Performance of a Compression-Ignition Engine Using Direct-Injection of Liquid Ammonia/DME Mixture

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Background

• **Motivation**
  - Ammonia (NH\textsubscript{3}) combustion does not generate CO\textsubscript{2}
  - Hydrogen carrier, renewable, etc.

• **Challenges**
  - Ammonia is very difficult to ignite
    - Octane number ~ 130
    - Autoignition T ~ 651 °C (gasoline: 440 °C; diesel: 225 °C)
  - Ammonia flame temperature is lower than diesel flame T
  - Ammonia emissions can be harmful
  - Potential high NOx emissions due to fuel-bound nitrogen
  - Gas phase at atmospheric pressure; Erosive to some materials
  - Low energy content (~40% of that of diesel fuel per unit mass)
Thermodynamics/Chemistry

• Stoichiometric chemical reaction

\[ \text{NH}_3 + 0.75 \cdot (\text{O}_2 + 3.76 \cdot \text{N}_2) \rightarrow 1.5 \cdot \text{H}_2\text{O} + 3.32 \cdot \text{N}_2 \]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Molecule</th>
<th>Boiling Point (°C)</th>
<th>(Air/Fuel)\text{\textsubscript{s}}</th>
<th>Latent Heat (kJ/kg)</th>
<th>Energy Content (MJ/kg-fuel)</th>
<th>Energy Content (MJ/kg-stoichiometric mixture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>CH\textsubscript{3}OH</td>
<td>64.7</td>
<td>6.435</td>
<td>1203</td>
<td>20</td>
<td>2.6900</td>
</tr>
<tr>
<td>Ethanol</td>
<td>C\textsubscript{2}H\textsubscript{5}OH</td>
<td>78.4</td>
<td>8.953</td>
<td>850</td>
<td>26.9</td>
<td>2.7027</td>
</tr>
<tr>
<td>Gasoline</td>
<td>C\textsubscript{7}H\textsubscript{17}</td>
<td>---</td>
<td>15.291</td>
<td>310</td>
<td>44</td>
<td>2.5781</td>
</tr>
<tr>
<td>Diesel</td>
<td>C\textsubscript{14.4}H\textsubscript{24.9}</td>
<td>---</td>
<td>14.3217</td>
<td>230</td>
<td>42.38</td>
<td>2.7660</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH\textsubscript{3}</td>
<td>–33.5</td>
<td>6.0456</td>
<td>1371</td>
<td>18.6103</td>
<td>2.6414</td>
</tr>
</tbody>
</table>
Approach #1

- Introduce ammonia to the intake manifold
- Create premixed ammonia/air mixture in the cylinder
- Inject diesel fuel to initiate combustion
  - Without modifying the existing injection system
Engine Setup

- John Deere (4 cylinder, 4.5 liter)
  - Operated at various load and speed conditions
  - Vapor ammonia introduced into the intake duct – after turbo, before manifold
Test Results – Constant NH$_3$ Flow Rate

- Engine torque increases suddenly once ammonia is inducted

**1400rpm Engine Torque**

- Diesel baseline
- Diesel + NH$_3$
- Energy replacement by NH$_3$

**1800rpm Engine Torque**

- Diesel baseline
- Diesel + NH$_3$
- Energy replacement by NH$_3$
Test Results – Constant Torque

- Fixed at specific diesel fueling, adjusted NH\textsubscript{3} flow rate to maintain constant torque
- Can achieve 5% diesel / 95% NH\textsubscript{3} energy ratio
NH₃ Exhaust Concentrations

- Concentrations vary depending on NH₃ fueling rate
- Further study is required to reduce NH₃ emissions.

Ammonia combustion efficiency
Approach #2

- Use direct liquid fuel injection
  - Confine combustion mixture near the center
  - To reduce exhaust ammonia emissions
- Ignition source – dimethyl ether (CH$_3$-O-CH$_3$)
  - Mixture of DME and NH$_3$
  - Fuel mixing and storage at high pressure
  - New fuel injection system – without fuel return
    - Injection pump, injector, electronic control
Engine Setup

- Yanmar diesel engine (L70V, 320 c.c.)
  - Rated power at 6.26 hp at 3480 rpm
- Develop new fuel injection and engine control systems
  - Bosch GDI type injector (up to 200 bar injection pressure)
Setup

- Mixing and storage of ammonia/DME at high pressure
- Exhaust emissions measurements
  - Horiba MEXA-7100DEGR (CO$_2$, CO, O$_2$, HC)
  - Horiba 1170NX (NO$_x$, NH$_3$)
  - AVL Smoke Meter (PM)

Emissions analyzers

Fuel mixing system
Operating Conditions

Operating map using original diesel injection system

- Peak Torque (3033 rpm / 10.54 ft-lbs)
- Peak Power (3480 rpm / 6.26 HP)

Mode 1 idle @ 1250 rpm / 0 HP
Test Results

- Baseline operation using 100% DME
  - Explore operating range before using NH3/DME mixture
  - For each operating point, various start-of-injection timings were tested
  - Provide flexibility for future optimization

\[
\begin{align*}
\text{SOI} &= -35 \sim 20 \text{ BTDC} \\
\text{SOI} &= -30 \sim 0 \text{ ATDC} \\
\text{SOI} &= -25 \sim 5 \text{ BTDC} \\
\text{SOI} &= -30 \sim 20 \text{ BTDC}
\end{align*}
\]
100% DME

- Mode 7 (2548 rpm) emissions

![Graphs showing emissions of Soot (FSN), NOx, CO, and HC as a function of SOI (ATDC).]
Effects of Ammonia Combustion (Mode 7)

- 100%DME vs. 20%NH3/80%DME
  - Soot remains at low level
  - NOx increases due to fuel-bound nitrogen
Effects of Ammonia Combustion (Mode 7)

- **100%DME vs. 20%NH3/80%DME**
  - Lower combustion temperature of ammonia causes more CO and HC emissions
  - Implication to fuel efficiency
Effects of Ammonia Combustion (Mode 21)

- Comparable combustion and fuel efficiency at this lower speed
Effects of Ammonia Combustion

- Exhaust ammonia emissions much lower than Approach#1
- Direct injection strategy benefits exhaust ammonia emissions
Alternate Injection Strategy

• To extend the operating range
• Proposed strategies
  • Double fuel injections
    • Offer flexibilities in fuel delivery
    • Used in industry for emissions and noise reduction
  • New fuel injector
    • Original: single hole
    • Alternate: eight holes – help with air utilization
Double Injection, 100% DME

- Current system modified for using double injections
  - Engine operations possible using double injections
  - Comparable fuel efficiency and emissions
  - Results based on Mode 7 (2548 rpm)
    - Pilot SOI= $-45 \sim -35$ ATDC
    - Pilot quantity=30% of total fuel
    - Main SOI= $-10$ ATDC

- Exploring other conditions
  - Varying the three injection variables
  - Other operating points

![Graph showing relationship between Pilot SOI (ATDC) and Soot (FSN), NOx (ppm)](attachment://graph.png)
Multi-Hole Injector

- Change from single hole to 8 holes
  - Higher exhaust NOx – may imply higher combustion temperature to sustain higher load operation
- Exploring combination of using 8-hole injector in combination with double injections
Summary

• Demonstrated ammonia combustion in diesel engines
• Port induction of ammonia coupled with direct-injection diesel fuel
  • Exhaust ammonia level at “thousands of ppm” under the conditions studied
• Direct injection of ammonia/DME
  • Exhaust ammonia level at “hundreds of ppm” under the conditions studied
  • Exploring optimal injection strategies for ammonia combustion
• Perspectives – effects of engine size
  • Challenges for small engine: more heat loss, higher engine speed required, lower fuel injection pressure
  • Large engine will favor ammonia combustion