Topic 3
Spray Mixing and Evaporation

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Index

- Spray A
  - High Speed Rayleigh – fuel mass fraction (Julien Manin)
  - Model Validation / Consolidation

- Spray C/D
  - Measurement summary
  - What do we know?
  - CFD validation

- Conclusions and outlooks
<table>
<thead>
<tr>
<th>Institution/Group</th>
<th>CFD code</th>
<th>Turbulence model</th>
<th>Spray modelling approach</th>
<th>Thermodynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aachen-RWTH</td>
<td>CIAO (in-house)</td>
<td>LES Dynamic Smagorinsky</td>
<td>Lagrangian DDM: Initial angle and drop size from DNS primary atom / no BU model</td>
<td>Ideal fluid EoS and droplet evaporation</td>
</tr>
<tr>
<td>CMT-UniOvi</td>
<td>OpenFOAM</td>
<td>RANS standard k-eps</td>
<td>Eulerian single fluid Σ-Y: Homogeneous mixture</td>
<td>Ideal fluid EoS and VLE</td>
</tr>
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<td></td>
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<td>C1eps=1.6</td>
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<tr>
<td>POLIMI</td>
<td>OpenFOAM</td>
<td>RANS standard k-eps</td>
<td>Lagrangian DDM: Blob / KH+RT</td>
<td>Ideal fluid EoS and droplet evaporation</td>
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<td></td>
<td>C1eps=1.55</td>
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<td></td>
</tr>
<tr>
<td>TUM_TUDELFT</td>
<td>INCA (in-house)</td>
<td>LES ALDM implicit filter</td>
<td>Eulerian single-fluid: Homogeneous mixture</td>
<td>Real fluid cubic EoS and VLE</td>
</tr>
<tr>
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<td>Grid size [mm] min/max</td>
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<td>Aachen-RWTH</td>
<td>3D (56 x 28 x 28)</td>
<td>60e-3 / 0.7</td>
<td>29.5e6</td>
<td></td>
</tr>
<tr>
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<td>2D-axisym (80 x 50)</td>
<td>9e-3 / 0.9</td>
<td>50e3</td>
<td></td>
</tr>
<tr>
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<td>2D-axisym (108 x 108)</td>
<td>127e-3 / 1.27</td>
<td>23e3</td>
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<tr>
<td>TUM_TUDELFT</td>
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<td>15.1e6</td>
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</tr>
</tbody>
</table>
Mixing field at 1000 us ASOI

SNL new Rayleigh data - avg

SNL new Rayleigh data - instant

TUM averaged

TUM Instantaneous

RWTH

CMT

Polimi
Penetration and liquid length: reference conditions
Spray A – Model Validation

- Parametric Variation: Ambient Temperature on penetration
  - No impact for Polimi and CMT
  - Slight impact for TUM

Tamb 700K

Tamb 1200K
Spray A – Model Validation

- Parametric Variation: Ambient Density
  - Very close for both the institutions
  - Slight impact for TUM
- Vapor phase penetration is well predicted for all the param. variations applied
Spray A – Model Validation

- Liquid length:
  - Polimi over predict the effect of Tamb
  - Reasonably good agreement for TUM and CMT
  - Effect of ambient density is under predicted
The Yf – T relationship has been analyzed for the reference case.

The scatter plot remains very close to the Adiabatic mixture.
- An exceptions can be observed in the first mm of the jet.

Some minor difference can be observed between the models.
- TUM and Polimi “knee” appears at richer mixture fractions (0.36 vs 0.39).
- The impact on the liquid length is significant (approx. 1mm).

ECN 5 Topic 3 - Detroit, March 31st, 2017
- The Yf – T relationship has been analyzed for the reference case

- The scatter plot remains very close to the Adiabatic mixture
  - An exceptions can be observed in the first mm of the jet

- The mixing line plot indicates that these differences become critical at 700 K
  - At reference conditions The impact on the liquid length is significant (approx. 1mm)
  - At 700 K is considerably bigger, and this could be the case of the different LL obtained
Mixing field at 1000 us ASOI

SNL new Rayleigh data - avg

SNL new Rayleigh data - instant

TUM averaged

TUM Instantaneous

RWTH

CMT

Polimi
Mixture fraction axial profile

- For consistency axial profile has been calculated averaging 1 mm around the axis
- Difference in data sampling

- Global consistency after 10 mm
- RWTH is consistently lower
More consistency can be found on the Radial profiles
- TUM has narrower profile and higher central velocity
- Global Equivalence ratio histogram
  - TUM instantaneous is very close to the averaged
  - RTWH peak is at lower mixture fraction
- At 0.5 ms there are experimental data!

- The impact of the LES averaging moves to the left the $Y_f$ peak
Conclusions I

- There is a good overall prediction at Reference conditions
- The vapor phase penetration is always well caught also for parametric variations
- Discrepancies appears for LL
  - An important source of differences is shown by the mixing line
  - Uniformation of the fuel properties is needed
- The Yf histograms shows more discrepancies
  - In particular the head of the spray shows different distributions
  - More investigation should be done for the end of the injection
  - Accurate prediction is mandatory for an accurate prediction of ignition
Spray A
- High Speed Rayleigh – fuel mass fraction
- Model Validation / Consolidation

Spray C/D
- What do we know?
- New experimental evidencies
- CFD validation

Conclusions and outlooks
Spray C - D

- Spray C liquid penetration consistently 3-4 mm shorter
- Difference in nozzle coefficients only depict a 1 mm difference
- High contrast liquid phase images enable detailed analysis
- Spray C is wider immediately outside the nozzle
- Beyond a point, referred to as similarity onset (SO), the sprays behave nearly identical

![Graphs and images related to spray C and D showing liquid penetration and radial distance.](image)
• The vapor penetrates slightly faster for Spray D
• Constant growth rate in the far-field indicative of self-similar behavior
• Both sprays display similar growth rates
• Dispersion angles based on constant radial growth with no assumption of spray origin
• Vapor phase radial profiles collapse when referenced to SO
 Spray C - D

- Consistently is observed a difference among spray C and D Vap. Penetration
- Reasonable agreement among institutions

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<tr>
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<th>Spray C</th>
<th>Spray D</th>
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</thead>
<tbody>
<tr>
<td>IFPEn</td>
<td>003</td>
<td>135</td>
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<tr>
<td>CMT</td>
<td>003</td>
<td>103</td>
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<tr>
<td>SNL</td>
<td>037</td>
<td>134</td>
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</tbody>
</table>
No agreement among liquid phase penetration (CMT and IFPEn data available)

At high P inj no difference could be observed for CMT data between Spray C/D

Strong cavitation might happen also for spray D injector
IFPEN Schlieren experiments

- Schlieren avg. radial profiles
IFPEN Schlieren experiments

- Schlieren avg. radial profiles

Spray C translated 3mm downstream

Spray C - D

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SNL Schlieren experiments

- Schlieren avg. radial profiles

**Avg Schlieren Profiles**

**Spray C translated 3mm downstream**
• **LIF measurements IFPEN**
  - DFB tracer calibrated (sensitivity to T and O2)
  - Unfortunately the analysis is still ongoing

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**Spray C-D**

[Graphs and images showing spray patterns and mixture fraction vs. axial position]
The comparison among Spray C-D radial profiles can help in understanding the differences in the mixing field?

- Not for the moment, more analysis is needed
Is the mixture fraction (liquid and vapor) width of Spray D possibly larger than Spray C at high fuel T?

440 K, 22.8 kg/m³, 0% O₂

- Perform experiments at “non-vaporizing” conditions at low ambient temperature such that liquid is found at all mixture fraction (i.e. \( Z_{\text{sat}} \) is near 0)

**Spray C**

Wide/turbulent
Liquid extinction persists at edge of spray

**Spray D**

Similar to Spray C, but looks as if there are fewer large intermittent structures
Comparison of hot/cold ambient shows significant differences in liquid radial width

- If it is believed that mixing-limited vaporization applies (Siebers), the liquid width is expected to be less at high T ambient conditions.

- But the fact that there is a reversal in order (Spray C vs Spray D) suggests that the radial distribution of mixture fraction is different for C vs D.
But the effect is even more significant if considering the likelihood of a lower Ca (hypothesis #2)

- Decreased Ca for Spray C in Musculus/Kattke model
- If Spray C has a lower Ca (higher cavitation at higher T), liquid could be wider at cold 440 K ambient, but thinner at 900 K ambient
- Curves are only theoretical, but the manner in which cavitation modifies the mixing layer distribution will be important
Conclusions II

At reference conditions:

Consistency in the penetration measurements

All the data gathered converge to a shifting of the Spray C virtual origin:
- Sandia and IFPEN Liquid length measurements
- Sandia and IFPEN Schlieren half-width profiles (data CMT not available)
- IFPEN LIF calibrated measurement

Information about near field behavior
- Long distance microscopy (SNL)
IFPEn Schlieren avg. radial profiles at 40 MPa
Spray C/D

• Why at 40 Mpa we are observing a stronger impact on Spreading angle?
  – Could hydraulic-flip explain this effect?

Soteriou, 950080

Battistoni et al. 2016-01-0860

Figure 17. Close-up views of instantaneous cavitation interactions inside the nozzle. \( \alpha \) is the volume fraction and the \( x \) denotes liquid fuel, fuel vapor and ambient \( N_2 \).
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Polimi and CMT-Ov sent their first results
CMT-Uni Oviedo CFD

ROI + Deff

Mapped BC

Radial Distance [mm] vs. Axial Position [mm]

• Axial Profile indicated a lower axial Yf for Spray D
  – Consistent to LL results
• Also the radial profile is slightly narrower
Conclusions III

• A variation in injection pressure indicate that things might be more complicated.
  • At pinj 40 MPa the axial profiles actually diverge

• First CFD comparison are available
  • It is possible to predict reasonably good the difference in penetration
  • However the differences in mixing have to be investigated further
    • Low agreement with experiments
      • LL
      • Yf radial profiles
Topic 3
Spray Mixing and Evaporation

Thanks for the attention!

Presenter: Michele BARDI
IFPEn, France
• How does atomization influence mixing?
  – Spray C/D comparison
    – Base hypothesis: spray C/D atomization differ because of cavitation
• Database consolidation
  » Timeframe: ECN5/ECN6
• Detailed comparison C/D
  – Mixture
  – Droplet size
  – LES simulations
    » Timeframe: 4 years from now
  – Analyze the relation between mixture and velocity
    • Simultaneous velocity and mixture measurements
      – Liquid/vapor/evaporating conditions
        » Timeframe: 5/10 years from now
    • High fidelity LES / DNS
      » Timeframe: 3/5 years from now
  – Understand the effect of parametric variations
    • Spray A Database consolidation
      » Timeframe: ECN6
What are the mechanisms governing mixing during transients?

- Start of injection: what are the mechanisms governing mixing at the jet head?
  - Compare available experimental and simulation results
    » Timeframe: ECN5/ECN6
  - Spray A/C/D velocity measurements and comparison to HF LES
    » Timeframe: 4 years from now
  - What is the effect of wall impingement on these mechanisms?
    » Timeframe: 5/6 years from now

- After end of injection: confirm/explain the entrainment wave mechanism
  - Perform and analyze mixing measurements
    » ECN6
  - Study the effect of rate shaping on mixture and velocity
    » Experiments/RANS/LES
    » Timeframe: 5/6 years from now