Soot particle measurements over a series of laminar pool flames and diffusion flames of biofuels and methyl esters

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• Cambridge Particle Meeting, 26 June, 2019, Cambridge
Background

1. BP Global, Statistical Review of World Energy 2018

Typical 10-15% mass ratio of oxygen$^{[4]}$

How low it can be?

Renewable
Zero carbon footprint
Lower soot emission$^{[2,3]}$
Soot formation of biodiesel in pool flame

- Many studies has been produced in engines.

- fewer measurements have been made in well controlled devices suitable for model comparisons, such as:

<table>
<thead>
<tr>
<th>Type of Flame</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spray flames</td>
<td>C. Allouis, et al. 1998</td>
</tr>
</tbody>
</table>

- Soot concentration is lower by an order of magnitude compared to diesel.

- **Unsaturation level** in biodiesel could be a prominent factor on soot formation.

▲ Singapore – Crude Oil Tank Fire, Jurong Island [1]

▲ Combustion of a biodiesel droplet [2]

Relevant regarding safety and storage, and fires during accidental spills

Related to droplet burning: they do not require full vaporization

[1]. http://www.hawkesfire.co.uk/singapore-crude-oil-tank-fire-jurong-island

[2]. Kue-Yong Pan, Ming-Chun Chiu, Droplet combustion of blended fuels with alcohol and biodiesel/diesel in microgravity condition, Fuel, Volume 113, 2013, Pages 757-765,
### Tested fuels

<table>
<thead>
<tr>
<th></th>
<th>CP</th>
<th>DU</th>
<th>GO</th>
<th>RB</th>
<th>ML</th>
<th>MM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lauric acid (C12:0)</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>1.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Myristic acid (C14:0)</td>
<td>0.0033</td>
<td>0.0091</td>
<td>0.0042</td>
<td>0.0037</td>
<td>0.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>Palmitic acid (C16:0)</td>
<td>0.1392</td>
<td>0.3167</td>
<td>0.2683</td>
<td>0.2164</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Stearic acid (C18:0)</td>
<td>0.6015</td>
<td>0.5646</td>
<td>0.5875</td>
<td>0.4305</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Oleic acid (C18:1)</td>
<td>0.1718</td>
<td>0.1096</td>
<td>0.1314</td>
<td>0.3214</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Linoleic acid (C18:2)</td>
<td>0.0684</td>
<td>0.0000</td>
<td>0.0086</td>
<td>0.0117</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Linolenic acid (C18:3)</td>
<td>0.0159</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0163</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td><strong>Unsaturation</strong></td>
<td><strong>0.3561</strong></td>
<td><strong>0.1096</strong></td>
<td><strong>0.1486</strong></td>
<td><strong>0.3937</strong></td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Average C Chain</td>
<td>17.7076</td>
<td>17.3303</td>
<td>17.4466</td>
<td>17.5523</td>
<td>12.0000</td>
<td>14.0000</td>
</tr>
<tr>
<td>MW (g/mol)</td>
<td>293.1923</td>
<td>288.4042</td>
<td>289.9553</td>
<td>290.9453</td>
<td>214.0000</td>
<td>242.0000</td>
</tr>
<tr>
<td>△H (MJ/kg)</td>
<td>40.6±1.5</td>
<td>39.4±1.1</td>
<td>39.4±1.1</td>
<td>37.5</td>
<td>38.02</td>
<td>39.03</td>
</tr>
<tr>
<td>General formula</td>
<td>C_{18.7}H_{36.7}O_{2}</td>
<td>C_{18.3}H_{36.4}O_{2}</td>
<td>C_{18.4}H_{36.6}O_{2}</td>
<td>C_{18.6}H_{36.3}O_{2}</td>
<td>C_{13}H_{26}O_{2}</td>
<td>C_{15}H_{30}O_{2}</td>
</tr>
<tr>
<td>C mass fraction</td>
<td>0.7657</td>
<td>0.7627</td>
<td>0.7634</td>
<td>0.7652</td>
<td>0.7290</td>
<td>0.7438</td>
</tr>
<tr>
<td>H mass fraction</td>
<td>0.1252</td>
<td>0.1264</td>
<td>0.1262</td>
<td>0.1248</td>
<td>0.1215</td>
<td>0.1240</td>
</tr>
<tr>
<td>O mass fraction</td>
<td>0.1091</td>
<td>0.1110</td>
<td>0.1104</td>
<td>0.1100</td>
<td>0.1495</td>
<td>0.1322</td>
</tr>
</tbody>
</table>

- $Y_i$ Mass fraction of species $i$
- $N_i$ Number of carbon-carbon double bond

Burners setup

Pool burner

Pre-vapourised diffusion burner

Measured fuel consumption rate
Laser induced incandescence (LII) setup

Uncertainty in LII signal $\leq 10\%$

LII signal intensity VS laser fluence
Detection wavelength


Calibration and signal-trapping correction

- Extinction to obtain \( f_v \), using Rayleigh Approximation

\[ K_{ext} = \frac{6\pi E(m_i)}{\lambda_s} f_v \rightarrow f_v \]

- Obtain \( C \) to calibrate all LII images

\[ f_v = S / C \rightarrow C \]

- Signal trapping

- **Camera**

\[ \Delta_{i,j} = \delta \left( \sqrt{j^2 - i^2} - \sqrt{(j-1)^2 - i^2} \right), i < j \leq N \]

\[ Cf_v(i) = S_m(i) \exp \left( \frac{6\pi E(m_i)}{\lambda_s} \sum_{j=i+1}^{N} f_v(j) \Delta_{i,j} \right) \]

\[ Cf_v(N-1) = S_m(N-1) \exp \left( \frac{6\pi E(m_i)}{\lambda_s} f_v(N) \Delta_{N-1,N} \right) \]

\[ Cf_v(0) = S_m(0) \exp \left( \frac{6\pi E(m_i)}{\lambda_s} \delta \sum_{j=1}^{N} f_v(j) \right) \]
D100 pure petroleum diesel flame, HAB=25 mm, maxima of $-\ln(I_t/I_0)$
Result and discussion

- Page 9-11 of this presentation has been removed as they contain some unpublished data.
Conclusions

- The tested real biodiesels have **similar oxygen composition but different degrees** of unsaturation.

- The measured $f_v$ produced by neat biofuels are **7 to 35%** of diesels in both configurations.

- **Degree of unsaturation** is the key factor for soot production of biodiesels.

- Blending leads to lower soot values.

- Pool flames produce **similar level of maximum soot volume fraction** but **more integrated soot volume fraction and larger particle size** comparing to pre-vapourised flames.
Thanks!

Acknowledgement

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