Modeling JP-8 Fuel Effects on Diesel Combustion Systems

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**Report Documentation Page**

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Agenda

- Introduction/Background
- JP-8 Evaporation Rate Modeling
- JP-8 Ignition Modeling
- Engine Predictions Results
- Conclusions
Introduction
One Fuel Forward Initiative


- Fuel differences
  - JP-8 properties
    - < 3000 ppm sulfur; variance allowed in fuel properties including cetane number and distillation curve
    - Referee grade more specific
  - JP-8 is Jet-A1 with three additives
    - fuel system icing inhibitor (MIL-DTL-85470), corrosion inhibitor and lubricity enhancer (MIL-PRF-25017), and static dissipator additive
  - Jet-A1 has lower freeze point than Jet-A (-53 F vs. -40 F)
- Engine benchmark to assess JP-8 impact
  - power loss and lubricity issues
Historical Perspective on JP-8 Engine Impact – Executive Summary

- Engine HP range of 150 – 750 BHP
  - represents various fuel system types
- Evaluated various fuel supply temperatures ranging from ambient (86 F) to 165 and 190 F (desert conditions)
- 3/5 engines developed fuel-related durability issues
- In-line Bosch pumps or rotary pumps exhibited higher power loss
Historical Perspective on JP-8 Engine Impact - Results

1. GM, Detroit Diesel Allison (DDA) 6.2 L IDI: rotary distributor pump, (Stanadyne), heavy wear after 400 hrs with 195 F fuel, recommend use of Artic pump kit for future pumps

2. Cummins 6CTA-8.3L: (M939 – 5 ton truck); fuel pump control issue that caused power surges at 1200 RPM related to starting strategy

3. GM, DDA 8V-71T (Paladin) – none.

4. Cummins VTA-903T (Bradley) fuel shut-off valve leakage after 100 test hours and transfer pump seized three times and gear shaft bushings froze up; Cummins resolved these problems

5. Teledyne Continental Motors AVDS-1790-2C (M60A1 and M88); two distributor pumps have large internal leakage that resulted in excessive power loss; proposed elimination of spillback
Fast Forward to More Modern Times

- Continental AVDS 1790 Up-rated to 1050 BHP
- Noted substantial piston erosion
  - prevalent in engines exposed to JP-8
- Concern over possible combustion system issue
Sieber's zero-dimensional approach

\[ L_b = \frac{b}{a} \sqrt{\frac{\rho f}{\rho_a}} \sqrt{\frac{C_a \cdot d}{\tan(\frac{\theta}{2})}} \left( \sqrt{\frac{2}{R_s} + 1} \right)^2 - 1 \]

Fuel to ambient gas flow rate ratio or evaporation coefficient

\[ B_s = \frac{Z_a(T_a, P_a - P_s) \cdot P_a \cdot M_f}{Z_f(T_s, P_s) \cdot (P_a - P_s) \cdot M_a} = \frac{h_a(T_a, P_a) - h_a(T_s, P_a - P_s)}{h_f(T_s) - h_f(T_f, P_a)} \]

fuel to air density ratio

area contraction coefficient

spray angle

enthalpy differences - air and fuel

air and fuel compressibility
Fuel Properties

- Saturation pressure and density relationships given by API handbook
- Compressibility and enthalpies precise curve-fits of API handbook data

\[
P_{r,s} < 0.2 \quad h_f(T_s) = A \cdot T_{r,s} - B
\]
\[
P_{r,s} \geq 0.2 \quad h_f(T_s) = -C \cdot T_{r,s}^2 + D \cdot T_{r,s} - E
\]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Critical Temperature (K)</th>
<th>Critical Pressure (bar)</th>
<th>Boiling Point (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dodecane</td>
<td>658</td>
<td>18.2</td>
<td>489</td>
</tr>
<tr>
<td>tetradecane</td>
<td>693</td>
<td>15.7</td>
<td>526</td>
</tr>
<tr>
<td>cetane</td>
<td>723</td>
<td>14.0</td>
<td>560</td>
</tr>
<tr>
<td>hopptadecane</td>
<td>736</td>
<td>13.4</td>
<td>575</td>
</tr>
<tr>
<td>HMN</td>
<td>692</td>
<td>15.7</td>
<td>513</td>
</tr>
<tr>
<td>DF-2</td>
<td>NA</td>
<td>NA</td>
<td>580*</td>
</tr>
<tr>
<td>JP-8</td>
<td>NA</td>
<td>NA</td>
<td>496*</td>
</tr>
</tbody>
</table>

\[
Z_f(T_s, P_s) = -a \cdot T_{r,s}^3 + b \cdot T_{r,s}^2 - c \cdot T_{r,s} + d
\]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
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<tr>
<td>dodecane</td>
<td>16.85</td>
<td>36.104</td>
<td>26.425</td>
<td>7.5406</td>
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<tr>
<td>tetradecane</td>
<td>17.924</td>
<td>36.143</td>
<td>24.71</td>
<td>6.6857</td>
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<tr>
<td>cetane</td>
<td>16.587</td>
<td>34.594</td>
<td>24.531</td>
<td>6.869</td>
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</table>
Measured JP-8 and DF-2 Distillation Behavior

- JP-8 and DF-2 samples from CONUS supply chain
- JP-8: 90% distillation point close to dodecane
- DF-2: 80 - 90% distillation points between cetane and heptadecane
Methodology for Multi-component Fuels

- Property and boiling point issue
- Limited data for multi-component fuels
- Employ weighting scheme

- **MLL**: Mean Liquid Length

\[
L_B = \sum_{i=1}^{N} x_i L_{b,i}
\]

- **MEC**: Mean Evaporation Coefficient

\[
B_s = \sum_{i=1}^{n} x_i B_{s,i} \quad T_b = \sum_{i=1}^{n} x_i T_{b,i} \quad \sum_{i=1}^{n} x_i = 1
\]

boiling point of component \(i\)

mass fraction of component \(i\)
- HMN density close to cetane but boiling point 40 K lower
- 35% dodecane – 65% tetradecane surrogate
- MEC superior method for matching data set
Test fuel was 67% HMN – 33% cetane
Boiling point close to tetradecane
Three modeling options – tetradecane, MEC, MLL
Any of three methods are reasonable
JP-8 Predictions

- 82% dodecane – 18% tetradecane surrogate
- JP-8 can be modeled as dodecane or employ the MEC or MLL methods
Nil published data!

Predictions made based on cetane number studies conducted by GM Research Lab, U-Wisconsin, AVL, and a German University.

Assumed 30% increase in the ignition delay period with a 10 cetane number decrease.

Is this true?

- L. Hoogterp spent 30 days at SNL conducting experiments.
## Engine Predictions

<table>
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<tr>
<th>Engine Parameter</th>
<th>Description</th>
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<tr>
<td>Number of Cylinders</td>
<td>12</td>
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<tr>
<td>Bore x stroke (mm)</td>
<td>146.1 x 146.1</td>
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<tr>
<td>Compression Ratio</td>
<td>14.5</td>
</tr>
<tr>
<td>Displacement (cc)</td>
<td>2447</td>
</tr>
<tr>
<td>Coolant System Media</td>
<td>air and oil</td>
</tr>
<tr>
<td>Boost System</td>
<td>turbocharged</td>
</tr>
<tr>
<td>Charge air cooler</td>
<td>air-to-air with bypass valve</td>
</tr>
<tr>
<td>Injection System</td>
<td>pump-line-nozzle</td>
</tr>
<tr>
<td>Peak Injection Pressure (bar)</td>
<td>~ 650</td>
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<tr>
<td>Fuel Types</td>
<td>diesel or JP-8</td>
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<tr>
<td>Nozzle Geometry (mm)</td>
<td>10 x 0.282</td>
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<tr>
<td>Rated Speed (RPM)</td>
<td>2400</td>
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<tr>
<td>Maximum Power (kW)</td>
<td>780</td>
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1. Per cylinder
2. Fuel pump delivery schedule adjusted based on fuel type.
3. Varies as a function of fuel type.
4. Military vehicles required to operate on world-wide variant diesel and JP-8 fuels. For this test, JP-8 cetane number was 49.

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Comparison of Predicted DF-2 and JP-8 Liquid Lengths

- Predictions based on measured fuel injection timing and GT-Power cycle simulation for initial in-cylinder thermodynamic conditions at SOI.
- Measured DF-2 boiling point is 85°C higher than JP-8.

- Ignition delays estimated from high speed injection/pressure data
  - JP-8 CN was 49

- Evaporated fuel mass

\[
m_{evap} = \int_{t_{SOI}}^{t_{IGN}} m_{inj} \, dt - \pi \cdot \frac{d^2}{4} \cdot L_b
\]

- Similar vapor fraction

NOTE: JP-8 predictions based on 49 CN
Effect of CN on JP-8 Liquid Length Predictions

- Projected JP-8 40 CN effect
  - Assume 30% increase in ignition delay versus 49 CN JP-8

- Lower CN JP-8 exhibited 30% to 40% increase in vapor fraction (i.e. 30% or > vaporized fuel at ignition)

- Anticipated higher pressure rise for lower CN JP-8 in comparison to higher CN JP-8 and DF-2

**NOTE:** JP-8 predictions based on 40 CN unless otherwise noted
Anticipated JP-8 Pressure Rise Impact

1. Hiroyasu and Arai spray penetration model

2. Predicted pressure rise based on 1st law analysis of combustion chamber

\[ \frac{dP}{dt} \approx \frac{k-1}{V} \left( \frac{m_b LHV - \frac{dV}{dt} P}{1 + \frac{1}{k-1}} \right) \cdot Q_{wall} \]

- Expansion term
- Peak premixed phase fuel burning rate; time scale approach
- Wall heat transfer; small during ID period; NEGLECT
Anticipated JP-8 Pressure Rise Impact

- Premixed fuel mass is integrated evaporated fuel during the ignition delay period

- Pressure rise rate increase of 10% to 36% increase operating on lower CN JP-8 versus DF-2

- Expansion term contributes 6% to 20% in overall pressure rise

- MONDAY MORNING QUARTERBACK:
  - 2004 CONUS JP-8 procurement data sets
  - Mean CN of 43.9
  - Range: 29 to 51 !!!!!
Concluding Remarks

**SUPERIOR TECHNOLOGY FOR A SUPERIOR ARMY**

- Methodology developed to assess JP-8 evaporation rate (liquid length)
  - Dodecane is a good surrogate for JP-8
  - The Mean Evaporation Coefficient (MEC) method demonstrated reasonable predictive capability for multi-component fuels

- Engine simulation study exhibited potential pressure rise rate issues for certain military engine types when utilizing JP-8 and DF-2
  - JP-8 distillation and ignition quality variances could contribute to such issues

- Suggested directional design changes to combustion system
  - Larger bowl diameter
  - Reduce hole size
  - High pressure common rail fuel system
  - Redesign intake manifolds to reduce cylinder trapped mass variability
THANK YOU!

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