Characteristics of the ignition and combustion of biodiesel fuel spray injected by a common-rail injection system for a direct-injection diesel engine

O A Kuti* 1, W G Xiangang 2, W Zhang 1, K Nishida 1, and Z H Huang 2

1Department of Mechanical Systems Engineering, University of Hiroshima, Higashi-Hiroshima, Japan
2State Key Laboratory of Multiphase Flow in Power Engineering, Xi’an Jiaotong University, Xi’an, People’s Republic of China

The manuscript was received on 27 January 2010 and was accepted after revision for publication on 11 June 2010.

DOI: 10.1243/09544070JAUTO1503

Abstract: The effect of injection pressures at 100 MPa and 200 MPa respectively on the ignition and combustion characteristics of biodiesel fuel spray injected by a common-rail injection system for a direct-injection diesel engine was investigated. Two biodiesel fuels (namely biodiesel fuel from palm oil (BDFp) and biodiesel fuel from cooking oil (BDFc)) and JIS #2 diesel fuel were utilized in this research. The Mie scattering technique was used to characterize both the non-evaporating and the evaporating spray formation processes. The OH chemiluminescence technique was used to determine the ignition and the lift-off length of the combusting flame. Two-colour pyrometry was applied for the soot formation processes. At all injection pressures, the biodiesel fuels (especially BDFp) gave a longer spray tip penetration and a smaller spray angle under the non-evaporating conditions while the liquid-phase penetration length was longer for the biodiesel fuels than for diesel under the evaporating conditions. From estimation using a simplified model for air entrainment by the sprays, the BDFp and BDFc exhibited lower mass ratios of air to fuel than diesel did. The ignition delay was longest for the BDFc while it was shortest for the BDFp. Both the experimental and the predicted flame lift-off lengths for the BDFp were the shortest, indicating the least percentage of entrained stoichiometric air upstream. There was no significant difference between the integrated and averaged \( KL \) factors at 100 MPa injection pressure for the BDFc and diesel fuels. At 200 MPa, the BDFc presented much lower integrated and averaged \( KL \) factors than diesel did. The averaged flame temperatures of the BDFc were found to be lower than that of diesel. The oxygen content in the BDFc played a significant role in the soot formation in comparison with the oxygen from the percentage of stoichiometric air entrained upstream of the lift-off length.

Keywords: diesel engine, biodiesel fuels, spray, ignition, combustion

1 INTRODUCTION

As a consequence of the further stringent emission control regulations imposed on conventional fuels such as diesel, the search for alternative fuels such as biodiesel has attracted more attention. Alternative fuels such as biodiesel are popularly gaining more ground in many countries owing to increased environmental awareness and the rising price of fossil fuels such as diesel [1]. Biodiesel fuel is an environmentally clean and renewable energy source. It is usually produced from animal fats or vegetable oils by the transesterification reaction. The oxygen content, which is about 11–15 wt %, enables biodiesel to enhance the combustion process and to reduce pollutant emissions from the diesel engine [2]. Biodiesel as an alternative fuel in diesel engines has a great potential for reducing the emissions of carbon monoxide (CO), carbon dioxide (\( \text{CO}_2 \)), hydrocarbons, particulate matter (PM), sulphur oxides (\( \text{SO}_x \)), and polycyclic aromatic hydrocarbons with slightly increased brake-
specific fuel consumption and nitrogen oxide (NO\textsubscript{x}) emissions [1]. The major threat facing the use of biodiesel in diesel engines is the formation and control of NO\textsubscript{x} emissions. NO\textsubscript{x} emissions are closely related to the oxygen concentration in the biodiesel fuel. To this end, it has been proposed that the addition of cetane-improving additives and a decrease in the bulk modulus of biodiesel are potential ways of decreasing the NO\textsubscript{x} emissions. Also, by applying early injection timing, the NO\textsubscript{x} emissions can be reduced drastically [3, 4]. Numerous research studies have been carried out on the spray and combustion characteristics of biodiesel fuel in diesel engines [5–11]. Furthermore, the impact of a high injection pressure as an effective method of improving the spray atomization and mixture preparation processes of diesel fuel in order to reduce PM emissions has also been reported [12–16]. However, few studies have reported the effect of a high injection pressure on the biodiesel spray, ignition, and soot formation characteristics. Therefore, this study investigated the characteristics of the ignition and combustion of a biodiesel fuel spray injected by a common-rail injection system in a quiescent constant-volume vessel. Injection pressures of 100 MPa and 200 MPa and ambient conditions typical of a diesel engine were used.

2 EXPERIMENTAL DETAILS

2.1 Experimental apparatus and methods

The experiments were conducted under simulated quiescent conditions in a constant-volume vessel. Figure 1 shows a schematic cross-section of the vessel. This vessel can produce typical thermodynamic conditions in the combustion chamber of a diesel engine. The ambient temperature could be elevated to 900 K with an electric heater fixed in the lower location of the vessel. The vessel has an internal diameter of 200 mm. To provide optical access, a quartz window with a diameter of 124 mm is mounted on one side of the chamber while the other side is obstructed by a black metal block. The inside surface of the chamber is covered with a glass fibre insulator to avoid direct heat radiation from the heater. An injector is installed in the centre of the vessel’s cover using an adapter, while the common rail is fixed on the top surface of the vessel’s cover. A thermocouple was used to measure the ambient temperature inside the chamber. A manually operated piston screw pump, i.e. a high-pressure generator (High Pressure Equipment Co. model 37-5.75-60) as shown in Fig. 1, was used to generate an injection pressure up to 200 MPa in the common rail.

The injector was electronically controlled by the injector driver, while the common-rail pressure was measured with a pressure transducer. A pulse generator (Stanford Inc., DG 535) was used to synchronize the operation of the charge-coupled device camera and injection system.

In order to obtain spray images under non-evaporating conditions, a xenon lamp and two reflecting mirrors were utilized to illuminate the fuel spray inside the vessel using the Mie scattering technique. High-temperature autoignition as defined in references [17] and [18] was detected using the OH chemiluminescence Imaging technique. The OH chemiluminescence
technique was also used to determine the flame lift-off length. For the soot formation experiments, the two-colour pyrometry technique (a time-resolved line-of-sight method) was utilized to provide the flame structure, KL factor, and temperature distributions. The KL factor characterizes the soot concentration in the flame. Figure 1 also shows the experimental arrangement for the spray, OH chemiluminescence, and two-colour pyrometry imaging. The difference is that there is no illumination for the OH chemiluminescence and two-colour techniques. A high-speed video camera (FASTCAM-APX RS, Photron Co.) was employed to take the direct photography images of sprays. For the spray, the camera was equipped with a lens (Nikon; 70–210 mm; f/4–5.6)). A frame rate of 10,000 frames/s, an exposure time of 1/10,000 s, a resolution of 512×512 pixels, and an aperture of f/4.0 were utilized to image the non-evaporating and the evaporating sprays. With the aid of a UV-Nikkor lens (Nikon; 105 mm; f/4.5) attached to an image intensifier (LaVision Inc., HS-IRO), the OH chemiluminescence images were captured. An OH bandpass filter of wavelength 313 nm (10 nm full width at half-maximum (FWHM)) coupled to the camera was utilized to observe the OH chemiluminescence. The gain and gate of the image intensifier were adjusted carefully to obtain identical flame images at wavelengths of 650 nm and 800 nm (10 nm FWHM). A temperature range between 1600 °C and 2600 °C was utilized in calibrating the two-colour system. Detailed theoretical analyses of the two-colour data based on the Hottel-Broughton method can be found in reference [19]. For convenience, Thermera HS4 software (Mitsui Optronics, version 4.61) was used to process the captured raw image data obtained from the two wavelengths, thus generating two-dimensional and line-of-sight false-colour maps of flame temperature and soot concentration. This soot concentration, which is expressed as the KL factor, was found to be proportional to the soot volume concentration. The same frame rates, resolutions, and exposure times for the non-evaporating and the evaporating sprays were used to capture the two-colour pyrometry images. To avoid saturation in the two-colour images, the aperture was changed to f/8.0.

2.2 Experimental conditions

The experimental conditions were determined by the real engine conditions. An ambient density of 15 kg/m³ was used to simulate engine conditions at a crank angle of −10° after top dead centre (ATDC). Two kinds of biodiesel fuel (namely biodiesel fuel from palm oil (BDFp) and biodiesel fuel from cooking oil (BDFc)) and JIS#2 diesel fuel were utilized in the experiments. The JIS#2 diesel fuel was considered as the base fuel. For the non-evaporating spray, the ambient temperature and pressure are 295 K and 1.36 MPa respectively. For the evaporating spray and combustion conditions, an ambient temperature of 885 K and an ambient pressure of 4.0 MPa were maintained. Table 1 shows a list of the experimental conditions, while Table 2 presents the main properties of the three fuels.

Table 1 Experimental conditions and nozzle specifications

<table>
<thead>
<tr>
<th>Property (units)</th>
<th>Spray experiment</th>
<th>Combustion experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>N₂</td>
<td>Air</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>15 (at −10° ATDC)</td>
<td>15 (at −10° ATDC)</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>1.36, 4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>295, 885</td>
<td>885</td>
</tr>
<tr>
<td>Injection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Common rail for DI diesel</td>
<td>Common rail for DI diesel</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Quantity (mg)</td>
<td>Diesel, 14.6; BDFp, 10; BDFc, 14.6</td>
<td>Diesel, 16.34; BDFp, 13; BDFc, 15.9</td>
</tr>
<tr>
<td>Duration (ms)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Nozzle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Single hole</td>
<td>Single hole</td>
</tr>
<tr>
<td>Hole diameter (mm)</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Hole length (mm)</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 2 Main properties of fuels

<table>
<thead>
<tr>
<th>Fuel property (units)</th>
<th>JIS#2 diesel</th>
<th>BDFp</th>
<th>BDFc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15°C (kg/m³)</td>
<td>830</td>
<td>874.4</td>
<td>885.1</td>
</tr>
<tr>
<td>Viscosity at 30°C (mm/s)</td>
<td>3.36</td>
<td>5.53</td>
<td>4.45</td>
</tr>
<tr>
<td>Surface tension at 20°C (mN/m)</td>
<td>30.6</td>
<td>32.6</td>
<td>33.1</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>&gt;60</td>
<td>&gt;182</td>
<td>&gt;180.5</td>
</tr>
<tr>
<td>Cetane number</td>
<td>58</td>
<td>64.6</td>
<td>51</td>
</tr>
<tr>
<td>Flow point (°C)</td>
<td>4</td>
<td>15</td>
<td>−5.0</td>
</tr>
<tr>
<td>Heating value (MJ/kg)</td>
<td>43.1</td>
<td>40.03</td>
<td>39.03</td>
</tr>
<tr>
<td>Sulphur content (ppm)</td>
<td>&lt;10</td>
<td>&lt;1</td>
<td>&lt;3</td>
</tr>
<tr>
<td>Carbon content (wt %)</td>
<td>86.1</td>
<td>76.5</td>
<td>77.1</td>
</tr>
<tr>
<td>Hydrogen content (wt %)</td>
<td>13.8</td>
<td>12.3</td>
<td>12.0</td>
</tr>
<tr>
<td>Oxygen content (wt %)</td>
<td>&lt;1</td>
<td>11.1</td>
<td>10.6</td>
</tr>
</tbody>
</table>
3 RESULTS AND DISCUSSION

3.1 Non-evaporating spray characteristics

In order to understand the effect of the different fuel properties on spray development, the fuel spray shape, spray tip penetration, and spray angle were used to characterize the overall spray structure. Figure 2 shows the spray characteristics images for the three fuels at 100 MPa and 200 MPa injection pressures. The BDFp produces a narrow spray shape, while the BDFc and diesel produces similar spray characteristics. The differences between the spray tip penetrations for the biodiesel fuels and those for diesel are shown quantitatively in Fig. 3. The spray tip penetration is defined as the maximum distance measured along the spray axis to which the spray can reach from the nozzle tip. A threshold intensity value of 10 in an 8 bit dynamic range (0–255 grey-scale range of images) of the camera was selected to process the spray images. At all injection pressures, the sprays of BDFp and BDFc are longer than those of diesel. The spray tip penetration lengths for the BDFp and BDFc increase more than those of diesel because of the higher viscosities, as shown in Table 2. The higher fuel viscosities of the BDFp and BDFc prevent break-up of the spray jet, thus resulting in an increase in the droplet size. A higher viscosity increases the droplet size, thus diminishing the air entrainment, which produces a longer spray penetration. At the two injection pressures, because of the higher viscosity, the BDFp produces a longer spray tip penetration than the BDFc does. The
surface tensions of the fuels also play a major role in atomization. Fuels with the least surface tension will produce the best atomization properties [20]. As presented in Table 2, the surface tension values of the BDFp and BDFc are very close and are higher than that of diesel. With the highest viscosity value in comparison with the other fuels, owing to the surface tension, there is the tendency that the BDFp will produce the highest Sauter mean diameter values compared with the other fuels. This will mean that the BDFp is not properly atomized during the injection processes, thus increasing the droplet size and diminishing the air entrained.

The quantitative analyses of the spray angle of the three fuels at the two injection pressures are shown in Fig. 4. The spray angles were analysed by drawing horizontal lines 30 mm downstream from the nozzle tip and measuring the angles between the edges of the spray on the horizontal lines and the nozzle tip. At the two injection pressures the biodiesel fuels exhibit smaller spray angles than the diesel fuel does. The BDFp produces the smallest spray angles in comparison with the BDFc and diesel. Just like the spray tip penetration, the smaller spray angles produced by the biodiesel fuels result from their higher viscosities, which leads to a worse spray atomization phenomenon.

### 3.2 Estimation of the air entrainment at any axial location of the spray

The air entrained in a spray plays a major role in the reduction in emissions during the combustion process. In this study, the Siebers [21] model on the entrainment of air into the quasi-steady non-evaporating fuel spray is applied in order to estimate quantitatively the mass of oxygen from the air entrained in the sprays. For a quasi-steady non-evaporating fuel spray, the total air entrainment up to any axial location to the amount of fuel injected can be estimated using the relationship

$$\frac{m_a}{m_f} = \sqrt{\frac{1 + 16(x/x^+)^2}{2} - 1}$$

---

**Fig. 3** Temporal variation in the non-evaporating spray tip penetration

**Fig. 4** Temporal variation in the non-evaporating spray angle
In equation (1), $\dot{m}_a$ is the total air entrainment rate, $\dot{m}_f$ is the fuel mass rate, $x$ is the axial distance, and $x^+$ is the characteristic length scale for the fuel jet defined by equation (2). In equation (2), $C_a$ is the orifice area contraction coefficient, $d$ is the orifice diameter, $\rho_f$ and $\rho_a$ are the injected fuel density and ambient gas density respectively; $\theta/2$ is the measured spreading half-angle of the fuel jet, $a$ is a constant having a value of 0.75, $C_d$ is the coefficient of discharge, and $C_v$ is the velocity coefficient. $C_d$ is the ratio of the mass flowrate injected in a cylinder to the theoretical mass flow rate computed from the Bernoulli equation. It can be calculated using the equation [22]

$$C_d = \frac{\dot{m}_f}{A_n \sqrt{2 \Delta P} \rho_l}$$

where $A_n$ is the nozzle cross-sectional area and $\Delta P$ is the difference between the injection pressure and the back pressure. Also, as defined in reference [23], under cavitation conditions, the relationship between $C_d$ and $C_a$ can be expressed as

$$C_d = C_a \sqrt{K_{cav}}$$

$$K_{cav} = \frac{P_{\text{inj}} - P_v}{\Delta P}$$

where $K_{cav}$ is the cavitation number, $P_{\text{inj}}$ is the injection pressure, and $P_v$ is the vapour pressure. As stated in the fuel property table [24], the $P_v$ values for the diesel and biodiesel fuels were taken to be 0.689 kPa and 0.207 kPa respectively. There are variations in the values of $C_a$ depending on the injection pressure and the fuel type. By using equations (4), (5), and (6) at 100 MPa, $C_a$ has values of 1 for diesel and BDFc while it is 0.79 for BDFp. At 200 MPa, the values of $C_a$ are 0.94, 0.89, and 0.737 for diesel, BDFc, and BDFp respectively. For the quasi-steady non-evaporating fuel spray, $\dot{m}_a$ at any axial location is equal to the total air entrainment rate into the fuel jet up to the axial location crossing the outer spray boundary. Also, the fuel mass rate $\dot{m}_f$ at any axial location is equal to the fuel injection rate. Equation (1) presents the cross-sectional averaged air-to-fuel mass ratio at any axial distance for a quasi-steady fuel spray. Figure 5 shows the estimated air-to-fuel mass ratio at any axial location from the location. From equations (1) and (2), the air-to-fuel mass ratio is dependent on the fuel density and spray angle. At the two injection pressures, the air-to-fuel mass ratio is greatest for diesel while it is lowest for the BDFp. The smallest value of the air-to-fuel mass ratio for the BDFp arises because the spray angle has a greater effect than the fuel density does.

3.3 Evaporating spray characteristics

As shown in Fig. 6, at 100 MPa and 200 MPa injection pressures respectively, the liquid length becomes smaller compared with the spray tip penetration under the non-evaporating conditions. At higher temperatures the surface evaporation of the spray and the movement of ambient gas by its momentum are enhanced, thus creating shorter spray tip penetration. As shown in Fig. 7, at 100 MPa and 200 MPa injection pressures respectively, the biodiesel fuels...
especially BDFc) produce longer liquid lengths than the diesel fuel does. Hence, the diesel fuel evaporates more than the biodiesel fuels. There is the tendency that the higher-boiling-point characteristics of the biodiesel compared with that of the diesel could have initiated the longer liquid length penetration. This phenomenon has been observed in previous work on liquid fuel visualization [1]. Also, the higher density of the biodiesel fuel contributes to the elongation of the liquid length in comparison with that of the diesel fuel. There is no significant increase in the liquid length with increasing injection pressure. This is in line with previous work by Siebers [25]. The non-significance of the liquid length of the evaporating spray under increasing injection pressure could result from the cancelling-out phenomenon of the increase in the liquid phase penetration and the faster atomization and mixing effect.

3.4 OH chemiluminescence imaging

To obtain information about the combustion characteristics of the fuels under investigation, OH chemiluminescence imaging was carried out. In this work, the ignition delay is defined as the period from the start of injection to the time of the appearance of the first OH chemiluminescence flame. Figure 8 presents the OH radical images of the ignition and combustion processes for the different fuels. As shown in the figure, the flames move more downstream when the injection pressure increases from 100 MPa to 200 MPa.
Also, Fig. 9 shows the ignition delays of the BDFp, BDFc, and diesel respectively under different injection conditions. The data were obtained in the temperature range 873–885 K. From the analyses, the ignition delay decreases as the injection pressure increases from 100 MPa to 200 MPa. This results from the enhanced mixing achievable at higher injection pressures. Also, the fuel type has an effect on the ignition delay. One of the factors that affect the ignition delay is the cetane number \[1\]. As shown in Table 2, the BDFp has the highest cetane number and this facilitates its shortest ignition delay when compared with the other fuels under all injection pressures. The BDFc produces the longest ignition delay owing to its lowest cetane number.

As shown in Fig. 8, the flame stabilizes at a quasi-steady location significantly downstream of the injector tip. The distance from the injector tip to this initial flame location is referred to as the flame lift-off length. Figure 10 shows the spatial variation in the relative intensity distribution of the OH radical flame at 100 MPa and 200 MPa injection pressures, measured downstream from the centre of the flame. The relative intensities were obtained by transforming the captured OH images into 8 bit greyscale images of the camera with a maximum intensity of 255 for the white colour. The lift-off length is the distance between the injector and the axial distance in which the cross-sectional averaged intensity is higher than a certain value known as the threshold (in this experiment a value of 20 out of 256, i.e. 8 per cent of the maximum intensity is selected). To the right of the graphical analyses of the relative intensities are the lift-off flame images. The white broken arrows on the images depict the lift-off lengths obtained by the different fuels measured from the injector tip. The peak relative intensity increases as the injection pressure increases to 200 MPa for all the fuels. Also, the lift-off length increases as the injection pressure increases.

A graphical comparison of the experimental and calculated lift-off lengths is shown in Fig. 11. The estimated lift-off length was determined using the model \[18\]

\[
H = C T_a^{-3.74} \rho_a^{-0.85} d^{0.34} U^{1} Z_{st}^{-1}
\]

where \(H\) is the calculated lift-off length, \(T_a\) is the ambient temperature, \(U\) is the actual injection velocity, \(Z_{st}\) is the stoichiometric mixture fraction, \(C_d\) is the discharge coefficient, and \(\Delta P_{inj}\) is the orifice pressure drop in the injector which can be obtained by finding the difference between the injection pressure and the ambient pressure. \(C\) is a proportionality constant having a value of \(7.04 \times 10^6\). The stoichiometry mixture fraction was obtained by using the equation \[27\]

\[
Z_{st} = \frac{\phi_{st} / (A/F)_{st}}{1 + \phi_{st} / (A/F)_{st}}
\]

where \(\phi_{st}\) is the equivalence ratio at stoichiometric conditions, while \((A/F)_{st}\) is the stoichiometric air-to-fuel mass ratio. Under stoichiometric conditions, \(\phi_{st}\) has a value of 1. \((A/F)_{st}\) is calculated using the carbon, hydrogen, and oxygen contents shown in Table 2, which gives estimated values of 14.71, 12.61, and 12.59 for diesel, BDFp, and BDFc respectively. Therefore the calculated \(Z_{st}\) values are 0.06363, 0.07347, and 0.07354 for diesel, BDFp, and BDFc respectively.

For all the fuels, the lift-off length increases as the injection pressure increases. The effect is caused by
the higher velocities in the spray as a result of increasing the injection pressure; this pushes the initial combustion zone (i.e. the lift-off length) further downstream. At all injection pressures, the biodiesel fuels produce shorter lift-off lengths than the diesel fuel does, with the BDFp producing the shortest lift-off length. The calculated and experimental lift-off lengths for the diesel fuel at 100 MPa injection pressure are close. The model under-predicted the lift-off lengths for the BDFp and BDFc at the two injection pressures while, for the diesel at 200 MPa, it follows to some extent the trends obtained by the experimental data at the two injection pressures. The calculated lift-off lengths for the BDFp and BDFc are close at all injection pressures. Previous results showed that fuels with shorter ignition delays have

Fig. 8 OH radicals in the ignition and combustion processes

Fig. 9 Variation in the ignition delay with the injection pressure
shorter lift-off lengths [18, 28]. Hence, the same effect holds for BDFp as for the other fuels.

### 3.5 Estimated air entrainment upstream of the lift-off length

The air entrained upstream of the lift-off length has a great impact on the soot formation process, which is expected to begin in the products of the rich reaction zone. In this study the estimated air entrainment upstream of the lift-off length in terms of the percentage of stoichiometric air, $\zeta_{st}(\%)$, was determined using the model [21]

$$
\zeta_{st}(\%) = 100 \sqrt{1 + 16 \left(\frac{L_o}{x^+} \right)^2} - 1 \left(\frac{A/F}_{st} \right)^2
$$

where $L_o$ is the lift-off length.

Figure 12 presents the graphical analyses of the effect of the injection pressure on the percentage of stoichiometric air. Since the lift-off lengths exhibited by the BDFp and BDFc are shorter while that of

---

Fig. 10  Variation in the OH radical intensity at the nozzle hole axis with the axial distance from the injector at $P_{inj} = 100$ MPa and 200 MPa ($t = 1.16–1.47$ ms ASOI) (au, arbitrary units)
diesel is the longest, the percentages of stoichiometric air entrained by the BDFp and BDFc are lower than for diesel. The BDFp entrains the lowest percentage of stoichiometric air because of its shortest lift-off length and spray angle. At 200 MPa, the percentage of stoichiometric air entrained by the BDFc increases tremendously while, for the BDFp, it increases gradually. The percentage of stoichiometric air entrained by the BDFc tends to become closer to that of diesel at higher injection pressures. This could arise because the spray angle of the BDFc is close to that of diesel in the quasi-steady state.

3.6 Flame temperature and KL factor

In this section, the spray flame characteristics of the fuel at the two injection pressures are analysed using the two-colour pyrometry technique. For comparative analyses the focus is on the data obtained from the BDFc and diesel fuels, since the two fuels have similar injected fuel masses. Figure 13 shows the line-of-sight and false-colour maps of the flame temperature and KL factor processed images obtained from two raw images at wavelengths of 650 nm and 800 nm respectively at 1.6 ms after start of injection (ASOI). The spatial resolution of the images is 4.6 pixels/mm. At 100 MPa, from the KL factor images, the two fuels exhibit similar soot concentration regions. At 200 MPa the soot concentration region is reduced drastically for the BDFc while there is no significant change for the diesel flame. As the injection pressure increases to 200 MPa, the flame penetrates further downstream.

Figure 14 shows the temporal variation in the evolution of the integrated KL factor and averaged flame temperature. At 100 MPa, for each fuel type, the integrated KL factor increases gradually, reaches a peak value, and then decreases with time. The soot formation continues to be dominant over soot oxidation after the end of injection (1.5 ms ASOI) for several milliseconds. At about 2.3–2.4 ms ASOI the KL starts to decrease, signifying the onset of soot oxidation. At 100 MPa, there is not much significant difference between the soot integrated KL factor trends for the two fuels. At 200 MPa, the integrated KL factors for the BDFc are lower than for diesel fuel. The KL factor for diesel does not change significantly, just like the results obtained at 100 MPa. At the two injection pressures, the time taken for the soot oxidation process is shorter for the BDFc than for the diesel.
fuel. Furthermore, at the higher injection pressure of 200 MPa, the BDFc has a shorter KL factor. This could be the result of the extended ignition delay timing exhibited by the BDFc, as explained in the previous section. More time is available for premixing with extended ignition delays, which reduces the PM formation [29]. As shown in Fig. 15, under the two injection pressures, the averaged flame temperature with time for the BDFc is lower than for diesel.

Furthermore, the averaged KL factor and temperature over a series of equidistant strip zones with the same width vertical to the axial line of the injector were used to analyse the spatial distributions of the averaged KL factor and temperature. The spatial distributions at different timings for the two fuels at the two injection pressures are shown in Fig. 16. It should be noted that the axial position represents the location of the centre-line of each strip zone. The averaged KL factor increases steadily with increasing axial distance, reaches a peak, and later decreases as the axial distance increases. The initial increase in the averaged KL factor indicates the dominance of soot formation over soot oxidation in the upstream region of the spray flame. As the flame begins to move further downstream with increasing axial distance, the averaged KL factor begins to decrease. This signifies that, as the axial distance increases further, the soot formed in the upstream flame begins to be oxidized, thus promoting the dominance of soot oxidation over soot formation in the downstream region. At 100 MPa and 2 ms ASOI, there is little difference between the averaged KL factors for the two fuels. The BDFc tends to produce more soot. The same observation was made in the previous section. The reason for this will be discussed in the next section. As the injection pressure increases to 200 MPa at 1.8 ms ASOI, the soot formed by the BDFc as the flames progress downstream is reduced tremendously in comparison with that formed by the diesel fuel. Also, as the injection pressure increases from 100 MPa at 2 ms ASOI to 200 MPa at 1.8 ms ASOI, the soot formation location for the BDFc increases further. The averaged flame temperature as shown in Fig. 17 increases gradually with increasing axial distance downstream, but it decreases at a location further downstream, especially at 100 MPa.

**Fig. 14** Temporal variation in the integrated KL factor (au, arbitrary units)

**Fig. 15** Temporal variation in the averaged flame temperature
By increasing the injection pressure to 200 MPa, the averaged temperatures of the BDFc decrease in comparison with those of diesel. The soot temperatures for BDFc are lower than those for diesel at the two injection pressures. From this point of view, soot formation and soot oxidation respectively can be promoted by increasing the local flame temperature. Also, the soot oxidation rate is limited by the oxygen concentration at the upstream location where the fuel concentrations are much higher. Therefore, in the upstream region, there is the tendency that increasing the local flame temperature with increasing axial distance causes increasing local soot concentration, since the soot oxidation rate is hindered by insufficient oxygen. In the downstream regions, a high local flame temperature results in a low local soot concentration. This is due to enhancement in the soot oxidation since there is sufficient air (oxygen) entrained. At the peak KL factor, there is a balance between soot formation and soot oxidation depending on both the local flame temperature and the oxygen concentration.

3.7 Correlation of the lift-off length and fuel oxygen content to soot formation

From the previous section, soot formation for the BDFc is lower than for the diesel fuel under the influence of increasing injection pressure. It should be noted that the soot formation process depends not only on physical processes such as spray atomization, mixing of fuel, and entrained air upstream of the lift-off length but also on chemical reactions. The oxygen content in the fuel undergoing combustion reaction plays an important role in the soot formation process. The overall oxygen molecules in the spray flame needed for soot oxidation could be said to consist of the oxygen content in the fuel molecules (chemical processes) and that in the entrained air upstream of the lift-off length (physical processes). It is important to investigate whether the oxygen content in the fuel as shown in Table 2 or the oxygen in the entrained air upstream of the lift-off length plays a major role in the soot reduction for the BDFc, as discussed in the previous section. The BDFc has the tendency to produce more soot than diesel does, since the air...
entrained upstream of the lift-off length is smaller. The two-colour method analyses in the previous sections revealed that the soot formed by the BDFc compared with that formed by diesel is reduced drastically by increasing the injection pressure to 200 MPa. It could be expected that the diesel fuel should produce less soot, since it entrained more air upstream of the lift-off length but, on the contrary, the BDFc produces less soot. This is an indication that, apart from the air entrainment which could enhance soot reduction, the oxygen content in the fuel could be a major factor in enhancing the soot reduction processes. As shown in Table 2, the oxygen content in the BDFc is 10.6 per cent compared with that in diesel, which is less than 1 per cent. According to reference [10], biodiesel fuels have the tendency to provide oxygen in the rich core of the spray during the combustion process, thus enhancing the reduction in soot formation. Hence, the oxygen in the rich core of BDFc sprays could have been responsible for the reduction in soot during the combustion process under increasing injection pressure. Therefore, the oxygen content in the BDFc plays a more significant role in soot formation with increasing injection pressure. The air entrainment upstream of the lift-off length had less effect on the reduction in soot formation in BDFc at 200 MPa injection pressure. It can be said that a trade-off between the oxygen in the air entrained upstream of the lift-off length and the oxygen content in the fuel controlled the soot formation processes of BDFc at the higher injection pressure. Unlike the diesel spray flame, the reduction in soot formation occurred as a result of air entrainment under increasing injection pressure. At 100 MPa, as shown in Figs 14 and 16 respectively, the poor spray atomization and mixing rate hindered the oxygen content in BDFc to promote soot reduction.

### 3.8 Ignition, lift-off length, and soot locations

The ignition, lift-off length, and first soot locations measured downstream from the injector locations are
presented qualitatively in Fig. 18 at 100 MPa injection pressure. It can be observed that, after autoignition, for all the fuels the flame changes location by moving upstream a little, thus forming a stable lift-off flame. The soot location has already been initiated before a stable flame is formed. The quantitative analyses shown in Fig. 19 reveal that the ignition, lift-off length, and first soot locations moved further downstream as the injection pressure increases from 100 MPa to 200 MPa. Also, the fuel type affected the ignition, lift-off length, and first soot locations. As the injection pressure increases, the ignition and first soot locations of the BDFc measured from the injector tip are furthest compared with the other fuels while the lift-off length location of the diesel fuel is the furthest. With respect to the fuel type and the injection pressure, the first soot location is the furthest while the lift-off length location is closest to the injector tip.

4 CONCLUSIONS

This research has investigated the characteristics of ignition and combustion of biodiesel fuel spray. The main findings from this study can be summarized as follows.

1. At 100 MPa and 200 MPa injection pressures under the non-evaporating and evaporating spray conditions, the biodiesel fuels have longer spray tip penetrations, longer liquid lengths, and smaller spray angles than the conventional diesel fuel does. The biodiesel spray entrains less air than diesel does.

2. Because the BDFc has the lowest cetane number, its ignition delay is the longest compared with the BDFp and diesel. Also, the BDFp produces the shortest lift-off length and lowest percentage of stoichiometric air.

3. There is no significant difference between the integrated and averaged KL factors respectively at 100 MPa injection for the BDFc and diesel fuel. At 200 MPa injection pressure, the BDFc presents much lower integrated and averaged KL factors than diesel does. The averaged flame temperatures of BDFc are lower than that of diesel.

4. The oxygen content in the BDFc plays a significant role in soot formation at 200 MPa injection pressure compared with the percentage of stoichiometric air entrained upstream of the lift-off length.

5. The ignition, lift-off length, and first soot locations moved further downstream as the injection pressure increases. The BDFc produced the furthest ignition and first soot locations.

ACKNOWLEDGEMENTS

This study was supported by ISUZU Advanced Engineering Center, Ltd. Also, thanks are due to the Nisseki oil company for measurement of the biodiesel fuel properties.

© Authors 2010

REFERENCES


12 Minato, A., Tanaka, T., and Nishimura, T. Investigation of premixed lean diesel combustion with

APPENDIX

Notation
\[ a \] constant in equation (2)
\[ (A/F)_{st} \] stochiometric air-to-fuel mass ratio
\[ ASOI \] after start of injection
\[ ATDC \] after top dead centre
\[ A_{n} \] nozzle cross-sectional area
\[ BDF_{c} \] biodiesel from cooking oil
\[ BDF_{p} \] biodiesel from palm oil
\[ C \] proportionality constant in equation (3)
\[ C_{a} \] orifice area contraction coefficient
\[ C_{d} \] coefficient of discharge
\[ C_{v} \] velocity coefficient
\[ d \] orifice diameter
\[ H \] calculated lift-off length
\[ K_{cav} \] cavitation number
\[ L_{o} \] lift-off length
\[ m_{a} \] total air entrainment rate
\[ m_{f} \] fuel mass rate
\[ P_{inj} \] injection pressure
\[ P_{v} \] vapour pressure
\[ T_{a} \] ambient temperature
\[ U \] injection velocity
\[ x \] axial distance
\[ x^{+} \] length scale of the characteristics
\[ Z_{st} \] stoichiometric mixture fraction
\[ D_{P} \] back pressure
\[ \zeta_{st} \text{(%)} \] percentage of stoichiometric air
\[ \theta/2 \] spreading half-angle of the fuel jet
\[ \rho_{a} \] ambient gas density
\[ \rho_{f} \] injected fuel density
\[ \phi_{st} \] equivalence ratio under stoichiometric conditions