Effects of Ultra-High Injection Pressure and Micro-hole Nozzle on Spray Formation and Combustion Characteristics of Waste Cooked Oil Biodiesel under Diesel Engine Conditions

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Outline

• Introduction
• Spray formation
• Combustion characteristics
• Conclusions
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• Introduction
• Spray Formation
• Combustion
• Conclusions
Role of advanced combustion systems in transportation
Major Concerns
Major challenge

Will fuel cell be the solution?
Will fuel cell be the solution?

Electricity promises to reduce emissions. However for larger engines if electricity will be used there will still be the need to incorporate diesel engine to form an hybrid system in order to meet up with power demand.

Also shortcomings could include:

- Charging points
- Infrastructure Cost
- Battery weight
“matching the range capability of a 44-tonne diesel lorry would require more than 30 tonnes of battery, leaving only about 12 tonnes for freight. “EVs as HGVs are just not feasible”

Addressing the central question of the debate – is it RIP for ICE? “I think probably not yet. Where we have to move large loads over long distances, then electric isn’t the right solution.”
What is the way forward?

- Fuel Injection Strategy
  - High Injection Pressure
  - Nozzle hole size

- Fuel Formulation
  - Alternative fuels i.e Biofuels (Biodiesel)
Motivation

Spray characteristics, such as spray penetration length, spray angle, liquid phase penetration length and air entrainment, of biodiesel fuels whose viscosity is higher than the diesel fuel

Role of cetane number and fuel oxygen content on combustion flame and soot characteristics of biodiesel sprays.
Outline

• Introduction
• Spray formation
• Combustion
• Conclusions
Non evaporating sprays
LIF-PIV (Gas entrainment) and Mie scattering

- Constant volume vessel used to simulate the real production engine.
- Conditions of what could be obtained at -10° ATDC in the engine was maintained inside the constant volume vessel.
- Operating conditions of 40 bars ambient pressure and 900K ambient temperature.
Evaporating sprays (Mie scattering)
# Experimental conditions

<table>
<thead>
<tr>
<th></th>
<th>Spray</th>
<th>Combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ambient gas</strong></td>
<td>N$_2$</td>
<td>Air</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>15 (-10° ATDC)</td>
<td></td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>1.36 (Non-evaporating)</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>4.0 (Evaporating)</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>295 (Non-evaporating)</td>
<td>885</td>
</tr>
<tr>
<td></td>
<td>885 (Evaporating)</td>
<td></td>
</tr>
<tr>
<td><strong>Nozzle</strong></td>
<td>Single hole</td>
<td></td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>0.08 and 0.16</td>
<td></td>
</tr>
<tr>
<td><strong>Injection</strong></td>
<td>Common rail system</td>
<td></td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>100 and 300</td>
<td></td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>Waste cooked oil biodiesel (WCO) and JIS#2 Diesel</td>
<td></td>
</tr>
<tr>
<td>Quantity (g/s)</td>
<td>$d_o = 0.08$mm</td>
<td>$d_o = 0.16$mm</td>
</tr>
<tr>
<td>100 MPa</td>
<td>1.65</td>
<td>9.4</td>
</tr>
<tr>
<td>300 MPa</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>100 MPa</td>
<td>1.61</td>
<td>9.3</td>
</tr>
<tr>
<td><strong>Injection duration (ms)</strong></td>
<td>1.5 (Evaporating spray and combustion)</td>
<td>2.2 (LIF-PIV)</td>
</tr>
<tr>
<td><strong>Number of nozzle holes for 55mg/stroke (1.5 ms)</strong></td>
<td>22</td>
<td>14</td>
</tr>
<tr>
<td><strong>80mg/stroke (2.2 ms)</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Experimental conditions

<table>
<thead>
<tr>
<th>Fuel Property</th>
<th>WCO biodiesel</th>
<th>JIS#2 Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density @ 15°C (kg/m³)</td>
<td>885</td>
<td>830</td>
</tr>
<tr>
<td>Viscosity @ 40°C (mm²/s)</td>
<td>4.45</td>
<td>3.36</td>
</tr>
<tr>
<td>Surface tension @ 20°C (mN/m)</td>
<td>33.1</td>
<td>30.6</td>
</tr>
<tr>
<td>Cetane number</td>
<td>51</td>
<td>45</td>
</tr>
<tr>
<td>Distillation temperature (°C)</td>
<td>360</td>
<td>320</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>&gt;180.5</td>
<td>&gt;60</td>
</tr>
<tr>
<td>Flow point (°C)</td>
<td>-5</td>
<td>4</td>
</tr>
<tr>
<td>Heating value (MJ/kg)</td>
<td>39.03</td>
<td>43.1</td>
</tr>
<tr>
<td>Sulphur content (ppm)</td>
<td>&lt;3</td>
<td>&lt;19</td>
</tr>
<tr>
<td>Carbon content (wt. %)</td>
<td>77.9</td>
<td>86.1</td>
</tr>
<tr>
<td>Hydrogen content (wt. %)</td>
<td>12.0</td>
<td>13.8</td>
</tr>
<tr>
<td>Oxygen content (wt. %)</td>
<td>10.1</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
Results

$P_{\text{inj}} = 100\text{MPa}, d_0 = 0.16\text{mm}, t_{\text{inj}} = 2.0\text{ms ASOI}$
Results

$P_{\text{inj}} = 100\text{MPa}, d_0 = 0.16\text{mm}, t_{\text{inj}} = 2.0\text{ms}$ ASOI

- Lateral entrainment
- Recirculation
- Gas pushed out and captured
Spray side surface region:
\[ \dot{m}_{a_{\text{ent.}}} = \int_0^{x_1} \rho_a \cdot V_n(x, \theta) \cdot dA(x, \theta) \]

Spray tip hemisphere region
\[ \dot{m}_{a_{\text{pushing}}} = \int_0^{\theta_1} \rho_a \cdot V_y(\theta) \cdot dA(\theta) \]

\[ \dot{m}_{a_{\text{cap}}} = \dot{m}_{a_{\text{penetrating}}} - \dot{m}_{a_{\text{pushing}}} \]
\[ = \rho_a \cdot V_{sp} \cdot \pi R^2 - \dot{m}_{a_{\text{pushing}}} \]

\[ \dot{m}_{a_{\text{total}}} = \dot{m}_{a_{\text{ent.}}} + \dot{m}_{a_{\text{cap}}} \]
Results (Spray tip penetration)
Results (Spray angle)
Results (Rate of mixing)

The graph shows the rate of mixing over time for different conditions. The x-axis represents time in milliseconds Adjusted Start Of Injection (ASOI), while the y-axis represents the ratio of mass of total fuel to mass of fuel injected ($m_{a-total}/m_f$). Different markers and line styles are used to distinguish between the conditions:

- WCO_100MPa_0.08mm
- Diesel_100MPa_0.08mm
- WCO_300MPa_0.08mm
- Diesel_300MPa_0.08mm
- WCO_100MPa_0.16mm
- Diesel_100MPa_0.16mm
Evaporating spray at 1.4ms ASOI

<table>
<thead>
<tr>
<th></th>
<th>WCO</th>
<th>Diesel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{inj}}$</td>
<td>100 MPa</td>
<td>300 MPa</td>
<td>100 MPa</td>
</tr>
<tr>
<td>$d_0$</td>
<td>0.08 mm</td>
<td>0.16 mm</td>
<td></td>
</tr>
</tbody>
</table>
Results (Liquid length)

![Graph showing spray liquid length over time for different fuels and pressures.](image-url)
Outline

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• Conclusions
Autoignition and Flame Structure (OH chemiluminescence)
# Autoignition and Flame Structure

<table>
<thead>
<tr>
<th>P_{inj}</th>
<th>100 MPa</th>
<th>300 MPa</th>
<th>100 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>d_o</td>
<td>0.08 mm</td>
<td>0.16 mm</td>
<td></td>
</tr>
</tbody>
</table>

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**WCO**

<table>
<thead>
<tr>
<th>0.7ms ASOI (Ignition)</th>
<th>1.4ms ASOI (Lifted Flame)</th>
<th>0.6ms ASOI (Ignition)</th>
<th>1.4ms ASOI (Lifted Flame)</th>
<th>1.0ms ASOI (Ignition)</th>
<th>1.4ms ASOI (Lifted Flame)</th>
</tr>
</thead>
</table>

**Diesel**

<table>
<thead>
<tr>
<th>0.8ms ASOI (Ignition)</th>
<th>1.4ms ASOI (Lifted Flame)</th>
<th>0.7ms ASOI (Ignition)</th>
<th>1.4ms ASOI (Lifted Flame)</th>
<th>1.2ms ASOI (Ignition)</th>
<th>1.4ms ASOI (Lifted Flame)</th>
</tr>
</thead>
</table>
Flame lift-off length

<table>
<thead>
<tr>
<th></th>
<th>WCO</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.7ms ASOI (Ignition)</td>
<td>0.8ms ASOI (Ignition)</td>
</tr>
<tr>
<td></td>
<td>1.4ms ASOI (Lifted Flame)</td>
<td>1.4ms ASOI (Lifted Flame)</td>
</tr>
<tr>
<td></td>
<td>0.6ms ASOI</td>
<td>0.7ms ASOI</td>
</tr>
<tr>
<td></td>
<td>1.0ms ASOI</td>
<td>1.2ms ASOI</td>
</tr>
<tr>
<td></td>
<td>1.4ms ASOI</td>
<td>1.4ms ASOI</td>
</tr>
</tbody>
</table>

\[\begin{array}{|c|c|c|c|}
\hline
P_{inj} & 100 \text{ MPa} & 300 \text{ MPa} & 100 \text{ MPa} \\
\hline
d_o & 0.08 \text{ mm} & & 0.16 \text{ mm} \\
\hline
\end{array}\]
Flame lift-off length (Air entrained upstream)

\[
\zeta_{st}(\%) = \frac{10}{3} \left[ \left( \sqrt{1 + 16 \left( \frac{L_o}{x^+} \right)^2} - 1 \right) \right]
\]

Source: Pickett, LM and Siebers, DL

Spray and Flame Interactions

Dec's conceptual model

<table>
<thead>
<tr>
<th>P_{inj}</th>
<th>100 MPa</th>
<th>300 MPa</th>
<th>100 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>d_{out}</td>
<td>0.08 mm</td>
<td>0.16 mm</td>
<td></td>
</tr>
</tbody>
</table>
Soot Formation
(Two colour pyrometry)

Pressure Transducer
Common Rail
Injector

Visible lens

Constant Volume Vessel
Two Color Filter
High Speed Video Camera

650 nm
800 nm
Soot Formation at 0.5ms AEOI

- **WCO**
  - $P_{\text{inj}}=100\text{MPa}$, $d_0=0.08\text{mm}$

- **Diesel**
  - $P_{\text{inj}}=100\text{MPa}$, $d_0=0.16\text{mm}$

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Manchester Metropolitan University
Soot Formation

At 300 MPa and 0.08 mm, no soot signal detected.

Integrated KL factor vs. Time (ms ASOI)
Implications of molecular oxygen content

- WCO_100MPa_0.08mm
- Diesel_100MPa_0.08mm
- WCO_300MPa_0.08mm
- Diesel_300MPa_0.08mm
- WCO_100MPa_0.16mm
- Diesel_100MPa_0.16mm

$T_{\text{inj}} = 2 \text{ ms ASOI}$

Integrated KL (a.u.):
- No Soot signal detected at 300 MPa with 0.08mm nozzle

Biodiesel Structure

Diesel structure
Outline

• Introduction

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• Conclusions
Conclusions

**Spray**

- The combined 300 MPa ultra high injection pressure with 0.08 mm micro-hole nozzle led to shorter spray penetration with wider spray dispersion angle when compared to the baseline condition (100 MPa injection pressure and 0.16 mm nozzle hole diameter).

- The combined effect of ultra high injection pressure with micro-hole nozzle enhanced mixing with larger ratio of gas flow rate to fuel rate.

- As a result of wider spray dispersion with much air entrained liquid length produced by the ultra high injection pressure and micro hole nozzle was shorter compared to the baseline condition.

- As a result of higher viscosity, higher surface tension, higher distillation temperature WCO spray penetrated more with less spray dispersion and produced longer spray tip penetration and liquid length compared to diesel.
Conclusions

Ignition and flame development
- As a result of enhancement in mixing, shorter ignition delay was attained by combination of ultra high injection pressure and micro-hole nozzle. WCO ignited faster compared to diesel due to higher cetane number.

- As injection pressure and nozzle diameter increased to 300 MPa and 0.16mm respectively, flame lift off length (FLOL) increased. However the combined effect of the 300MPa and 0.08mm nozzle led to more air entrained upstream of lifted flame.

- WCO FLOL was shorter than diesel with less quantity of air entrained upstream of its flame.

Soot Formation
- Soot reduced to minimum through the combined ultra-high injection pressure and micro-hole nozzle with signal undetected optically.

- Through the 300MPa and 0.08mm nozzle WCO produced less soot with the molecular oxygen content playing a vital role.
Acknowledgement

This work was done at the University of Hiroshima at Prof. Keiya Nishida’s Fluid and Spray Engineering Laboratory.
THANK YOU FOR YOUR LISTENING