ABSTRACT

Comparison of single-droplet combustion characteristics between biodiesel and diesel is experimentally investigated under various Reynolds numbers. The fuel was fed into a porous sphere of 6 mm in a diameter to simulate as the fuel droplet. After igniting a droplet at Re=93, the Reynolds number is controlled stepwise from 93 to 192 and then from Re=192 to 93 those are defined as the upper-branch and lower-branch observations, respectively. Multiple-state phenomena are observed for biodiesel droplet at $119 < Re \leq 154$ and diesel droplet at $101 < Re \leq 145$. The burning rate of a biodiesel droplet to that of a diesel droplet is in the ratio of about 1.4 to 1 in envelope flames. There is no apparent difference of burning rate between a biodiesel droplet and a diesel droplet in wake flames. The burning rates decrease by factors of 4.35 for the biodiesel droplet and 3.03 for the diesel droplet when the envelope flame is transformed into a wake flame in upper-branch observations. The flame of a burning diesel droplet exhibits deeper yellow color than that of a biodiesel droplet.

Keywords: Biodiesel, Droplet, Burning rate, Envelope flame, Wake flame, Multiple-state phenomena

1. INTRODUCTION

In recent years, many researches [1-4] were conducted to develop alternative fuels because of the shortage of petroleum products and its increasing cost. Biodiesel is considered as a promising alternative fuel to the fossil diesel for fully or partial replacement because it may be directly used as fuel for diesel engines without any prior modification of the design or equipment. Biodiesel is also assessed as a renewable fuel because it is free from sulfur and aromatic compounds. Experimental researches [5-10] on the emission characteristics of diesel engine fueled biodiesels showed that pure biodiesel and its blends with conventional diesel can significant reduce carbon monoxide (CO), hydrocarbon (HC), and particulate matter (PM). By compared to conventional diesel, the application of biodiesel to diesel engines still has several properties those need to be improved, such as lower engine power output and higher emissions of nitrogen oxides. Therefore, it is important to conduct more researches to formulate optimal operation conditions as biodiesel is used as fuel for diesel engines. Recent advances on computer capabilities and numerical algorithms have greatly promoted numerical simulation as an analytical tool in performance improvement of diesel engines. However, vaporization and combustion characteristics of biodiesel droplets have not been well studied to provide appropriate droplet models those are necessary for numerical simulation of diesel engine fueled biodiesels.

In the conventional investigations involving droplet vaporization and combustion in sprays, the models were usually established through single-droplet combustion characteristics at various droplet and ambient conditions. Experimental studies by Spalding [11], as well as Gollahalli and Brzustowski [12, 13] observed that flame structures of a burning droplet in a convective flow field are quite different from those of a stationary droplet because of the appearance of two types of flame configurations: an envelope flame at a low relative speed and a wake flame at a high relative speed. Gollahalli and Brzustowski [12, 13] also found that the droplet burning rate was reduced by a factor of three after the flame mode transforms from an envelope type to a wake type. Due to the results of irreversibility associated with ignition, extinction, blow-off, and reattachment of the flame occurring in specific operating conditions, the numerical studies of Jiang et al. [14, 15], as well as Chiu and Huang [16, 17] advocated a droplet in a convective flow field exhibits much more complex multi-state behaviors about state multiplicity including envelope flame combustion, wake flame combustion and vaporization modes at given environmental conditions. It is recognized the droplet state can be uniquely determined only when both environmental conditions and the initial state of the droplet are known.

The objective of the present study is to examine single-droplet combustion characteristics of biodiesel and diesel respectively. Flame configurations and burning rates of a convective fuel droplet are experimentally investigated at various Reynolds numbers. Based on the numerical procedures of Jiang et al. [14, 15], as well as Chiu and Huang [16, 17], the present study also adapts appropriate experimental procedures (defined as upper-branch and lower-branch observations respectively) to examine whether single-droplet combustion characteristics of biodiesel and diesel exhibit multiple-state phenomena or not. The article begins with a description of experimental method. Results concerning the flame structure and burning rate of diesel droplet and biodiesel droplet are then described. The article concludes with a comparison of single-droplet combustion characteristics between biodiesel and diesel.

2. EXPERIMENTAL METHODS
2.1 Experimental Apparatus

The experiment is a variation on the classic porous-sphere model [11-13]. A sketch of the experimental apparatus is shown in Fig. 1. Fuel is supplied to a porous sphere of 6mm in diameter mounted at an angle of 110° to the approach air to simulate a fuel droplet. The entire spherical surface is kept wet with the fuel and no drips that the fuel flow rate is then considered as the burning rate. The droplet is suspended 40 mm above a nozzle of 64 mm exit diameter, which provides a metered air with a uniform velocity profile in the exit plane by a cylindrical mixing chamber (100 mm in diameter and 500 mm tall) equipped with screens and small steel beads. The flames occurred in a vertically upward flow field are directly photographed by a digital video camcorder. The burning rate and the air flow rate are monitored using two rotameters respectively. The ambient temperature is measured at the center of the nozzle exit by a K-type thermocouple. Hence the ambient Reynolds number can be expressed as follows:

\[ Re = \frac{4m_a D_l}{\mu \pi D^2} \]  

where \( D \) is diameter of the nozzle exit, \( D_l \) is diameter of the porous sphere, and \( m_a \) is air flow rate.

All tests are carried out in an environment of atmospheric pressure and an ambient temperature of 298 K. The Reynolds number is controlled in the ranges of 93 to 192.

2.2 Experimental Procedure

To investigate possible multiple-state phenomena of a convective fuel droplet, the Reynolds number is controlled stepwise from 93 to 192 and then from \( Re=192 \) to 93 those observed at different Reynolds numbers, respectively. The experimental procedure is summarized as follows:

1. The droplet is ignited by the ignition coil at \( Re=93 \). The entire spherical surface is kept wet with the fuel and no drips by adjusting fuel flow rate. After all test conditions are steady, the fuel flow rate is considered as the droplet burning rate. The flame is directly photographed by digital video camcorder.
2. The Reynolds number is controlled stepwise from 93 to 192. The droplet burning rate and the flame structure are observed at different Reynolds numbers, respectively. The above experimental procedure is defined as the upper-branch observation.
3. After the upper-branch observation has been completed, then reverse the Reynolds number stepwise from 192 to 93. The droplet burning rate and the flame structure are observed at different Reynolds numbers, respectively. The above reversed procedure is defined as the lower-branch observation.
4. Repeat the above steps three times to calculate the mean value of the experimental data.

2.3 Test Fuels

The tested biodiesel was produced from soybean oil and methyl alcohol via a transesterification reaction, which was provided by a large biodiesel producer in the USA. On the other hand, the tested diesel was a commercial product obtained from the Chinese Petroleum Company (CPC) in Taiwan. Some major properties of those two tested fuels, which were measured through different ASTM test methods by CPC, were listed in Table 1. The biodiesel may be assessed as a renewable fuel because it exhibits far lower sulfur content (<0.001 wt%) and higher oxygen content (11.75 wt%) than those of the diesel (0.0258 and 0.014 wt% for sulfur and oxygen contents, respectively). Higher oxygen content of the biodiesel may also induce higher combustion temperature. Lower heating value of the biodiesel (92% value of the diesel) may induce lower engine power output under the same operation conditions. Higher viscosity and specific gravity of the biodiesel than those of the diesel may also cause large mean droplet size at the same injection conditions.

3. RESULTS AND DISCUSSION

3.1 Flame Structure

Figures 2 and 3 show direct photographs of droplet flames, at various Reynolds numbers of both upper-branch and lower-branch observations, for biodiesel and diesel respectively.

1. Upper-branch observation

For the upper-branch observation where droplet is ignited by the ignition coil at \( Re=93 \), Fig. 2 shows that the biodiesel droplet burns with an oval-shaped envelope flame at relatively lower Reynolds numbers of \( Re \leq 154 \). If the Reynolds number is increased more than the critical value (i.e. \( Re \geq 156 \)), the flame suddenly transforms into a smaller-sized wake flame stabilized in the near-wake region. Fig. 3 shows the upper-branch observation of the diesel droplet also behaves similar transition of flame structure: an envelope flame at \( Re \leq 145 \) and a wake flame at \( Re \geq 148 \) respectively. The above results are consistent with experimental observations by Spalding [11], as well as Gollahalli and Brzustowski [12, 13].

2. Lower-branch observation

For the lower-branch observation by reversing the Reynolds number stepwise from 192 to 93, Fig. 2 shows that the biodiesel droplet burns with the same flame structures as those observed by upper-branch observation at \( Re \geq 156 \) and \( Re \leq 119 \). However, results of the lower-branch observation shows that the biodiesel droplet burns with the different flame structure than those by upper-branch observation at \( 119 < Re \leq 154 \). The biodiesel droplet burns with a wake flame at \( Re=154 \) of lower branch and, subsequently, transforms into a side flame at \( Re=121 \). Finally, a side flame confluences at the forward stagnation region of the biodiesel droplet to form an envelope flame at \( Re=119 \) of lower branch. Similarly, flame structures of the diesel droplet by lower-branch and upper-branch observations behave the same states at \( Re \geq 148 \) and \( Re \leq 101 \), but different states at \( 101 < Re \leq 145 \) as shown in Fig. 3. The diesel droplet burns with a wake flame at \( Re=145 \) and 121 of lower branch and, subsequently,
transforms into a side flame at Re=109. Finally, a side flame confluences at the forward stagnation region of the diesel droplet to form an envelope flame at Re=101 of lower branch.

By comparing the flame structures between biodiesel and diesel, one finds that: (1) Dual-state region, where the flame configuration of a droplet is different by upper-branch and lower-branch observations, are observed for biodiesel droplet at $119 < \text{Re} \leq 154$ and diesel droplet at $101 < \text{Re} \leq 145$; (2) The flame of a burning diesel droplet exhibits deeper yellow color than that of a biodiesel droplet; and (3) More soot formation rate of a burning diesel droplet is also observed than that of a biodiesel droplet.

3.2 Droplet burning rates

Figure 4 shows droplet burning rates, at various Reynolds numbers of both upper-branch and lower-branch observations, for biodiesel and diesel respectively.

(1) Upper-branch observation

Figure 4 shows that values of the burning rate are deeply affected by the flame structure in upper-branch observation. For the droplet burns with an envelope flame (at Re $\leq 154$ and Re $\leq 145$ for biodiesel and diesel, respectively), the burning rate increases as the Reynolds number increases that enhances convective heat transfer from the leading flame to the droplet surface. The burning rate of a biodiesel droplet to that of a diesel droplet is in the ratio of about 1.4 to 1 in envelope flames. It was also found that the burning rates decrease by factors of 4.35 for the biodiesel droplet and 3.03 for the diesel droplet when the envelope flame is transformed into a wake flame in upper-branch observation. The above observation is in good qualitative agreement with experimental data by Gollahalli and Brzustowski [12], who observed the burning rate decreases by a factor of 3 when the envelope flame is transformed into a wake flame at Re = 138 for a 6 mm porous sphere fed by n-pentane. On the other hand, there is no apparent difference of burning rate between a biodiesel droplet and a diesel droplet in wake flames. For the droplet burns with a wake flame (at Re $\geq 156$ and Re $\geq 148$ for biodiesel and diesel, respectively), the burning rate decreases as the Reynolds number increases so that the size of the wake flame is decreased.

(2) Lower-branch observation

In lower-branch observation by reversing the process of the upper-branch observation, figure 4 shows that values of the burning rate are also deeply affected by the flame structure. One finds that the burning rates of the biodiesel droplet are the same as those of a forward path at Re $\geq 156$ and Re $\leq 119$ where both upper-branch and lower-branch observations behave the same flame structures. At $119 < \text{Re} \leq 154$, the burning rates observed in the lower-branch observation are lower than those observed in the upper-branch observations because the biodiesel droplet burns with an envelope flame in upper-branch observation but a wake flame or side flame in lower-branch observation. Similarly, burning rates of the diesel droplet by lower-branch and upper-branch observations behave the same values at $\text{Re} \geq 148$ and $\text{Re} \leq 101$, but different values at $101 < \text{Re} \leq 145$ as shown in Fig. 4.

Based on the above experimental results, one finds that: (1) single-droplet combustion characteristics of both biodiesel and diesel are observed to behave multi-state phenomena those have been numerically investigated by Jiang et al. [14, 15], as well as Chiu and Huang [16, 17], to elucidate multiple flame configurations and burning rates of a convective droplet at various ambient conditions; (2) The burning rate of a biodiesel droplet is more than that of a diesel droplet (in the ratio of about 1.4 to 1) in envelope flames, but without apparent difference in wake flames; and (3) Since dual-state region are observed by upper-branch and lower-branch observations, the droplet state can be uniquely determined only when both the environmental condition and the initial state of the droplet are known.

4. CONCLUSIONS

Single-droplet combustion characteristics, at various Reynolds numbers, were experimentally investigated for biodiesel and diesel, respectively. The experimental results of this study can be summarized as follows.

(1) Multiple-state phenomena are observed for biodiesel droplet at $119 < \text{Re} \leq 154$ and diesel droplet at $101 < \text{Re} \leq 145$, where behave multiple flame configurations and burning rates at the same Reynolds numbers.

(2) The burning rate of a biodiesel droplet to that of a diesel droplet is in the ratio of about 1.4 to 1 in envelope flames. There is no apparent difference of burning rate between a biodiesel droplet and a diesel droplet in wake flames.

(3) The burning rates decrease by factors of 4.35 for the biodiesel droplet and 3.03 for the diesel droplet when the envelope flame is transformed into a wake flame in upper-branch observations.

(4) The flame of a burning diesel droplet exhibits deeper yellow color than that of a biodiesel droplet.

The present study is carried out at a low ambient temperature. More experimental investigation on a biodiesel droplet burning in hot air flows, which is of particular interest for practical spray combustion, will be presented in the near future.

5. ACKNOWLEDGEMENTS

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Table 1 Properties of biodiesel and diesel used in this study.

<table>
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<tr>
<th>Fuel properties</th>
<th>Density at 15.5°C (g/cm³)</th>
<th>Viscosity at 40°C (mm²/s)</th>
<th>Cetane index</th>
<th>Heating value (Cal/g)</th>
<th>Carbon content (wt%)</th>
<th>Hydrogen content (wt%)</th>
<th>Oxygen content (wt%)</th>
<th>Sulfur content (wt%)</th>
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<td>53.9</td>
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<td>0.0258</td>
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Fig. 1 Sketch of the experimental apparatus.

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<th>Re=119</th>
<th>Re=121</th>
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<tr>
<td>Lower branch</td>
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</table>

Fig. 2 Direct photographs of biodiesel droplet flames at various Reynolds numbers.
Fig. 3 Direct photographs of diesel droplet flames at various Reynolds numbers.

Fig. 4 Droplet burning rates at various Reynolds numbers.

7. NOMENCLATURE

- \( D \): diameter of the nozzle exit [m]
- \( D_t \): diameter of the porous sphere [m]
- \( m \): droplet burning rate [kg/s]
- \( m_a \): air flow rate [kg/s]
- \( \text{Re} \): Reynolds number (see Eq.(1))
- \( \mu \): air viscosity at the nozzle exit [kg/m\( \cdot \)s]

8. REFERENCES

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