Topic 3 – Vaporizing Diesel Spray
Spray A and Spray B

Presenter: Caroline Genzale, Georgia Tech
September 5th, 2015
Some history: We’ve made several attempts to standardize liquid length measurements within the ECN.

**ECN1**: Detection of liquid boundary near the LL is sensitive to optical method and setup

Extinction offers referenced intensity measurement.
Some history: We’ve made several attempts to standardize liquid length measurements within the ECN.

**ECN2:** Adoption of DBI imaging to measure $I/I_0$

- “Extinction profiles measured on the centerline are somewhat different between institutions.”
- “The variations observed are believed to come from differences in optical arrangement (mainly illumination and collection angles).”
- “A methodology must be setup to consistently measure liquid length from extinction without the influence of beam steering.”

**ECN4:** Fredrick Westlye will provide us an update on this topic next!
More history: We’ve seen consistent predictions of liquid/vapor penetration between CFD codes, but not in the details of the spray.

**ECN2:** Significant differences between CFD codes in the predicted spray structure.
More history: We’ve seen consistent predictions of liquid/vapor penetration between CFD codes, but not in the details of the spray.

**ECN3:** Even when downstream profiles are consistent, upstream spray structure can vary greatly. These regions can be coincident with LOL region.
Following up on prior themes:
• Further assess institutional variations in DBI measurements and develop a standardized (and consistent) measurement approach for liquid penetration.
• Pursue further insight into phase transition behavior at Spray A conditions.

Vaporization data at new target conditions:
• Spray A multiple injection conditions
• Spray B
• Spray C and D injectors
Following up on prior themes:

• Deep dive into near-nozzle spray structure variations between codes and sensitivities to ambient conditions.
• Understand impact of these differences on combustion predictions.

Simulations at new target conditions:

• Spray A multiple injection conditions.
Spray A Parametric Modeling Study

CMT
Adrian Blanco, Raul Payri

PoliMi
Tommaso Lucchini, Gianluca D’Errico

GA Tech
Gina Magnotti, Caroline Genzale

Bosch
Edward Knudsen

Sandia
Guilhem Lacaze, Joe Oefelein
Target conditions for Spray A parametric modeling study

- Injector 675
- 89.4 μm, $C_a = 0.98$, $A_{\text{eff}} = 6.15 \times 10^{-9}$ m$^2$, $\rho_{\text{liq}} = 713$ kg/m$^3$
- Standard injection rate profile provided to all institutions

<table>
<thead>
<tr>
<th>Parametric Variable</th>
<th>$O_2$ [%]</th>
<th>$T_{\text{amb}}$ [K]</th>
<th>$\rho_{\text{amb}}$ [kg/m$^3$]</th>
<th>$P_{\text{inj}}$ [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard Spray A</strong></td>
<td>0</td>
<td>900</td>
<td>22.8</td>
<td>1500</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>0</td>
<td>700</td>
<td>22.8</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1200</td>
<td>22.8</td>
<td>1500</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>0</td>
<td>900</td>
<td>7.6</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>900</td>
<td>15.2</td>
<td>1500</td>
</tr>
<tr>
<td><strong>Injection Pressure</strong></td>
<td>0</td>
<td>900</td>
<td>22.8</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>900</td>
<td>22.8</td>
<td>1000</td>
</tr>
</tbody>
</table>
Comparison of spray and CFD models

<table>
<thead>
<tr>
<th>Code</th>
<th>PoliMi</th>
<th>GA-Tech</th>
<th>CMT</th>
<th>Bosch</th>
<th>Sandia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spray model</td>
<td>Blob, KH-RT</td>
<td>Blob, KH-RT</td>
<td>Eulerian Σ-Y model</td>
<td>Eulerian dense fluid</td>
<td>Eulerian dense fluid</td>
</tr>
<tr>
<td>Evaporation model</td>
<td>Frossling drop evaporation</td>
<td>Frossling drop evaporation</td>
<td>State relationships from locally homogeneous flow assumption</td>
<td>Peng-Robinson EOS</td>
<td>Real fluid model</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>RANS, k-ε</td>
<td>RANS, k-ε</td>
<td>RANS, k-ε</td>
<td>LES</td>
<td>LES Dynamic Model</td>
</tr>
<tr>
<td>Mesh Dimensionality Grid size</td>
<td>2D 0.5 mm</td>
<td>3D 0.0625 – 2 mm</td>
<td>2D 0.009 mm – 0.7 mm</td>
<td>3D w/ internal nozzle 3.2M cells</td>
<td>3D 0.002 mm – 0.1 mm</td>
</tr>
</tbody>
</table>
Standard Spray A Condition
Simulations of quasi-steady liquid penetration cluster around the experimental data, similar to previous workshops.

Liquid boundary definition:
Axial position where path-averaged liquid volume fraction is 0.15%
Differences in fuel vapor fraction upstream arise from combined effects of spray model and momentum coupling.
Jet dispersion well matched, but predicted spray structures vary significantly between institutions as we approach the LL.

Spray A

time averaged spray structure

1 - 3 ms

7.5 mm
Predicted spray structures vary significantly between institutions as we approach the LL.

Spray A

time averaged spray structure
1 - 3 ms

9.0 mm
SMD profiles can take on different distribution behaviors as breakup and evaporation proceed.

Spray A
time averaged spray structure
1 - 3 ms

Which solution is the “accurate” one?
Spray A Parametric Study:
Exploration on what information we’d really like to have to validate evaporating sprays
Revisit of global model response to parametric variations in ambient and operating conditions.
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Revisit of global model response to parametric variations in ambient and operating conditions.
How do the spray and evaporation models respond to changes in ambient and operating conditions?

Density Parametric Variation
- \( \rho = 7.6 \text{ kg/m}^3 \)
- \( \rho = 15.2 \text{ kg/m}^3 \)
- \( \rho = 22.8 \text{ kg/m}^3 \)

Temp Parametric Variation
- \( T_{\text{amb}} = 700 \text{ K} \)
- \( T_{\text{amb}} = 900 \text{ K} \)
- \( T_{\text{amb}} = 1200 \text{ K} \)

Inj. Press. Parametric Variation
- \( P_{\text{inj}} = 50 \text{ MPa} \)
- \( P_{\text{inj}} = 100 \text{ MPa} \)
- \( P_{\text{inj}} = 150 \text{ MPa} \)

CMT

PoliMi
Comparison of LVF behavior and accumulated mass... they both show *some* sensitivity to ambient conditions.
Gradients near LL show that LVF shows more sensitivity to correctly capture the liquid boundary.

**Density Parametric Variation**

**Temp Parametric Variation**

**Inj. Press. Parametric Variation**

**PoliMi**

\[ \Delta \text{LVF} \]

\[ \text{Accumulated Mass} \% \]

Axial Distance from LPL [mm]

- \( \rho = 22.8 \text{ kg/m}^3 \)
- \( \rho = 15.2 \text{ kg/m}^3 \)
- \( \rho = 7.6 \text{ kg/m}^3 \)

- \( T_{am_b} = 1200 \text{ K} \)
- \( T_{am_b} = 900 \text{ K} \)
- \( T_{am_b} = 700 \text{ K} \)

- \( P_{inj} = 50 \text{ MPa} \)
- \( P_{inj} = 100 \text{ MPa} \)
- \( P_{inj} = 150 \text{ MPa} \)

\( \rho \in \{22.8, 15.2, 7.6\} \text{ kg/m}^3 \)

\( T_{am_b} \in \{1200, 900, 700\} \text{ K} \)

\( P_{inj} \in \{50, 100, 150\} \text{ MPa} \)
Is there a potential pathway forward to validated modeling of the local liquid structure and evaporation process?

Modeling of light extinction measurements could provide some validation at vaporizing conditions.

Quality extinction measurements needed (next talk).

Validation of near-spherical droplets in these regions (previous talk).
Old news revisited: Validation of evaporating sprays solely against liquid and vapor penetration measurements does not adequately validate the evaporation process.

Somewhat old news revisited: It is difficult to isolate effects of spray model choices on near-nozzle mixture discrepancies.

- Lagrangian models lead to errors in gas momentum exchange
  - Error cascades to affect breakup and vaporization models
  - Eulerian models don’t necessarily predict evaporation well either

To accurately validate evaporating sprays, we need a validation methodology that responds to changes in the mixing and evaporation rate appropriately.

- Liquid volume fraction is physically consistent with extinction and scattering measurements AND drops rapidly near the liquid length.
- High quality extinction measurements may help.

Conclusions from Spray A parametric modeling study:
Spray A Multiple Injections

Modeling

**CMT:** Adrian Blanco, Raul Payri

**Polimi:** Tommaso Lucchini, Gianluca D’Errico

Experiments

**Sandia:** Julien Manin, Scott Skeen, Lyle Pickett
Spray A multiple injection target conditions

- Same model setup as parametric study. Nozzle 675.

<table>
<thead>
<tr>
<th>Condition</th>
<th>O₂ [%]</th>
<th>T_amb [K]</th>
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Multiple injection simulations compare well between institutions and with Sandia vapor penetration data.

Split Injection 0.5 ms – 0.5 ms dwell – 0.5 ms

Pilot-Main 0.3 ms – 0.5 ms dwell – 1.2 ms

Sandia vapor data
Transient mixing process is well matched between CMT and PoliMi downstream of liquid regions.
Spray B

Experiments

**CMT:** Alberto Viera, Raul Payri

**Nozzle 211200**

**Sandia:** Julien Manin, Scott Skeen, Lyle Pickett

**KAIST:** Yongjin Jung

**Nozzle 211201**
Simultaneous Mie scatter and DBI at CMT

HS Camera
Mie-scatter
32 kfps

Blue LED

Continuous light source

HS Camera with long-range microscopic lens
DBI
82.1 kfps
Two different liquid penetration measurement techniques and two spray orientations:

• **Horizontal Configuration**
  – Mie scattering: Phantom v710, 105 mm, f/2.8, 80 kfps

• **Vertical Configuration**
  – Diffused back illumination (DBI), Photron, 100 kfps
Sandia has shown that liquid penetration profile is correlated with transient spreading angle behavior.

Jung et al. SAE 2015-01-0946
CMT also measures a transient liquid penetration rate, but with a shorter penetration length.
Moving forward with Spray A multiple injections and Spray B:

- First look at modeling multiple injections: predictions of mixture profiles and transient behavior is not any worse that steady-state Spray A.
  - Near-nozzle mixture discrepancies, but these are rapidly diffused by vaporization and transient mixing process.

Spray B measurements:

- Transients in measured liquid penetration is well correlated with transient spreading angle behavior.
- Measurements at CMT display similar transient behavior, but injection conditions are different so it’s hard to make further conclusions.
- Seems to be a consistent trend that CMT measures shorter LL’s than Sandia.
- Modeling of the transient behavior will require more than the usual Lagrangian spray modeling approach.
Old news revisited: Validation of evaporating sprays solely against liquid and vapor penetration measurements does not adequately validate the evaporation process.

Somewhat old news revisited: It is difficult to isolate effects of spray model choices on near-nozzle mixture discrepancies.
  - Lagrangian models lead to errors in gas momentum exchange
    • Error cascades to affect breakup and vaporization models
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To accurately validate evaporating sprays, we need a validation methodology that responds to changes in the mixing and evaporation rate appropriately.

Liquid volume fraction is physically consistent with extinction and scattering measurements AND drops rapidly near the liquid length.

High quality extinction measurements may help.
Some history: We’ve made several attempts to standardize liquid length measurements within the ECN.

**ECN3:** Still differences in measured LL between institutions. No significant advancement of “standardized” LL measurement method.

<table>
<thead>
<tr>
<th>Spray A Measured Liquid Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandia - 675</td>
</tr>
<tr>
<td>11.7</td>
</tr>
</tbody>
</table>

**Parametric Spray A Conditions**

<table>
<thead>
<tr>
<th></th>
<th>Sandia - 675</th>
<th>CMT - 675</th>
<th>$\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 K, 7.6 kg/m³</td>
<td>16.0</td>
<td>22.8</td>
<td>43%</td>
</tr>
<tr>
<td>700 K, 22.8 kg/m³</td>
<td>14.5</td>
<td>17.6</td>
<td>21%</td>
</tr>
</tbody>
</table>

**ECN4:** Fredrick Westlye will provide us an update on this topic next!