Combustion Characteristics of Recycled Lubricating Oil as Diesel Fuel

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ABSTRACT

Lubricating oil is mainly composed of distillates easy to self-ignite and contains little amount of aromatic hydrocarbon. Therefore, Used Lubricating Oil (ULO) may be used as a diesel fuel if abrasives are filtered properly. On the other hand, Heavy Fuel Oil (HFO) is composed of approximately 50% of residual components which is believed to be a cause of combustion trouble and problems related to it are more frequently reported.

In this paper, the adaptability of ULO was examined with both the fundamental combustion characteristics and the practical application to a diesel engine using four experimental equipment. As results: (1) burning phenomenon of ULO shows shorter ignition delay and less soot than HFO; (2) adding ULO to HFO improves smoke, NOx and SFC of HFO combustion with a high-speed diesel engine.

INTRODUCTION

At present, Used Lubricating Oil (ULO) from engines is usually disposed by being burnt in furnaces or boilers. Though ULO contains not only abrasives but also many kinds of additives whose effects on combustion are not yet clarified, ULO has two merits as a fuel for diesel engines. Firstly, lubricating oil is mainly composed of distillates easy to self-ignite. Secondly, lubricating oil contains little amount of aromatic hydrocarbon which deteriorates ignition quality and is believed to be the main origin of soot formed during the combustion process. Therefore, if ULO is filtered properly and effects of additives on combustion are clarified, ULO may be used as a diesel fuel.

On the other hand, recently the ignition quality of Heavy Fuel Oil (HFO) for marine diesel engines is deteriorating and problems related to it are more frequently reported. This is caused firstly by less components easy to evaporate and secondly by a higher content of aromatic hydrocarbons. So, the authors have carried out the research work to clarify whether the mixture of HFO and ULO can be a solution to these problems or not.

In this paper, fundamental combustion characteristics of ULO and the practical adaptability of ULO to diesel engines were examined. The following experiments were conducted:
(1) Analysis of the thermogravimetric curves using a thermobalance.
(2) Examination of the single droplet combustion characteristics.
(3) Visualization of the spray combustion in a D.I. test engine.
(4) Performance and emission tests with a high-speed marine diesel engine.

EXPERIMENTAL APPARATUS AND PROCEDURE

Test Fuel
Three kinds of fuels whose properties are summarized in Table 1 were prepared for the study.

| Table 1 Fuel Properties |
|-------------------------|-----------------|---------------|-----------------|
|                         | Heavy Fuel Oil  | Used Lub. Oil | Sample Oil      |
| Density kg/m³ (15°C)    | 931             | 893           | 867             |
| Kinematic Viscosity mm²/s (50°C) | 66.9         | 67.8           | 18.54           |
| Flash Point °C           | 40              | 244           | 212             |
| Residual Carbon wt%      | 14.2            | 1.89           | 0               |
| Sulfur wt%               | 3.0             | 0.24           | 0.10            |
| Composition              |                 |               |                 |
| Saturated hydrocarbon    | 17.9            | 78.7           | 73.6            |
| Aromatic hydrocarbon     | 54.4            | 16.4           | 26.4            |
| Resin hydrocarbon        | 14.9            | 4.9            | 0               |
| Asphaltene wt%           | 12.8            | 0             | 0               |
One is HFO, which is composed of approximately 55 vol.% of residual components (distillation temperature higher than 500°C) and approximately 45 vol.% of distillate components whose distillation temperature is lower than 250°C.

The second oil is ULO which is the lubricating oil from a marine diesel engine. It was used for over 2000 hours as system oil in a 2342GT/2869kW ship’s main engine. ULO is composed of higher temperature distillate components.

The third is a Sample Oil which represents the lubricating oil components.

Compositional analysis value of Saturated hydrocarbon, Aromatic hydrocarbon, Resin and Asphalten were carried out by alumina-gel chromatographic analysis and IP 143/90.

**Experimental Apparatus and Procedure**

The following four experimental equipment were prepared for the study.

1. A system for the visualization of a single droplet combustion.
2. A rapid compression machine for the visualization of a single spray.
3. A test engine for the visualization of the burning spray.
4. A high-speed marine diesel engine for performance and emission tests.

The scheme of the single droplet combustion system is shown in Fig.1. Furnace and ceramic jacket are used for heating the oil droplet. Quartz filament, support and stand are used for holding the droplet. Heat resisting glass, thermocouple and high-speed video system are used for observation.

1 μl of experimental oil picked up by a microsyringe was put onto the quartz string (0.2mm diameter). The furnace, preheated to a temperature of 450, 500 and 600°C, was then quickly moved over the droplet. The behavior of the droplet under each temperature was recorded by a high-speed video system (200 frames/sec) using a back-light condition.

The rapid compression machine and the test engine for the combustion visualization are shown in reference (2) and (3).

Specifications of the high-speed marine diesel engine is shown in Table 2 and the scheme of the fuel supply system is shown in Fig.2. HFO and ULO were heated to 85°C and 79°C, respectively, to lower the kinematic viscosity to 20 mm²/s.

The high-speed marine diesel engine was started using gas oil which is the proper fuel for the engine. At 75% load (marine characteristics), the fuel was changed to HFO and ULO. The suction air temperature at the air-cooler outlet was kept at 50°C in all tests. At this condition, the cylinder pressure, the needle lift and the fuel injection pressure against the crank angle were measured. At the same time,
emission data of NOx, O₂, CO, CO₂ and smoke density were measured.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Distillation Characteristics

Fig. 3 shows the thermogravimetric curves (TG curve) of HFO, ULO and the Sample Oil. All fuels were set inside N₂ gas flow (the flow rate was kept at 50m³/min) in order to prevent self ignition. The rising rate of the ambient temperature was 20°C/min.

It can be seen in the Fig. 3 that the evaporating start temperature of HFO is very low, because the light components evaporate easily. A second weight decrease happens again at 400°C. This is the reason why the residual components begin to be dissolved by heat energy (heat cracking) at this temperature. At last about 20% residual components remain at a temperature of 500°C.

On the other hand, the TG curve of ULO shows that none of the components are evaporating till about 250°C. And at high temperature almost all weight is lost within a range of approximately 150°C.

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>450</th>
<th>500</th>
<th>600</th>
</tr>
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<tr>
<td>Time sec</td>
<td>0.47</td>
<td>0.53</td>
<td>0.51</td>
</tr>
<tr>
<td>ULO</td>
<td></td>
<td></td>
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<tr>
<td>ULO</td>
<td>6.00</td>
<td>5.74</td>
<td>6.50</td>
</tr>
<tr>
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<td>9.00</td>
<td>6.50</td>
<td>8.11</td>
</tr>
<tr>
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<tr>
<td>ULO</td>
<td>11.00</td>
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</tr>
<tr>
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</tr>
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</tr>
<tr>
<td>HFO</td>
<td></td>
<td></td>
<td>2.98</td>
</tr>
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</table>

Fig. 3  T-G Curves of HFO, ULO and Sample Oil

The TG curve of Sample Oil shows about the same tendency as ULO.

Combustion Characteristics

Fig. 4 shows the change of the single droplet set inside the furnace. The time for each photo means after the start of heating. Firstly, the relationship between the single droplet of ULO and ambient

Fig. 4  Combustion Characteristics of Single Droplet
temperature is clarified. The droplet of ULO has evaporated almost completely at 450°C, which can be easily convinced also according to Fig. 3. In case of 500°C, the droplet ignites at 5.74 sec and forms an envelope-flame with little soot. And in case of 600°C, though ignition delay becomes shorter, the appearance of the flame is almost the same as at 500 °C. The condition of the quarts filament when the flame has gone out is sticking black soot.

On the other hand, HFO does not ignite at 500°C, but the droplet first becomes smaller and then expands into a distorted sphere. In case of 600°C, the droplet ignites at 1.23 sec and first forms an envelope-flame. At 2.70 sec, it can be seen that the small flames eject out from the envelope-flame. At 2.98 sec, the envelope flame changes its shape accompanying a stripe shaped soot, and the flame scatters just before going out.

To summarize the observation of the single droplet combustion, it can be said from the viewpoint of ignition delay and soot formation that ULO is better than HFO, because the former contains less Aromatic hydrocarbon and no residual components.

Fig. 5 shows the photos with back-diffused light of HFO and Sample Oil sprays taken from the underside of the piston of the rapid compression machine. Comparing the two at 1.4 ms after the start of injection, though the fuel spray travel and the shape of the spray are almost same, only Sample Oil has already ignited near the center of the spray. At 1.9 ms, Sample Oil spray is enveloped in flame.

In case of HFO, the spray ignites at 2.45 ms after the start of injection and burns up at 2.6 ms. However, the flame has not come close to the injection nozzle, because the evaporation could not be completed at
$P_c = 66 \text{ bar}, T_c = 500^\circ \text{C}$

$P_{mi} = 15 \text{ bar}, \text{Engine Speed} = 400 \text{ rpm}$

$\text{Inj. Nozzle} = 0.23 \text{ mm} \times 4 \times 2$

$\text{Inj. Press.} = 1000 \text{ bar}$

$\text{Inj. Timing} = 4^\circ \text{ BTDC}$

**Fig. 7** Combustion Characteristics in Visual Test Engine

The reason for this is that HFO contains many residual components which are difficult to evaporate before ignition. Even after ignition, the temperature of the fuel-rich spray core remains relatively low. Thus, when the spray is cooled down on the piston it easily forms soot. Another effect of this is that the flame of ULO burns out earlier than the flame of HFO as can be seen at 38 deg. ATDC.

**Performance and Emission Tests**

To examine the practical adaptability of ULO to diesel engines, performance and emission tests were carried out using the high-speed marine diesel engine. The reason why such a high speed engine was used is that the influence of the fuel characteristics would be revealed more emphasized than the medium speed engines$^{6,9}$.

Fig.8 shows the effect of mixture ratio of HFO and ULO on ignition delay, smoke density, NOx and specific fuel consumption (SFC). According to the figure, the more ULO is added to HFO, the better results of smoke, NOx and SFC can be achieved. Especially the improvement of smoke density is remarkable and for example only 25% ULO addition has an acceptable effect. In Fig.8, ignition delay of HFO in the high-speed marine diesel engine is about 1.5 times longer than ULO.

Fig.9 shows the difference in the heat release rate between the two fuels. In Fig.9, owing to the longer ignition delay of HFO, the ignition timing of
HFO is much later than ULO, though the fuel injection timing is both the same. With the same reason, the peak of the pre-mixed combustion of HFO is higher than that of ULO.

However, looking over the diffusive combustion rate after the premixed combustion in Fig. 9, HFO shows longer lingering combustion than ULO. Such a lingering combustion were seen also in case of HFO in Fig. 7.

CONCLUSIONS

Considering the results of above mentioned experiments, the following conclusions were derived about the combustion of the Used Lubricating Oil (ULO).

1. Comparing ULO with Heavy Fuel Oil (HFO) by observations of single droplet, single spray and flames in combustion chamber, the former shows much better ignition quality and combustion characteristics.
2. Adding ULO to HFO improves smoke, NOx and SFC of HFO combustion with a high-speed diesel engine.

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