Experimental study on physical properties and combustion characteristics of water-diesel emulsion

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Abstract—This study is on measuring the physical properties such as dynamic viscosity and surface tension, and analyzing the combustion characteristics of emulsion fuel comparing with pure diesel. Diesel and emulsion had Newtonian fluid characteristics independent on shear rate. Dynamic viscosity of emulsion was the highest in others and diesel was higher than water. Surface tension of emulsion was almost one-third of water and little higher than diesel. A droplet combustion experiment was carried out at 300, 500, and 700 °C of atmospheric temperature and 1, 10, and 20 bar of atmospheric pressure conditions. And initial size of a diesel and an emulsion droplet was range in 900 ±100 µm. At 1, 300, 500, and 700 °C of atmospheric temperature and 1, 10, and 20 bar of atmospheric pressure conditions, combustion could observe both cases. The ignition delay of emulsion was longer than diesel and the flame lifetime of emulsion was shorter than diesel because of strong micro explosion. Total droplet lifetime of emulsion was longer than diesel except for a case at 10 bar and 700 °C because of long ignition delay.

Index Terms—Emulsion, Water-Diesel emulsion, Droplet combustion, Physical property

I. INTRODUCTION

In recent years many researchers have studied on alternative fuel for improving combustion efficiency and reducing emission simultaneously but conventional fuel has limitation to satisfy those two challenging tasks. Especially, several emissions such as particulate matter (PM), nitrogen oxide (NOx), and carbon monoxide (CO) have regulated an amount of emission in whole world because these emissions are hard to disappear in environment and harmful for public health [1]. As solving these problems, emulsion fuel has paid attention to new alternative fuel. Especially the W/O emulsion fuel, which means water-in-oil, has shown high efficiency and low emission without any additional apparatus and cost [2]. When an emulsion fuel combusted, the flame temperature in charge of major reason of thermal NOx became lower than the flame temperature from conventional fuel as a result NOx emission could be reduced. Furthermore when superheated water vapor from producing because of different evaporation temperature between water and oil emerged from an emulsion droplet, a droplet was exploded, it called micro explosion, which has an effect of better fuel atomization [3]. A surfactant can reduce surface tension of water and oil, which makes wide contact area and decreases interfacial tension between water and oil phase, it can synthesize stable water in oil emulsion fuel and make smaller droplets of water [4].

Ithnin et al. experimentally studied on effect of water-in-diesel emulsion fuel of combustion performance and emission characteristics on direct injection engine varying engine load conditions. Added water percentages were 5% to 20% at intervals of 5%, and 2% of surfactant contained in emulsion fuel. Fuel containing 20% of water had maximum cylinder pressure and pressure rise rate compared with other cases. Also, it produced higher maximum rate of heat release in all cases. Emulsion fuel had well emission characteristics of low NOx and PM. But the CO and CO2 emissions increased at low and high load condition compared with pure diesel. Overall, emulsion fuel was researched to have better performance so it could be and appropriate alternative fuel [5].

Ochoterena et al. optically studied on spray development and combustion of water-in diesel emulsion and micro emulsion fuels. Spray development and combustion were studied in and optically observed combustion chamber vessel similar to a diesel engine. Droplet break-up process penetration, vapor penetration and combustion start were optically observed. The droplets of an emulsion fuel penetrated further than the droplets of conventional fuel. An atomization of emulsion fuel droplets enhanced compared with conventional fuel. And soot concentration and flame temperature reduced comparing to regular diesel fuel [6]. Combustion research of a liquid droplet at high temperature and pressure environment is one of basic studies on spray combustion for using in various fields such as industrial furnace, incinerator, internal engine, and etc. What combustion characteristics of a single droplet investigates, is essential for understanding complicated process of spray combustion [7].

Ghassemi et al. experimentally studied at the different environmental conditions under normal gravity. Heptane and hexadecane were used as the binary fuel with different evaporation rates and boiling temperatures. They found that the evaporation of the binary fuel droplet accompanied a bubble formation at low pressure and led to incomplete micro-explosion. But the bubble formation disappeared at higher pressure environment [8].
This research is experimental study on measuring the physical properties such as dynamic viscosity and surface tension, and analyzing the combustion characteristics of emulsion fuel comparing with pure diesel. The evaporation and combustion process of an emulsion droplet as well as ignition delay and flame lifetime was observed using high speed camera.

II. EXPERIMENTAL APPARATUS

A. Properties measurement

First measured property was dynamic viscosity of pure diesel and emulsion fuel. All cases were measured at 15, 30, and 60 °C between melting point and boiling point of water. Dynamic viscosity could be measured by rheometer during increase in shear rate. When Newtonian fluid has uniform dynamic viscosity independent of shear rate so it can be calculated from average value. Surface tension was measured by tensiometer (K20, KRUSS) through wilhelmy plate method at same temperature conditions.

B. Combustion experiment procedure

Figure 1 is the schematic diagram of experimental apparatus [9]. As using the temperature controller, atmospheric temperature inside electric furnace could uniformly increase and temperature variation inside the furnace maintained within ±5 °C of targeted temperature. When temperature inside electric furnace reached at targeted temperature, an emulsion droplet was suspended at the tip of K-type thermocouple (Omega Engineering, Inc.) using an injector. A diameter of injector hole was very small size (100 μm) and the range of suspended an emulsion droplet diameter was 90±100 μm. Thermocouple was removed the shield at the tip and its bead was welded by Cr-Al wires. The diameter of a wire was 50 μm and the bead size was 100 μm. Thermocouple would have some errors because heat capacity of metal wires caused heat loss inside a droplet. Harada et al. studied the measurement error of thermocouple suspended a droplet at the bead. In this study, 50 μm wire of thermocouple had an error less than 10 %. Although thermocouple had an error less than 10 %, it had good agreement with experiment and numerical result in reference [10].

The electric furnace descended to downwards along the two guide bars as using the lever after a droplet was suspended at the tip of thermocouple. When electric furnace arrived at experimental position, surrounding environment of a droplet instantaneously became high atmospheric temperature in a moment and a droplet started to vaporize and then combust. The process of a single droplet evaporation and combustion was recorded by high speed camera (operating at a rate of 200 frames per second) through the quartz window.

<table>
<thead>
<tr>
<th>Boiling temperature of water and diesel at 1 bar</th>
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<tbody>
<tr>
<td>Boiling temperature (°C)</td>
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<td>--------------------------</td>
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C. Synthesis of emulsion fuel

The distillated water (OCI Inc.) was used and diesel (GS Caltex) was used as oil in emulsion that has different boiling temperature with distillated water in table.1. Diesel is mixture of several chemicals hence its range of boiling point is diverse. The emulsion fuel was mixed by 1:1 mass ratio of water and diesel in total 10 ml. Water and diesel are immiscible chemicals so ultrasonicator(Sonics & Materials Inc.) was used as mixing apparatus. It operated total 10 minutes, which mixed 5 seconds and then stopped 15 seconds to prevent increase in emulsion temperature.

III. RESULTS

A. Physical properties

As already mentioned, dynamic viscosity has uniform value independent of shear rate in case of Newtonian fluid. Figure 2, 3 are change in dynamic viscosity of diesel and emulsion respectively along getting higher shear rate. Actually dynamic viscosity of emulsion fuel was getting slightly lower as increasing the shear rate because it was separated to water and diesel at high shear rate. But it had similar average because decrease rate of viscosity values was very small after shear rate of 40.

Figure 4 is the dynamic viscosity of emulsion fuel along shear rate. The dynamic viscosity values of water along the temperature were almost same as reference values [11]. Dynamic viscosity of emulsion fuel was the highest in other cases. This reason is that dispersed particle in emulsion formed the flocks and encapsulated in continuous phase hence increasing the effective concentration. At high shear rate.
flocks were destroyed leading to decrease in viscosity because of separated phases [12].

The measured surface tension values are shown in table 2. The surface tension of water already was known in reference [11] therefore measured on diesel and emulsion. The surface tension values of diesel were almost one-third of water. The surface tension value of emulsion was little higher than diesel because of water. Above emulsion phase almost consisted of diesel, which is lower density than water, hence surface tension values of emulsion were almost similar with diesel.

![Dynamic viscosity of diesel along shear rate](image1)

![Dynamic viscosity of emulsion fuel along shear rate](image2)

![Dynamic viscosity of water, diesel, and emulsion along temperature](image3)

**Table 2**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>15</th>
<th>30</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water[11]</td>
<td>73.5</td>
<td>71.2</td>
<td>66.2</td>
</tr>
<tr>
<td>Diesel</td>
<td>27.8</td>
<td>26.6</td>
<td>23.9</td>
</tr>
<tr>
<td>Emulsion</td>
<td>31.7</td>
<td>29.8</td>
<td>24.9</td>
</tr>
</tbody>
</table>

(Unit: mN/m)

B. Combustion behavior of a droplet

Combustion experiment was carried out at 300, 500, and 700 °C of atmospheric temperature and 1, 10, and 20 bar of atmospheric pressure conditions. And initial size of a diesel and emulsion droplet was range in 900 ±100 µm. In case of an emulsion droplet at 1 bar and all temperature conditions, a droplet could not suspend at the tip of thermocouple because of strong micro explosion in fig. 5. The major cause of micro explosion was the sudden explosion of superheated water inside an emulsion droplet. The boiling temperature of water is lower than diesel so water vapor was stacked inside liquid diesel and then it abruptly came out from a droplet at high temperature condition. Also a pure diesel droplet could not combust at 1 bar and all temperature conditions. Proper mixture with fuel and air could not form because of fast diffusion hence it didn’t satisfy the flammability limit.

At 10, 20 bar and 500, 700 °C conditions, both a diesel and an emulsion droplet combusted. When a diesel droplet combusted in fig.6, micro explosion phenomenon didn’t happen but an emulsion droplet was shown different characteristics. At 500 °C, an emulsion droplet combusted after water evaporated in fig.7. But micro explosion happened after a droplet ignited at 700 °C. Therefore micro explosion vigorously happened and a droplet atomized in fig.8. At high ambient temperature condition, both diesel and water in emulsion were simultaneously evaporated and then fast ignited.

Figure 9 is the ignition delay of a droplet. The ignition delay means the time from exposure of a droplet at high temperature condition to ignition of a droplet. Figure 9-(a) is the ignition delay as increase in pressure at 500 °C and fig.9-(b) is at 700 °C. Generally the ignition delay of diesel was lower than one of emulsion. This is reason that water disturbed to form the mixture. As evaporated water vapor mixed with fuel vapor and air, mixture became fuel lean case. To satisfy the flammability limit, more time consumed than diesel. At 500 °C, ignition delay was higher as increase in pressure because of water evaporation. At relatively low temperature, water evaporated at first and then an emulsion droplet ignited. As increase in pressure, latent heat of water was lower which means easy to evaporation but diffusion coefficient was also lower which means hard to evaporation. This result means that the effect of diffusion was dominant hence an emulsion droplet was hard to vaporize at high pressure and relatively low temperature. On the contrary the ignition delay was shorter as increase in pressure at relatively high temperature. Even though diffusion coefficient of water and diesel was
lower, latent heat of water and diesel also decreased and high temperature helped to vaporize a droplet and ignition fast occurred caused by fast chemical reaction.

Figure 10 is the flame lifetime of a droplet. The flame lifetime means the time from ignition to extinction of the flame around a droplet. At 20 bar and 500 °C condition, it could not acquire the data because of long ignition delay. Though the flame lifetime was measured by the flame images captured by high speed camera, the limit time of high speed camera was maximum 9 seconds that’s why it could not be measured. But the flame lifetime can guess to have value lower than diesel value. Generally flame lifetime was longer at high temperature because a droplet size was bigger compared with at lower temperature when it burned which was related to ignition delay. The flame lifetime of emulsion was shorter than diesel’s one because of micro explosion of emulsion. The flame of an emulsion droplet went away with atomized droplets as shown in fig.8. At relatively low pressure, micro explosion occurred stronger so flame lifetime was short on emulsion. In case of diesel, flame lifetime at high pressure was shorter on the contrary with emulsion. The mixture formed near a diesel droplet hence flame occurred close location of a droplet at high pressure in fig.11. Because heat feedback between flame and a droplet was huge during combustion, located flame near a droplet promoted evaporation. Heat feedback was main factor to determine flame lifetime.

Figure 12 is the droplet lifetime at each condition. The droplet lifetime means the time merged ignition delay and flame lifetime. Even though emulsion had shorter flame lifetime, total droplet lifetime was longer than diesel because of long ignition delay except for case at 10 bar and 700 °C. At 10 bar and 700 °C, the reason why emulsion had shorter droplet lifetime than diesel was micro explosion which happened the strongest any other cases. Even though ignition delay was longer, a droplet atomization made that combustion was more effective.
IV. CONCLUSION

This study is on measuring the physical properties of diesel and emulsion fuel and observing the combustion characteristics of a diesel and emulsion droplet. The followings are summarized conclusions from results.

1. Both diesel and emulsion fuel had the characteristics of Newtonian fluid.

2. Emulsion had the highest dynamic viscosity value. Because dispersed particles in emulsion formed flocks and encapsulated at moderate shear rate, effective concentration increased.

3. Surface tension of emulsion was little higher than surface tension of diesel because of the effect of water.

4. The ignition delay of emulsion was longer than diesel because water vapor diluted the mixture composed by fuel vapor and air.

5. The flame lifetime of emulsion was shorter than diesel because strong micro explosion. During combustion of an emulsion droplet, micro explosion made atomized droplet and flame was taken away with atomized droplets.

6. Total droplet lifetime of emulsion was longer than diesel except for a case at 10 bar and 700 °C because of long ignition delay.

From this result, it is shown that emulsion is more effective combustion characteristics than pure diesel at 10 bar and 700 °C.

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REFERENCES


