Engine Combustion Network

Topic 3
Spray Mixing and Evaporation

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Model description

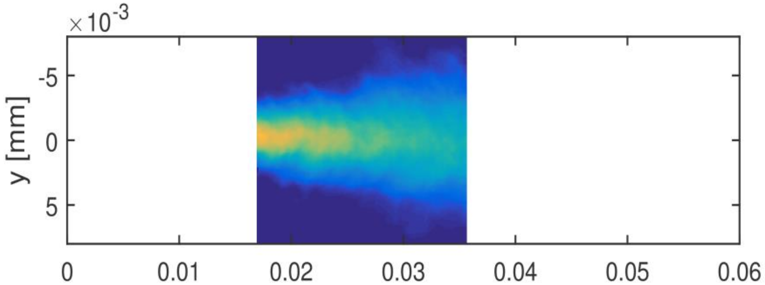
Institution/Group	CFD code	Turbulence model	Spray modelling approach	Thermodynamics
Aachen-RWTH	CIAO (in-house)	LES Dynamic Smagorinsky	Lagrangian DDM: Initial angle and drop size from DNS primary atom / no BU model	Ideal fluid EoS and droplet evaporation
CMT-UniOvi	OpenFOAM	RANS standard k-eps C1eps=1.6	Eulerian single fluid Σ-Y: Homogeneous mixture	Ideal fluid EoS and VLE
POLIMI	OpenFOAM	RANS standard k-eps C1eps=1.55	Lagrangian DDM: Blob / KH+RT	Ideal fluid EoS and droplet evaporation
TUM_TUDELFT	INCA (in-house)	LES ALDM implicit filter	Eulerian single-fluid: Homogeneous mixture	Real fluid cubic EoS and VLE

Model description

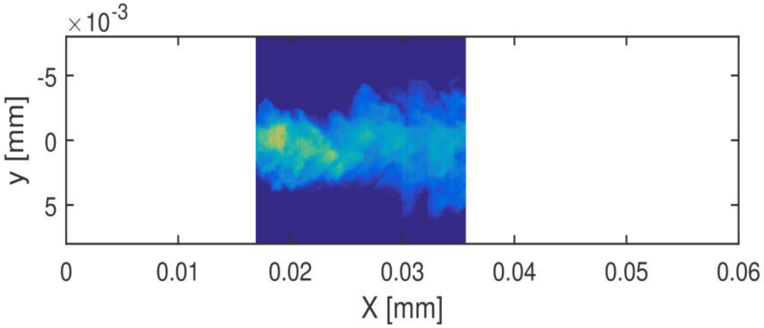
Institution/Group	Dimensionality [mm]	Grid size [mm] min/max	No. cells
Aachen-RWTH	3D (56 x 28 x 28)	60e-3 / 0.7	29.5e6
CMT-UniOvi	2D-axisym (80 x 50)	9e-3 / 0.9	50e3
POLIMI	2D-axisym (108 x 108)	127e-3/ 1.27	23e3
TUM_TUDELFT	3D (100 x 60 x 60)	6.84e-3 / 0.44	15.1e6

➢ Mixing field at 1000 us ASOI

SNL new Rayleigh data - avg



SNL new Rayleigh data - instant



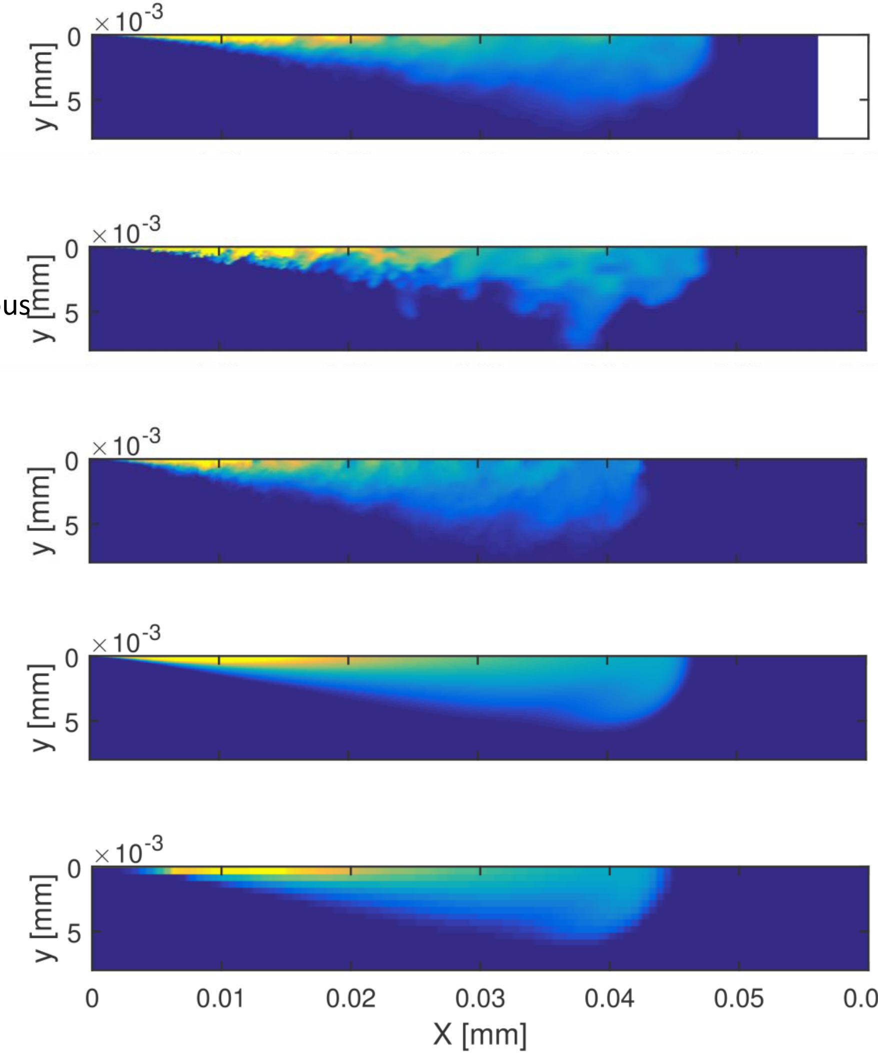
TUM averaged

TUM Instantaneous

RWTH

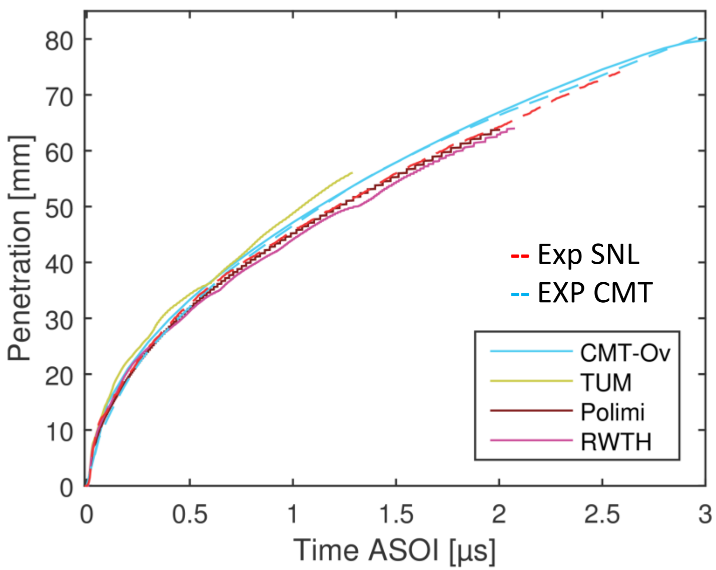
CMT

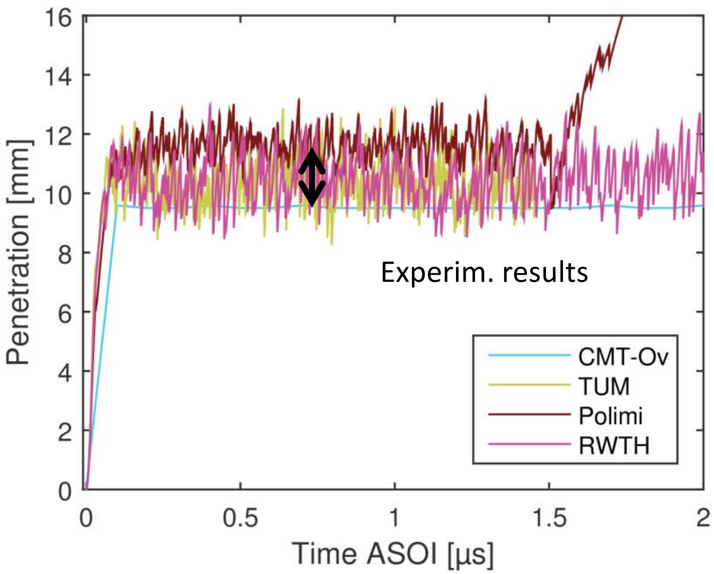
Polimi



Spray A – Model Validation

- Penetration and liquid length: reference conditions

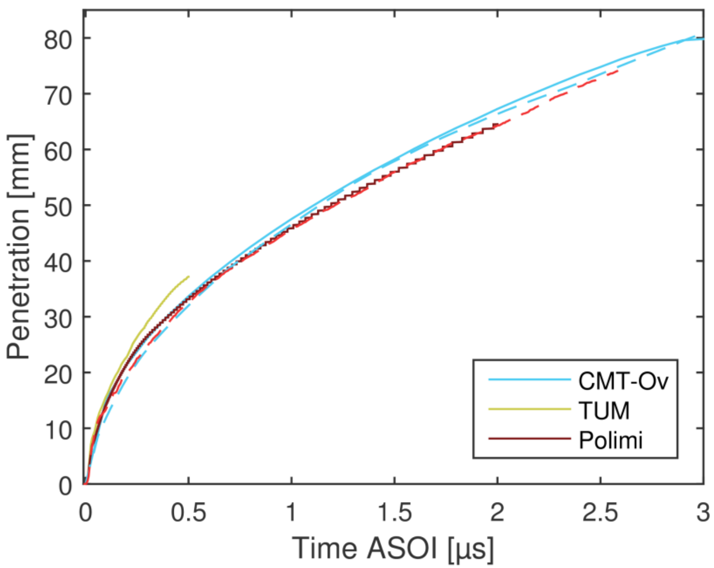




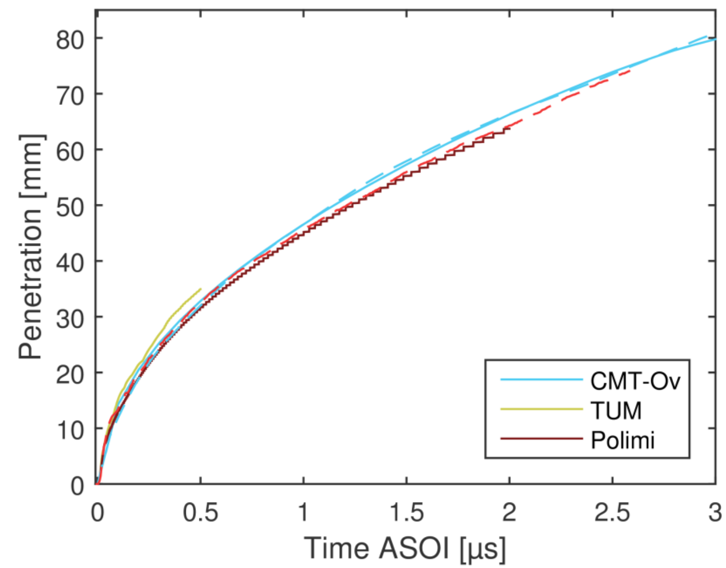
Spray A – Model Validation

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

Tamb 700K

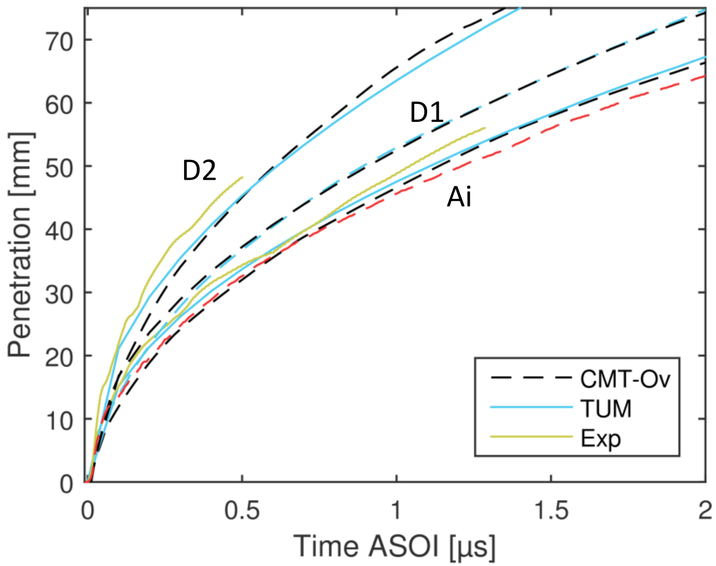


Tamb 1200K



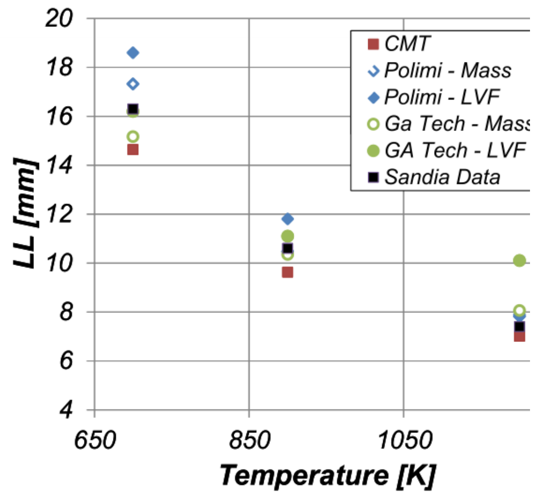
Spray A – Model Validation

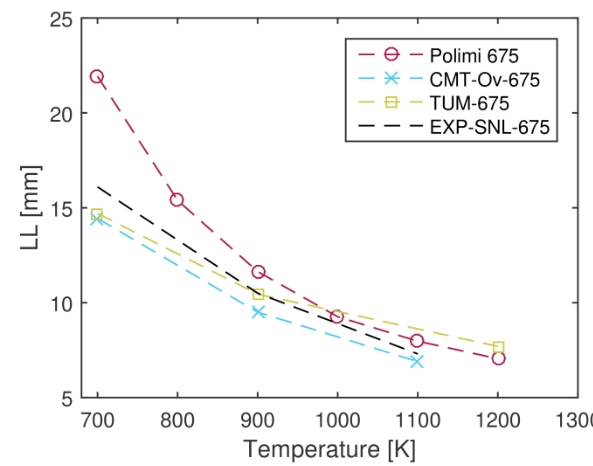
- Parametric Variation: Ambient Density
  - Very close for both the institutions
  - Slight impact for TUM
- Vapor phase penetration is well predicted for all the param. variations applied

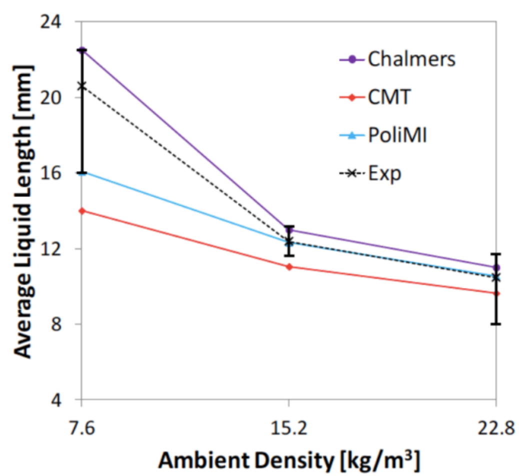


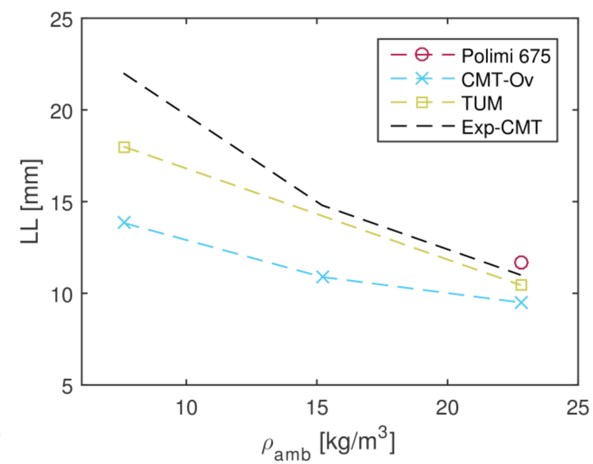
Spray A – Model Validation

- Liquid length:
  - Polimi over predict the effect of Tamb
  - Resonably good agreement for TUM and CMT
  - Effect of ambient density is under predicted



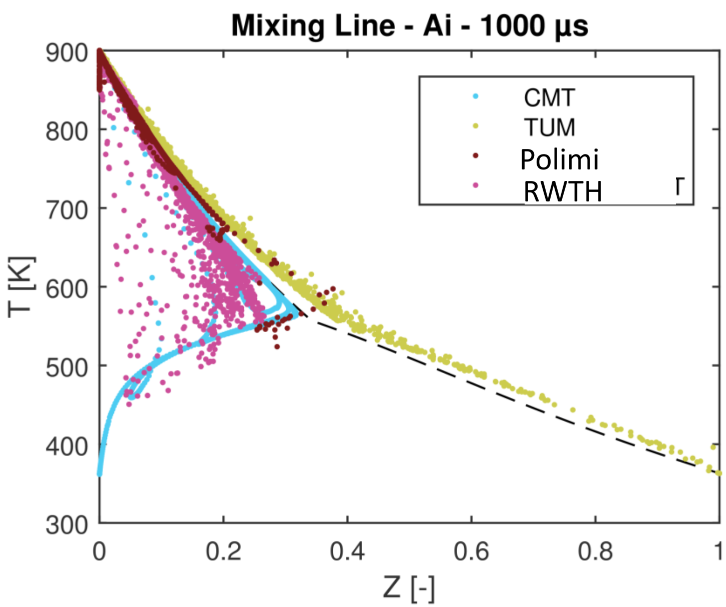


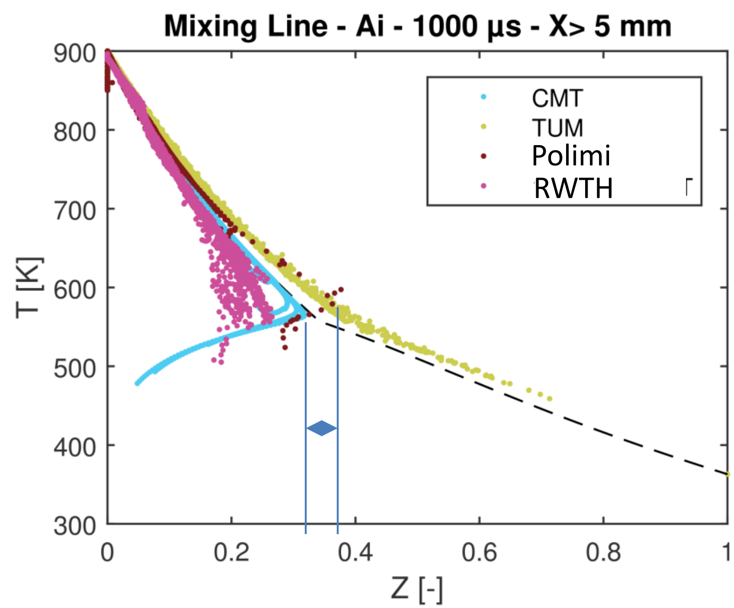




Mixing Line

- 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

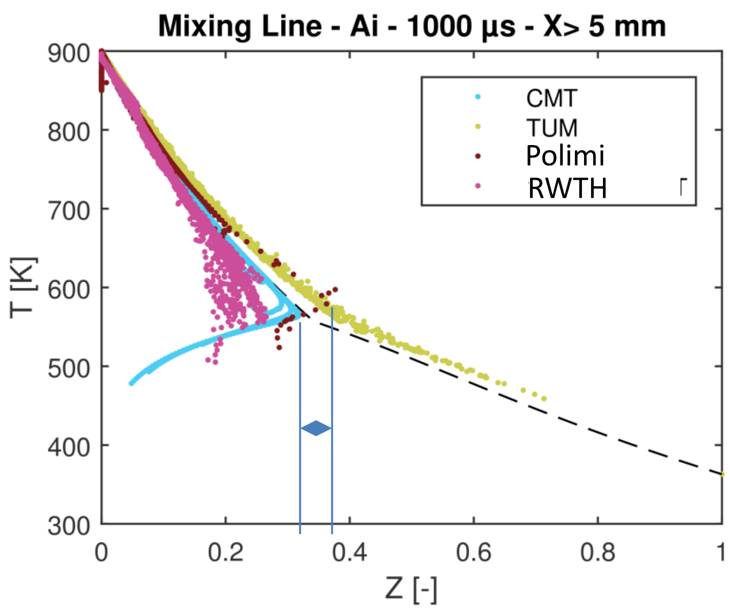


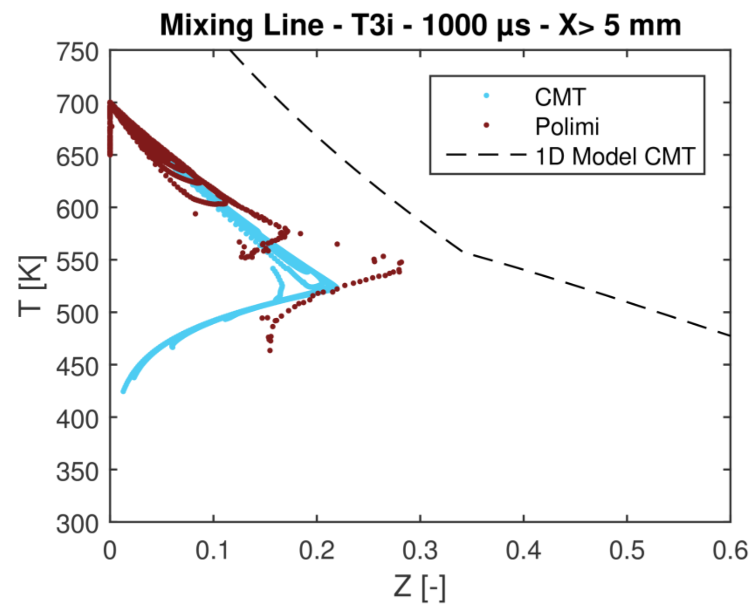


- Some minor difference can be observed between the models
  - TUM and Polimi “knee” appears at richer mixture fractions (0.36 vs 0.39)
  - The impact on the liquid length is significant (approx. 1mm)

Mixing Line

- 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

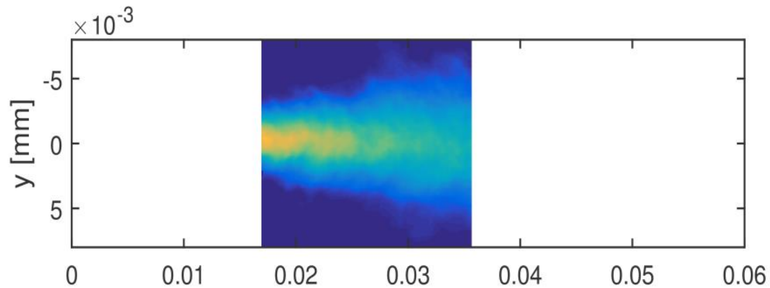




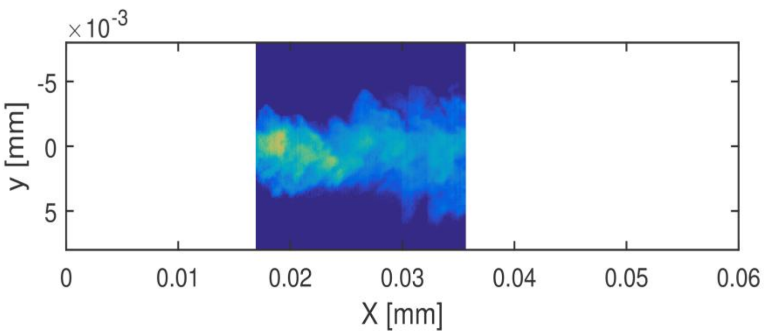
- The mixing line plot indicates that these differences become critical at 700 K
  - At reference conditionsThe impact on the liquid length is significant (approx. 1mm)
  - At 700 K is considerably bigger, and this could be the case of the different LL obtained

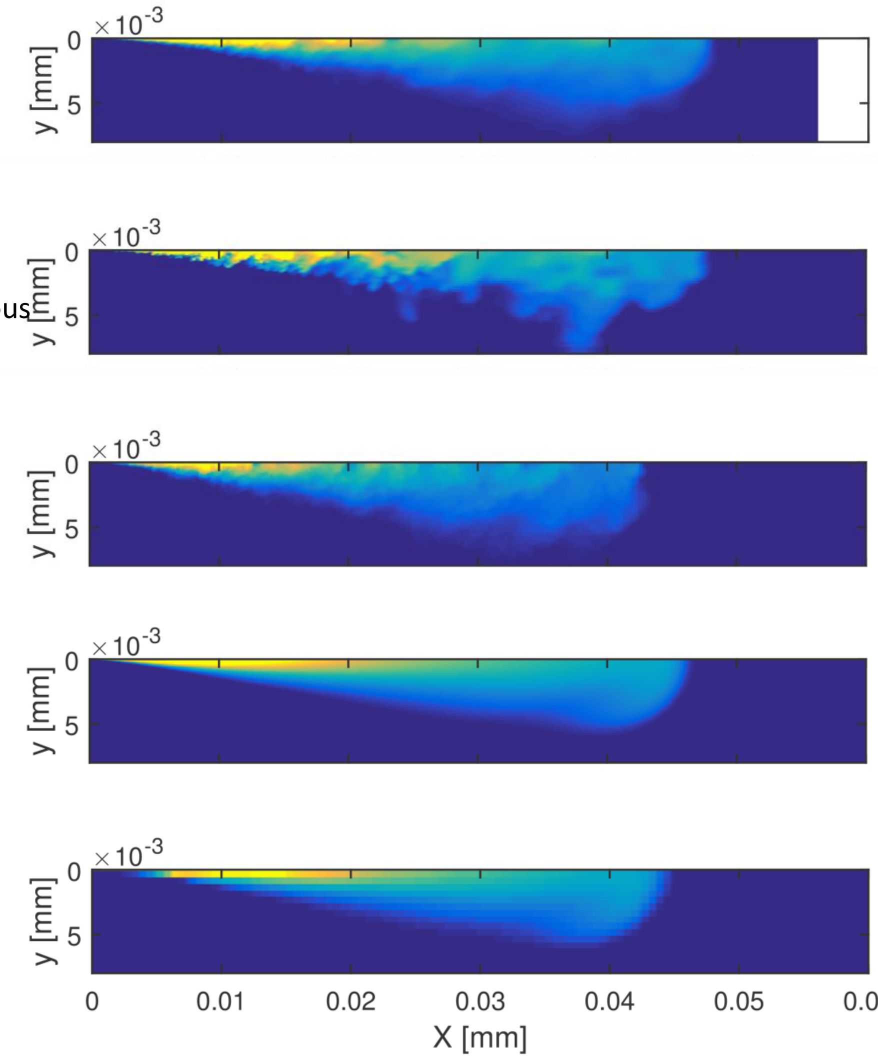
- Mixing field at 1000 us ASOI

SNL new Rayleigh data - avg



SNL new Rayleigh data - instant





TUM averaged

TUM Instantaneous

RWTH

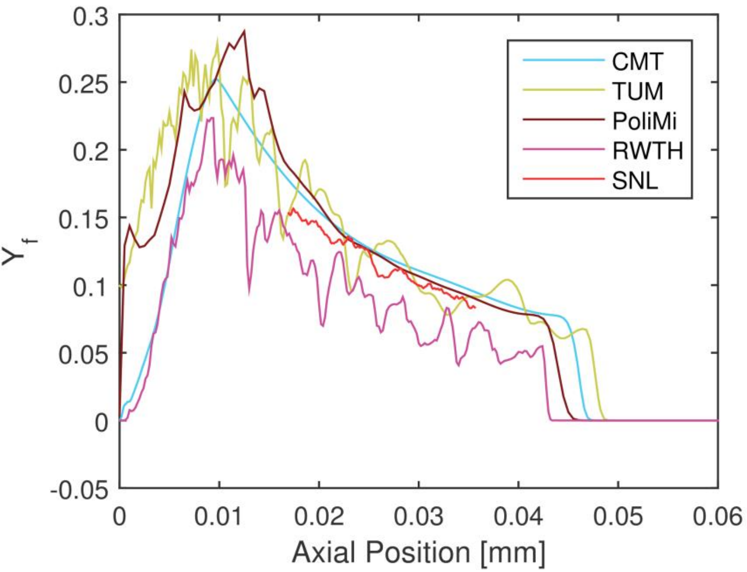
CMT

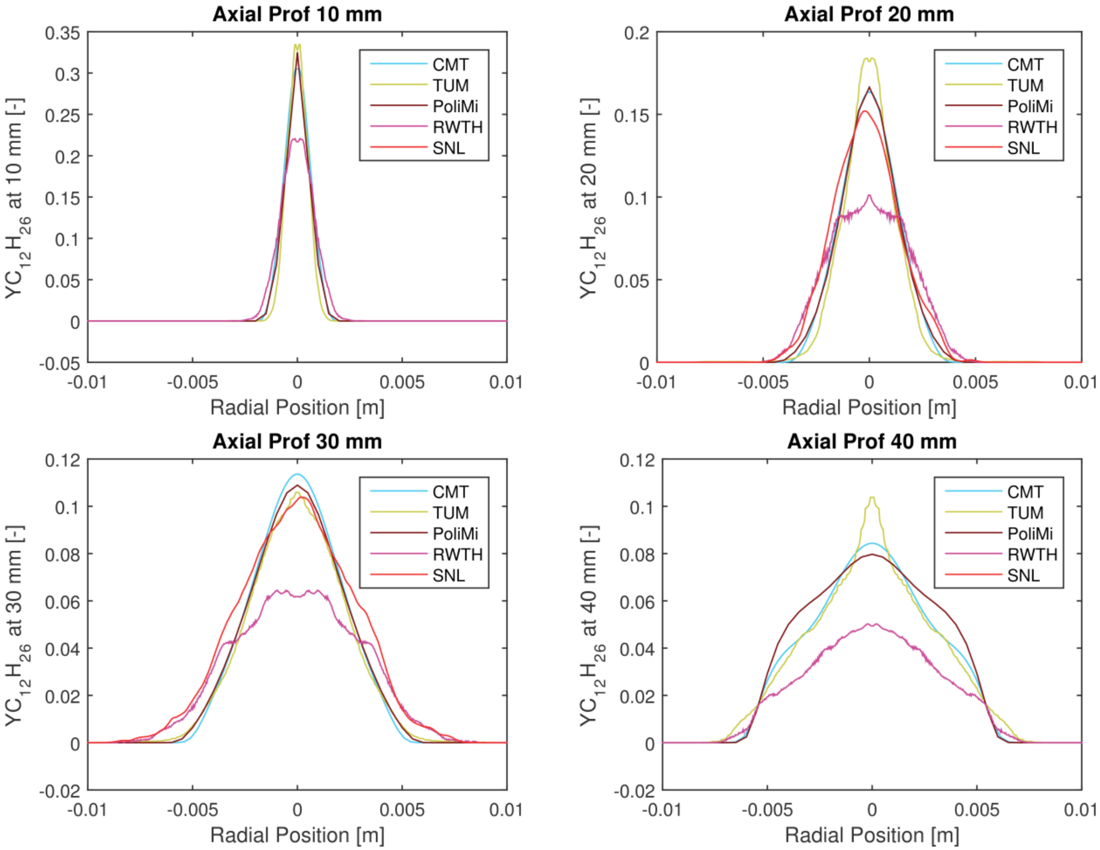
Polimi

Mixture fraction axial profile

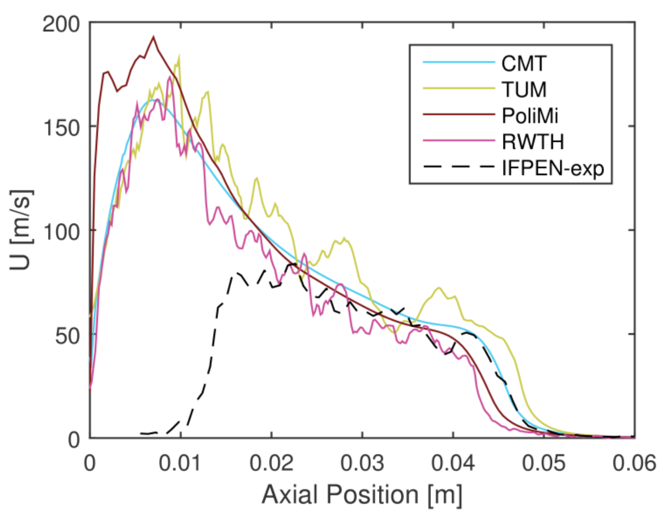
- For consistency axial profile has been calculated averaging 1 mm around the axis
  - Difference in data sampling

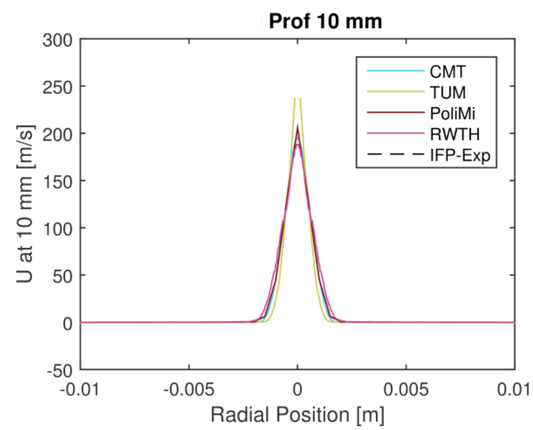
- Global consistency after 10 mm
  - RWTH is consistently lower

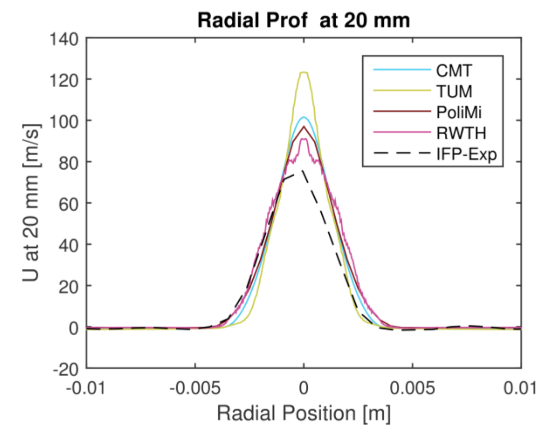


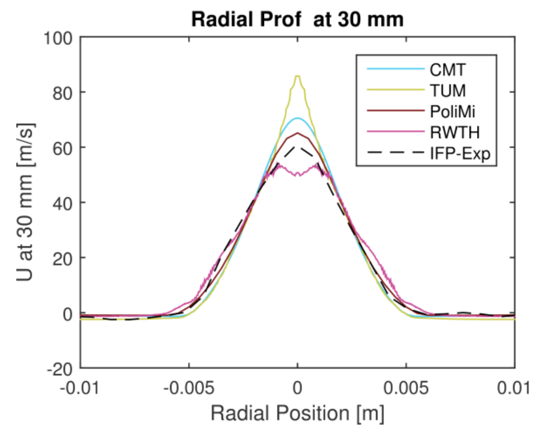


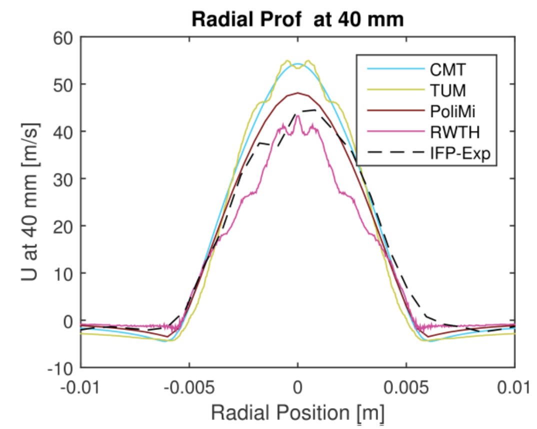
- More consistency can be found on the Radial profiles
  - TUM has narrower profile and higher central velocity





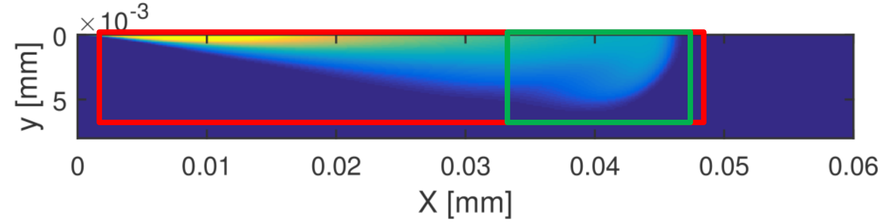


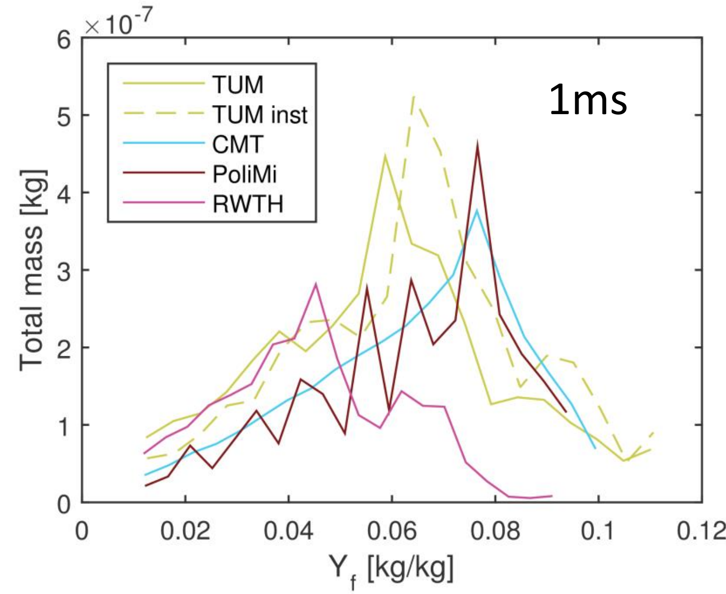


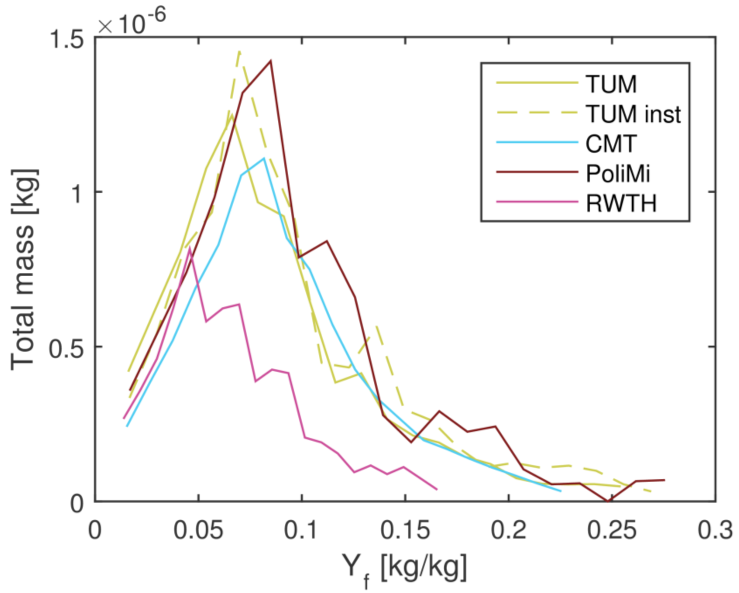


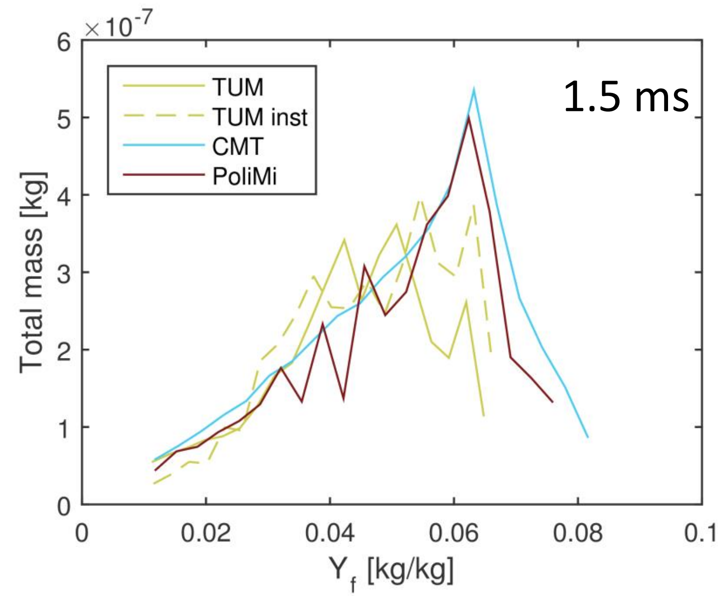
Mixture fraction distribution

- Global Equivalence ratio histogram
  - TUM instantaneous is very close to the averaged
  - RTWH peak is at lower mixture fraction



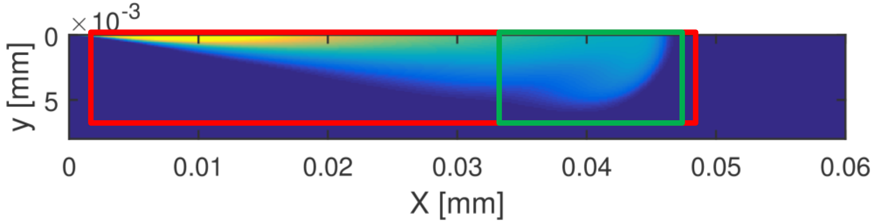


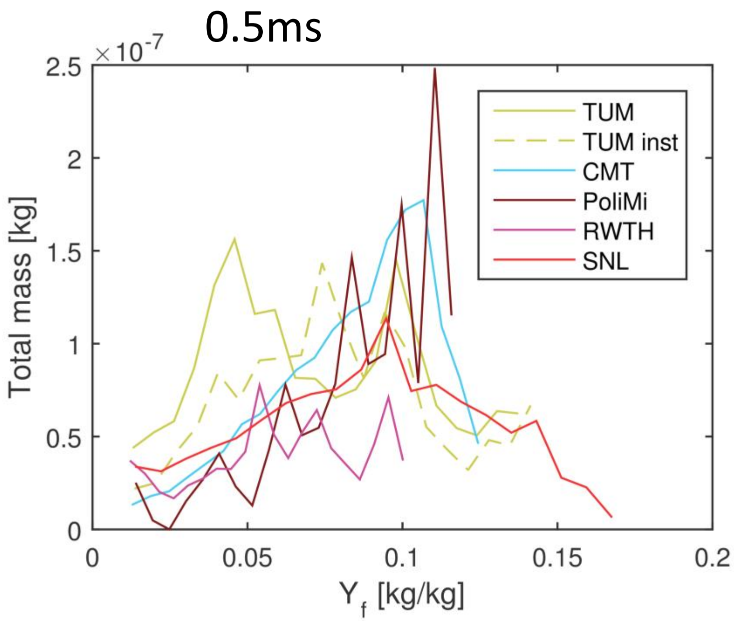




Mixture fraction distribution

- ➢ At 0.5 ms there are experimental data!





- ➢ The impact of the LES averaging moves to the left the Yf 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 distribustions
  - More investigation should be done for the end of the injection
  - Accurate prediction is mandatory for an accurate prediction of ignition

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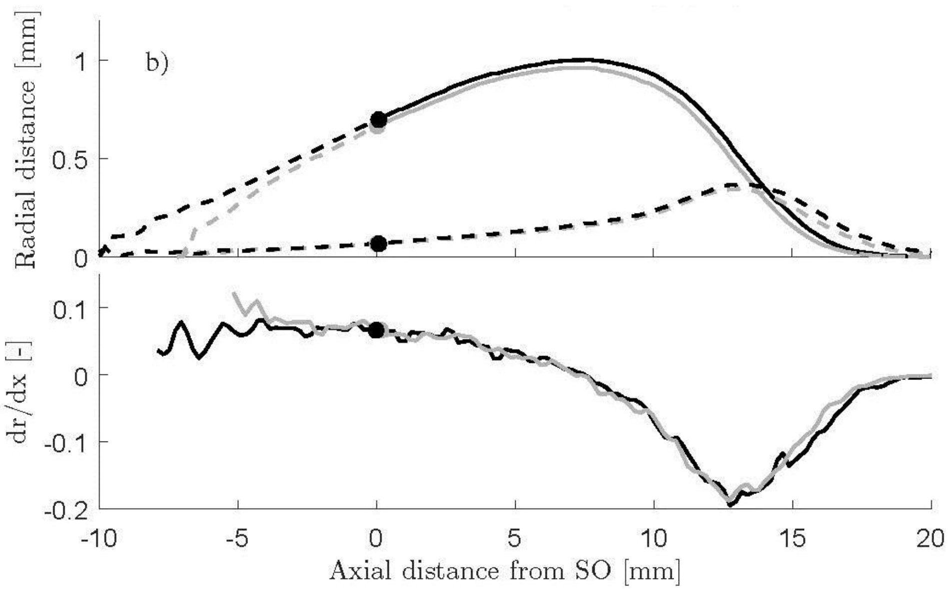
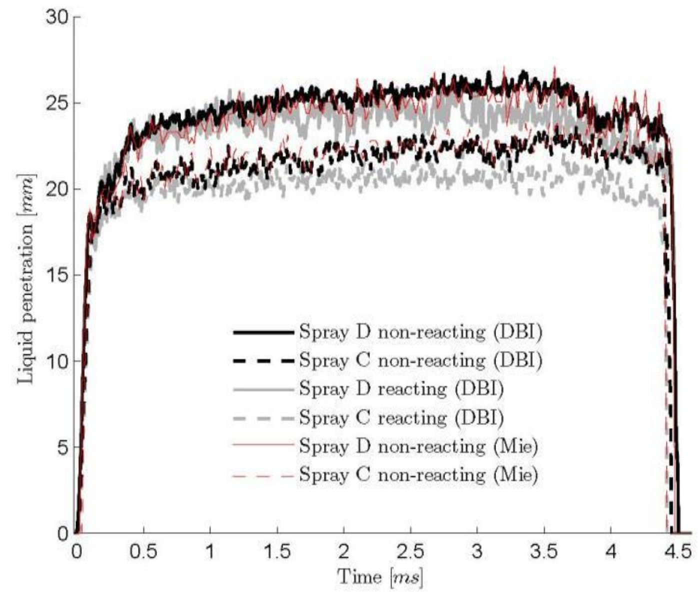
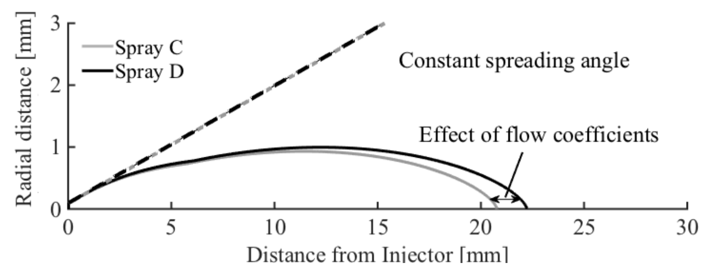
- Spray A
  - High Speed Rayleigh – fuel mass fraction
  - Model Validation / Consolidation
- Spray C/D
  - What do we know?
  - New experimental evidencies
  - CFD validation
- Conclusions and outlooks

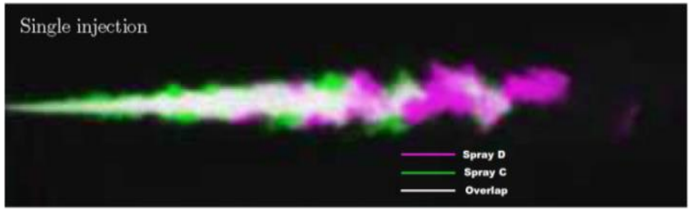
Spray C - D

- 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
-



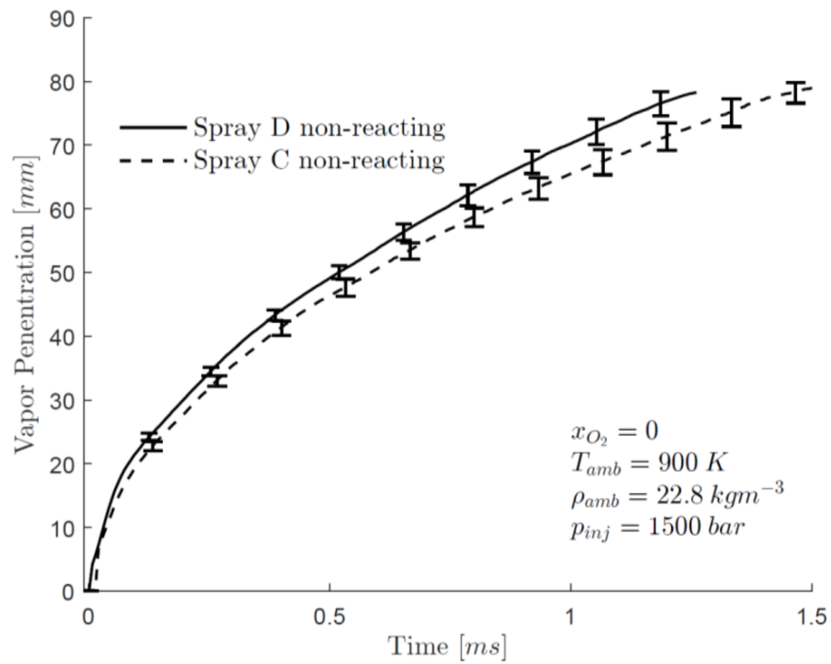


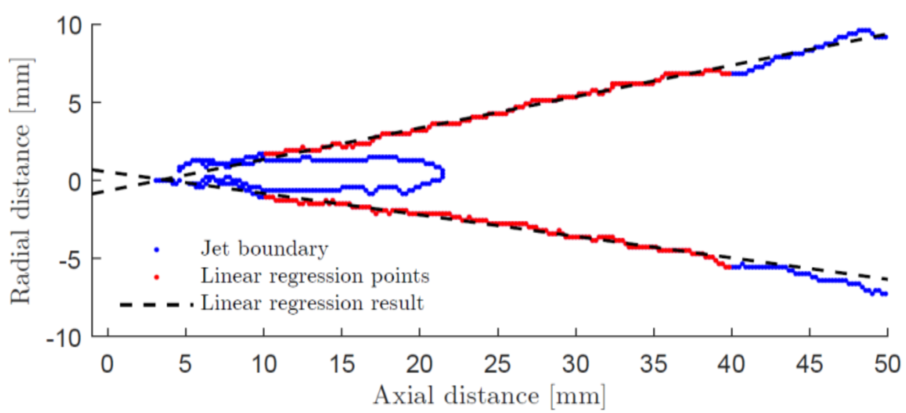


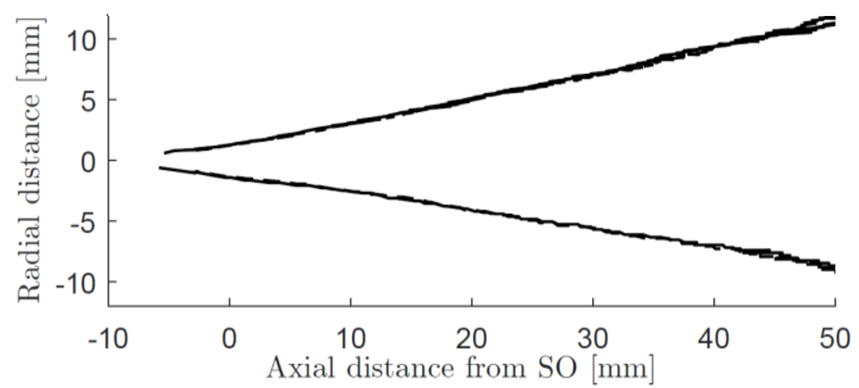


Spray C - D

- 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





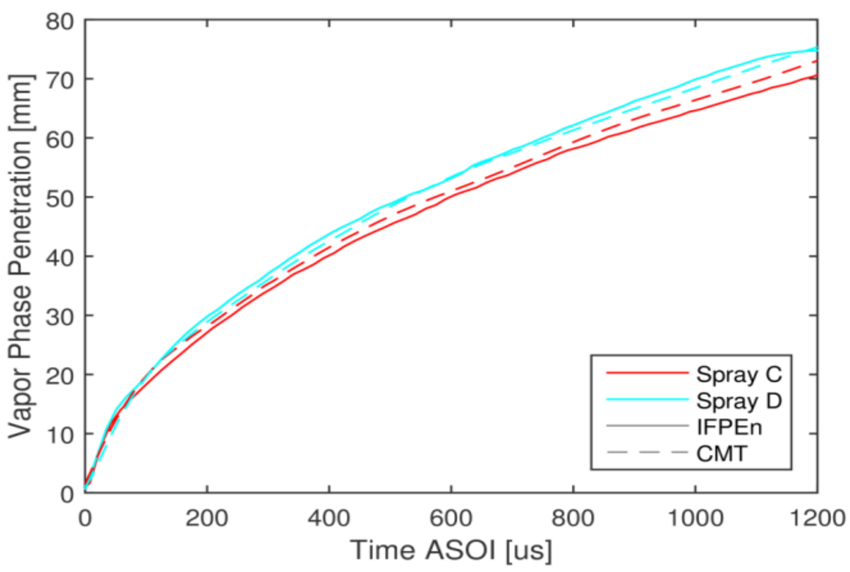


Spray C - D

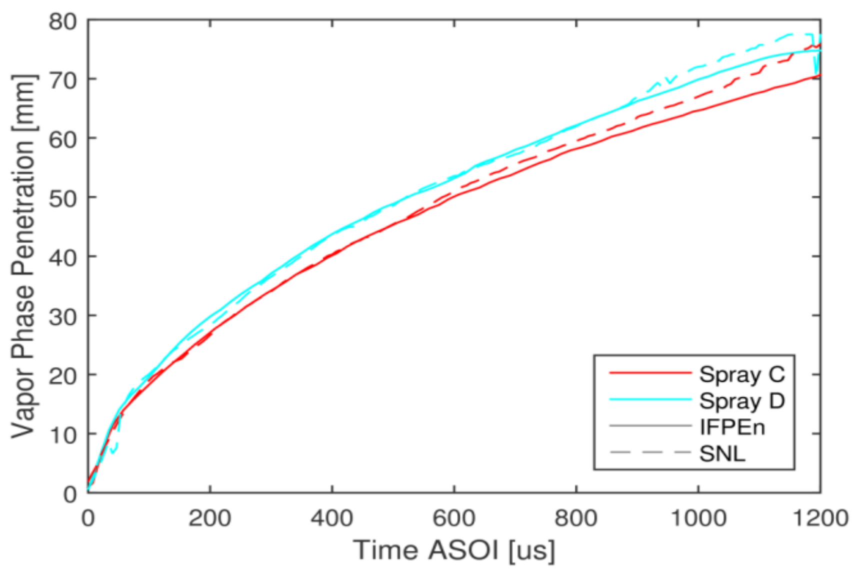
- Consistently is observed a difference among spray C and D Vap. Penetration
- Reasonable agreement among institutions

	Spray C	Spray D
IFPEn	003	135
CMT	003	103
SNL	037	134

Ifpen VS CMT



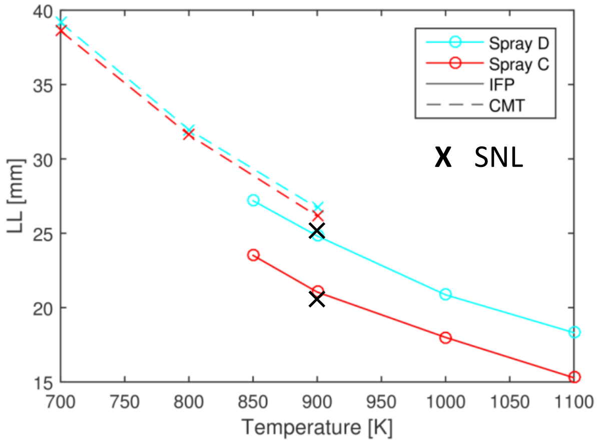
IFPEN vs SNL



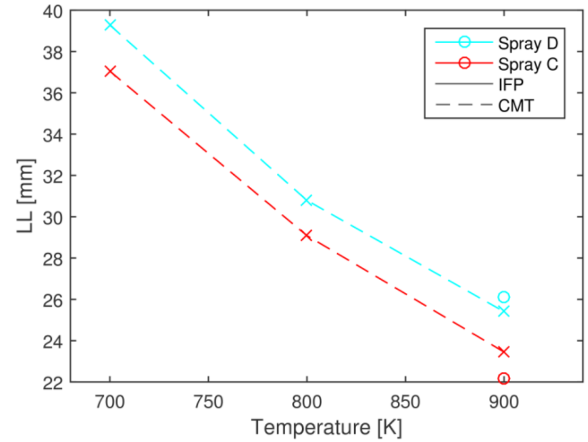
Spray C - D

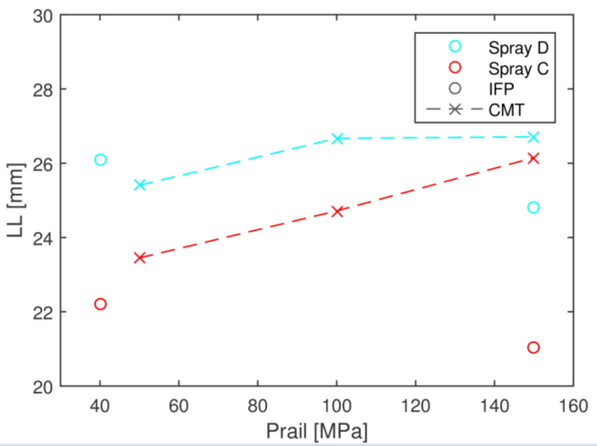
- No agreement among liquid phase penetration (CMT and IFPEn data available)

P inj150 MPa



P inj 50 Mpa (IFPEN 40MPa)



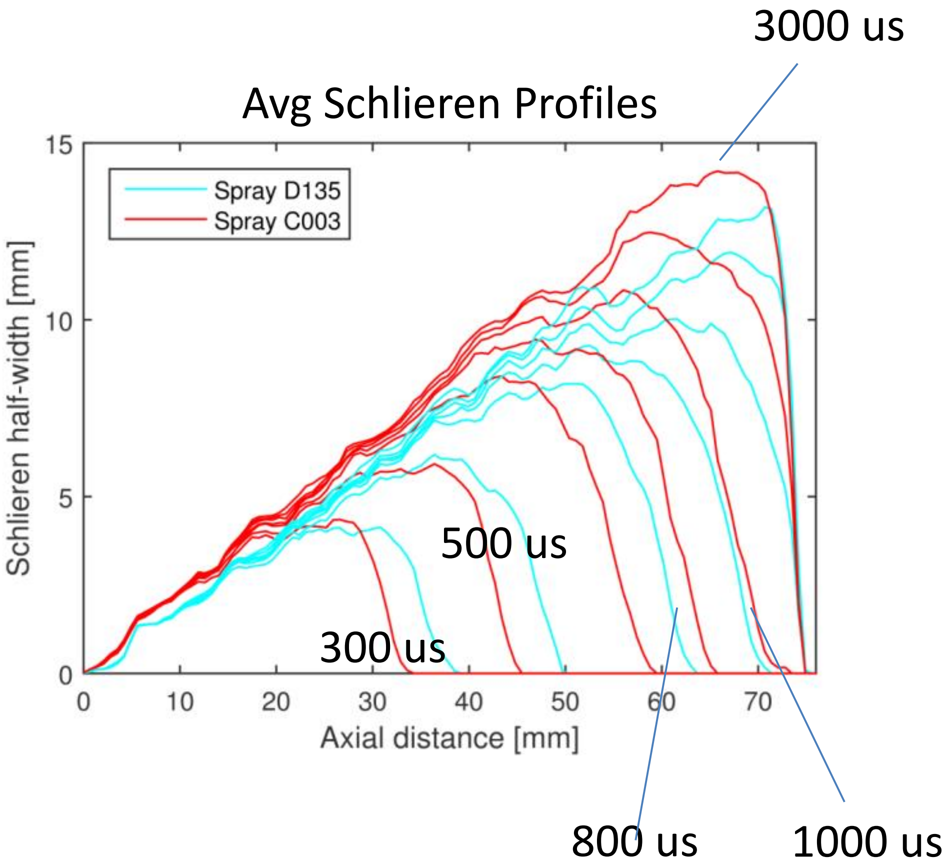


- At high P inj no difference could be observed for CMT data between Spray C/D
  - Strong cavitation might happen also for spray D injector

Spray C - D

IFPEN Schlieren experiments

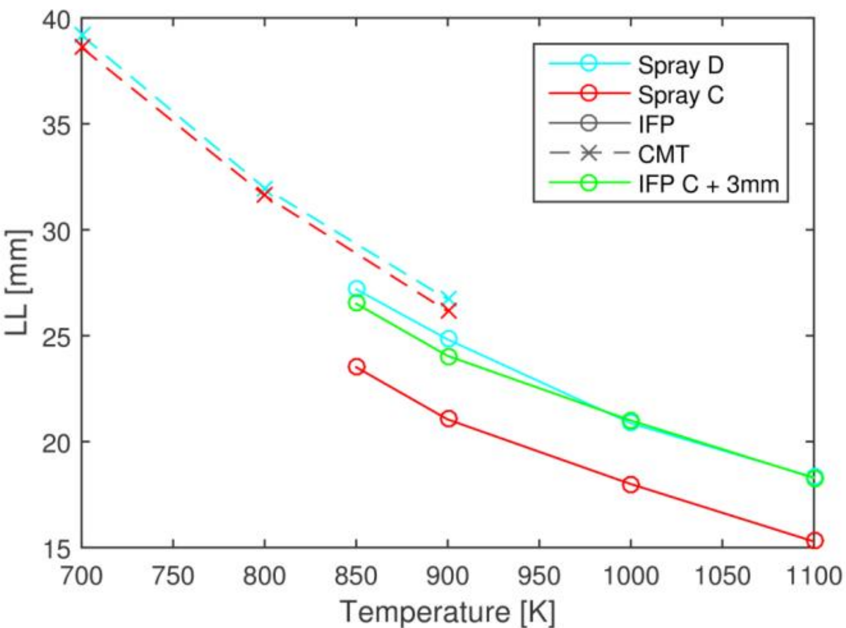
- Schlieren avg. radial profiles



IFPEN Schlieren experiments

- Schlieren avg. radial profiles

3000 us

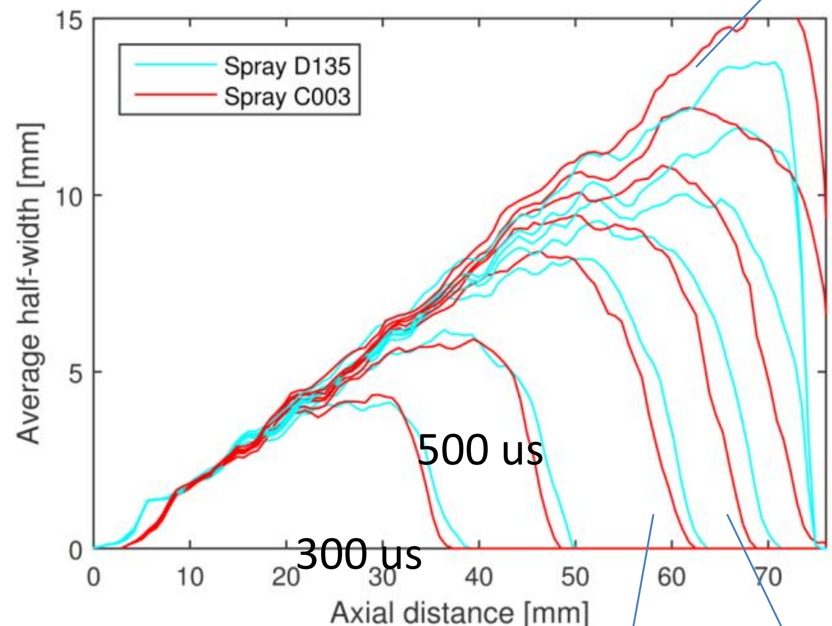


800 us

1000 us

Spray C translaed 3mm downstream

3000 us



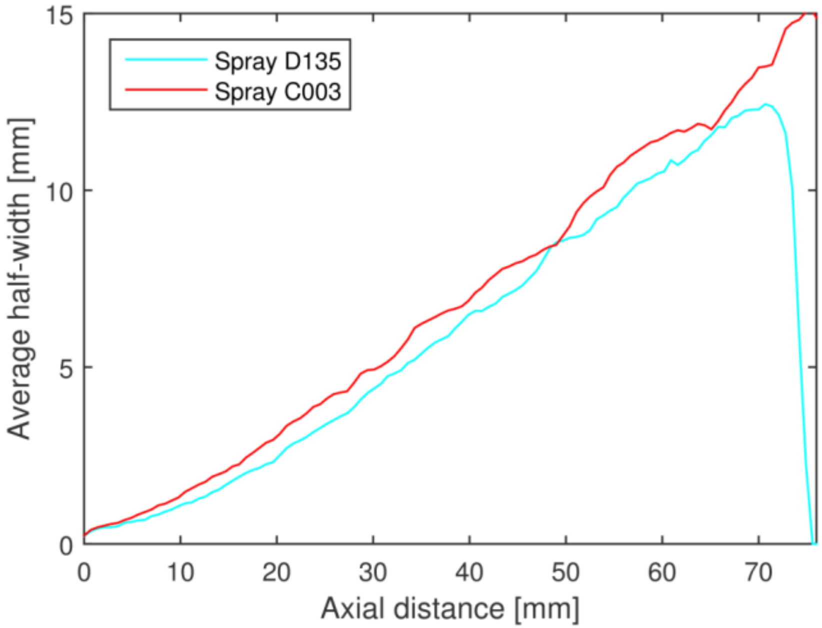
800 us

1000 us

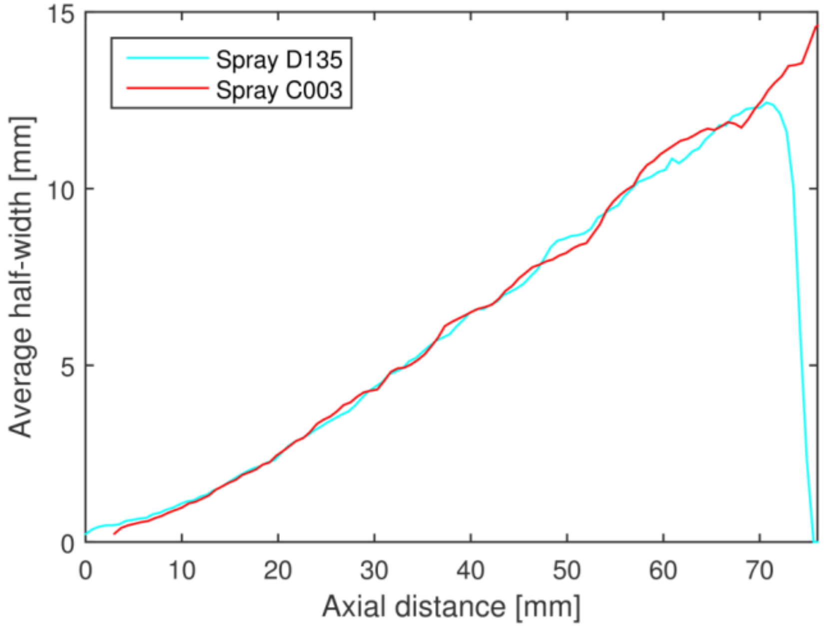
SNL Schlieren experiments

➢ Schlieren avg. radial profiles

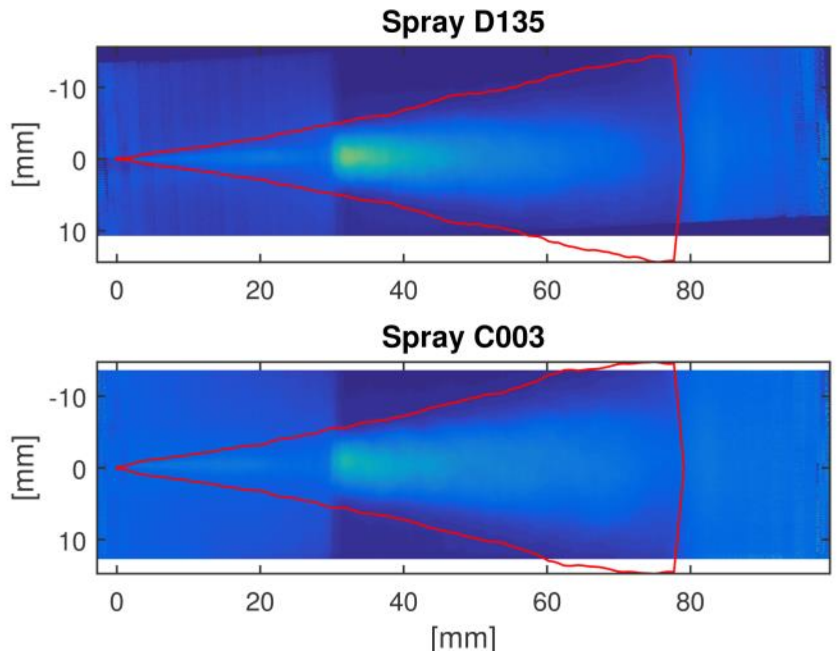
Avg Schlieren Profiles

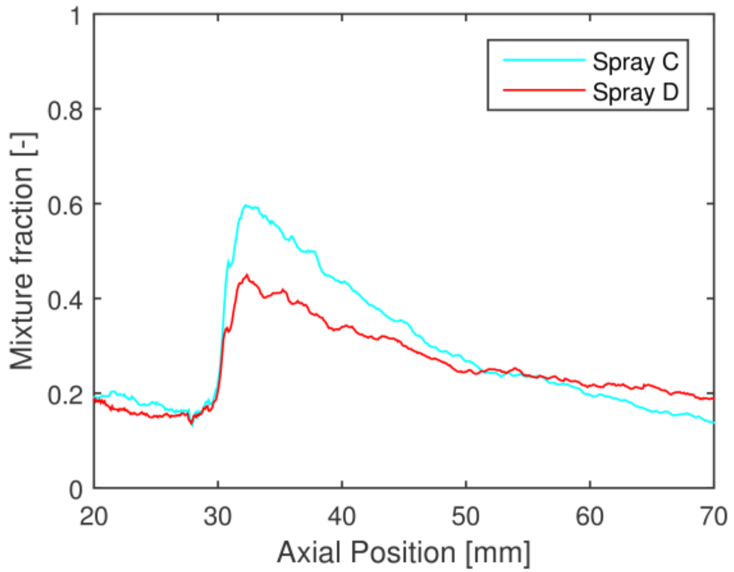


Spray C translaed 3mm downstream

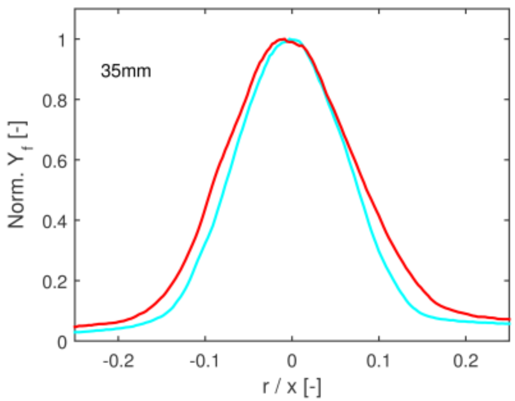


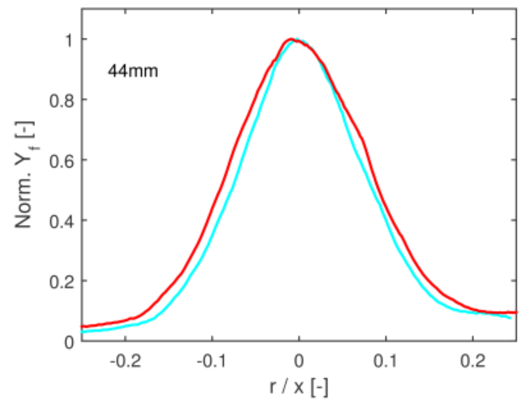
- LIF measurements IFPEN
  - DFB tracer calibrated (sensitivity to T and O2)
  - Unfortunately the analysis is still ongoing

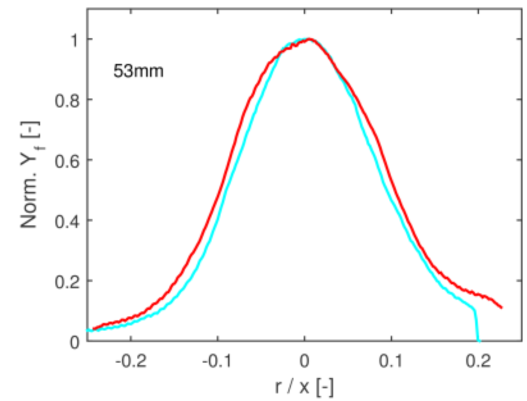




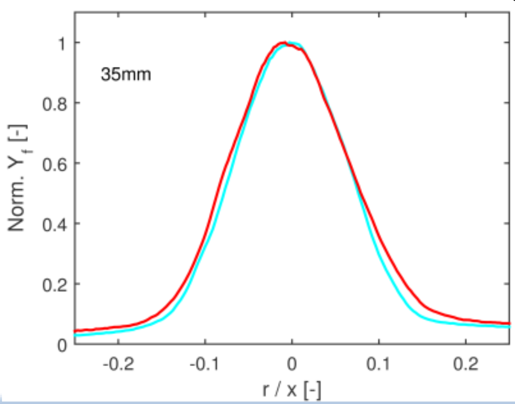
- The comparison among Spray C-D radial profiles can help in understanding the differences in the mixing field?
  - Not for the moment, more analysis is needed

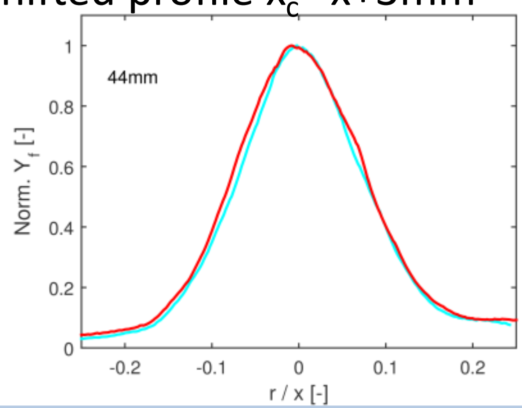


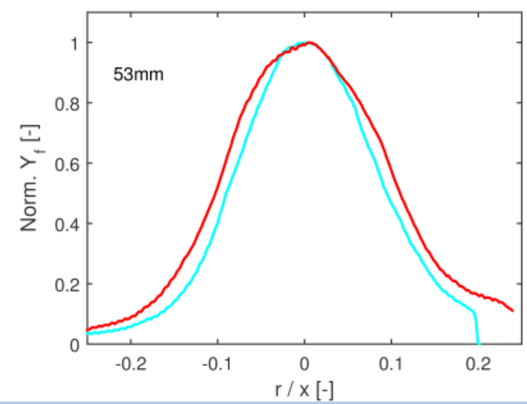




Shifted profile $x_c = x + 3mm$







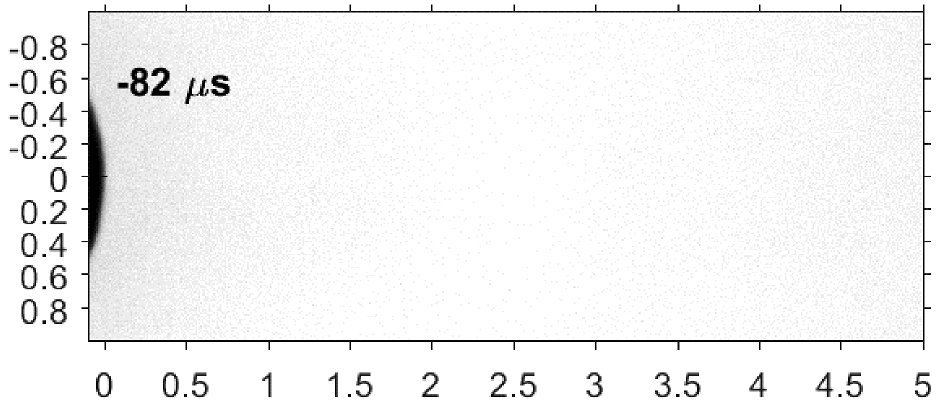
Is the mixture fraction (liquid and vapor) width of Spray D possibly larger than Spray C at high fuel T?

440 K, 22.8 kg/m^3, 0% O_2

- Perform experiments at “non-vaporizing” conditions at low ambient temperature such that liquid is found at all mixture fraction (i.e. Z_sat is near 0)

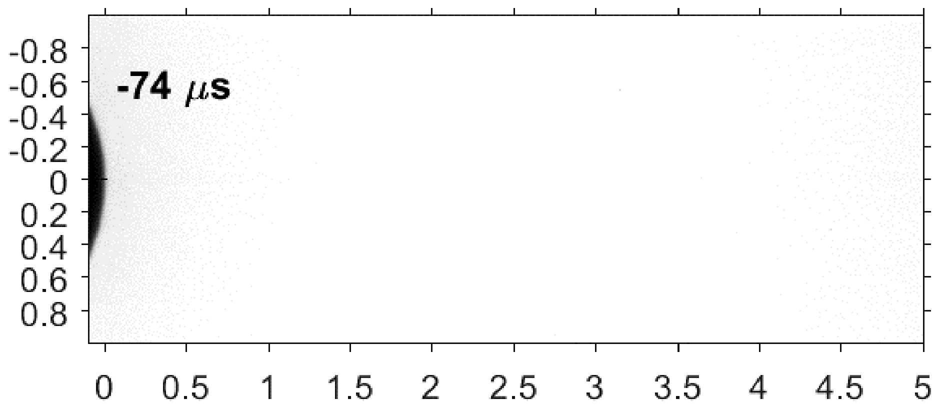
Spray C

Wide/turbulent
Liquid extinction persists at edge of spray

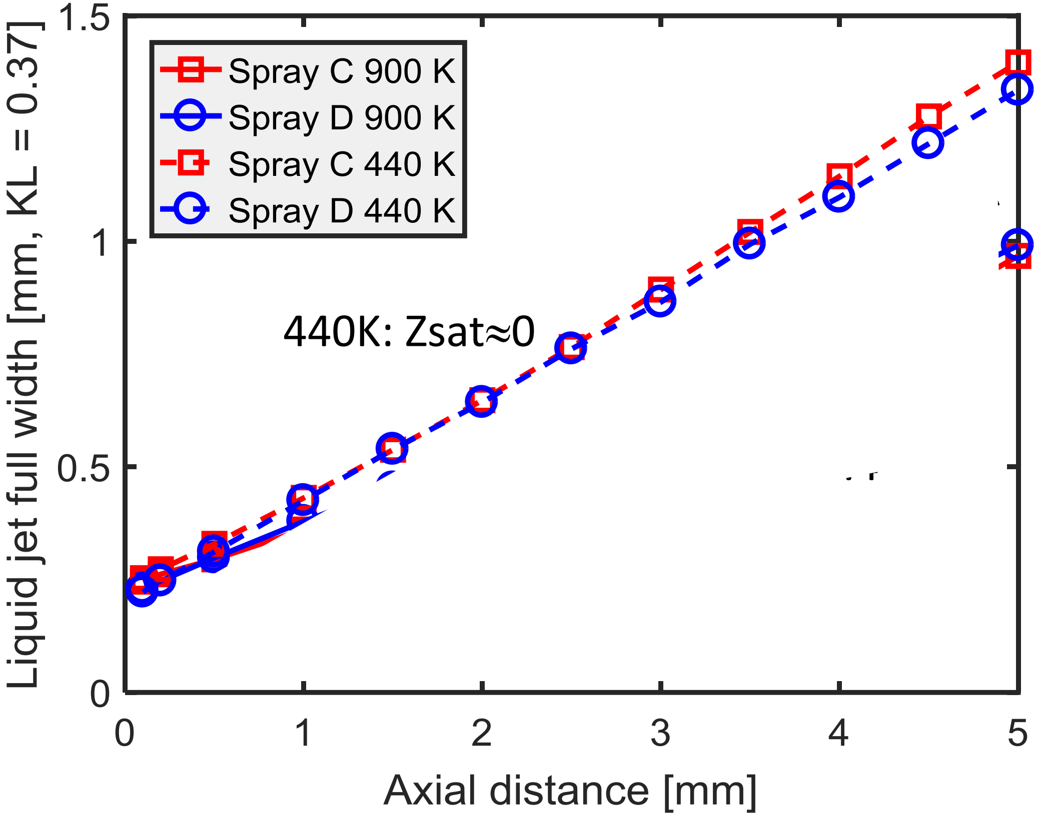


Spray D

Similar to Spray C, but looks as if there are fewer large intermittent structures



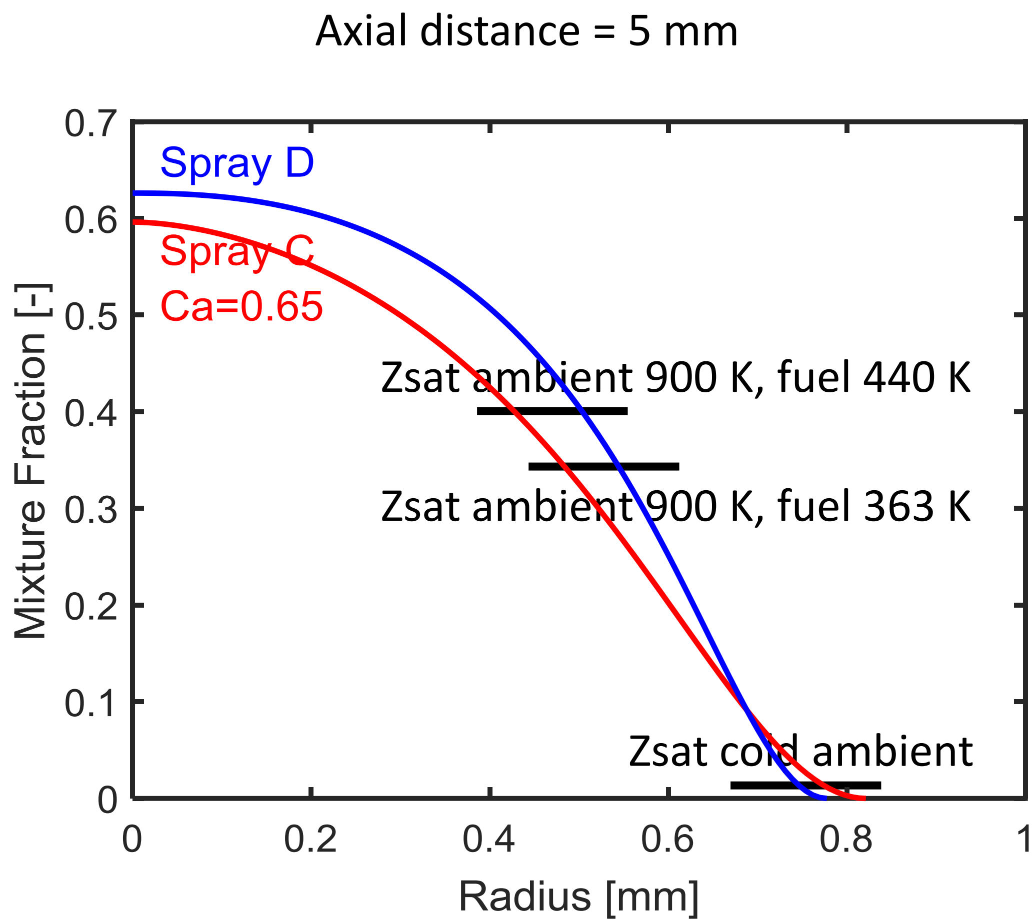
Comparison of hot/cold ambient shows significant differences in liquid radial width



- 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:

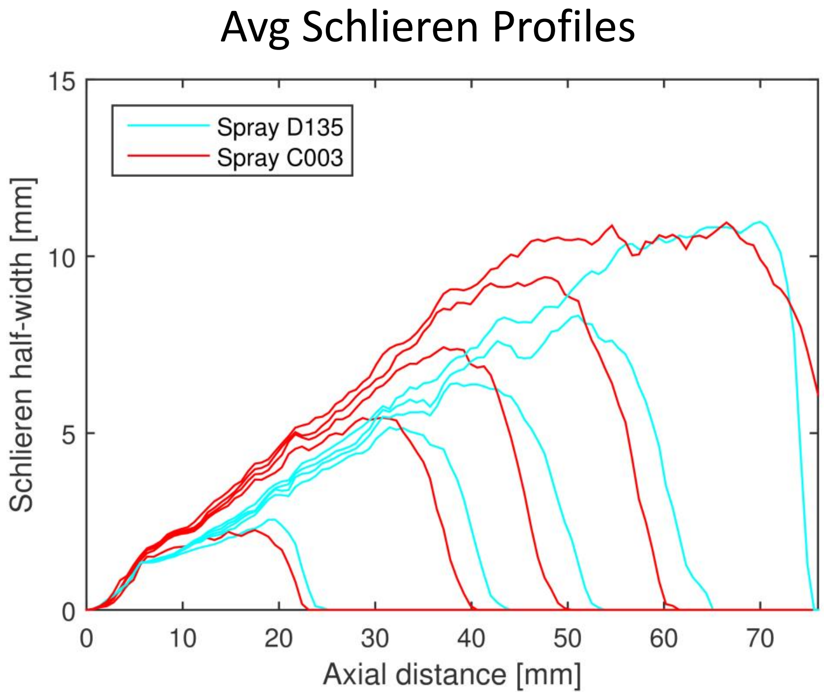
- Sandia and IFPEN Liquid length measurements
- Sandia and IFPEN Schlieren half-width profiles (data CMT not available)
- IFPEN LIF calibrated measurement

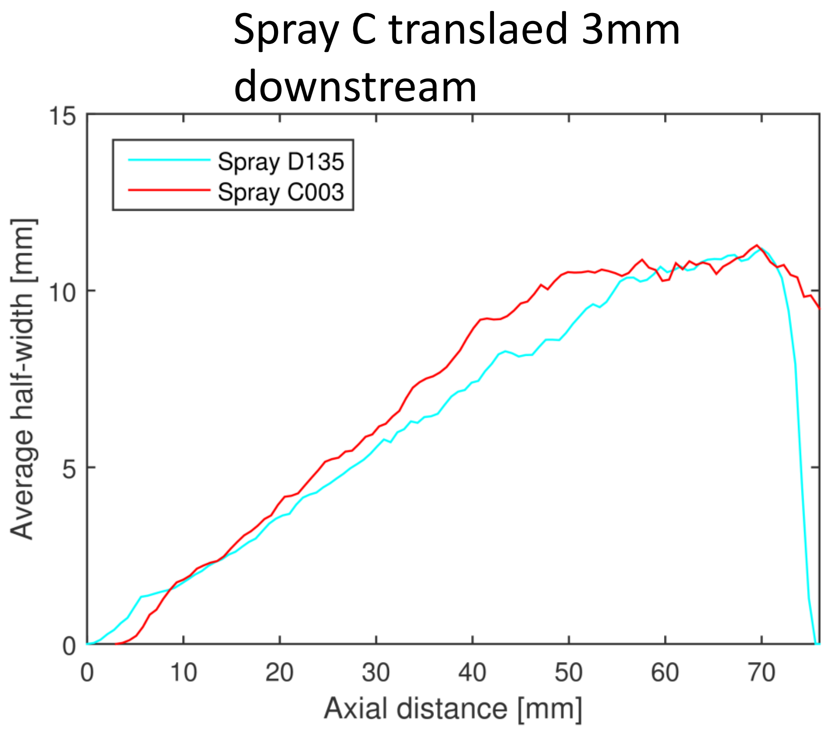
Information about near field behavior

- Long distance microscopy (SNL)

Spray C-D

- 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

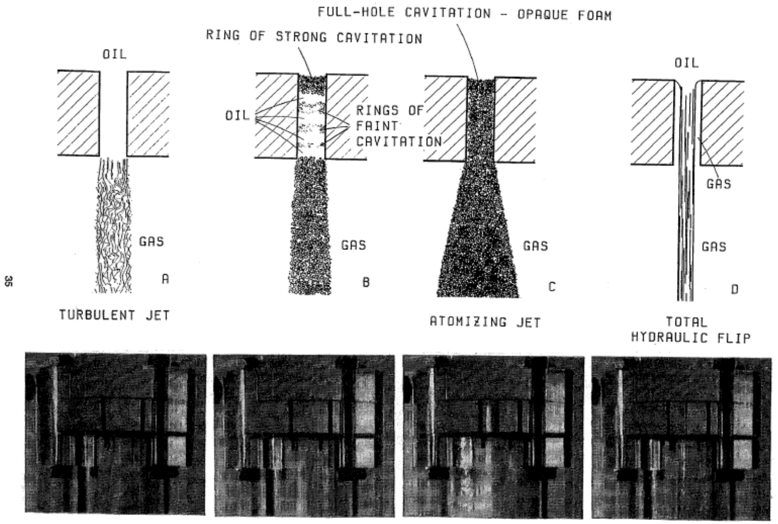


FIG 5 DEVELOPMENT OF CAVITATION AND TOTAL HYDRAULIC FLIP FOR FLOW INTO GAS

Battistoni et al. 2016-01-0860

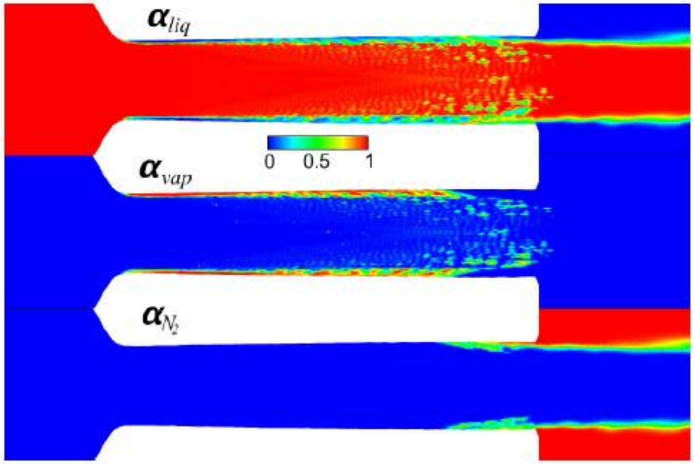
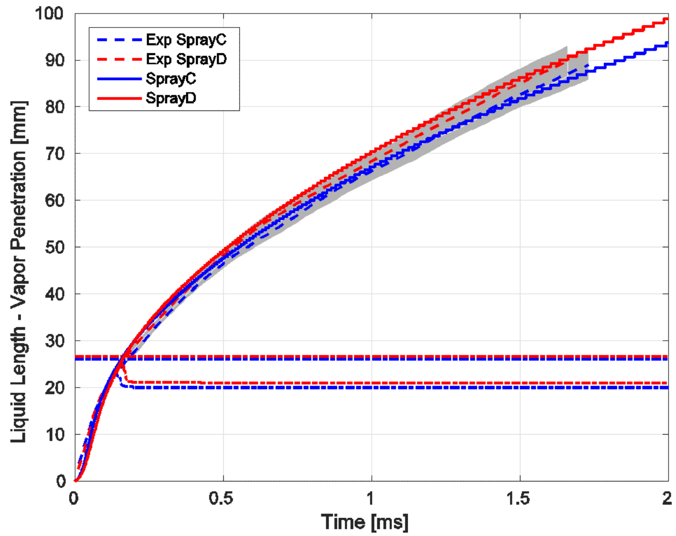
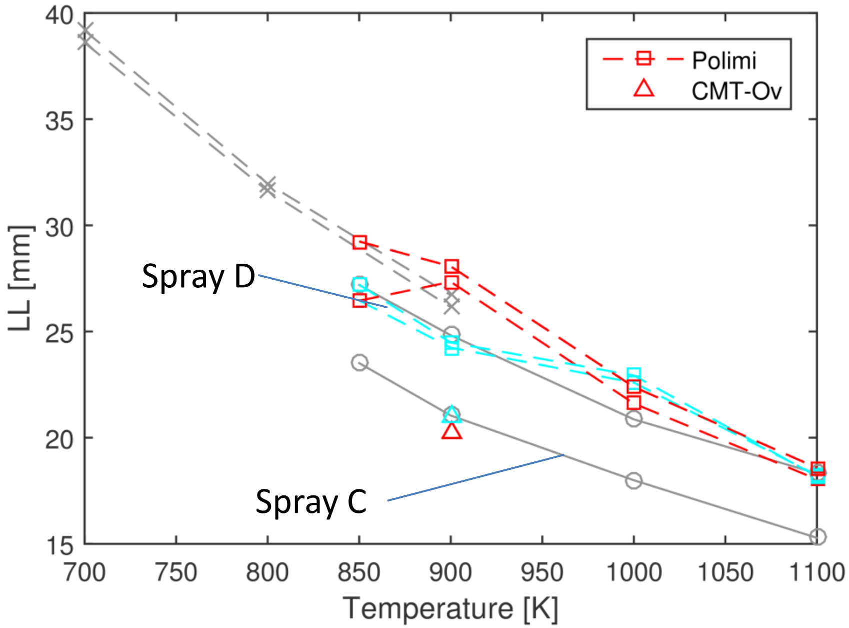


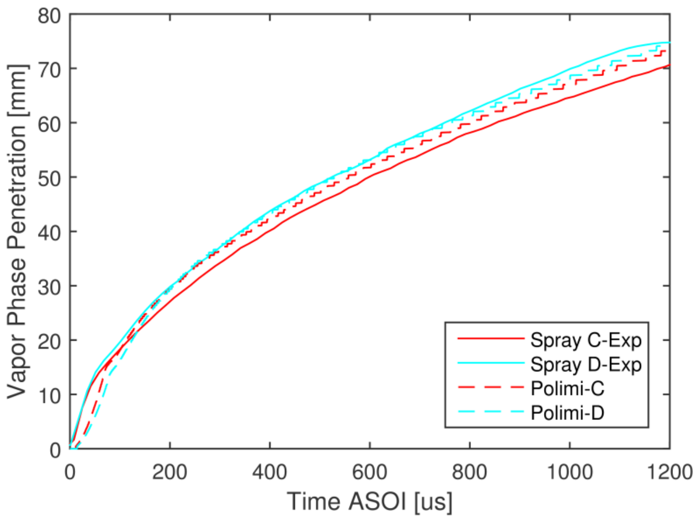
Figure 17. Close-up views of instantaneous cavitation interactions inside the nozzle. α_x is the volume fraction and the x denotes liquid fuel, fuel vapor and ambient N_2.

Index

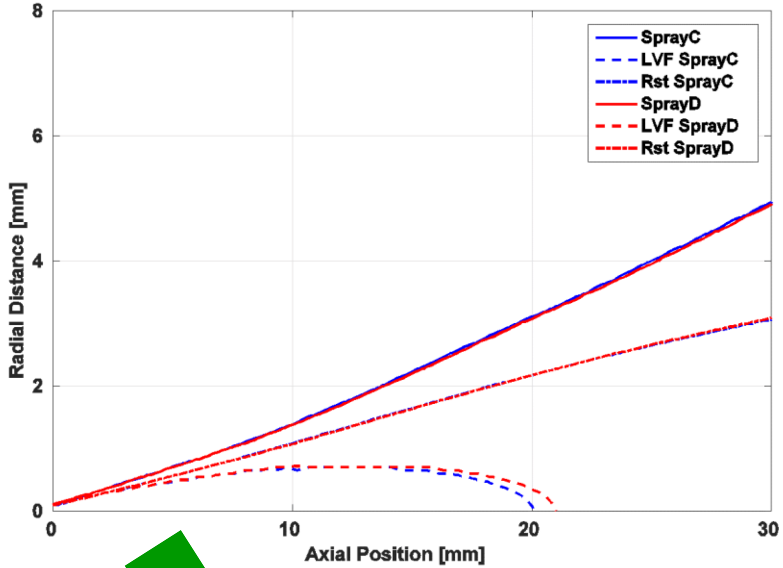
Polimi and CMT-Ov sent their first results

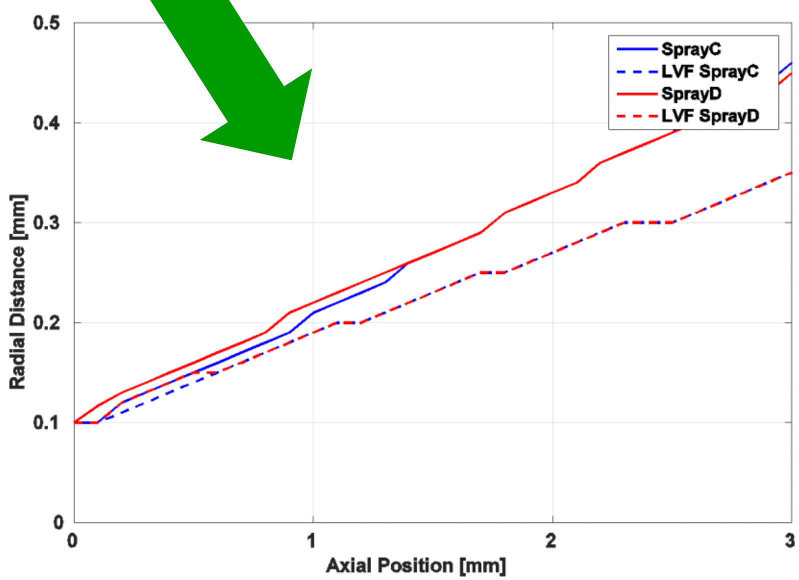




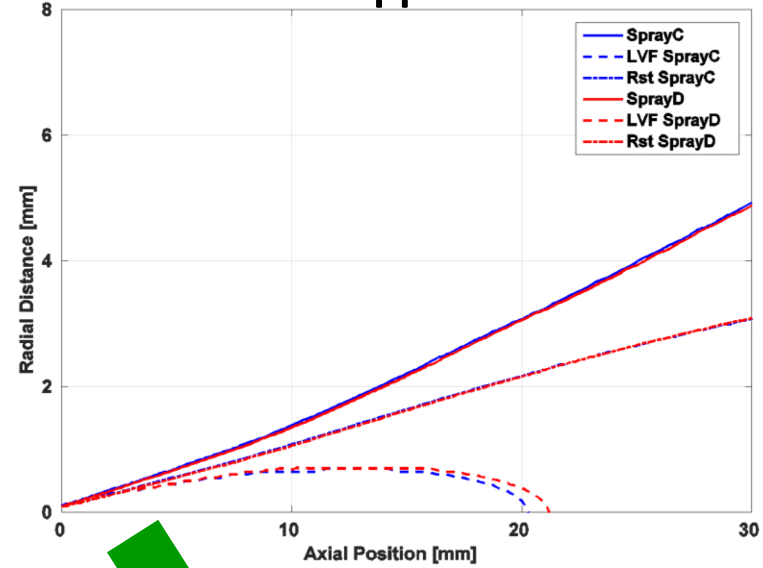


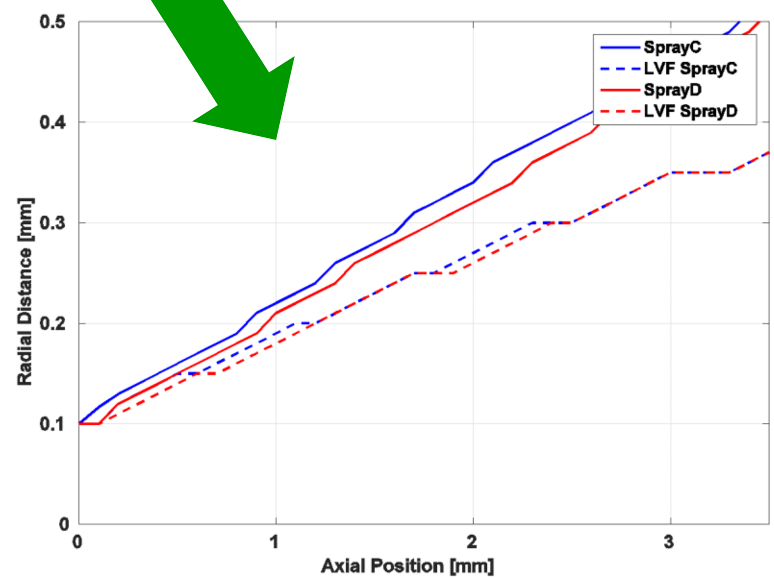
ROI + Deff



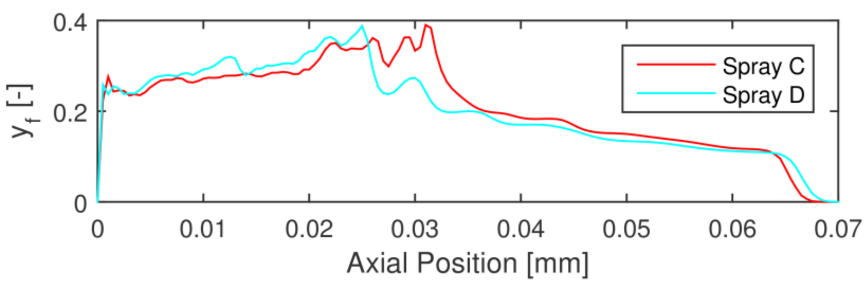


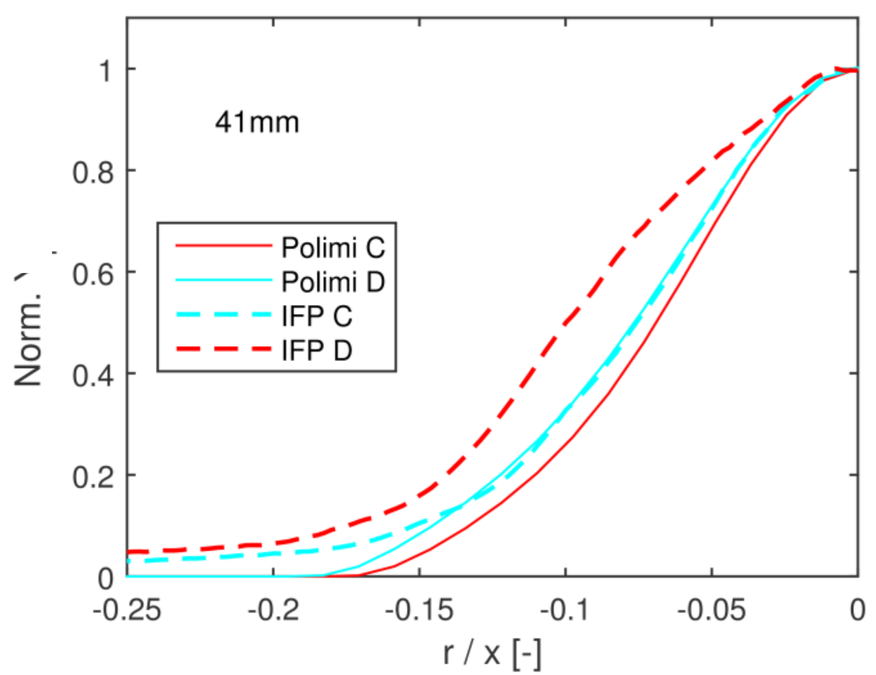
Mapped BC





- 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

Topic 3: (draft) roadmap (research directions)

- How does atomization influences 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

Topic 3: (draft) roadmap (research directions)

- 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