Demonstrate Ammonia Combustion in Diesel Engines

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Background

• Motivation
  • Ammonia (NH₃) combustion does not generate CO₂
  • Biorenewable; Hydrogen carrier, key to hydrogen economy, etc.

• Challenges
  • Ammonia is very difficult to ignite
    • Octane number ~ 130
    • Autoignition T ~ 651 °C (gasoline: 440 °C; diesel: 225 °C)
  • Erosive to some materials
  • Fuel induction system modification
  • Less energy content – maximize energy substitution using NH₃
  • Others …..
Approach

- Introduce ammonia to the intake manifold
- Create premixed ammonia/air mixture in the cylinder
- Inject diesel (or biodiesel) to initiate combustion
  - Without modifying the existing injection system
Presentation Outline

• Ammonia combustion properties and implications
• Chemical kinetics study
• Experimental setup
• Baseline engine performance with diesel fuels
• Engine test using dual fuel – diesel/NH₃
• Emissions results
• Summary
Thermodynamics/Chemistry

- Stoichiometric chemical reaction

\[ \text{NH}_3 + 0.75 \cdot (\text{O}_2 + 3.76 \cdot \text{N}_2) \rightarrow 1.5 \cdot \text{H}_2\text{O} + 1.91 \cdot \text{N}_2 \]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Molecule</th>
<th>Boiling Point (°C)</th>
<th>(Air/Fuel)</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>CH₃OH</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>C₂H₅OH</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>C₇H₁₇</td>
<td>---</td>
<td>15.291</td>
<td>310</td>
<td>44</td>
<td>2.5781</td>
</tr>
<tr>
<td>Diesel</td>
<td>C₁₄.₄H₂₄.₉</td>
<td>---</td>
<td>14.3217</td>
<td>230</td>
<td>42.38</td>
<td>2.7660</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH₃</td>
<td>-33.5</td>
<td>6.0456</td>
<td>1371</td>
<td>18.6103</td>
<td>2.6414</td>
</tr>
</tbody>
</table>
Thermo-Chemistry

- Adiabatic flame temperature of NH$_3$/diesel mixture
- NH$_3$ energy fraction with different equivalence ratios

Adiabatic T is the final equilibrium T. In engines, we need to know how fast the reaction goes!
Chemical Kinetics – Methane/Ammonia

- Ignition delay – important parameter in CI engines
- Replacing HC fuel with NH3 will delay ignition

**Autoignition of CH4-NH3-Air System**

- 9.5%-CH4/0%-NH3
- 4.5%-CH4/5.0%-NH3
- 1.5%-CH4/8.0%-NH3

Need to rely on HC fuel to initiate combustion!
Chemical Kinetics – Diesel/Ammonia

- Ignition delay in a constant-volume chamber
  - Diesel/NH3 system

![Graph showing system temperature over time with NH3 content]
Test Engine

• John Deere 4045 Engine
  • Turbocharged, 4-cylinder, 4.5 liter displacement
  • Popular Deere engine – various tracker & Genset applications
  • Peak torque range – 280 ft-lb at 1400 rpm

• Test conditions
  • Various engine speeds (1000 ~ 1800 rpm)
    • Various engine loads (5% ~ 100%) for each speed
    • Each speed/load point – with and without NH3 induction
  • Test data – torque, BSFC, emissions
  • Only selected data are shown
Ammonia Fueling System

- Fuel system
  - Vapor ammonia introduced into the intake duct – after turbo, before manifold
Test Results – Constant NH3 Flow Rate

- Using one ammonia tank and single fuel line

\[\text{1400rpm Engine Torque}\]

\[\text{Energy replacement by NH3}\]

\[\text{Diesel+ NH3}\]

\[\text{Diesel baseline}\]

\[\text{1800rpm Engine Torque}\]

\[\text{Energy replacement by NH3}\]

\[\text{Diesel+ NH3}\]

\[\text{Diesel baseline}\]
Test Results – Constant Torque

- Induce more NH3
- Fixed at different diesel fueling, adjusted NH3 flow rate to maintain constant torque
  - Can achieve 5% diesel / 95% NH3 energy ratio

BSFC_diesel & BSFC_NH3 calculated separately based on individual flow rate and torque contribution
Test Results – Variable Torque

- **Goal** – to achieve maximum energy substitution
  - Diesel fueling was maintained at approximately 5%
  - Adjusted NH3 rate for desirable engine torque

Can achieve high NH3 ratio but poor fuel economy
Test Results – Using Biodiesel

- B100 was used
- Can achieve similar results as regular diesel fuel
Emissions Measurement

- Gaseous emissions – HC, CO, CO2, NOx, O2
- Emission analyzer modification for this study
  - Certain materials were replaced by stainless steel
- Baseline diesel conditions

These data will be used for comparisons
CO2 Results

- Maintained constant torque by varying diesel & NH3

(Repeated plot from previous)

CO2 reduction

All the CO2 comes from diesel combustion
NH3 Results

- Speculation – burning NH3 will …..
  - Increase NOx – due to fuel-bound nitrogen
  - Reduce NOx – due to lower combustion temperature
- Constant torque conditions

![Graph showing NOx emissions vs. Diesel Load for Diesel-NH3, 100% Torque.](image)

- High NOx due to N in NH3
- Low NOx due to low comb T
- NOx for 100% diesel
More on NOx Emissions

- Repeated testing

Another effect – NH3 can reduce NOx in diesel SCR (selective catalytic reduction)

Urea → NH3

\[(\text{NH}_2\text{CO} + \text{H}_2\text{O}) \rightarrow 2\text{NH}_3 + \text{CO}_2\]

SCR Catalyst

\[4\text{NH}_3 + 4\text{NO} + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}\]
\[2\text{NH}_3 + \text{NO} + \text{NO}_2 \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O}\]
\[8\text{NH}_3 + 6\text{NO}_2 \rightarrow 7\text{N}_2 + 12\text{H}_2\text{O}\]
HC Results

- Maintained constant torque conditions

**Graph:**
- **Diesel-NH3, 100% Torque**
- **Y-axis:** HC (ppm)
- **X-axis:** Diesel Load (%)
- **Legend:**
  - HC for 100% diesel
  - Decreasing HC due to lower diesel fueling
  - Increasing HC due to lower comb T

**Questions:**
- Additional reasons for HC increase?
- Re-combination between C (from diesel) and H (from NH3)?
Biodiesel/NH3 Emissions

- Same trend as in the diesel case
  - B100 produced lower HC than regular diesel at baseline
Summary

• Demonstrated ammonia combustion in diesel engines
  • Premixed NH3/air with direct-injection diesel for ignition
  • Effective in CO2 reduction while maintaining the same engine torque output

• Reasonable fuel economy between 20~60% diesel fueling

• NOx emissions are not a concern as originally expected
  • Lower NOx for certain diesel fueling range
  • HC has an opposite trend to NOx

• Further investigations are required for –
  • Emissions formation mechanisms
  • Precise control of NH3/diesel flow rates for optimal fuel economy and exhaust emissions