Transesterification of waste oil into biodiesel: Process Development, CFD simulation and Engine performance testing

ATHENS 2014 International Conference on Sustainable Solid Waste Management, 12-14 June 2014, Royal Olympic Athens Hotel, Athens, Greece

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OUTLINE

• Problem statement
• Objective
• Biodiesel overview
• Transesterification process
• Homogeneous base Transesterification via batch reactor
• Homogeneous base Transesterification via continuous process
• Numerical Simulation of Transesterification
• Engine emission testing
• Conclusion
Environmental protection and conservation

PROBLEM STATEMENT

Emissions

Waste

Abu Dhabi: 80 tons waste/day

Biodiesel

Lessen their negative environmental impact.

Establishing world class waste management systems
OBJECTIVE

• Achieve optimal process metrics i.e. residence time, production configuration, biodiesel yield and catalyst choice. (Acceptable fuel properties within the ASTM Standards).

• Develop a continuous transesterification reactor following numerical simulation.

• Test the performance and emissions of diesel engine using different fuel blends
SCOPE OF WORK

Material collection (WCO)

 Batch process parametric study
  1. Batch process experimental Assessment
  2. Engine testing

 Transesterification process
  Pretreatment
    Titration
    Transesterification
  Separation/Purification
  Properties Assessments
    Yield
    Flash point
    Density
    Viscosity
    Boiling point
    Smoke opacity
    Reid vapor pressure
    Heating value
    GC/MS
    Composition

 Development of continuous process
  1. Reactor design
  2. CFD analysis

Masdar Institute
BIODIESEL OVERVIEW

What is Biodiesel?

• Mono alkyl esters derived from renewable sources
• Has comparable physical and chemical properties to petroleum diesel.
• Biodegradable, nontoxic, and renewable
  – Reduce GHG emissions and lower harmful emissions
• Variable feedstock sources including WCO

<table>
<thead>
<tr>
<th>Non-edible</th>
<th>Edible</th>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jatropha</td>
<td>Soybean</td>
<td>Waste cooking</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>Palm</td>
<td>Tallow</td>
</tr>
<tr>
<td>Castor</td>
<td>Canola oil</td>
<td>Soap stock</td>
</tr>
<tr>
<td>Pongamia pinnata</td>
<td>Sunflower</td>
<td>Trap grease</td>
</tr>
<tr>
<td>Sea mango</td>
<td>Olive</td>
<td></td>
</tr>
<tr>
<td>Seashore mallow</td>
<td>Olive</td>
<td></td>
</tr>
<tr>
<td>Camelina</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Karanja</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Triglyceride lipids react with alcohol using a catalyst to form alkyl esters and glycerol:

- **Triglyceride + Alcohol → FAME + Diglyceride**
- **Diglyceride + Alcohol → FAME + Monoglyceride**
- **Monoglyceride + Alcohol → FAME + Glycerol**

- Superior lubricity and flashpoint, lower to no sulfur content, reduction in most exhaust emissions.
Transesterification process

Catalytic

Homogeneous
- Acid
  - H₂SO₄ or HCl
  - FFA content > 5%
- Alkaline
  - NaOH or KOH
  - FFA content < 3%
  - Ambient temperature and pressure

Heterogeneous
- Acid
  - FFA content > 5%
- Base
  - CaO, MgO
  - Extracellular and intracellular lipases
  - less energy intensive

Non-Catalyst

Supercritical
- Higher temperature, pressure and molar ratio of methanol to oil
- short reaction time

Enzymatic
MATERIAL & METHODS

Raw material:
- Collection of WCO from local restaurants & School Cafeteria
- Pretreatment of WCO:
  - Solid removal: Filtration through a 15-20 µm filter
  - H₂O removal: Heating to 70-100 °C for one hour

Titration:
- 5g of pretreated waste oil
- 50ml of isopropyl alcohol,
- 5 drops of phenolphthalein pH indicator.
- Titrate 0.1 M NaOH solution added to the mixture.

Evaluate acid value:

\[
\text{Acid value} = \frac{Vol_{\text{NaOH}} (ml) \times Conc_{\text{NaOH}}(M) \times MW_{\text{KOH}}}{Sample \ weight \ (g)}
\]
Most commercial biodiesel transesterification processes are using a homogeneous alkaline catalyst.

Homogeneous alkaline vs. acid catalysts:
- Faster reaction time
- Less methanol consumption
- Less aggressive and corrosive catalyst.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Benefits/Advantages</th>
<th>Drawbacks/ limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkali catalysts including</td>
<td>Least expensive</td>
<td>Water content less than 0.05 wt.%</td>
</tr>
<tr>
<td>NaOH</td>
<td>Simple to perform</td>
<td>FFA content of less than 3%.</td>
</tr>
<tr>
<td>KOH</td>
<td>Proceeds near condition</td>
<td>Complex separation and purification process</td>
</tr>
<tr>
<td>CH₃ONa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₃OK</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1. Filtration and water removal;
2. FFA neutralization;
3. Catalyzed transesterification;
4. Separation and purification

5. Product assessment (ASTM);
   - Density and Vapor pressure;
   - Viscosity
   - Flash Point;
   - Distillation, boiling, T90

**HOMOGENEOUS BASE TRANSESTERIFICATION**

**MATERIAL & METHODS**

**Processing method:**

1. Filtration and water removal;
2. FFA neutralization;
3. Catalyzed transesterification;
4. Separation and purification

5. Product assessment (ASTM);
   - Density and Vapor pressure;
   - Viscosity
   - Flash Point;
   - Distillation, boiling, T90

![Flowchart diagram showing the processing method for homogenous base transesterification](flowchart-diagram.png)
HOMOGENEOUS BASE TRANSESTERIFICATION VIA BATCH REACTOR

**Design of Experiment:**

- Factors influence the transesterification process:
  - **3Tees**, i.e. Reactor configuration
  - Molar ratio of alcohol to oil
  - Amount & type of catalyst

- Study different WCO to alcohol ratios and catalyst conc. at T=60°C and 400 rpm

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Alcohol</th>
<th>Molar alcohol:oil</th>
<th>Catalyst</th>
<th>Catalyst conc. (%)</th>
<th>Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.1</td>
<td>Methanol</td>
<td>12:1</td>
<td>NaOH</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Exp.2</td>
<td>Methanol</td>
<td>12:1</td>
<td>NaOH</td>
<td>0.75</td>
<td>2</td>
</tr>
<tr>
<td>Exp.3</td>
<td>Methanol</td>
<td>12:1</td>
<td>NaOH</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>Exp.4</td>
<td>Methanol</td>
<td>6:1</td>
<td>NaOH</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Exp.5</td>
<td>Methanol</td>
<td>12:1</td>
<td>NaOH</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
RESULTS & DISCUSSION

FAME (biodiesel) Yield and Purity:

Biodiesel yield in alkaline homogeneous (NaOH) catalyst transesterification of WCO using methanol
RESULTS & DISCUSSION

FAME (biodiesel) Chromatogram analysis:

Fatty acid methyl ester (FAME) profile (relative %) WCO biodiesel.

<table>
<thead>
<tr>
<th>FAME</th>
<th>WCO FAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>C14=Myristic acid</td>
<td>1.2</td>
</tr>
<tr>
<td>C16=Palmitic acid</td>
<td>36.9</td>
</tr>
<tr>
<td>C18:0=Stearic acid</td>
<td>6.7</td>
</tr>
<tr>
<td>C18:1=Oleic acid</td>
<td>31.6</td>
</tr>
<tr>
<td>C18:2=Linoleic acid</td>
<td>18.9</td>
</tr>
<tr>
<td>C20=Arachidic acid</td>
<td>0.7</td>
</tr>
<tr>
<td>C20:1=Gadoleic acid</td>
<td>0.3</td>
</tr>
<tr>
<td>C22=Behenic acid</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Chromatogram of FAME analysis of waste cooking oil.
### RESULTS & DISCUSSION

**Evaluation of biodiesel properties:** Temp at 60 °C and 500 rpm stirring

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Flash point (°C)</th>
<th>Density (kg/m³)</th>
<th>Viscosity (mm²/s)</th>
<th>Acid value (mg KOH/g)</th>
<th>Boiling point (°C)</th>
<th>T-90 °C</th>
<th>Gross heating value MJ/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.1</td>
<td>177</td>
<td>890</td>
<td>4.64</td>
<td>0.79</td>
<td>326</td>
<td>338</td>
<td>40.180</td>
</tr>
<tr>
<td>Exp.2</td>
<td>182</td>
<td>843</td>
<td>4.65</td>
<td>0.67</td>
<td>320</td>
<td>346</td>
<td>40.357</td>
</tr>
<tr>
<td>Exp.3</td>
<td>179</td>
<td>839</td>
<td>4.72</td>
<td>0.45</td>
<td>320</td>
<td>352</td>
<td>40.137</td>
</tr>
<tr>
<td>Exp.4</td>
<td>163</td>
<td>838</td>
<td>4.68</td>
<td>0.73</td>
<td>322</td>
<td>347</td>
<td>40.396</td>
</tr>
<tr>
<td>Exp.5</td>
<td>157</td>
<td>842</td>
<td>4.63</td>
<td>0.84</td>
<td>318</td>
<td>340</td>
<td>40.223</td>
</tr>
<tr>
<td>Petro diesel</td>
<td>88</td>
<td>811</td>
<td>3.97</td>
<td>0.22</td>
<td>185</td>
<td>370</td>
<td>45.800</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Opacity Value (%) Assuming 100Hp setup</th>
<th>Opacity Value (%) Assuming 200Hp setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiesel</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Petroleum diesel</td>
<td>11</td>
<td>19.9</td>
</tr>
</tbody>
</table>

 opacity value (%) Assuming 100Hp setup and 200Hp setup.
## RESULTS & DISCUSSION

### Biodiesel Distillation Curve

<table>
<thead>
<tr>
<th>Volume %</th>
<th>0</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>65</th>
<th>70</th>
<th>75</th>
<th>80</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st drop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. point (°C)</td>
<td>320</td>
<td>328</td>
<td>328.5</td>
<td>329</td>
<td>330</td>
<td>331</td>
<td>333</td>
<td>334</td>
<td>335</td>
<td>337</td>
<td>340</td>
<td>344</td>
<td>350</td>
</tr>
</tbody>
</table>

- Boiling points and weight fractions of alkane and alkene hydrocarbons in biodiesel
- 77.102 wt% n-alkenes and 22.898 wt% n-alkanes

### Low volatility of biodiesel

<table>
<thead>
<tr>
<th>Hydrocarbon</th>
<th>Boiling points °C</th>
<th>Density, $\rho$ (g/ml)</th>
<th>Volume, $V$ (ml)</th>
<th>V2-V1 (ml)</th>
<th>Mass = $\rho \times V$ (g)</th>
<th>Mass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{18}H_{36}$</td>
<td>320.0</td>
<td>0.789</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$C_{19}H_{38}$</td>
<td>328.0</td>
<td>0.790</td>
<td>15</td>
<td>15</td>
<td>11.85</td>
<td>19.17</td>
</tr>
<tr>
<td>$C_{19}H_{40}$</td>
<td>330.0</td>
<td>0.786</td>
<td>30</td>
<td>15</td>
<td>11.79</td>
<td>19.07</td>
</tr>
<tr>
<td>$C_{20}H_{40}$</td>
<td>340.8</td>
<td>0.796</td>
<td>75</td>
<td>45</td>
<td>35.82</td>
<td>57.94</td>
</tr>
<tr>
<td>$C_{20}H_{42}$</td>
<td>343.0</td>
<td>0.789</td>
<td>78</td>
<td>3</td>
<td>2.367</td>
<td>3.83</td>
</tr>
</tbody>
</table>
KINEMATICS AND REACTION CONSTANT EVALUATION

Overall reaction:

\[ TG(A) + 3M \rightarrow 3ME + GL \]

Overall reaction rate:

\[ \frac{dX}{dt} = K(1 - X)^n ; \]

Considering a 1st order reaction:

\[ \ln \left( \frac{1}{1-x} \right) = Kt \]

Arrhenius Equation

\[ K = A \cdot e^{(-E/RT)} \]

The activation energy \( E \) at \( T = 45, 60, 70^\circ C \)

\[ = 25,496 \text{ J/mol} \]

and pre-exponent factor \( A = 4.1744 \)

\( A \) and \( E \) can be used in high Fidelity simulation
## KINEMATICS AND REACTION CONSTANT EVALUATION

\[ Ax = b \quad x = A^{-1}b \]

\[ K = A e^{-\frac{E}{RT}} \]

\[ \ln K = \ln A - \frac{E}{RT} \]

\[ \begin{align*}
TG + A & \quad E + DG \\
DG + A & \quad E + MG \\
MG + A & \quad E + GL \\
TG + 3A & \quad 3E + GL
\end{align*} \]

### Reaction rate constant

<table>
<thead>
<tr>
<th>Reaction rate constant</th>
<th>K1</th>
<th>K2</th>
<th>K3</th>
<th>K4</th>
<th>K5</th>
<th>K6</th>
<th>K7</th>
<th>K8</th>
</tr>
</thead>
<tbody>
<tr>
<td>WCO at 50°C (this work)</td>
<td>0.0169</td>
<td>0.0994</td>
<td>0.0194</td>
<td>0.0531</td>
<td>0.0205</td>
<td>0.0015</td>
<td>2.5E-9</td>
<td>0.00056</td>
</tr>
<tr>
<td>WCO at 60°C (this work)</td>
<td>0.0202</td>
<td>0.0975</td>
<td>0.0314</td>
<td>0.1106</td>
<td>0.0400</td>
<td>0.0018</td>
<td>2.5E-9</td>
<td>0.00037</td>
</tr>
<tr>
<td>Noureddini and Zhu [2]</td>
<td>0.049</td>
<td>0.102</td>
<td>0.218</td>
<td>1.280</td>
<td>0.239</td>
<td>0.007</td>
<td>7.84E-5</td>
<td>1.5E-5</td>
</tr>
<tr>
<td>Activation Energy kJ/kmol</td>
<td>E1</td>
<td>E2</td>
<td>E3</td>
<td>E4</td>
<td>E5</td>
<td>E6</td>
<td>E7</td>
<td>E8</td>
</tr>
<tr>
<td>WCO at 50-60°C (this work)</td>
<td>0.1579</td>
<td>0.0172</td>
<td>0.4218</td>
<td>0.6438</td>
<td>0.5865</td>
<td>2.7648</td>
<td>0.01208</td>
<td>0.78100</td>
</tr>
<tr>
<td>Noureddini and Zhu [2]</td>
<td>0.0632</td>
<td>0.0477</td>
<td>0.0955</td>
<td>0.0704</td>
<td>0.0308</td>
<td>0.0461</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
HOMOGENEOUS BASE TRANSESTERIFICATION VIA CONTINUOUS PROCESS

- Reactant is continuously pumped into the reactor
- To enhance the reaction:
  - Configuration must allow an increase in surface area per unit volume, efficient entrainments and mixing to enhance mass transfer, and component solubility at low pumping power.
  - Small flow mass → transfer limited two phase flow.
  - High flow rate → shorter residence time.
HOMOGENEOUS BASE TRANSESTERIFICATION VIA CONTINUOUS PROCESS

Reactor configuration

- 2 coincided separated chambers.
- Low pressure drop, ease of temperature control through and nearly isothermal reaction condition.
- One peristaltic pump (pumps the fluid from the primary reservoir into the yield reservoir).
- Reactants are introduced circumferentially to increase flow residence time while following as a swirling trajectory.
- Extraction of the product could be done in two stages → measure the efficiency of each loop and observing the conversion of the mixture to biodiesel:
HOMOGENEOUS BASE TRANSESTERIFICATION VIA CONTINUOUS PROCESS

1. Titration
2. Experiments Processing

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Alcohol</th>
<th>Molar alcohol:oil</th>
<th>Catalyst</th>
<th>Catalyst conc. (%)</th>
<th>Time (hours)</th>
<th>Flow rate (ml/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.1</td>
<td>Methanol</td>
<td>12:01</td>
<td>NaOH</td>
<td>0.5</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Exp.2</td>
<td>Methanol</td>
<td>12:01</td>
<td>NaOH</td>
<td>0.5</td>
<td>2</td>
<td>300</td>
</tr>
<tr>
<td>Exp.3</td>
<td>Methanol</td>
<td>6:01</td>
<td>NaOH</td>
<td>0.5</td>
<td>2</td>
<td>100</td>
</tr>
</tbody>
</table>

3. Yield after experiments

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Residence time (min)</th>
<th>Yield %</th>
<th>Yield % (Batch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.1</td>
<td>14</td>
<td>94.85</td>
<td>90</td>
</tr>
<tr>
<td>Exp.2</td>
<td>10</td>
<td>86</td>
<td>90</td>
</tr>
<tr>
<td>Exp.3</td>
<td>14</td>
<td>91.87</td>
<td>64.5</td>
</tr>
</tbody>
</table>

- Alcohol to oil molar ratio
- Flow rate
- Continuous vs. batch at 6:1 molar ratio:
  - Advantage of efficient mixing of the flow
Properties of biodiesel produced from waste cooking oil (WCO) oil at 60 °C and 100 ml/min, Diesel and Biodiesel Requirement

<table>
<thead>
<tr>
<th>Tests</th>
<th>Unit</th>
<th>Result</th>
<th>Biodiesel Requirement</th>
<th>Petro-diesel Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid Number, Total</td>
<td>mg KOH/g</td>
<td>0.25</td>
<td>0.8 max</td>
<td>0.22</td>
</tr>
<tr>
<td>Cetane Number</td>
<td></td>
<td>63.3</td>
<td>48–65</td>
<td>40–55</td>
</tr>
<tr>
<td>Corrosion, copper (3 HR @ 100°C</td>
<td></td>
<td>1</td>
<td>3 max</td>
<td>1</td>
</tr>
<tr>
<td>Density at 15°C</td>
<td>kg/m³</td>
<td>879.4</td>
<td>880</td>
<td>850</td>
</tr>
<tr>
<td>Flash Point</td>
<td>°C</td>
<td>175</td>
<td>130-170</td>
<td>88</td>
</tr>
<tr>
<td>Cloud Point</td>
<td>°C</td>
<td>+13.0</td>
<td>-3 –15</td>
<td>-35 – 5</td>
</tr>
<tr>
<td>Pour Point</td>
<td>°C</td>
<td>+12.0</td>
<td>-5 –10</td>
<td>-35 – 15</td>
</tr>
<tr>
<td>CFPP</td>
<td>°C</td>
<td>+10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity @40°C</td>
<td>CST</td>
<td>4.962</td>
<td>4.0–6.0</td>
<td>1.3–4.1</td>
</tr>
<tr>
<td>Lubricity (HFRR)</td>
<td>Micron</td>
<td>280</td>
<td>320</td>
<td>520</td>
</tr>
</tbody>
</table>
A fine hybrid hexagonal and pyramid mesh is generated comprised of 281,382 cells & 729,741 faces for the two chambers and connecting tubing.

<table>
<thead>
<tr>
<th>Species</th>
<th>Chemical formula</th>
<th>Molecular weight</th>
<th>Viscosity (kg/m.s)</th>
<th>Cp (J/kg.°C)</th>
<th>Density Kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>CH₄O</td>
<td>32</td>
<td>3.96e-4</td>
<td>1.470e3</td>
<td>791.8</td>
</tr>
<tr>
<td>Waste oil</td>
<td>C₅₂H₁₀₄O₆</td>
<td>849</td>
<td>1.61e-2</td>
<td>2.2e3</td>
<td>883.3</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>C₁₈H₃₆O₂</td>
<td>284</td>
<td>1.12e-3</td>
<td>1.187e3</td>
<td>870</td>
</tr>
<tr>
<td>Glycerol</td>
<td>C₃H₈O₃</td>
<td>92</td>
<td>1.412e0</td>
<td>0238.6</td>
<td>1261</td>
</tr>
</tbody>
</table>
NUMERICAL SIMULATION OF TRANSESTERIFICATION OF WASTE COOKING OIL IN TABULAR REACTOR

Mathematical System:

1) Continuity, Momentum, Energy, TKE (k), TDR (e):

\[
\frac{\partial}{\partial t} \phi + \frac{\partial}{\partial x_i} (u_i \phi) = - \frac{\partial}{\partial x_i} \left( \Gamma \frac{\partial \phi}{\partial x_i} \right) + S_\phi
\]

Time rate advective diffusion source

2) Transportation equation for \( m_i \) species:

\[
\frac{\partial}{\partial t} (\rho m_i) + \frac{\partial}{\partial x_i} (\rho u_i m_i) = \frac{\partial}{\partial x_i} \left( \rho D_{i,m} + \frac{\mu}{Sc_i} \right) \frac{\partial m_i}{\partial x_i} + R_i + S_i
\]

3) Reaction kinetics:

\[
\sum_{i=1}^{N} v'_{i,r} S_i \leftrightarrow \sum_{i=1}^{N} v''_{i,r} S_i; \quad R_{i,r} = M_{i,r} (v''_{i,r} - v'_{i,r}) \left( k \prod_{j=1}^{N} C^{n^*_j}_{j,r} \right); \quad k = A e^{(-E/RT)}
\]

\( k_f,r \) \( k_b,r \)
NUMERICAL SIMULATION OF TRANSESTERIFICATION OF WASTE COOKING OIL IN TABULAR REACTOR

**Cold flow:**
Flow trajectory colored by the resident time

**Reacting flow:**
Molar fraction of species across the reactor at low mass flow conditions within the laminar regime (Re=1, based on the smallest tube diameter of 1cm)

- WCO: 0.18
- Methanol: 0.54
- FAME: 0.21
- Glycerol: 0.07

\[ X = 28\% \]
NUMERICAL SIMULATION OF TRANSESTERIFICATION OF WASTE COOKING OIL IN TABULAR REACTOR
COMBUSTION AND EMISSIONS CHARACTERISTICS OF DIESEL AND BIODIESEL FUEL BLENDS IN SINGLE CYLINDER DIESEL ENGINE

Comparison of pressure and emissions from the diesel engine using bio-diesel fuel blends (B05, B10, and B20) and conventional petroleum diesel fuel.

Test engine 1:

<table>
<thead>
<tr>
<th>Engine Model</th>
<th>G. CUSSONS SERIAL NO. P8160/132</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Type</td>
<td>4 stroke</td>
</tr>
<tr>
<td>Combustion System</td>
<td>Direct Injection</td>
</tr>
<tr>
<td>No. of Cylinders</td>
<td>Single</td>
</tr>
<tr>
<td>Cooling System</td>
<td>Air cooled</td>
</tr>
<tr>
<td>Bore x Stroke</td>
<td>76.2 x 111.1mm</td>
</tr>
<tr>
<td>Max Speed</td>
<td>2000 rpm</td>
</tr>
<tr>
<td>Max. Torque</td>
<td>7.5 N.m</td>
</tr>
</tbody>
</table>

Test engine 2: Eight horse power diesel engine.

Dynamometer: Measuring Torque and RPM, giving the engine HP by:
Horsepower = (RPM * Torque) / 5252

Gas analyzer: Measuring conc. of O₂, CO, CO₂, HC, and NOx
Engine test Procedure

– Run the engine for 2 minutes to allow the engine to clear any residue from previous tests with different fuel blends, and warm up the engine and catalyst.
– After the 2 minutes, warm up the engine at low RPM for 5 minutes
– Increase the engine speed to medium RPM and run the engine for 5 minutes
– Finally set the engine to high RPM and run it for 5 minutes
In-Cylinder pressure of Petroleum Diesel and biodiesel blends Fuels

Engine cylinder pressure, versus time (seconds) - Petroleum Diesel fuel at low and high RPM.

Engine cylinder pressure, versus time (seconds) - Biodiesel Fuel Blends at high RPM
Emission characteristics of Petroleum Diesel

Engine emissions at different RPM – Petroleum Diesel fuel
Results:

- **HC emissions** for the B20 decreases by about 20% compared to PD.
- The **CO emissions** decrease by about 12% for the B20.
- Small decrease (< 2%) in **engine power** (HP) for B20.
- **CO₂** and **NOₓ** emissions increase slightly for B20.

Overall percentage differences of biodiesel fuel blends with respect to petroleum Diesel.
CONCLUSION

• Biodiesel was produced by homogeneous alkaline transesterification

• The highest yield was achieved by using the lower catalyst concentration of 0.5% NaOH

• All fuel properties fell within the requirements of American standard for biodiesel fuel

• Optimal process was found to follow 1st order reaction rate with a rate constant of 0.01 min⁻¹ and the activation energy was found to be 25,496 J/mol (opportunity for High Fidelity analysis and innovative reactor development)

• A new reactor configuration is proposed showing that increasing the flow rate, decrease the yield from 94.6% to 86% and gives better results especially with the 6:1 molar ratio

• The outcomes of the engine testing showed that the engine is stable since the cycles are almost identical.

• The hydrocarbons HC and CO emissions decreased by increasing the amount of biodiesel blended with Petroleum Diesel. The HC and CO emissions decreased respectively by 20 % and 12 % for the B20 compared to the Petroleum Diesel.

• NOₓ emissions increased by 2% and the change of the engine power was negligible (<2%).
Thank You


• Patents: I.Janajreh, R.Abd Rabu. Dual Chamber Tubular Reactor for Continuous Transesterification of Waste Cooking Oil