]} \] 
\[ n: \text{Number of bubbles [-]} \] 
\[ D: \text{Depth of field [mm]} \] 
\[ x: \text{Distance from the center of the depth of field [mm]} \]

2.4. Verifying accuracy

The volume method (Figure 3) was used as the master method to verify the accuracy of the aeration rate found in the previous section. As shown in the comparisons in Figure 4, the results of the image analysis and the results of the volume method matched with a correlation coefficient of more than 0.9.
3. Measurements in an Operating Engine

The bubbles in a commercially available 3.0L V6 engine (with VVT and without a balance shaft or turbocharger) were measured. It was broadly divided into three areas (the timing chain area, the crankcase area, and the valve train area) in the engine, and the bubble characteristics were measured at these three areas and at the bottom of the oil pan using image analysis.

3.1. Test method

Viewing windows were added to the timing chain case, crankcase, oil-draining hole, and to the bottom of the oil pan of the engine, and the bubbles in the oil at each area were measured (Figure 5).

The bubbles at the steady state (in which the amount of bubbles entrained equal the amount dissipated) were measured using the regular lubrication oil route (Oil route 1 in Figure 5). The bubbles entrained in the lubricated area were measured using the route with oil with zero bubbles (Oil route 2). A 5W-30 grade special oil without defoaming agent was used for these tests. This oil has an effect on only defoaming and no effect on foaming.

3.2. Test result

Examples of the photographs that were taken are shown in Figure 6. The upper row shows the bubbles in each part of engine at equilibrium (Oil route 1), and the lower row shows the entrained bubbles (Oil route 2). The bubble diameter distribution and aeration rate were calculated based on the photographs that were taken.

(1) Bubble diameter distribution at equilibrium (Oil route 1)

Figure 7 shows the bubble diameter distribution at each lubricated area and at the bottom of the oil pan at 80°C at an engine speed of 4000rpm. Each of the bubble diameter distributions measured at the lubricated areas has a peak bubble diameter of 20μm and almost identical distributions.

There were fewer bubbles at the bottom of the oil pan because some bubbles dissipated in the oil pan.

(2) Diameter distribution of bubbles entrained in lubricated areas (Oil route 2)

The bubble diameter distributions at an oil temperature of 80°C at engine speeds of 2000 and 4000 rpm are shown in Figure 8. Because the oil was supplied to the lubricated areas after the bubbles were completely dissipated, the bubbles measured were all bubbles that were entrained when the oil passed through the lubricated area.

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Fig. 5 Method for measuring bubble diameter distribution

Fig. 6 Images of bubbles

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The peak bubble diameter in different lubricated areas was different, and the peak bubble diameter was the smallest in the chain area, where it measured 20μm. The peak bubble diameters in each lubricated area remained almost constant at different engine speeds even though the number of bubbles changed. Based on this fact, it is conjectured that the diameter distribution of the bubbles that are entrained in lubricated areas are determined by the lubrication mechanism and the design values of the parts.

As the images in the lower row of Figure 6 show, the bubbles entrained in the valve train area were few in number, but bubbles exceeding 300μm could occasionally be found. It is conjectured that the oil accumulates in the valve train area and bubbles in the oil merge until falling back to the oil-draining hole.

As described in Ref. (1), the bubble diameter distributions of each area were roughly the same at the steady state (Figure 7). On the other hand, the diameter of entrained bubbles at each area is not the same (Figure 8), and these two facts contradict each other. So it is thought that the mechanism into which the bubble diameter changes exists, and this mechanism is considered in the next section.

4. Consideration about Bubble Diameter Change

The bubbles that became entrained in the lubricated areas have different diameter distributions depending on the area, but at equilibrium, the bubbles have almost the same diameter distribution regardless of the area. A possible reason for this is that the bubbles from the bottom of the oil pan become entrained as initial bubbles. These initial bubbles are sucked up by the oil strainer and undergo a change in diameter before reaching the various lubricated areas.

One mechanism that we thought of to explain the change in bubble diameter was the dissolution and precipitation of bubbles. Small bubbles have a large relative surface area and can easily dissolve, and any bubbles that are pressurized inside the oil routes dissolve in the oil(9). To verify the hypothesis that the bubble diameters of the bubbles that form from the dissolved bubbles when the pressure on the oil is released at the lubricated areas are changed, we carried out the test below.

4.1. Verification test

Oil containing bubbles was pressurized to 300kPa in a glass tube at room temperature using a piston (equivalent to 2000rpm in an actual engine). The pressure was then released to make bubbles precipitate (Figure 10). The bubbles before dissolution and after precipitation were measured and compared.

4.2. Result of verification

After precipitation, there were more bubbles measuring 20 to 50μm compared to before dissolution and fewer bubbles that were 60μm and larger, while the peak bubble diameter shifted to 20μm (Figure 11).
Based on the above, it is supposed that dissolution at higher pressures and precipitation at lower pressures changes the bubble diameter distribution, and that this is one reason why there are more 20μm bubbles at equilibrium in each lubricated area.

5. Conclusions

We developed a method of measuring air bubbles in lubricating oil that is based on image analysis. Through this method, we were able to measure the bubble diameter distribution and aeration rate of the oil in an operating engine without samples and without physical contact.

Also, we measured the bubbles in an actual engine using this measurement method and found the following.

(1) The bubble diameter distribution of each areas (the timing chain area, the crankcase area, and the valve train area) had a peak bubble diameter of 20μm at steady state, and had almost the same distribution.

(2) The diameter distribution of the bubbles that become entrained in each area is not the same. The diameter distribution probably determined by lubrication mechanism and design of the part.

(3) The peak bubble diameter shifted to 20μm through processes of dissolution and precipitation. In an actual engine, it is supposed that the bubbles are sucked up by the oil strainer, dissolve in the oil at main gallery and precipitate at each lubricant areas. This is one reason why there are more 20μm bubbles at steady state.

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