Engine Combustion Network

Topic 1.3: Evaporative spray and parametric studies

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Summary

1) Motivations
2) Experiments
3) Validation of numerical models
4) Conclusions

Motivations

- Fuel air mixing governs Diesel combustion process, hence understanding and properly describing the related phenomena is very important both on numerical and experimental side.

- Diesel engines operate in a wide range of speed and loads and also new combustion modes are under investigation:
  - Injection pressure variation: 500 – 2000 bar
  - Ambient conditions: 700 – 1100 K, 40 – 100 bar

- Understanding spray vaporization, mixing with air and effects of operating conditions is very important.

Objectives

⇨ Define a set of operating conditions to build a database of experiments for Spray-A and Spray-B configuration.

Experiments

- Understanding results repeatability in different institutions.
- Understanding influence of different nozzle serial numbers on spray evolution (Spray A and Spray B).

Simulation

- To compare "ready to be used in engines" approaches (Eulerian-Lagrangian, Eulerian-Eulerian, …) and, within the same approach, different sub-models.
- How different models reproduce the effects of different operating conditions on spray evolution?

Test matrix

- On the basis of the objectives of the session, a test matrix was built to carry out both experiments and simulations.

  - Spray-A: large number of points (11) to be tested and simulated.

  - Spray-B: let's start and see what happens (4 points)

  - One fuel: dodecane

Test matrix – Spray A

Priority level	T [K]	density [kg/m^3]	Pressure [MPa]	Fuel	T $_{fuel}$ [K]	Injection duration [ms]
1	900	22.8	150	n-dodecane	363	≥1.5
2	900	22.8	100	n-dodecane	363	≥1.5
3	900	22.8	50	n-dodecane	363	≥1.5
4	900	7.6	150	n-dodecane	363	≥1.5
5	900	15.2	150	n-dodecane	363	≥1.5
6	700	22.8	150	n-dodecane	363	≥1.5
7	1000	22.8	150	n-dodecane	363	≥1.5
8	1100	22.8	150	n-dodecane	363	≥1.5
9	700	22.8	50	n-dodecane	363	≥1.5
10	440	22.8	150	n-dodecane	363	≥1.5
11	303	22.8	150	n-dodecane	363	≥1.5

Test matrix – Spray A

Priority level	T [K]	density [kg/m^3]	Pressure [MPa]	Fuel	T_{fuel} [K]	Injection duration [ms]
1	**900**	**22.8**	**150**	**n-dodecane**	**363**	**≥1.5**
2	900	22.8	100	n-dodecane	363	≥1.5
				n-dodecane	363	≥1.5
				n-dodecane	363	≥1.5
				n-dodecane	363	≥1.5
				n-dodecane	363	≥1.5
7	1000	22.8	150	n-dodecane	363	≥1.5
8	1100	22.8	150	n-dodecane	363	≥1.5
9	700	22.8	50	n-dodecane	363	≥1.5
10	440	22.8	150	n-dodecane	363	≥1.5
11	303	22.8	150	n-dodecane	363	≥1.5

Baseline condition

Widely tested by all institutions

Test matrix – Spray A

	T [K]	density [kg/m³]	Pressure [MPa]	Fuel	T fuel [K]	Injection duration [ms]
1	900	22.8	**150**	n-dodecane	363	≥1.5
2	900	22.8	**100**	n-dodecane	363	≥1.5
3	900	22.8	**50**	n-dodecane	363	≥1.5
4	900	7.6	150	n-dodecane	363	≥1.5
				decane	363	≥1.5
				decane	363	≥1.5
				decane	363	≥1.5
				decane	363	≥1.5
				decane	363	≥1.5
				decane	363	≥1.5
				decane	363	≥1.5

Injection pressure variation

1 – 2 – 3

Very important for engine operation: variation of load and speeds

Test matrix – Spray A

Priority level	T [K]	density [kg/m^3]	Pressure [MPa]	Fuel	T fuel [K]	Injection duration [ms]
1	900	**22.8**	150	n-dodecane	363	≥1.5
2	900	22.8	100	n-dodecane	363	≥1.5
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5	900	**15.2**	150	n-dodecane	363	≥1.5
				decane	363	≥1.5
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				decane	363	≥1.5
				decane	363	≥1.5
				decane	363	≥1.5
				decane	363	≥1.5

Ambient density variation

1 – 4 – 5

Engine load variation at same speed

Ambient temperature variation

1 – 6 – 7 - 8

Different conditions at SOI

				uel	T fuel [K]	Injection duration [ms]
1	**900**	22.8	150	n-dodecane	363	≥1.5
2	900	22.8	100	n-dodecane	363	≥1.5
3	900	22.8	50	n-dodecane	363	≥1.5
4	900	7.6	150	n-dodecane	363	≥1.5
5	900	15.2	150	n-dodecane	363	≥1.5
6	**700**	22.8	150	n-dodecane	363	≥1.5
7	**1000**	22.8	150	n-dodecane	363	≥1.5
8	**1100**	22.8	150	n-dodecane	363	≥1.5
9	700	22.8	50	n-dodecane	363	≥1.5
10	440	22.8	150	n-dodecane	363	≥1.5
11	303	22.8	150	n-dodecane	363	≥1.5

Test matrix – Spray A

Low-mid temperature conditions 9-10

Important condition for modelers: spray breakup expected to play a big role due to reduced ambient temperatures and injection pressure (only 9)

6	700	22.8	150	n-dodecane	363	≥1.5
7	1000	22.8	150	n-dodecane	363	≥1.5
8	1100	22.8	150	n-dodecane	363	≥1.5
9	700	22.8	**50**	n-dodecane	363	≥1.5
10	**440**	22.8	150	n-dodecane	363	≥1.5
11	303	22.8	150	n-dodecane	363	≥1.5

Test matrix – Spray A

Non-evaporating condition

Important condition for modelers:

1. Is my high-temperature nice spray working well also at non-evaporating conditions?

2. Does spray tuning at non-evaporating conditions make sense for high temperature cases?

8	1100	22.8	150	n-dodecane	363	≥1.5
9	700	22.8	50	n-dodecane	363	≥1.5
10	440	22.8	150	n-dodecane	363	≥1.5
11	**303**	22.8	150	n-dodecane	363	≥1.5

Test matrix – Spray B

Priority level	T [K]	density [kg/m^3]	Pressure [MPa]	Fuel	T fuel [K]	Injection duration [ms]
1	900	22.8	150	n-dodecane	363	1.5
2	440	22.8	150	n-dodecane	363	1.5
3	303	22.8	150	n-dodecane	363	1.5
4	1100	22.8	150	n-dodecane	363	1.5

Reduced version of the spray-A test matrix to understand quickly effects of ambient temperature.

Both matrixes were created after a detailed investigation of what different institutions planned to test by the data submission deadline.

Contibutors

Experiments

- CMT
- IM/MTU
- IFPEN
- KAIST
- SANDIA
- TU/E

Simulations

- ANL
- CHALMERS
- CMT
- POLIMI
- SANDIA

Contributions: experiments – Spray A

Operating point	CMT	IFPEN	SANDIA	TU/E
1	**L^s V** Mf Ve	**L V** Mf **Ve**	**L V Mf** Ve	**L V** Mf Ve
2	**L^s V**	L V	L V	L V
3	**L^s V**	L V	L V	L V
4	**L^s V**	L V	**L** V	L V
5	**L^s V**	**L V**	L V	L V
6	**L^s V** Mf Ve	L V Mf Ve	**L** V Mf Ve	L V Mf Ve
7	L V	**L** V	L V	L V
8	L V	**L** V	L V	L V
9	**L^s V**	L V	L V	L V
10	L V Mf Ve	L V Mf Ve	**L** V Mf Ve	L V Mf Ve
11	L V	L V	L V	L V

L : liquid penetration vs time; V : vapor penetration vs time; L^s: steady-state liquid length
Mf : mixture fraction distribution; Ve : velocity distribution

Contributions: simulations – Spray A

Operating point	ANL	CHALMERS	CMT	POLIMI	SANDIA
1	**L V Mf Ve**	**L V Mf Ve**	**L V Mf Ve**	**L V Mf Ve**	**L V Mf Ve**
2	L V	**L V**	**L V**	**L V**	L V
3	L V	**L V**	**L V**	**L V**	L V
4	L V	**L V**	**L V**	**L V**	L V
5	L V	**L V**	**L V**	**L V**	L V
6	L V Mf Ve	L V Mf Ve	**L V Mf Ve**	**L V Mf Ve**	L V Mf Ve
7	L V	**L V**	**L V**	**L V**	L V
8	L V	L V	**L V**	**L V**	L V
9	L V	L V	**L V**	**L V**	L V
10	L V Mf Ve	**L V Mf Ve**	**L V Mf Ve**	**L V Mf Ve**	L V Mf Ve
11	L V	L V	**L V**	**L V**	L V

L : liquid penetration; V : vapor penetration;
Mf : mixture fraction distribution; Ve : velocity distribution

Contributions: experiments – Spray B

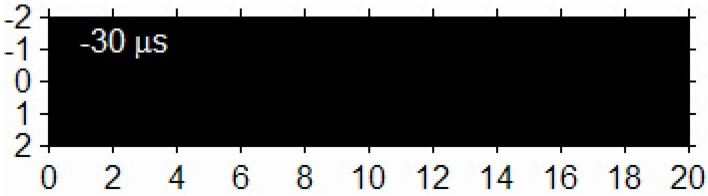
Operating point	SANDIA	IM/MTU	KAIST	IFPEN	CMT
1	**L V** Mf Ve	L V Mf Ve	**L** V	L V Mf Ve	L V Mf Ve
2	L V	L V	L V	L V	L V
3	L V	**L** V	L V	L V	L V
4	L V	L V	L V	L V	L V

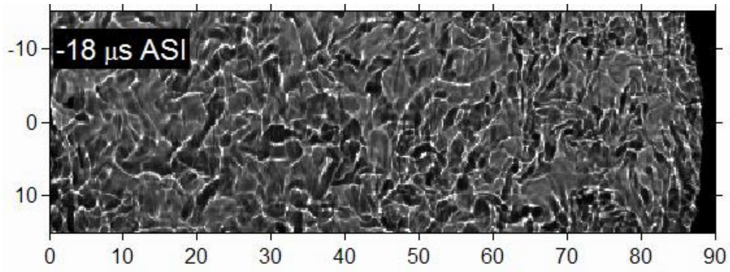
L : liquid penetration; V : vapor penetration;
Mf : mixture fraction distribution; Ve : velocity distribution

Experiments

Introduction and background

- Two main parameters aim at describing the development and vaporization of sprays: liquid and vapor penetration





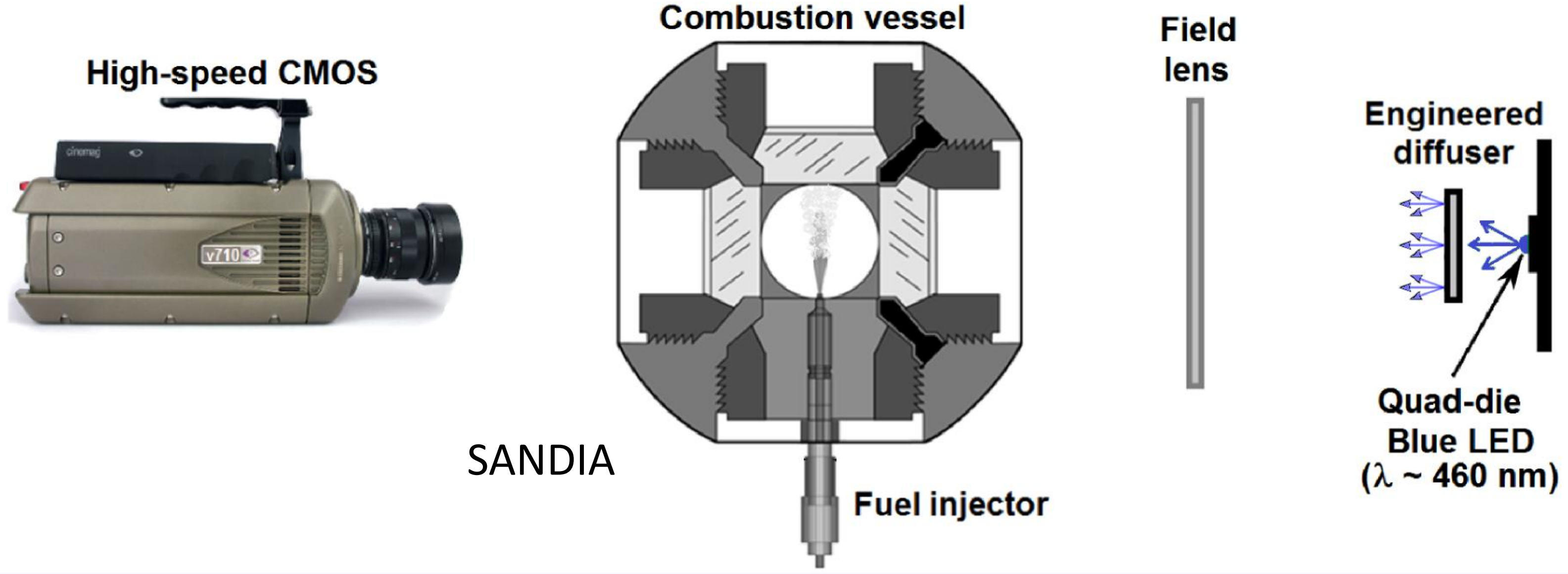
- Recommendations regarding experimental methods available to measure these parameters have been provided after the first workshop

- Liquid length measurements:
  - The standard liquid length measurement methodology should be diffused back-illumination (DBI) to reduce the experimental setup sensitivity for liquid boundary detection

- Vapor penetration experiments:
  - Vapor boundary should be measured using focused shadowgraph technique with high sensitivity and Sandia-developed processing algorithm

Diffused back-illumination (DBI) arrangement

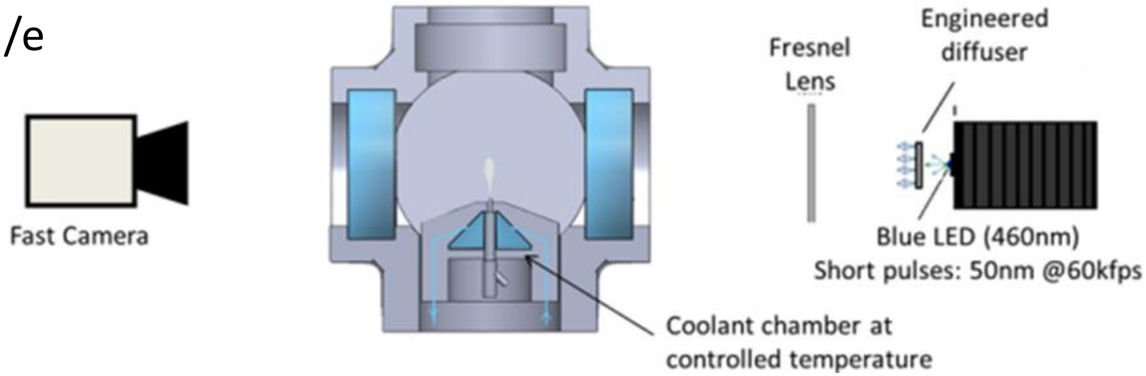
- High pressure and high temperature spray vessel (pre-burn or constant flow types)
- Ambient temperature: 300 - 1100 K
- Ambient density: 7.6 - 22.8 kg/m^3
- ECN injector A: Single axial hole (Nozzle 210675, 210677, 210678 and 210679)
- ECN injector B: Three holes (Nozzle 211196, 211198, 211199 and 211200)
- High-speed imaging system (12-bit, up to 150000 frames per second)
- Background light is efficiently diffused via engineered diffuser and field lens
- High-speed LED designed at Sandia provides a short time-gated illumination
- Light extinction is used to extract liquid boundary (penetration)

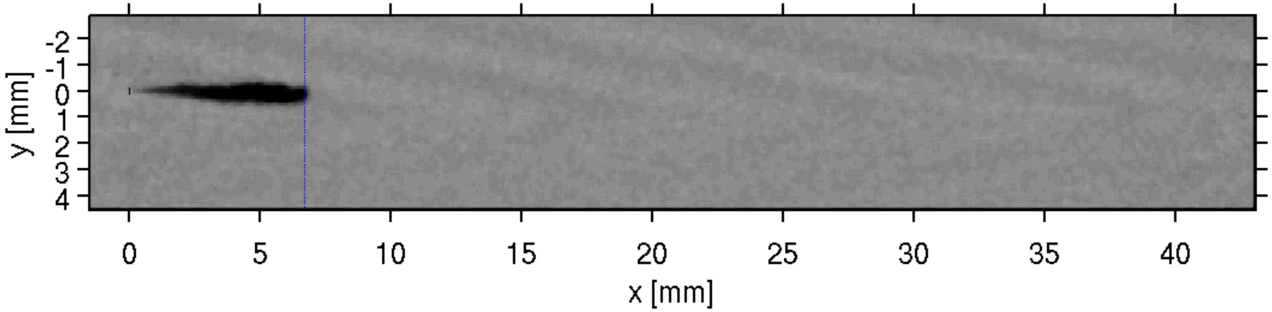


SANDIA

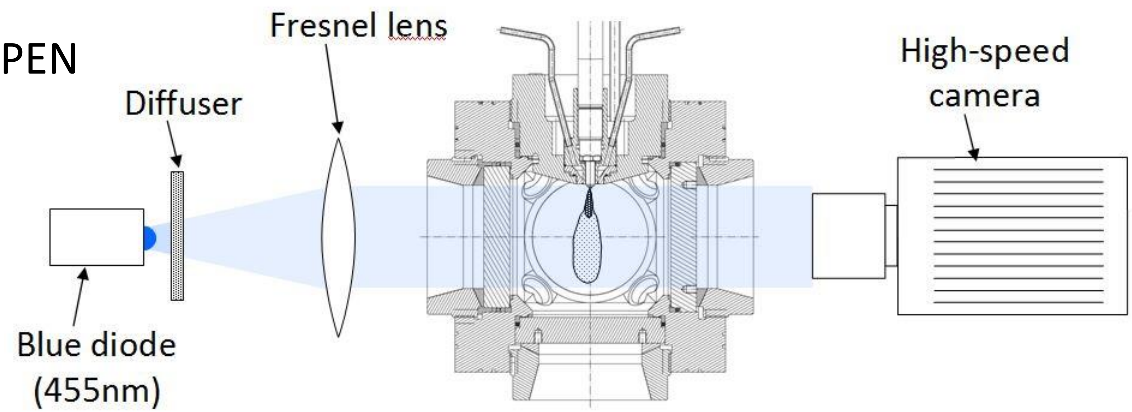
DBI optical setups

CMT-TU/e



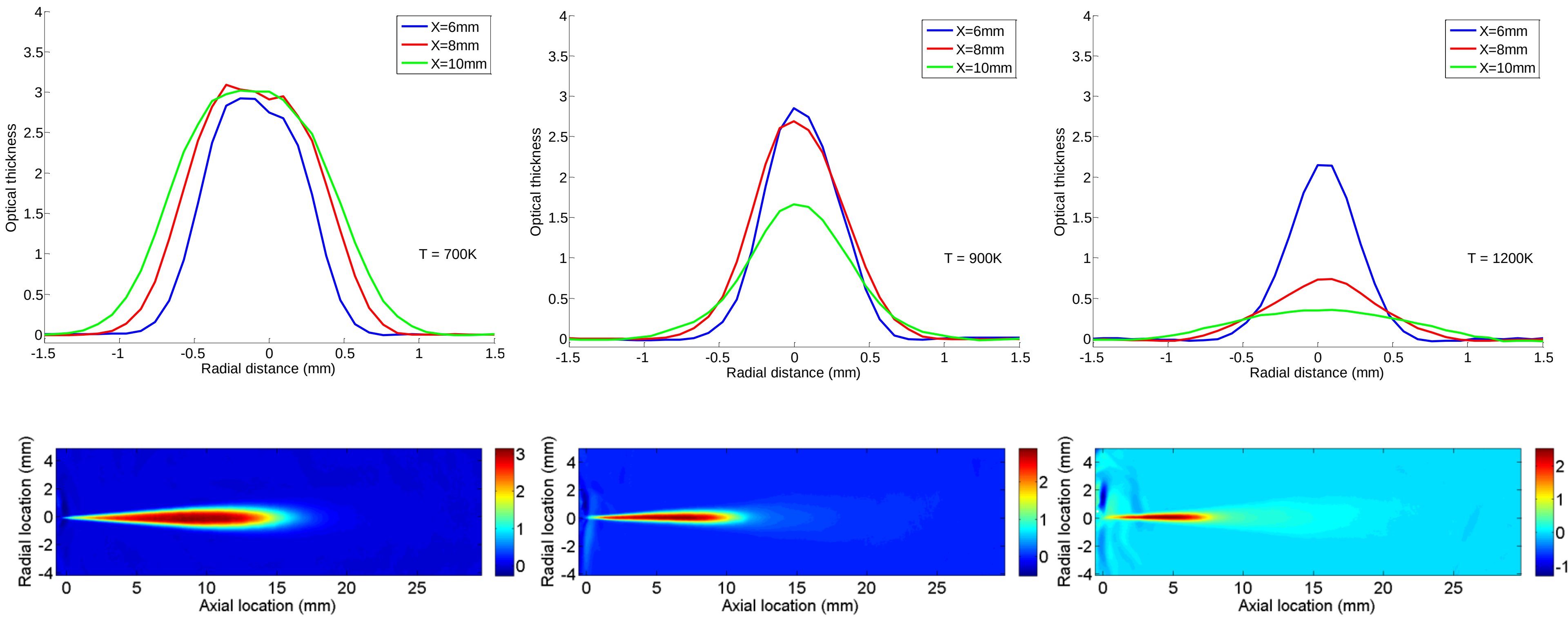


IFPEN



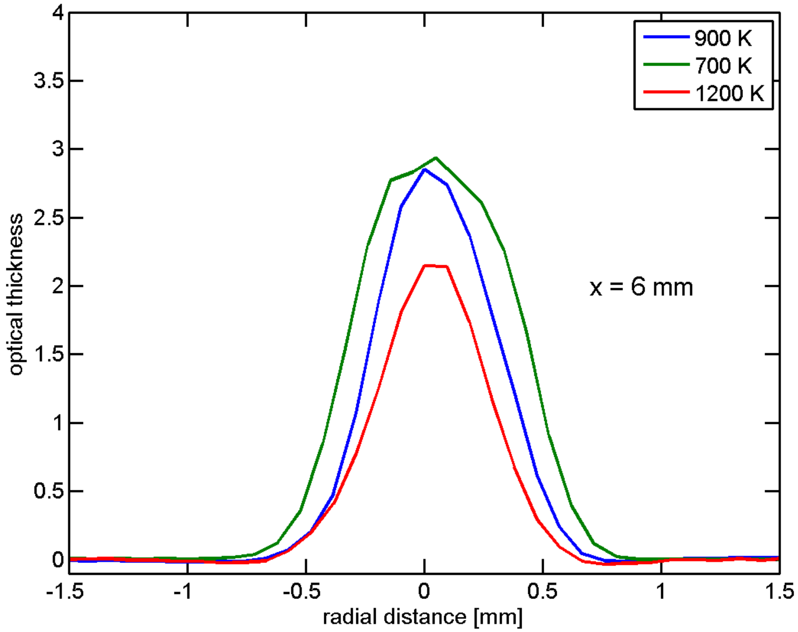
Liquid length procedure

Sandia and IFPEN use laser extinction to detect the extinction of the spray near the liquid. The measured extinction (optical thickness) provides a measure of light extinction because of liquid scatter and/or absorption. This extinction is the used measure to evaluate how much light has been attenuated through the spray droplets.

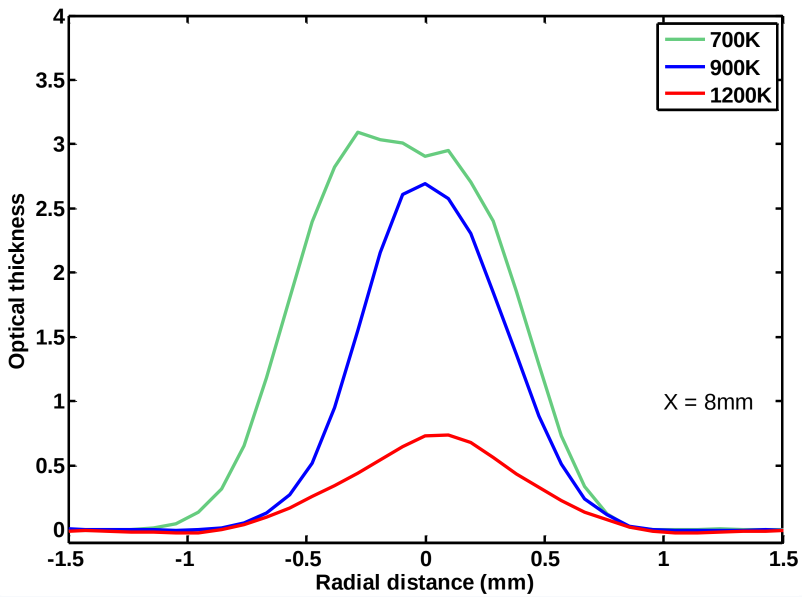


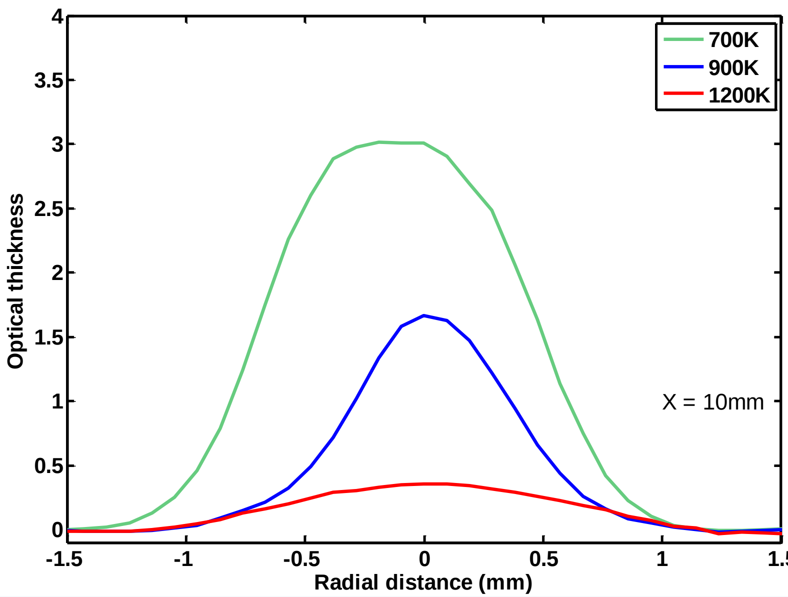
Liquid boundary is processed at an optical thickness of 0.6, which targets the optical thickness at the traditional Mie-scatter Siebers threshold (3% of maximum)

Liquid length procedure



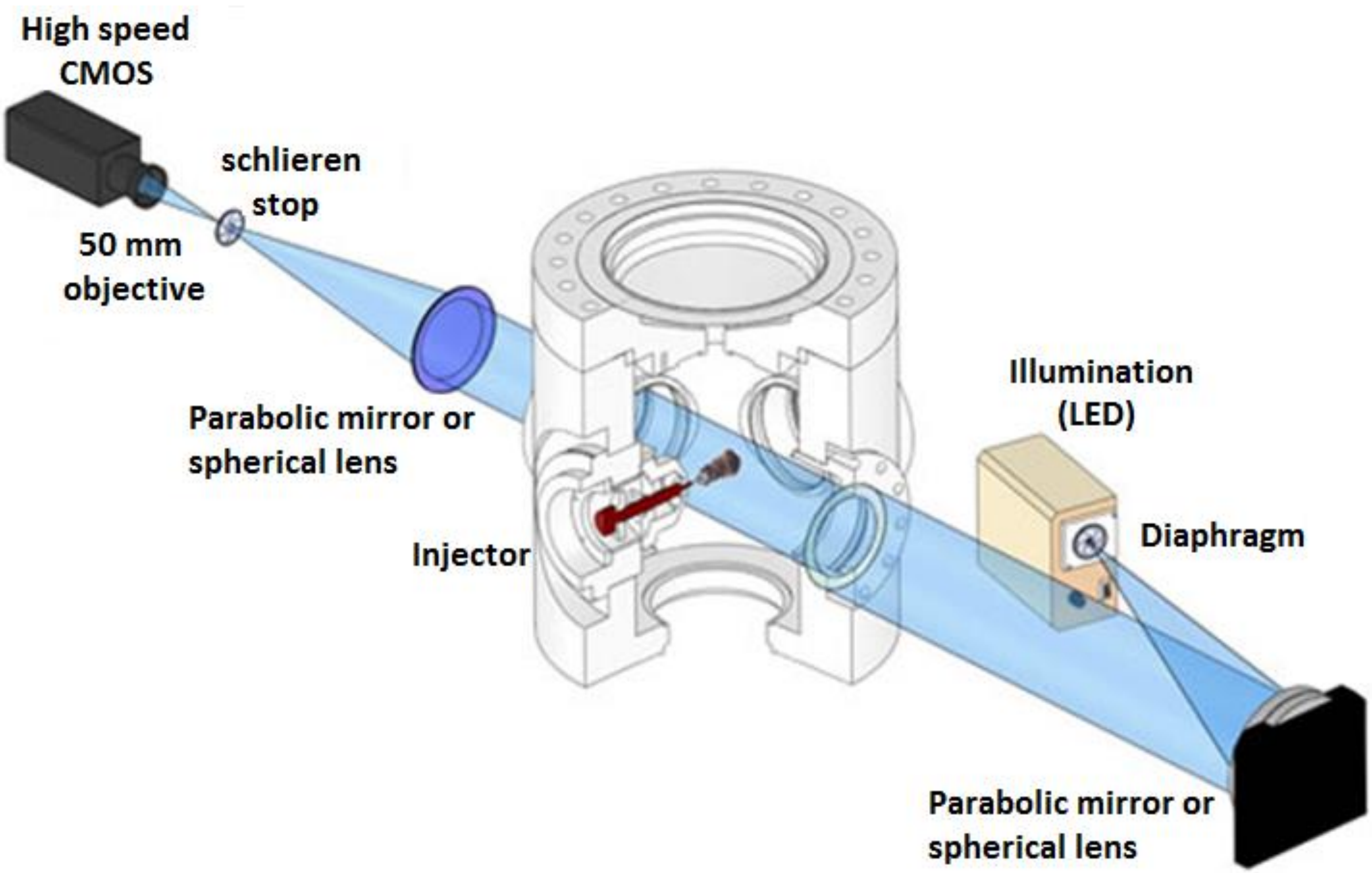
The extinction peak decreases with increasing of the ambient temperature because of evaporation process



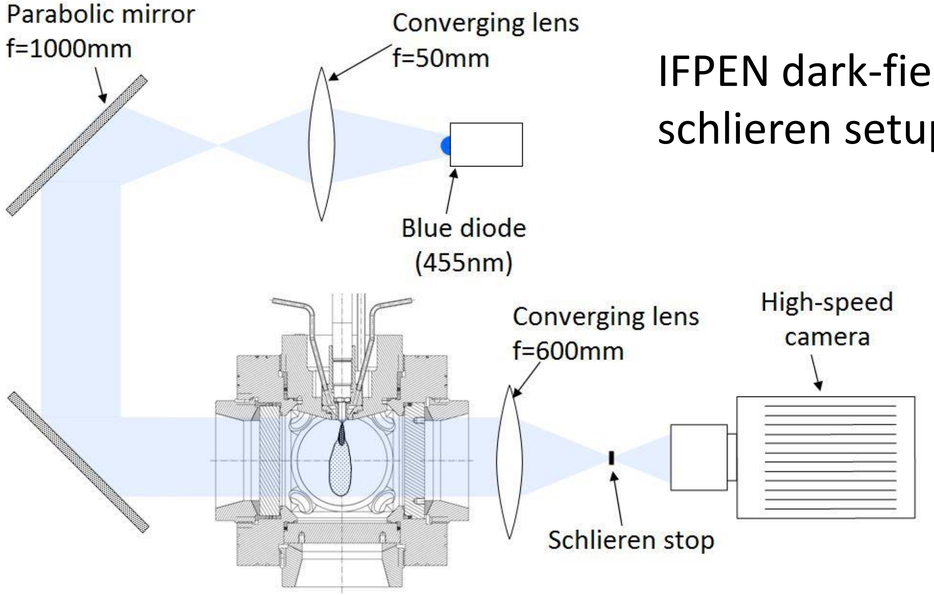


High-speed schlieren arrangement

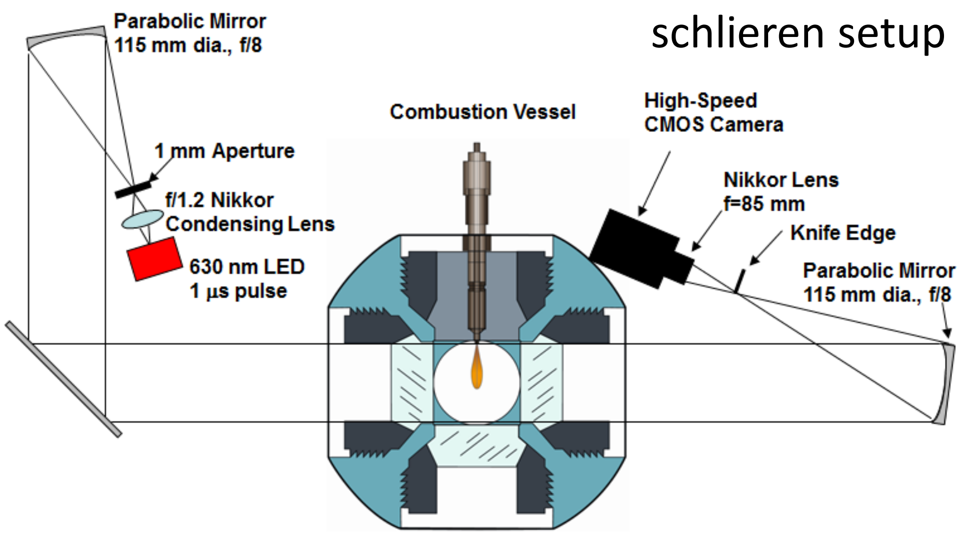
- High-speed imaging setups are relatively close between institutions
- CMT used a line-of-sight schlieren
- IFPEN used dark-field schlieren while the others used bright-field schlieren (Z-type)



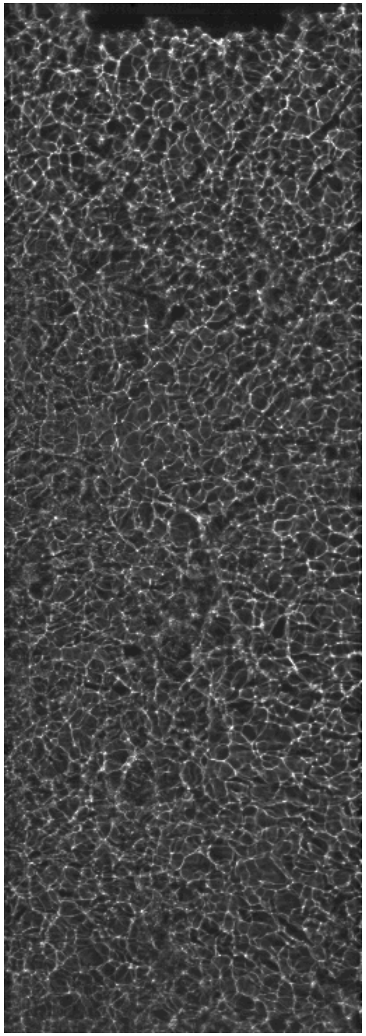
High-speed schlieren arrangements



IFPEN dark-field schlieren setup



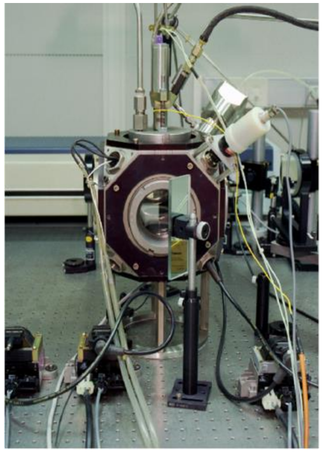
Sandia bright-field schlieren setup



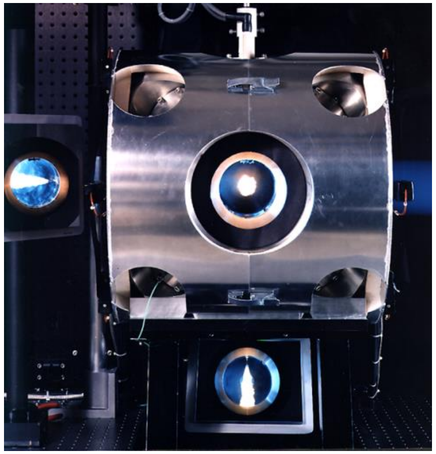
The facilities

- Constant volume pre-burn vessels (CVP)

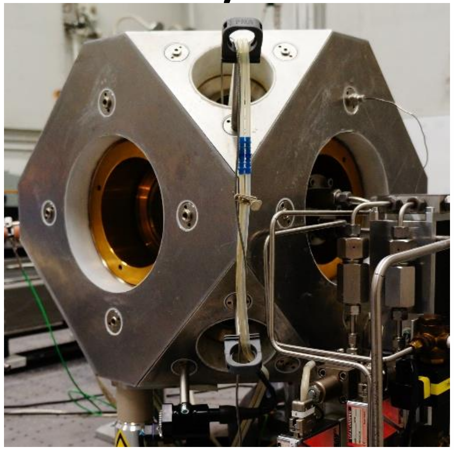
IFPEN



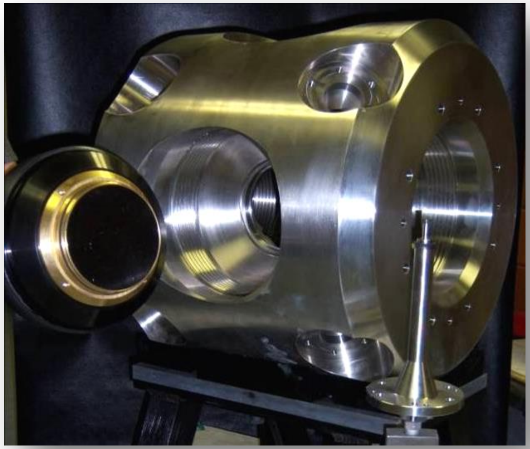
SNL



TU/e

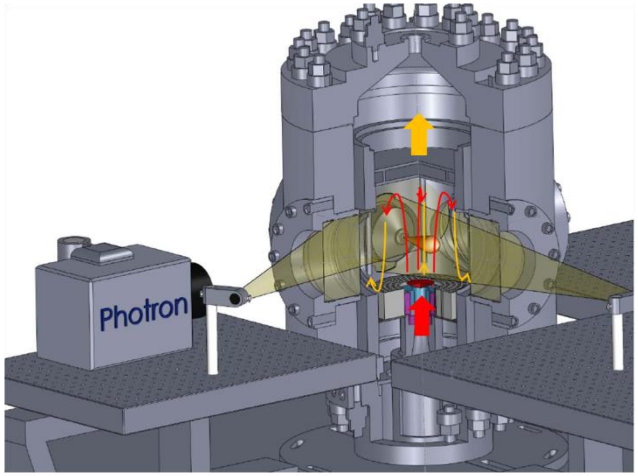


MTU



- Constant flow/pressure facilities(CFP)

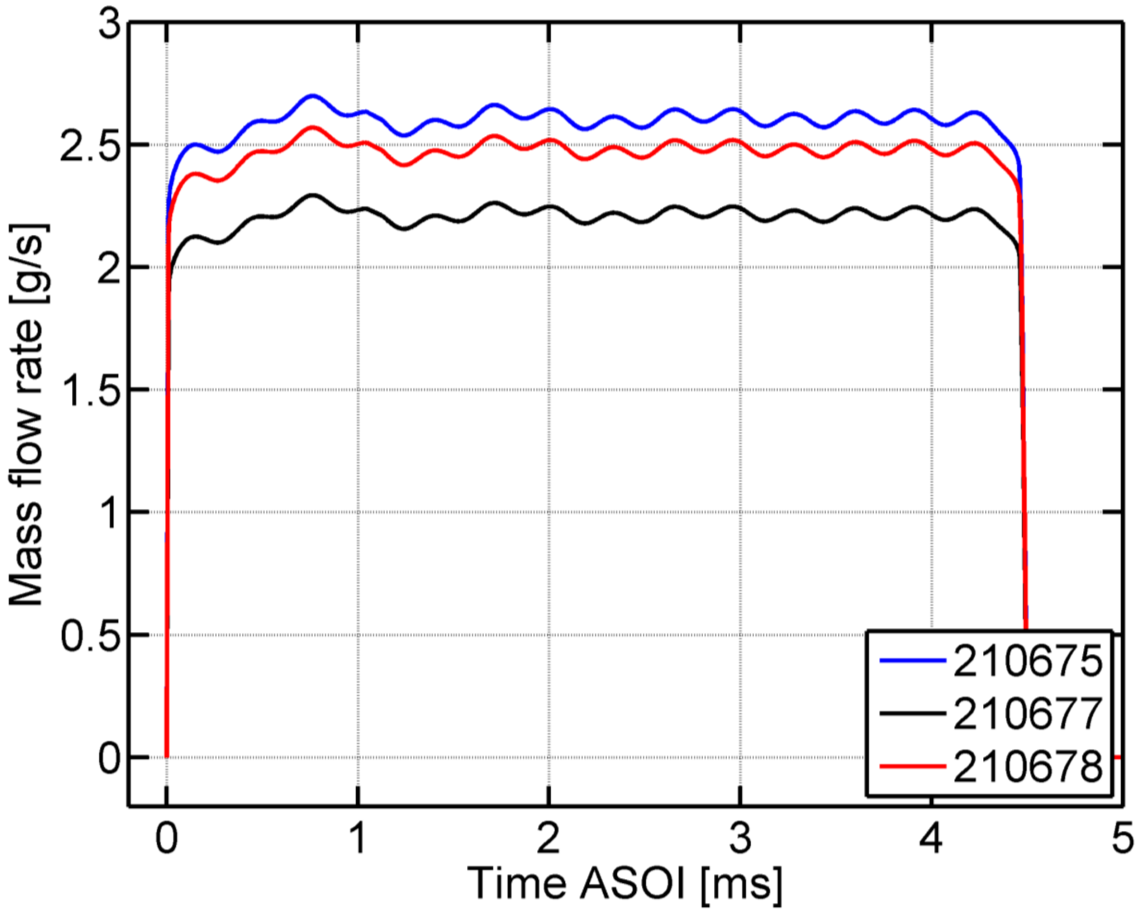
CMT



Spray-A test matrix

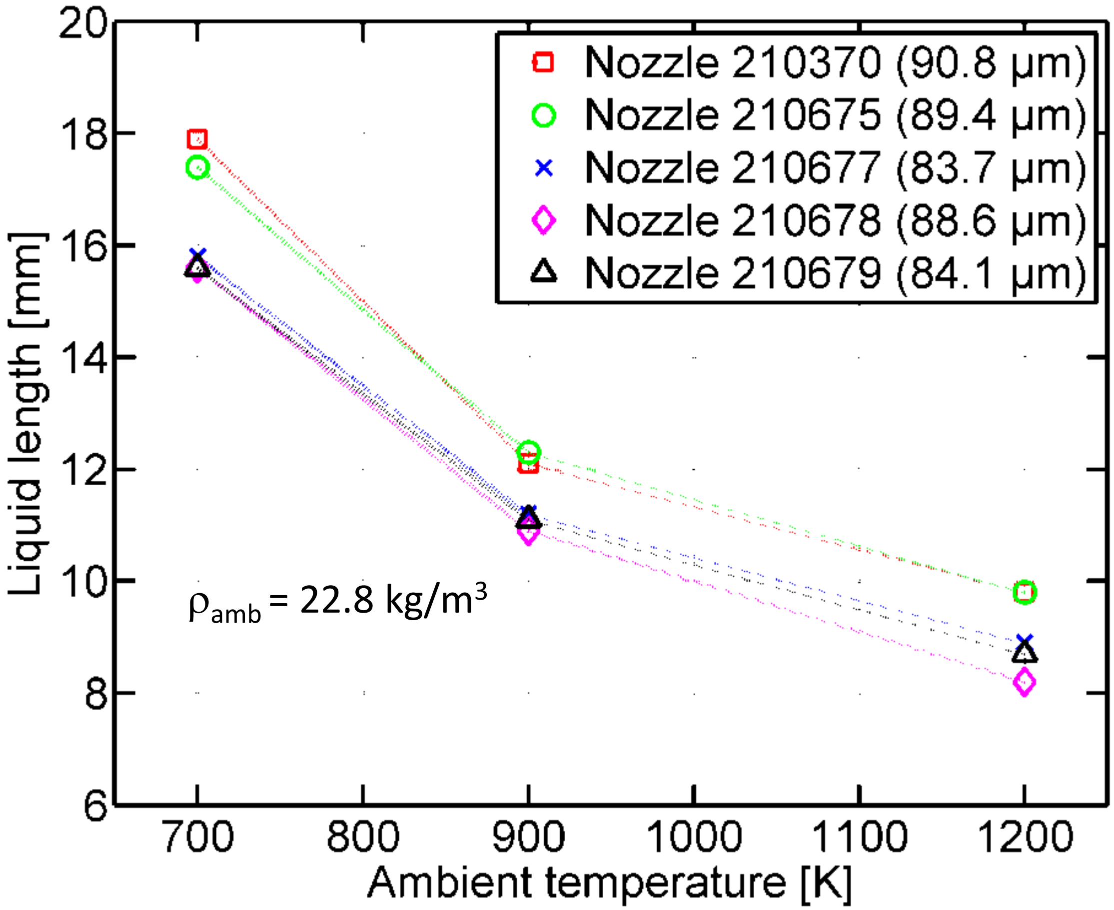
Required experimental test						Received experimental data		
Priority level	T [K]	density [kg/m^3]	Pressure [MPa]	T fuel [K]	Injection duration [ms]	Contributors	Nozzle #	Data
1	900	22.8	150	363	≥1.5	Sandia TU/e IFPEN CMT	210675 210679 210678 210675	Liquid&Vapor penetration
2	900	22.8	100	363	≥1.5	CMT	210675	Liquid&Vapor penetration
3	900	22.8	50	363	≥1.5	CMT	210675	Liquid&Vapor penetration
4	900	7.6	150	363	≥1.5	Sandia CMT	210675	Liquid penetration Liquid&Vapor penetration
5	900	15.2	150	363	≥1.5	IFPEN CMT	210678 210675	Liquid&Vapor penetration
6	700	22.8	150	363	≥1.5	Sandia CMT	210675	Liquid penetration Liquid&Vapor penetration
7	1000	22.8	150	363	≥1.5	IFPEN	210678	Liquid penetration
8	1100	22.8	150	363	≥1.5	IFPEN	210678	Liquid penetration
9	700	22.8	50	363	≥1.5			
10	440	22.8	150	363	≥1.5	Sandia	210675	Liquid penetration
11	300	22.8	150	363	≥1.5			

Expected differences between injectors - Spray A



- The ECN injectors present some significant scatter in actual internal geometry and outlet diameters
- ROI measurements for 3 injectors show variation on quasi-steady mass flow as high as 15%
- Such differences are expected based on outlet diameter dispersion (≈ 5 - 6 µm)

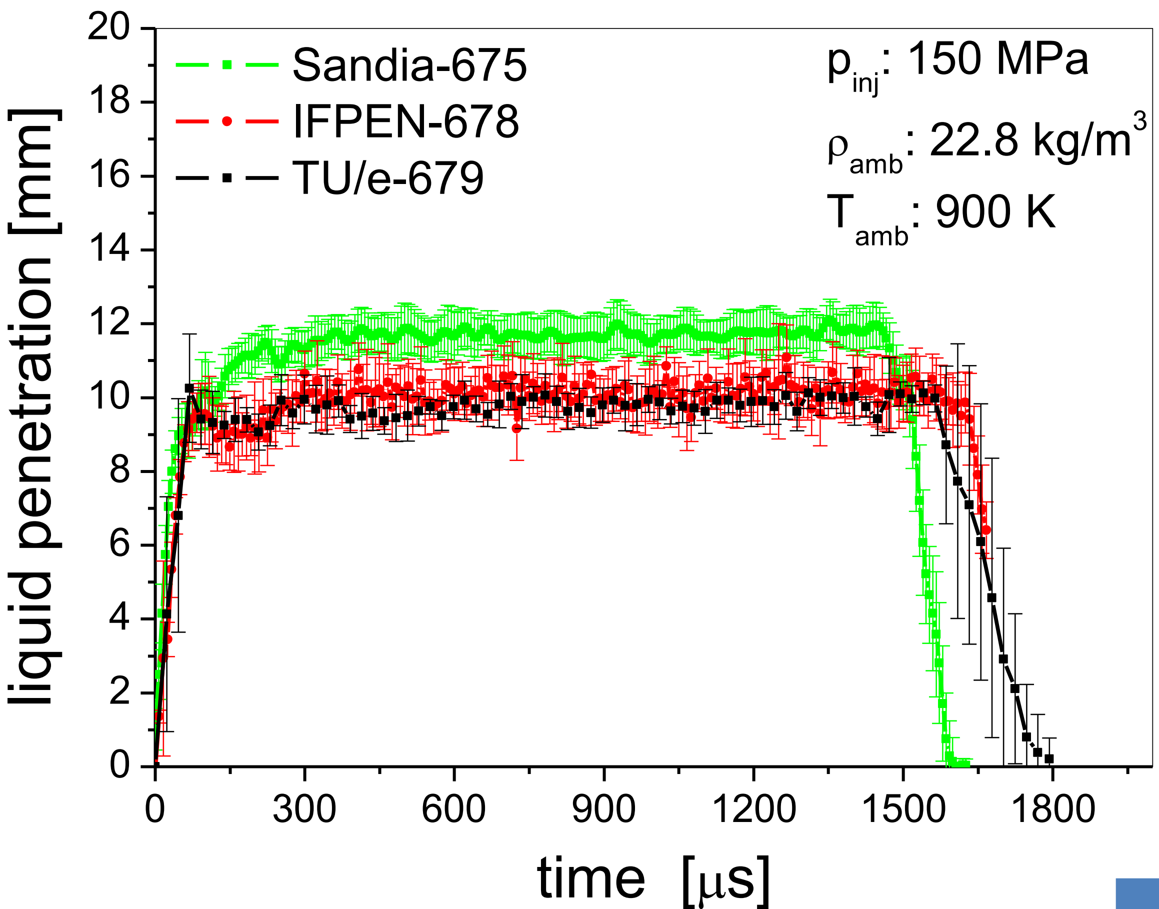
Experimental liquid length of "Spray A" injectors



- Liquid length has been tested in the same configuration at Sandia for the 5 injectors of the ECN dataset
- The liquid length for all the injectors follow the expected trend and keep a certain relationship as ambient temperature is changed

- Nozzle 210675 shows longer liquid-phase penetration than the others (≈1 mm) due to the largest hole diameter
- These differences have to be taken into consideration when comparing experimental results using a different injector of the set

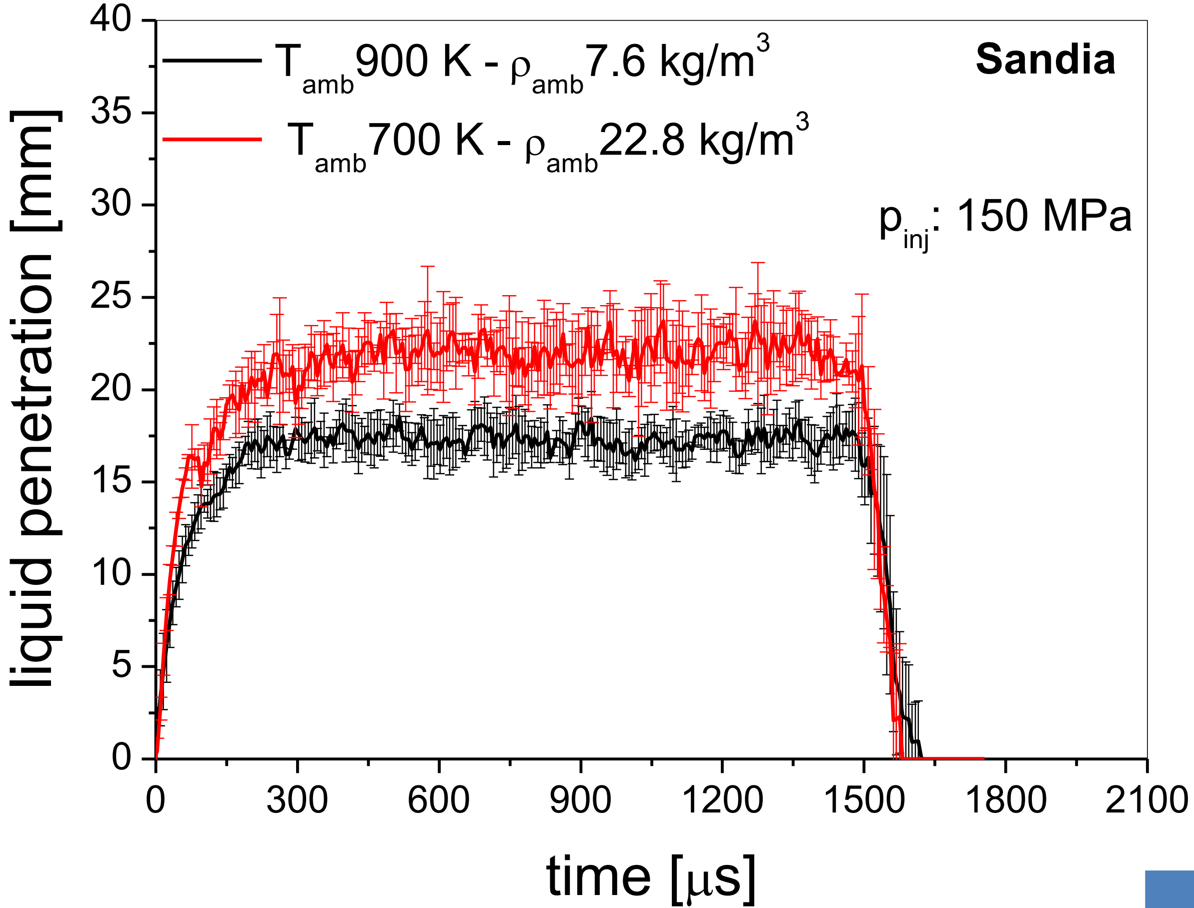
Institutions comparison: Liquid penetration –Spray A



- Liquid-phase penetration results show some variations that fall within the expectations
- The shapes look very similar
- Good agreement beetwen IFPEN, TU/e and CMT in terms of steady-state liquid value
- The SNL one is higher than the others (≈10%)

Steady-state liquid length			
Sandia	CMT	IFPEN	TU/e
11.7	9.74	10.54	10.33

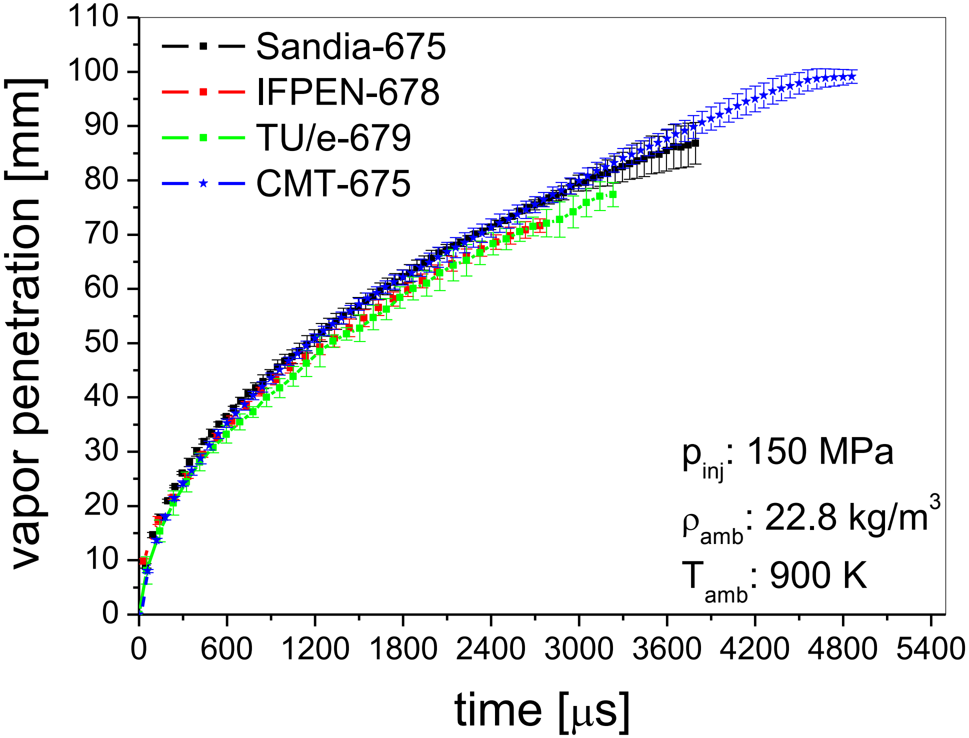
Sandia results: Liquid penetration – Spray A

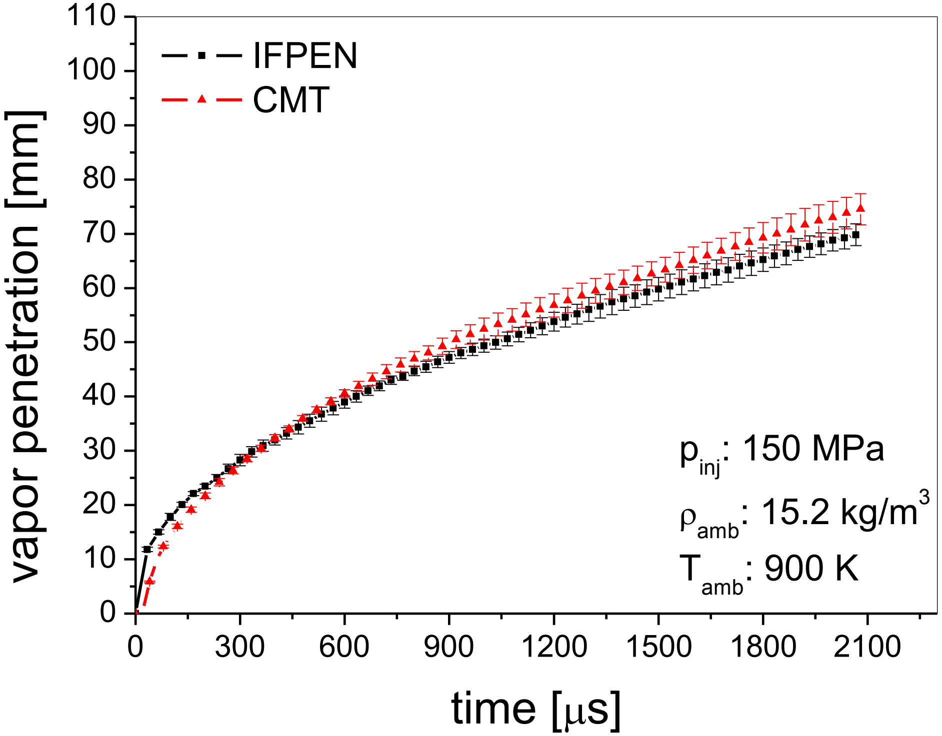


- The trends of the liquid length is according to the ambient conditions
- Steady liquid values from CMT are lower than Sandia ones
- The reason could be a different used methodology to calculate the liquid length and different nozzle temperature

Steady-state liquid length		
Point	CMT	Sandia
900/7.6	15.98	22.8
700/22.8	14.49	17.6

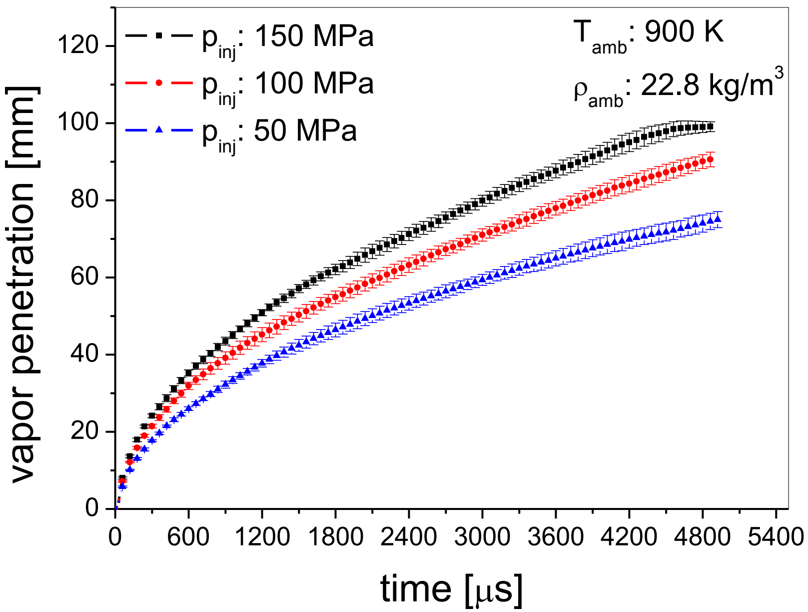
Institutions comparison: Vapor penetration – Spray A

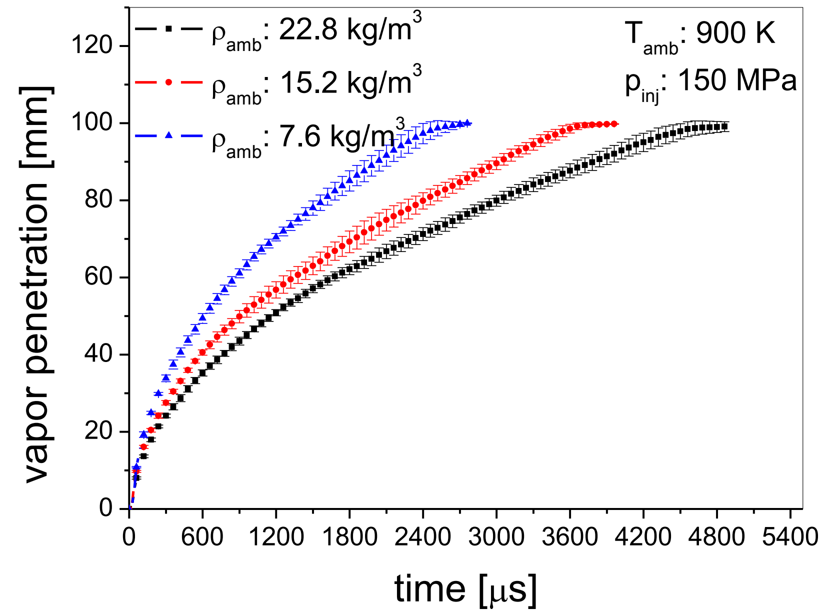


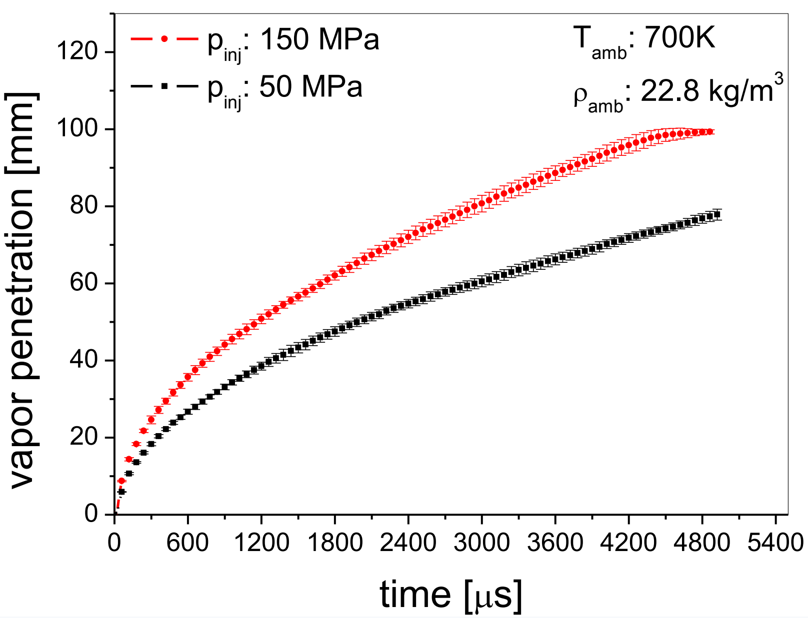


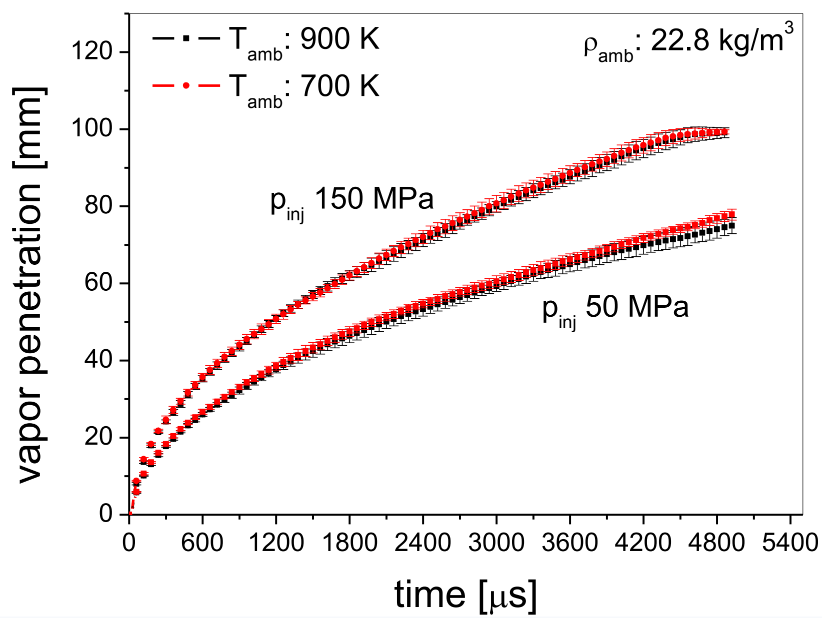
- Sandia and CMT measured almost identical penetration with the same injector
- Light differences with other institutions, in agreement with the different ROI

CMT: Vapor penetration – Spray A





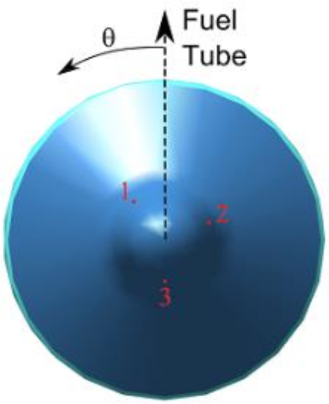




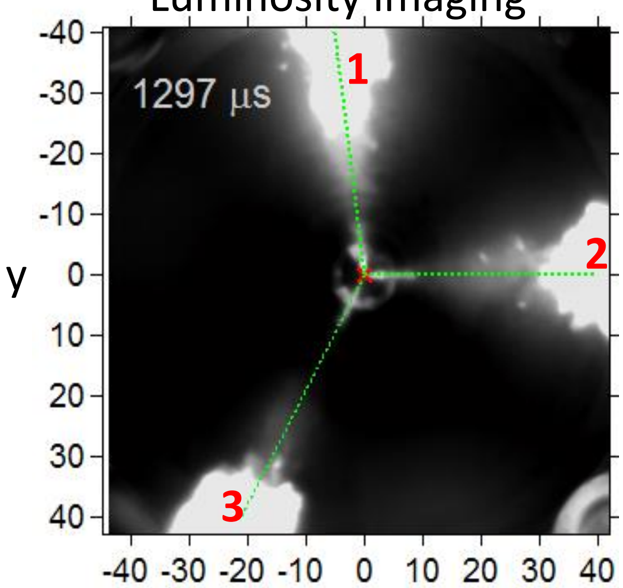
Spray B injector nozzle specifications

Spray B is a three-hole Bosch injector with the same orefice specifications as Spray A

Specifications for Spray B injectors	
Common rail fuel injector	Bosch solenoid-actived, generation 2.4
Fuel injector nominal nozzle outlet diameter	0.090 mm
Nozzle k-factor	$k = (d_{inlet} - d_{outlet})/10 = 1.5$
Nozzle shaping	Smoothed by hydro-erosion
Mini-sac volume	0.2 mm^3
Discharge coefficient at 10 MPa pressure drop	C_d = 0.86 (room temperature using diesel fuel)
Number of holes	3
Hole angular position	θ = 36.4°, -63.2° and 180°
Orefice orientation relative to injector axis	Ψ = 72.5° (145° full included angle)

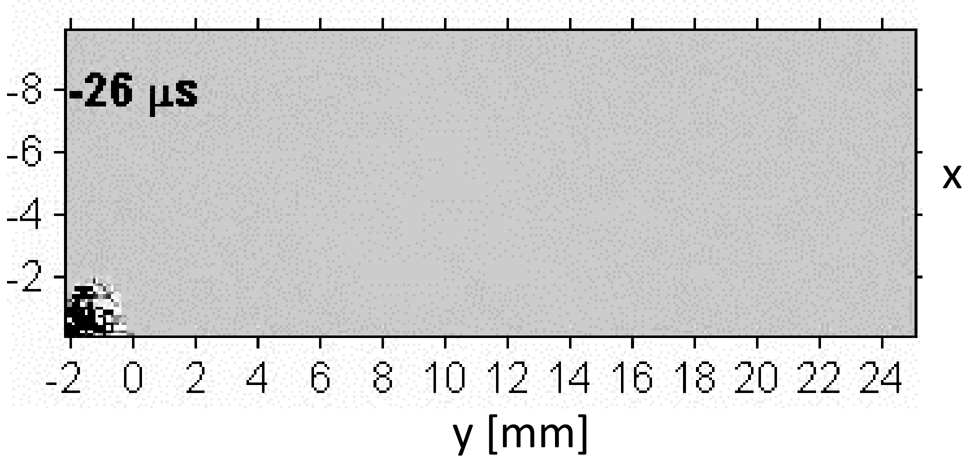


Luminosity imaging



The **hole of main interest** is the one drilled **opposite to the fuel tube (hole #3)**

Diffused back-illumination of hole 3



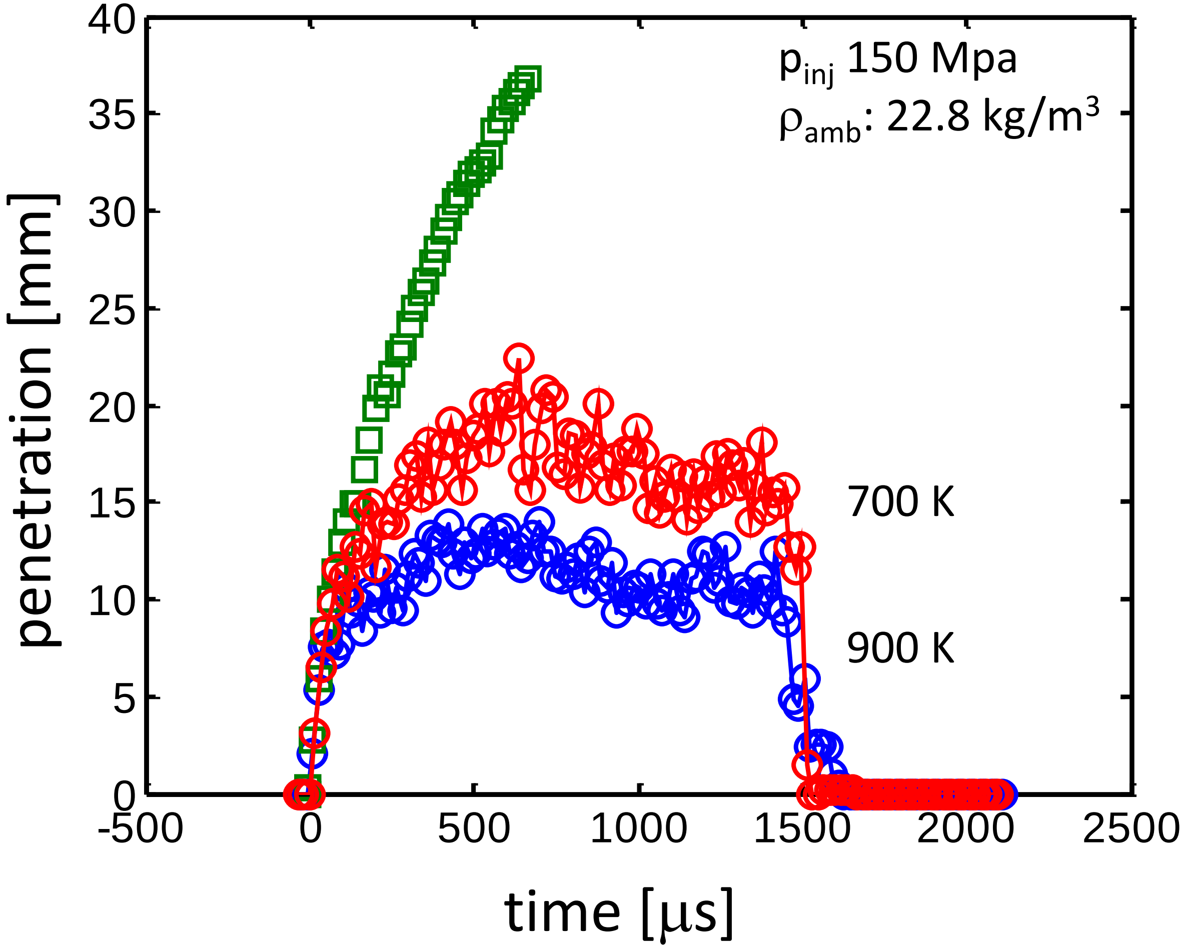
Spray-B test matrix

Required experimental test						Received experimental data		
Priority level	T [K]	density [kg/m^3]	Pressure [MPa]	T fuel [K]	Injection duration [ms]	Contributors	Nozzle #	Data
1	900	22.8	150	363	1.5	Sandia	211200	Liquid&vapor penetration, Spray # 3
2	440	22.8	150	363	1.5			
3	300	22.8	150	363	1.5	Istituto Motori/ MTU	211198	Liquid penetration all plumes
4	1100	22.8	150	363	1.5			

Additional Spray-B tests

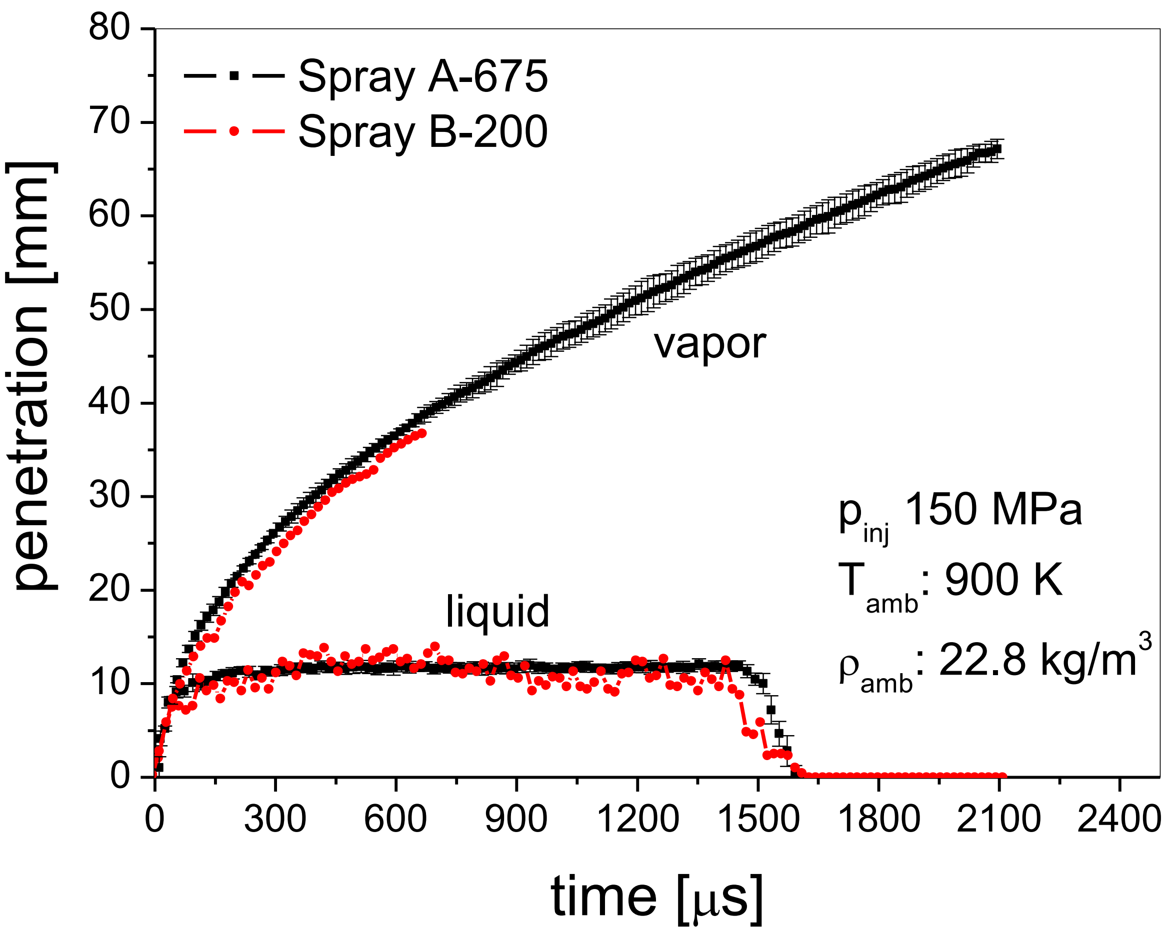
T [K]	density [kg/m^3]	Pressure [MPa]	T fuel [K]	Injection duration [ms]	Contributors	Nozzle #	Data
930	23.15	150-100-50	363	1.5	KAIST	211196	Liquid penetration spray #3
850	23.15	150-100-50	363	1.5	KAIST	211196	Liquid penetration spray #3
750	23.15	150-100-50	363	1.5	KAIST	211196	Liquid penetration spray #3
300	22.8	100-50	363	1.5	Istituto Motori/ MTU	211198	Liquid penetration all plumes
300	15.2	150-100-50	363	1.5	Istituto Motori/ MTU	211198	Liquid penetration all plumes

Spray B results - Sandia



The vapor boundary was extracted from DBI high-speed movies

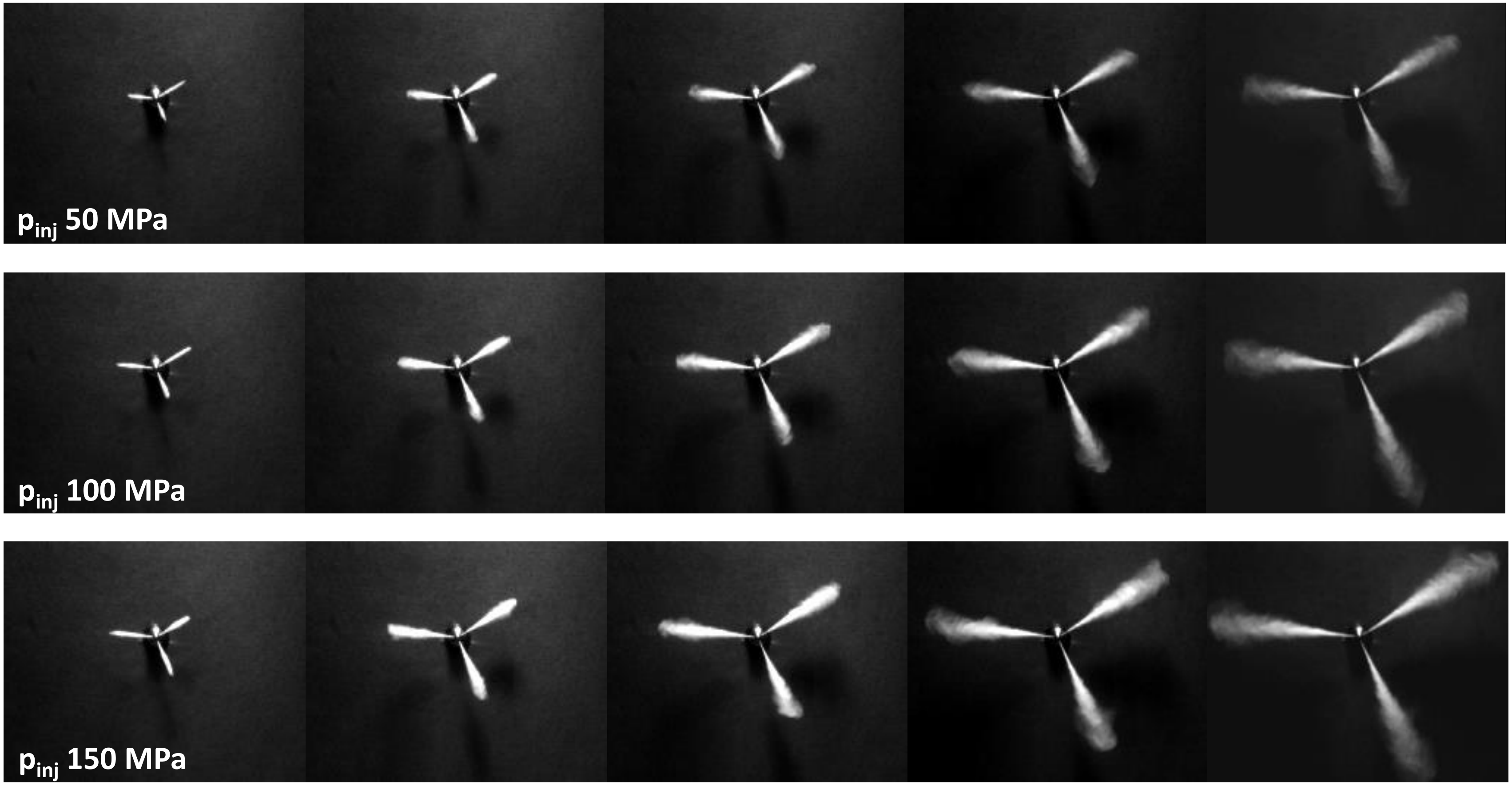
Spray A vs Spray B - Sandia



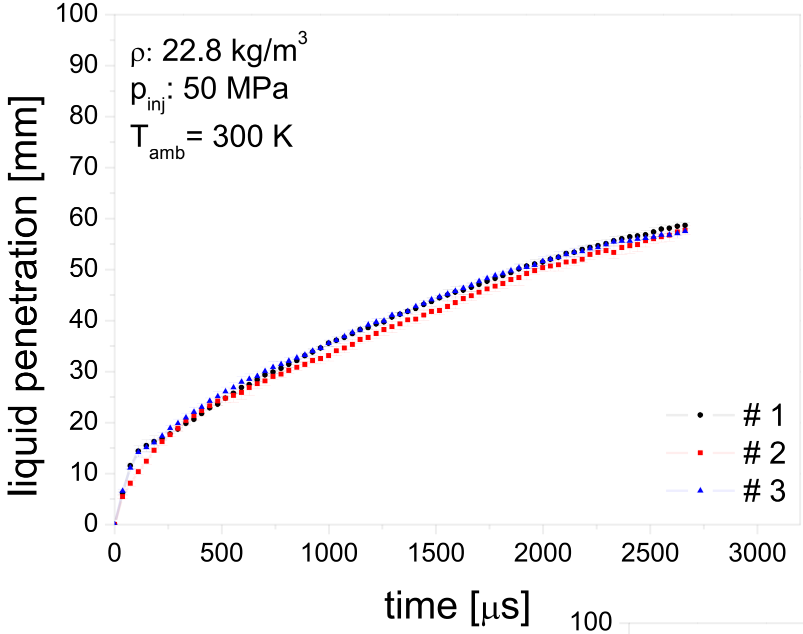
- Same orifice specifications for Spray A and Spray B injectors
- Excellent agreement in terms of liquid and vapor penetration trend
- Spray B profiles look more fluctuating than Spray A ones, it could be related to a different flow in the injector

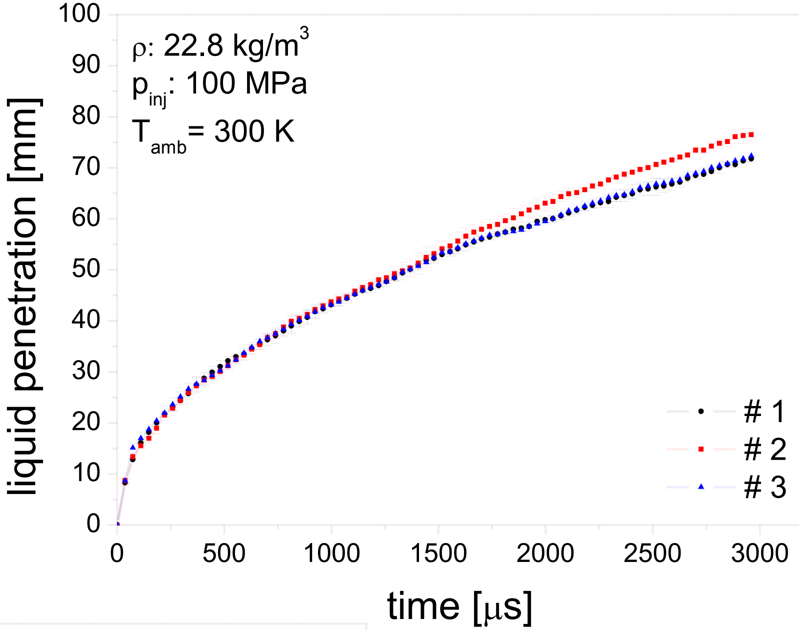
Liquid spray sequence @ ρ:22.8 kg/m^3 – IM/MTU

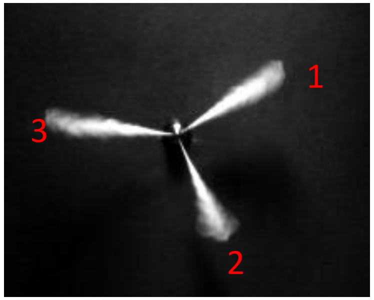
t_{ASOI} = 74 μs | t_{ASOI} = 259 μs | t_{ASOI} = 518 μs | t_{ASOI} = 999 μs | t_{ASOI} = 1591 μs

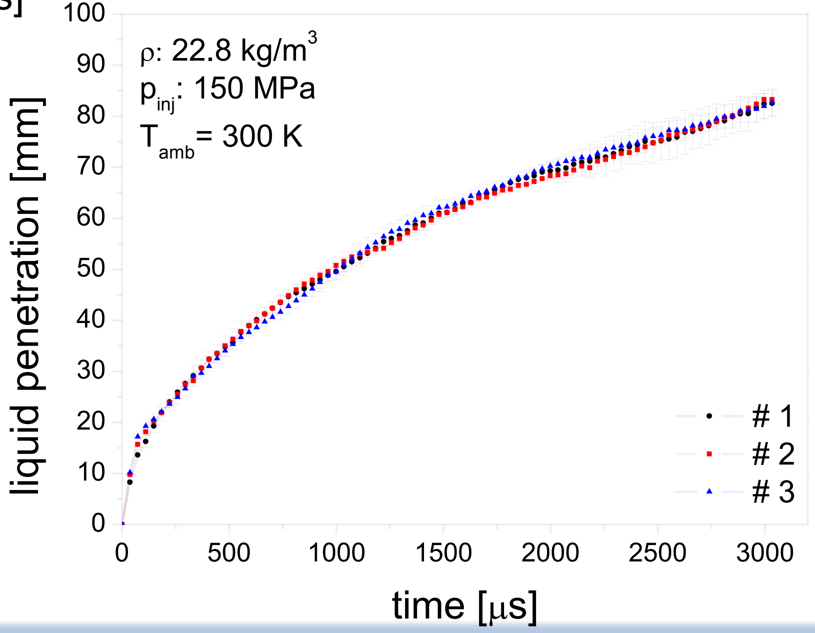


Liquid penetration @ ρ_{amb}: 22.8 kg/m^3 – IM/MTU

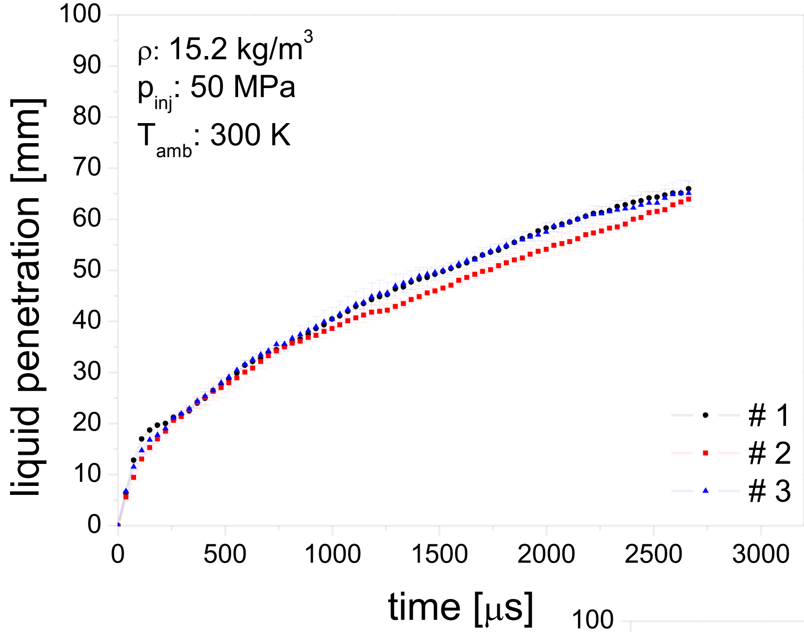


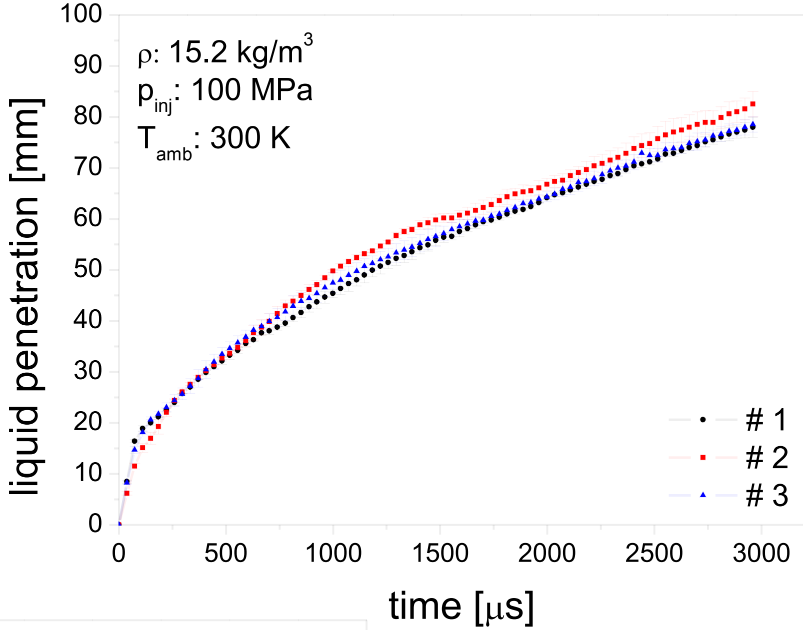


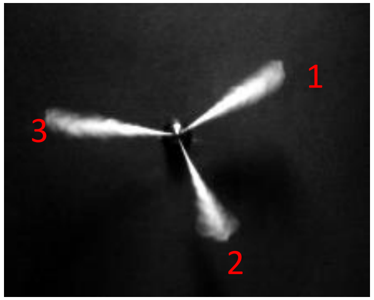


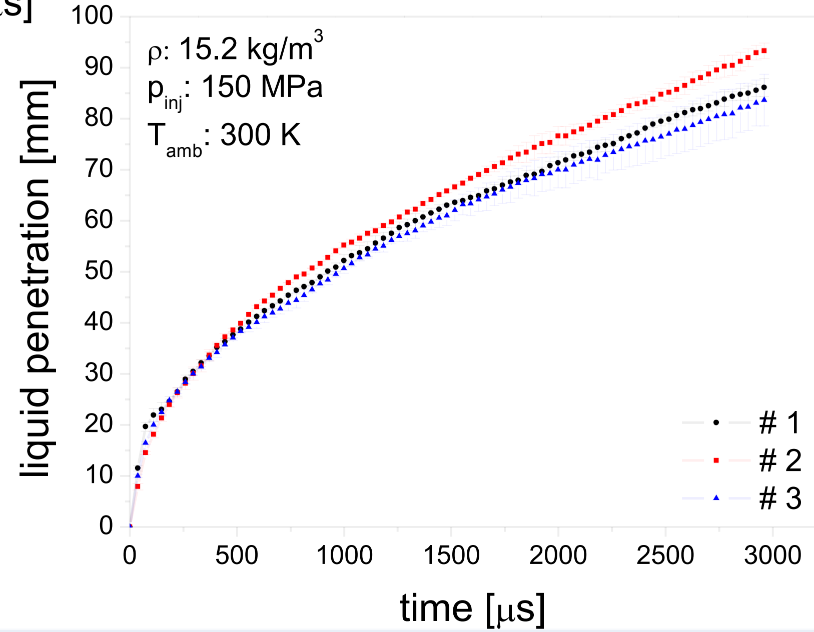


Liquid penetration @ ρ_{amb}: 15.2 kg/m^3 – IM/MTU

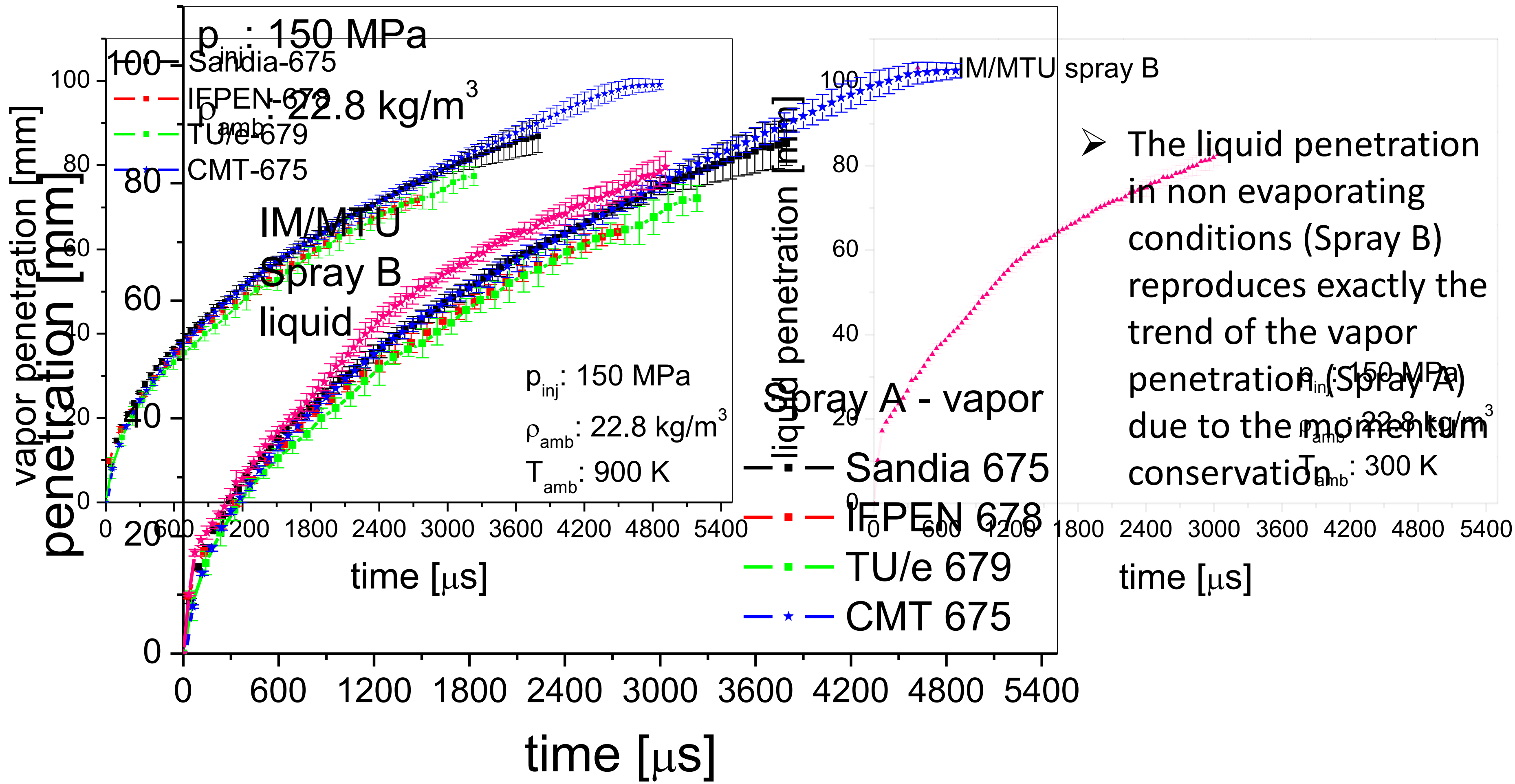






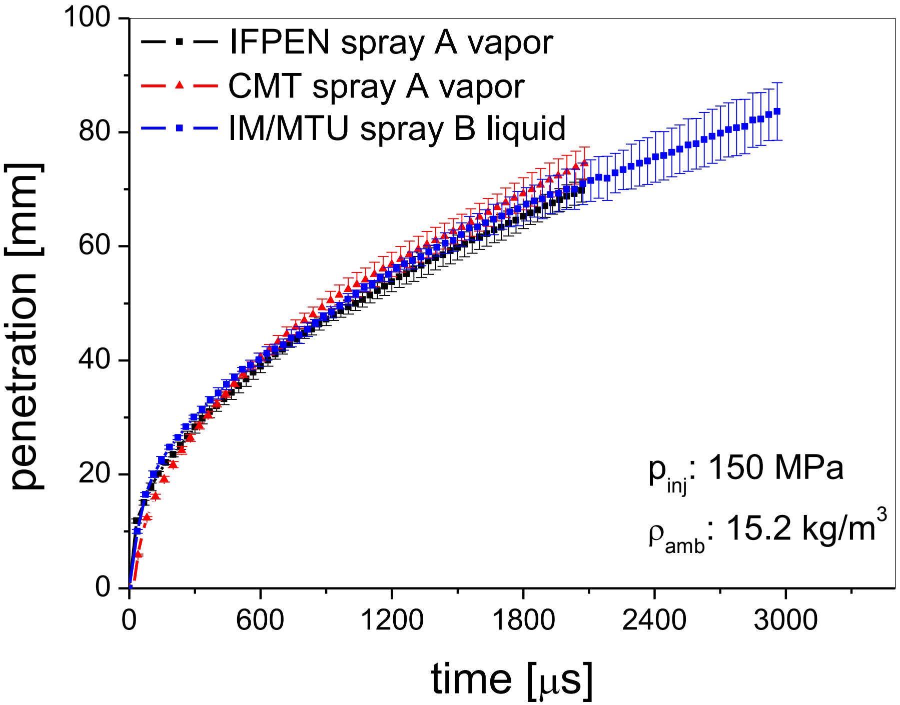


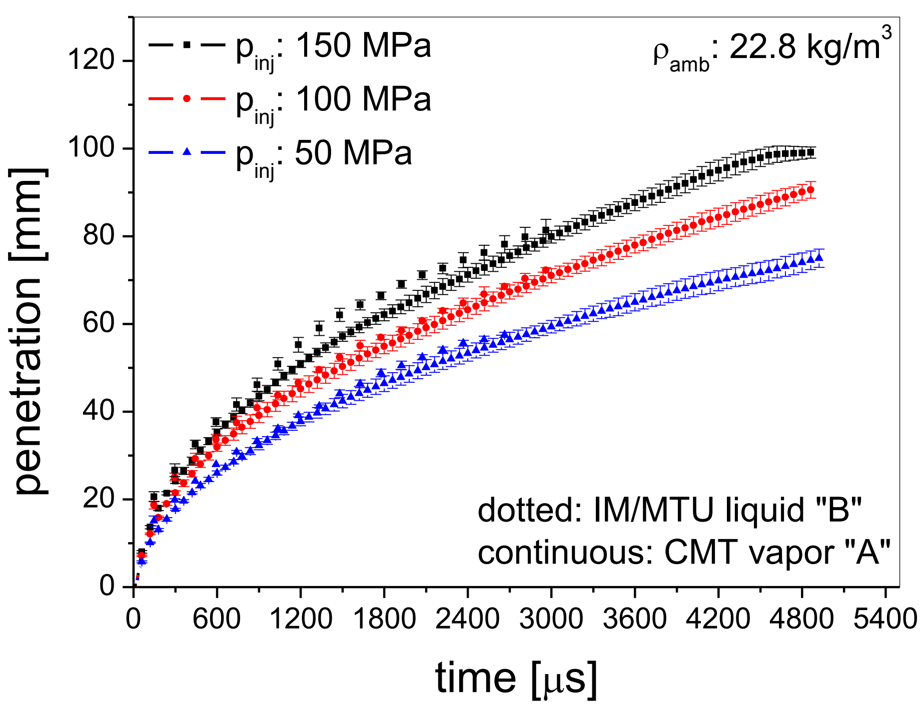
Vapor Spray A vs Liquid Spray B



- The liquid penetration in non evaporating conditions (Spray B) reproduces exactly the trend of the vapor penetration (Spray A) due to the momentum conservation

Vapor Spray A vs Liquid Spray B





Conclusions

- Diffused back-illumination and schlieren have been used as the reference diagnostics to measure liquid and vapor penetration, respectively, in order to quantify and compare the results between the institutions for both Spray "A" and "B".
- The differences measured in spray penetration can be explained mainly by the nozzle diameter differences.
- Experimental liquid penetration as a function of time is relatively close for all laboratories, showing similar fluctuations, except for Sandia injector that showed the highest values regarding the steady-state liquid length.
- The baseline Spray "A" condition (150 MPa, 900 K, and 22,8 kg/m^3) was widely tested by all institutions and the results were completely consistent with each other in terms both of liquid and vapor penetration.
- Preliminary tests on Spray "B" confirmed a similar behavior with respect to the Spray "A" in terms of liquid and vapor penetration.

Acknowledgements

- Sandia: Lyle M. Pickett, Julien Manin
- CMT: Raul Payri, Jose M. Pastor, Jose M. Garcia-Oliver
- IFPEN: Bruneaux Gilles, Louis-Marie Malbec
- TU/e: Maarten Meijer
- Kaist: Choongsik Bae, Jaeheun Kim
- IM/MTU: Luigi Allocca, Alessandro Montanaro, Seong-Young Lee, Jaffrey Naber

Simulations

Contributors

- Argonne National Labs (**ANL**)
- Chalmers University of Technology (**CHALMERS**)
- CMT Motores Termicos (**CMT**)
- Politecnico di Milano (**POLIMI**)
- SANDIA National Labs (**SANDIA**)

Methodology - General

	ANL	CHALMERS	CMT	POLIMI	SANDIA
Code	CONVERGE	OpenFOAM + VSB2	OpenFOAM + Σ-Y model	OpenFOAM + LibICE	Raptor
Mesh					including nozzle
Spray model					ense fluid model
Turbulence	LES, Dynamic Model	RANS, k-ε	RANS, k-ε	RANS, k-ε	LES, Dynamic Model
Notes	LES with 20 realizations	VSB2 model	Σ-Y model	LibICE spray model	Real fluid model, LES

5 Institutions with 5 substantially different approaches.

Comparison: MESH

		Mesh size [μm]	Mesh Type
ANL	**EL**	62.5 - 1000	3D
CHALMERS	**EL**	125 - 330	3D
CMT	**E**	9 – 1000	2D
POLIMI	**EL**	100 – 1000	2D
SANDIA	**E**	4 – 400	3D

Σ-Y approaches and Dense Fluid model go well below nozzle size:

- minimum mesh resolution less than 10 μm.

Contributors with Lagrangian models are now aware of the need to properly resolve scales with the same order of nozzle size.

Maximum employed mesh resolution: 1 mm

Mesh structure

- Axy symmetric: can intrinsically account for the axy-symmetry of liquid and gas jet.
- Cartesian mesh: numerical diffusivity affects results along different radial directions

Comparison: Turbulence models

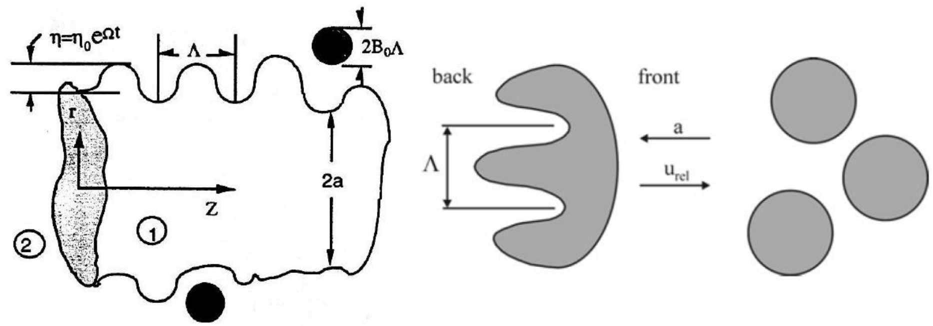
	Type	Model	Notes	Initialization
ANL	LES	Dynamic structure	20 flow realizations	Random seeds
CHALMERS	RANS	Standard k-ε	$C_1 = 1.55$, $\sigma_{eps} = 1.65$	Uniform k-ε
CMT	RANS	Standard k-ε	$C_1 = 1.6$, $\sigma_{eps} = 1.3$	Uniform k-ε
POLIMI	RANS	Standard k-ε	$C_1 = 1.55$, $\sigma_{eps} = 1.4$	Uniform k-ε
SANDIA	LES	Smagorinski	1 realization	Inflow generator

- Increasing C_1 in standard k-ε model is a common practice also used in simulation of turbulent gas jets (see past Proceedings of the SANDIA TNF workshop).
- LES/Lagrangian: initial flow field and particles generates fluctuations
- LES/Dense fluid: fuel inlet boundary condition generating fluctuations

Comparison: Spray sub-models

Only two institutions are using standard Lagrangian approach. In both cases KHRT was used.

	B_1	B_0	C_{rt}	C_τ
ANL	7	0.6	0.1	1.0
POLIMI	23.5	0.6	0.2	0.2



Why different constants?

1) Codes are different, of course…
2) Turbulence models are different, but…
3) Mesh structures are VERY DIFFERENT (2d axy-symmetric vs 3d Cartesian), hence different interaction between gas phase and spray are expected and tuning cannot be the same.

Comparison: Tuning

Other approaches

CHALMERS - VSB2 : Bubble radius size for liquid-gas thermodynamic equilibrium computation.

CMT – Σ-Y Model: Initialization and tuning constants for generation and destruction of Σ field.

SANDIA – Dense fluid model: no constants

Contributions: Lagrangian

- Many contributions to combustion sessions used standard Lagrangian approach
  - ➢ only POLIMI taking part to non-reacting spray session as well with the same approach.
- We encourage who is performing reacting simulations also to carry out non-reacting simulations to verify the consistencies of their approaches

Look back!

ECN Methodology

Nozzle flow → Near Nozzle → Evaporative sprays → Combustion

Comparison: Simulation setup

	Time-step	Discretization		
		Time	Convection	Diffusion
ANL	Co < 0.75	Euler Implicit	2nd order	CD 2nd order
CHALMERS	$\Delta t = 1\ \mu s$	Euler Implicit	1st + 2nd order	CD 2nd order
CMT	Co < 2	Euler Implicit	Gamma NVD	CD 2nd order
POLIMI	$\Delta t = 1\ \mu s$	Euler Implicit	Limited linear	CD 2nd order
SANDIA	$Co_{acoustic} < 0.5$	Runge-Kutta (4th order)	QUICK (3rd ord) + upwind with switching	CD 2nd order

- Numerical accuracy is of great importance to predict fuel-air mixing.
- Good to see everybody is using 2nd order accurate space discretization schemes

Comparison: boundary conditions

- All institutions used 675 injector geometry as suggested

	Injection rate profile	Nozzle diameter [μm]	Initial droplet size [μm]
ANL	Generated by CMT	90	90
CHALMERS	Generated by CMT	89.4	80
CMT	Generated by CMT	89.4	-
POLIMI	Generated by CMT	89.4	89.4
SANDIA	Generated by CMT	89.4	-

- Almost consistent approaches for what concerns initial and boundary conditions….

ECN

Comparison: definitions

	Vapor penetration	Liquid penetration	Mixture fraction variance
ANL	$Y_{C12H26,v}$ = 0.001	90% by liquid mass	LES Averaging
CHALMERS	[illegible]	0.1% by liquid [illegible]	[illegible] equation
CMT	[illegible]	[illegible] volume fraction	[illegible] equation
POLIMI	$Y_{C12H26,v}$ = 0.001	99% by liquid mass mass	Transport equation
SANDIA	**Y_{C12H26} = 0.05**	**Y_{C12H26} = 0.79**	LES Averaging

Time to see results!

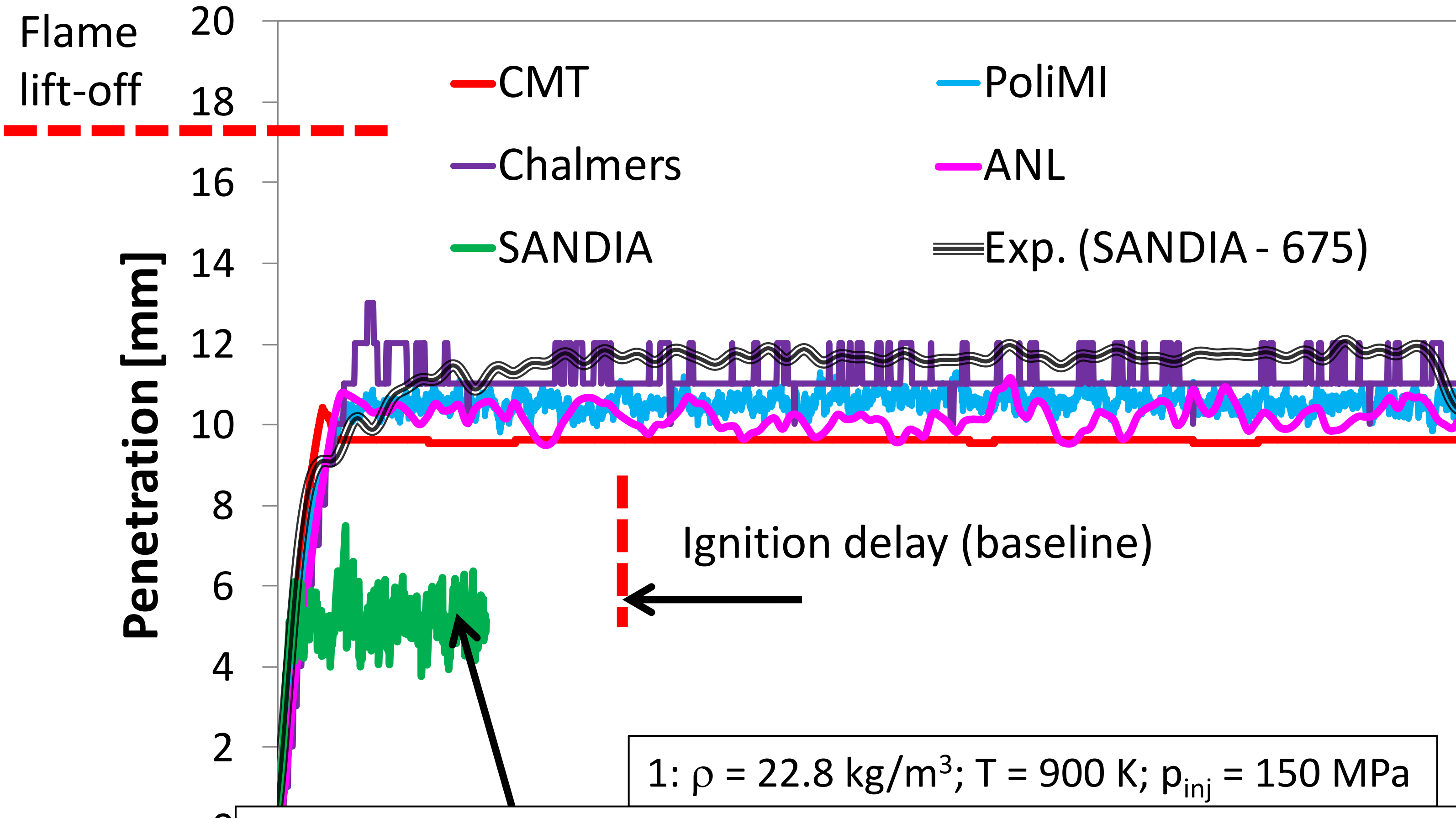
Still inconsistencies for liquid penetration definitions. SANDIA is using a quite high mass fraction to locate vapor penetration compared to different institutions

Baseline condition

	T [K]	density [kg/m^3]	Pressure [MPa]	Fuel	T $_{fuel}$ [K]	Injection duration [ms]
1	900	22.8	150	n-dodecane	363	≥1.5

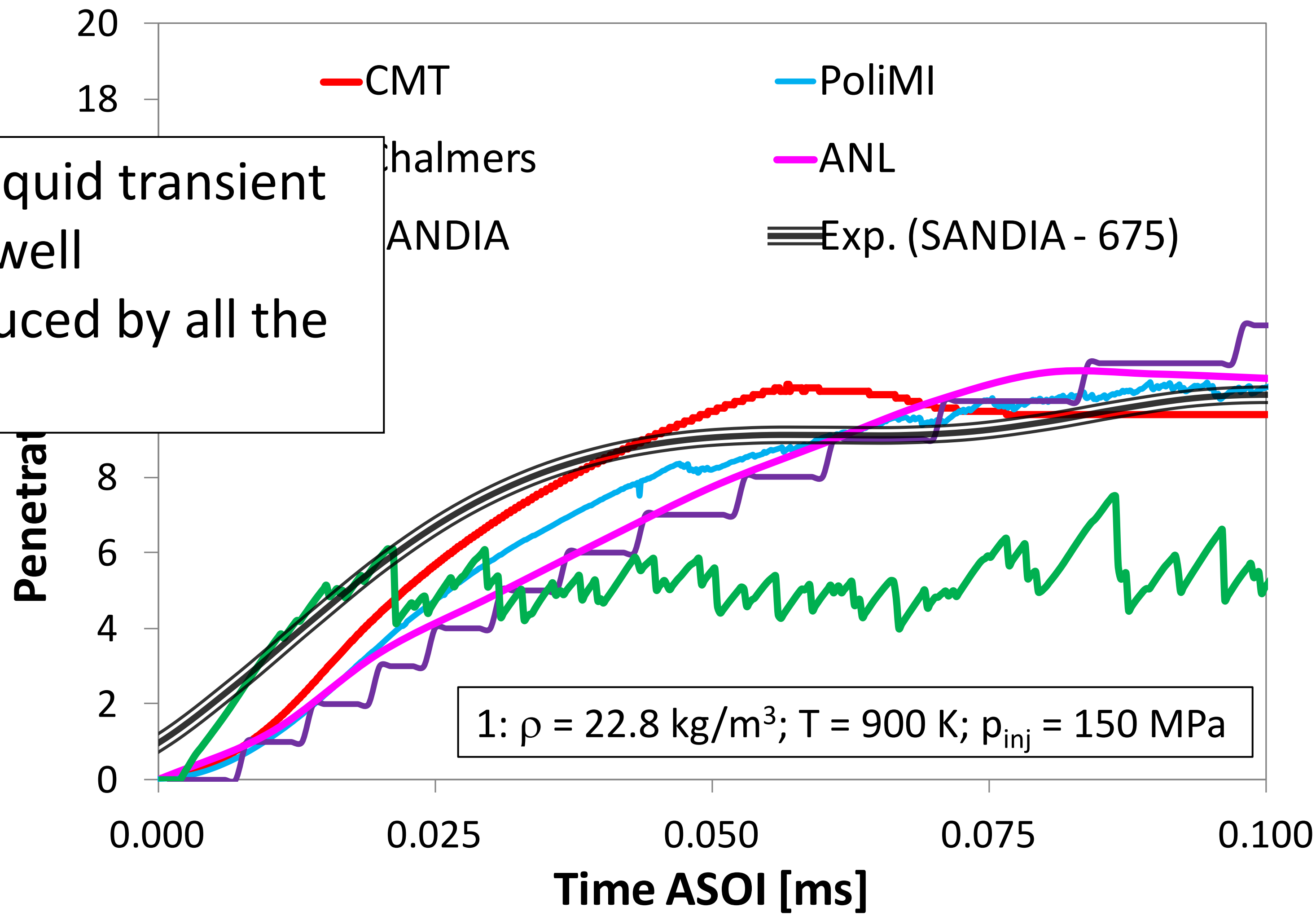
- Studied by all-institutions
- Large amount of data for validation: penetrations, velocity, mixture fraction
- Model tuning performed for such conditions

Baseline condition: liquid penetration vs time



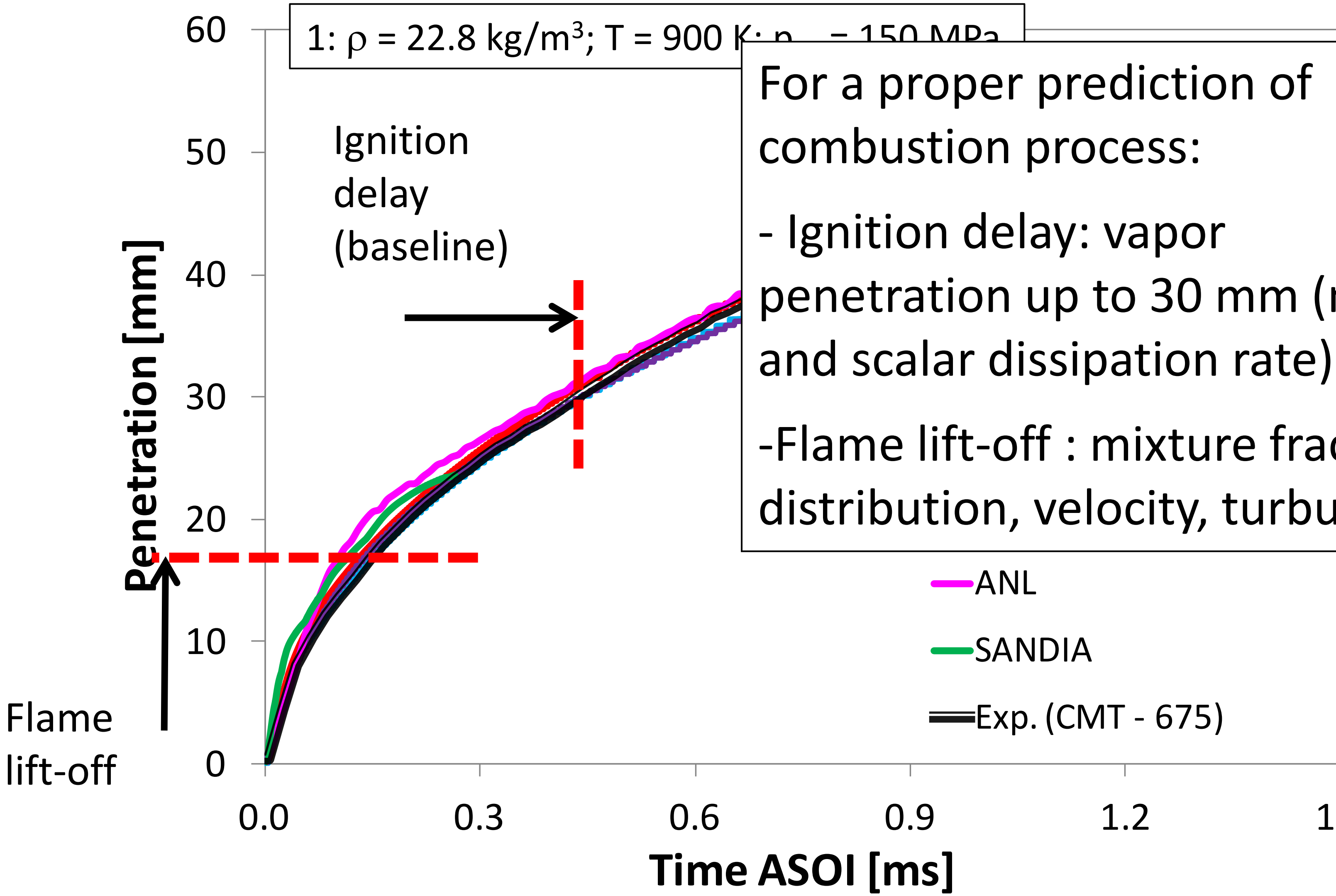
SANDIA results affected by liquid length definition.
How to interpret, with the SANDIA model, the steady-state liquid length measured by DBI or Mie scattering?

Baseline condition: liquid penetration vs time



Initial liquid transient rather well reproduced by all the models

Baseline condition: vapor penetration vs time

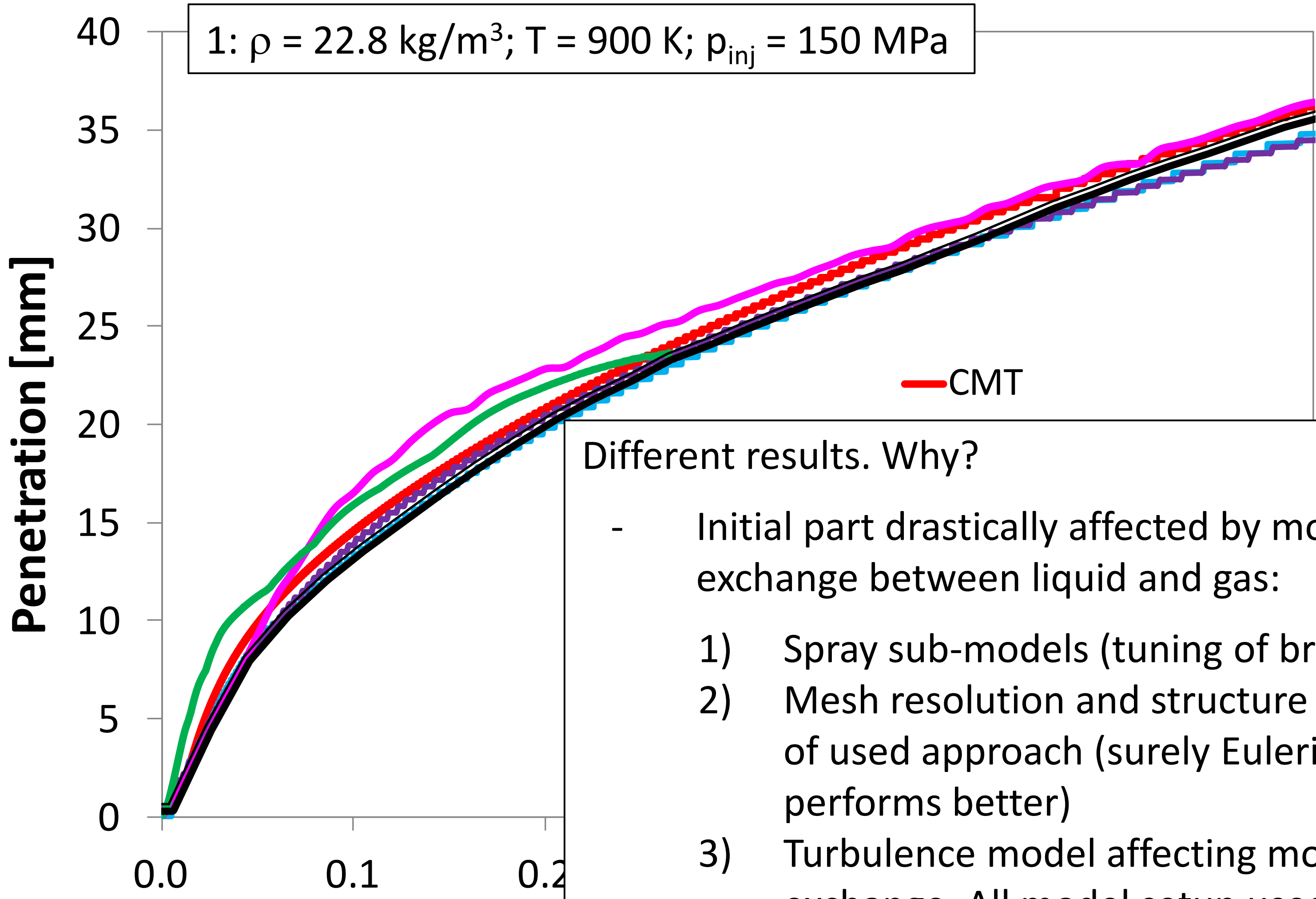


For a proper prediction of combustion process:

- Ignition delay: vapor penetration up to 30 mm (mixing and scalar dissipation rate)

-Flame lift-off : mixture fraction distribution, velocity, turbulence

Baseline condition: vapor penetration vs time



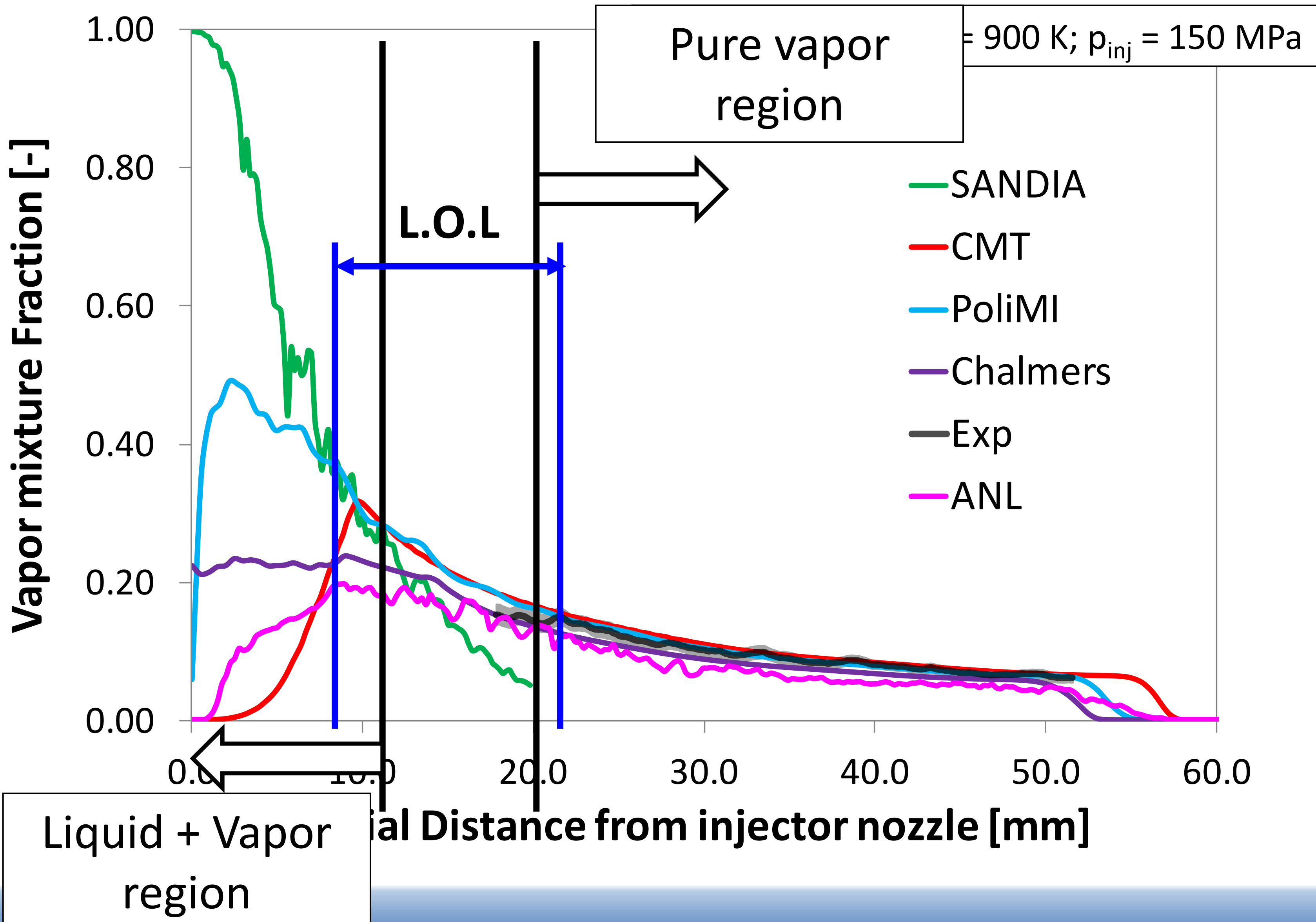
Different results. Why?

- Initial part drastically affected by momentum exchange between liquid and gas:
  1) Spray sub-models (tuning of breakup)
  2) Mesh resolution and structure and effect of used approach (surely Eulerian model performs better)
  3) Turbulence model affecting momentum exchange. All model setup used are different.
  4) Please suggest….

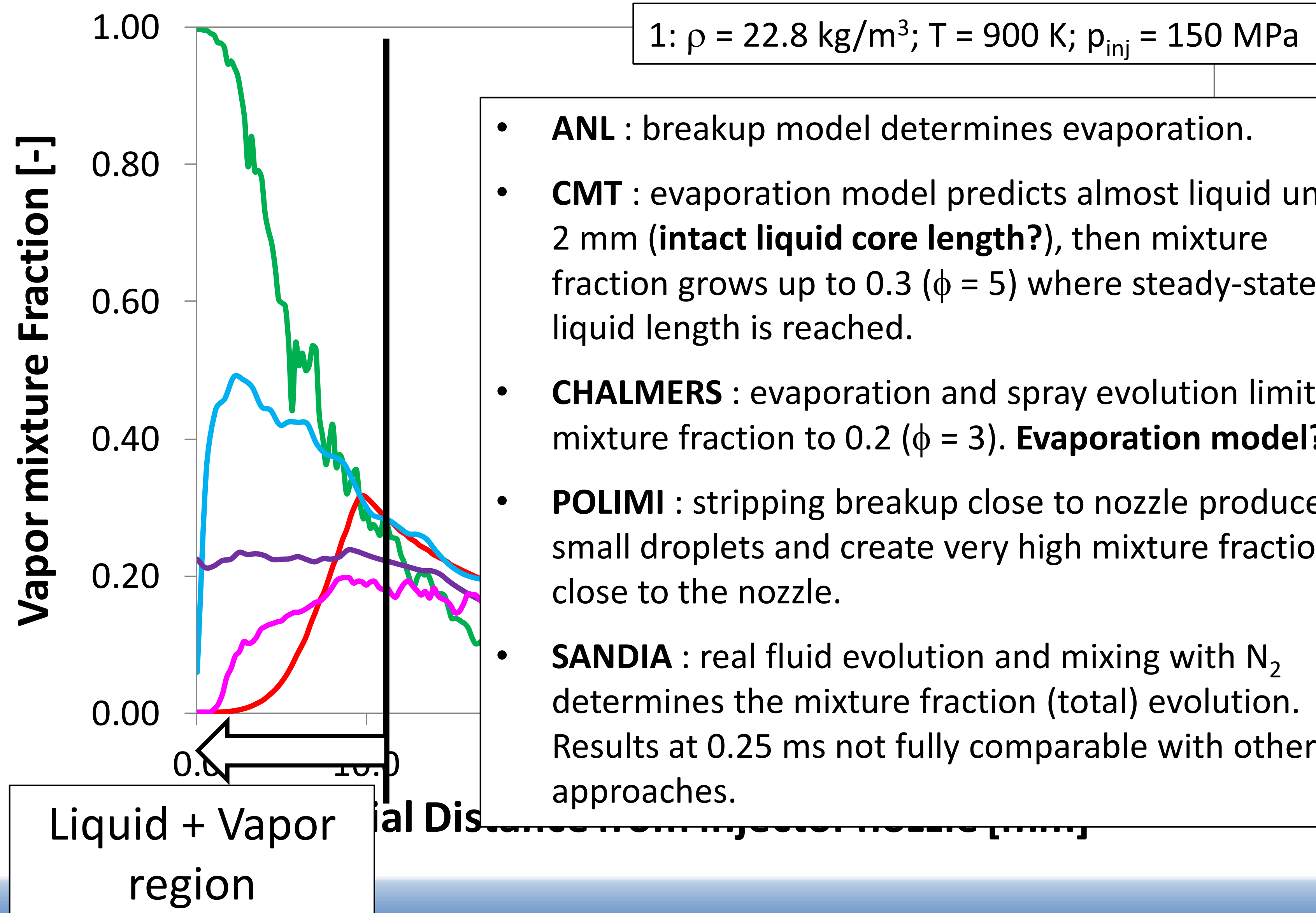
Baseline condition: vapor penetration vs time

- **More validation for baseline**
  - Vapor mixture fraction distribution: fuel-air mixing locally
  - Vapor mixture fraction variance distribution: scalar dissipation rate and turbulence-chemistry interaction
  - Velocity field: momentum exchange

Baseline condition: axial mixture fraction at 1.5 ms

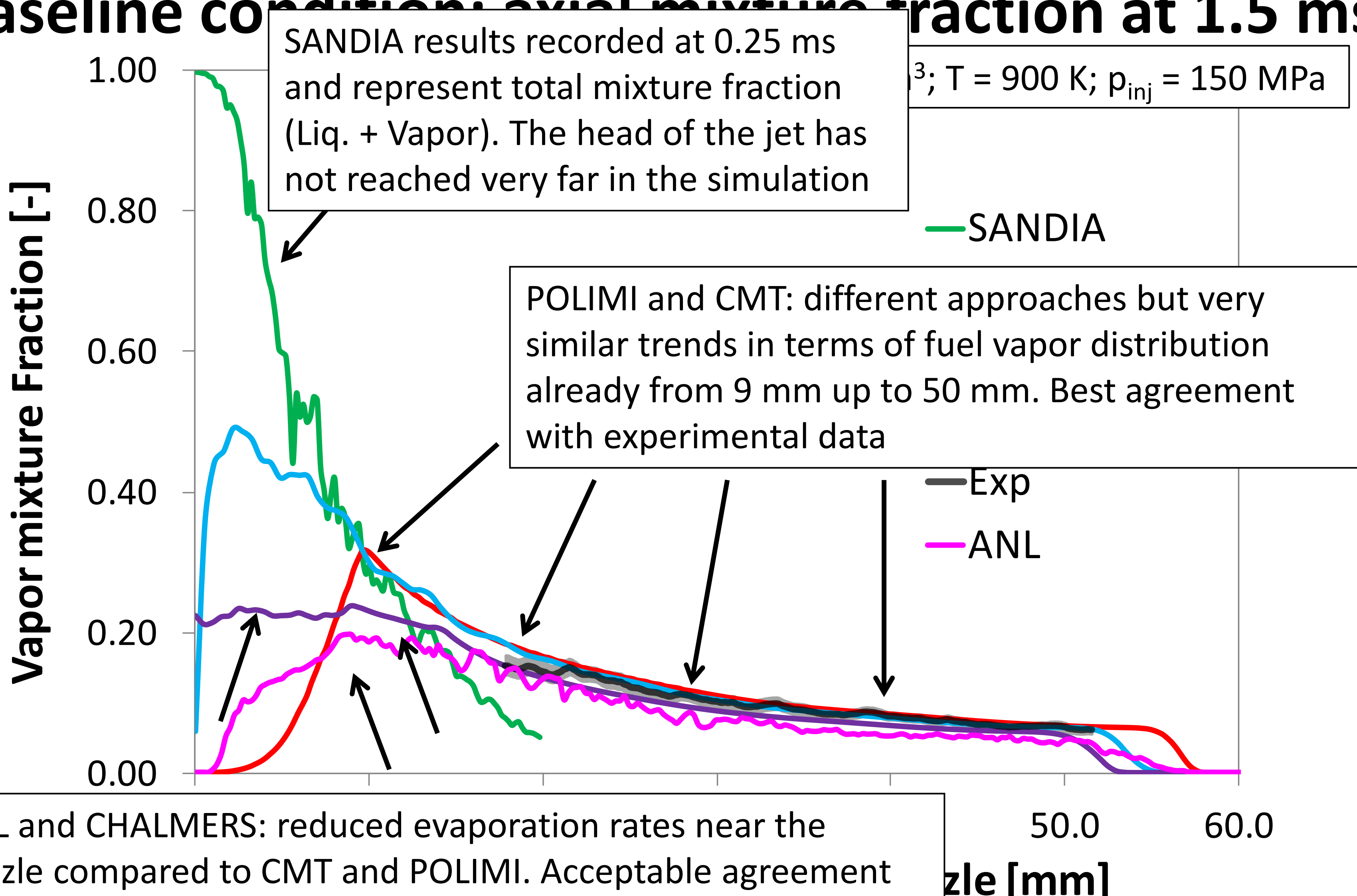


Baseline condition: axial mixture fraction at 1.5 ms



- **ANL** : breakup model determines evaporation.
- **CMT** : evaporation model predicts almost liquid until 2 mm (**intact liquid core length?**), then mixture fraction grows up to 0.3 (ϕ = 5) where steady-state liquid length is reached.
- **CHALMERS** : evaporation and spray evolution limits mixture fraction to 0.2 (ϕ = 3). **Evaporation model?**
- **POLIMI** : stripping breakup close to nozzle produces small droplets and create very high mixture fractions close to the nozzle.
- **SANDIA** : real fluid evolution and mixing with N_2 determines the mixture fraction (total) evolution. Results at 0.25 ms not fully comparable with other approaches.

Baseline condition: axial mixture fraction at 1.5 ms

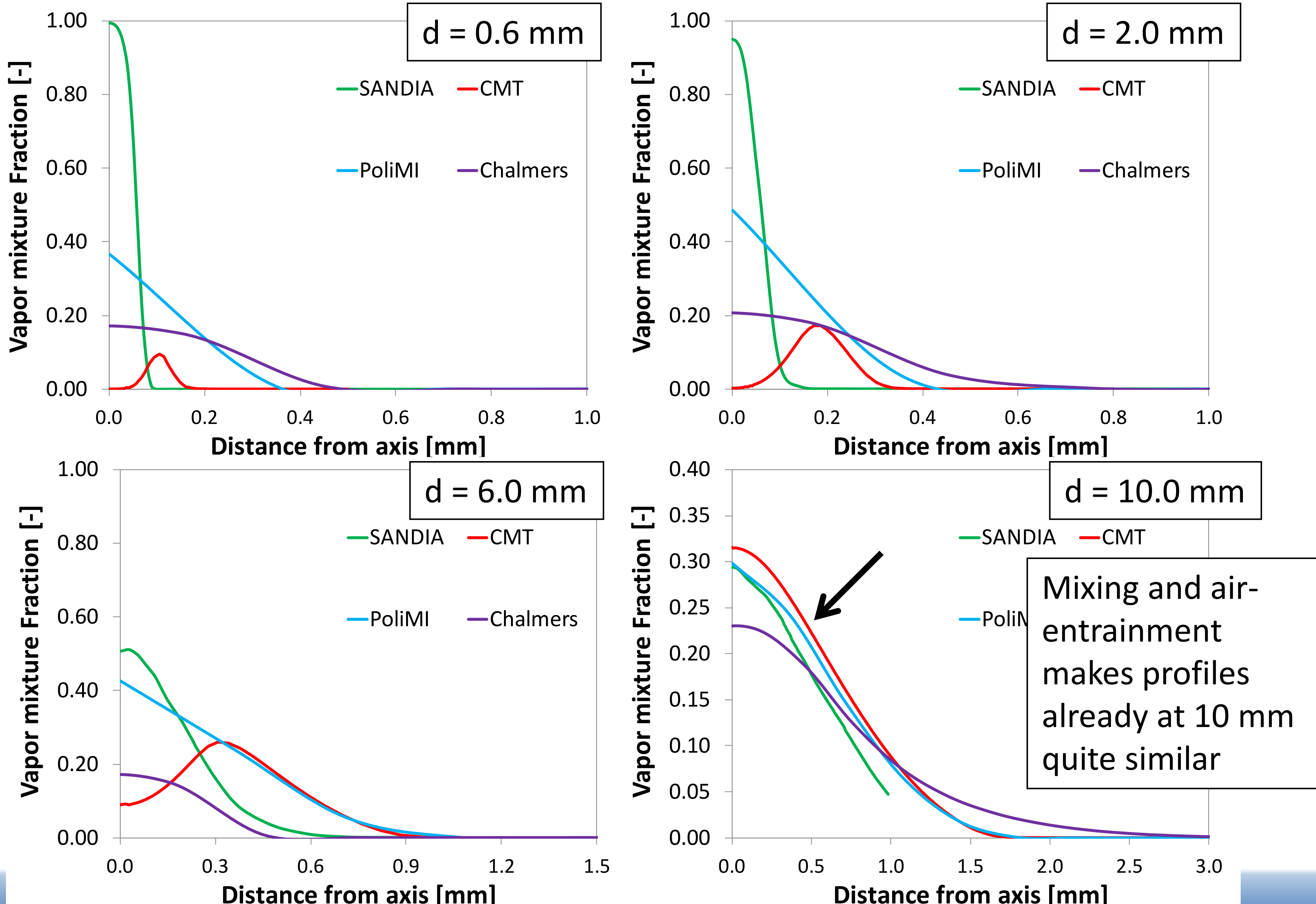


ANL and CHALMERS: reduced evaporation rates near the nozzle compared to CMT and POLIMI. Acceptable agreement (but slightly underestimated) with experimental data

Baseline condition: axial mixture fraction at 1.5 ms

- **Some general comments**
  - Very similar behavior in the far field
  - Very different behavior where liquid evolve, evaporates and mixes with air.
    1) Which is the most correct one?
       - Need to experimentally characterize fuel-air mixing in the near field
    2) When such differences in fuel-air mixing modeling can be relevant for combustion simulations?

Baseline condition: radial mixture fraction at 1.5 ms



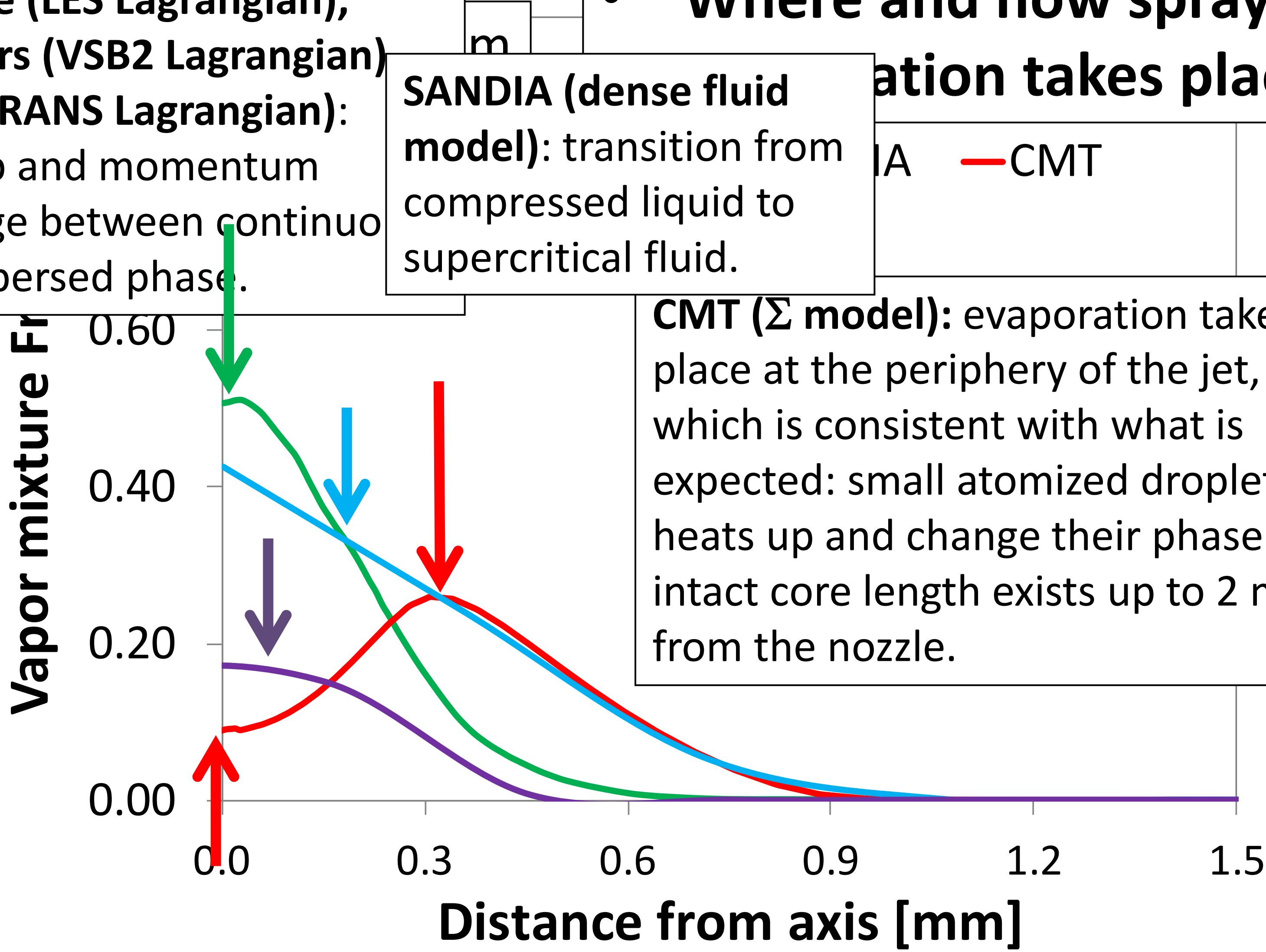
Baseline condition: radial mixture fraction at 1.5 ms

Argonne (LES Lagrangian), Chalmers (VSB2 Lagrangian) Polimi (RANS Lagrangian): breakup and momentum exchange between continuo and dispersed phase.

SANDIA (dense fluid model): transition from compressed liquid to supercritical fluid.

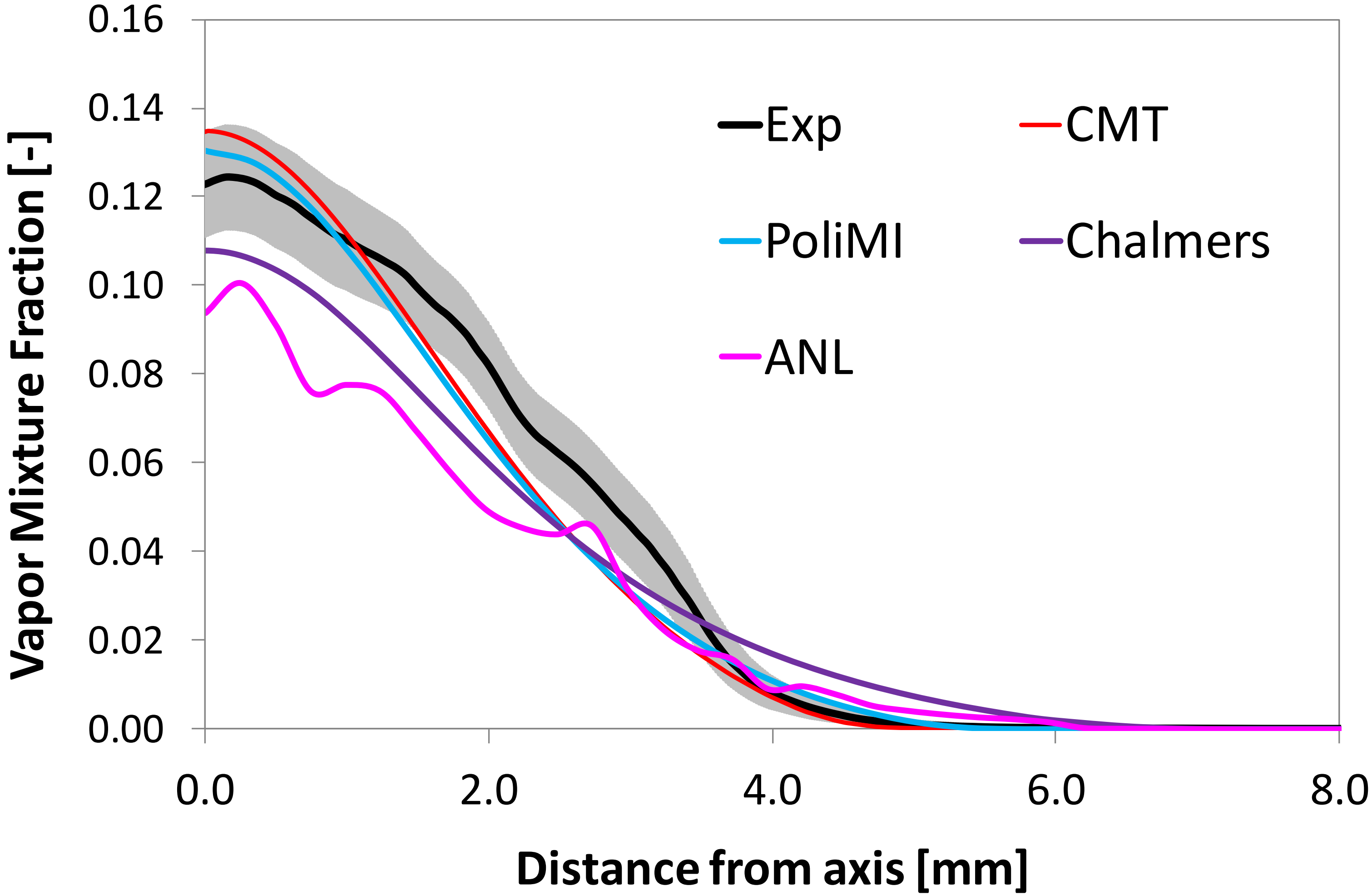
- **Where and how spray ation takes place?**

CMT (Σ model): evaporation takes place at the periphery of the jet, which is consistent with what is expected: small atomized droplets heats up and change their phase. An intact core length exists up to 2 mm from the nozzle.

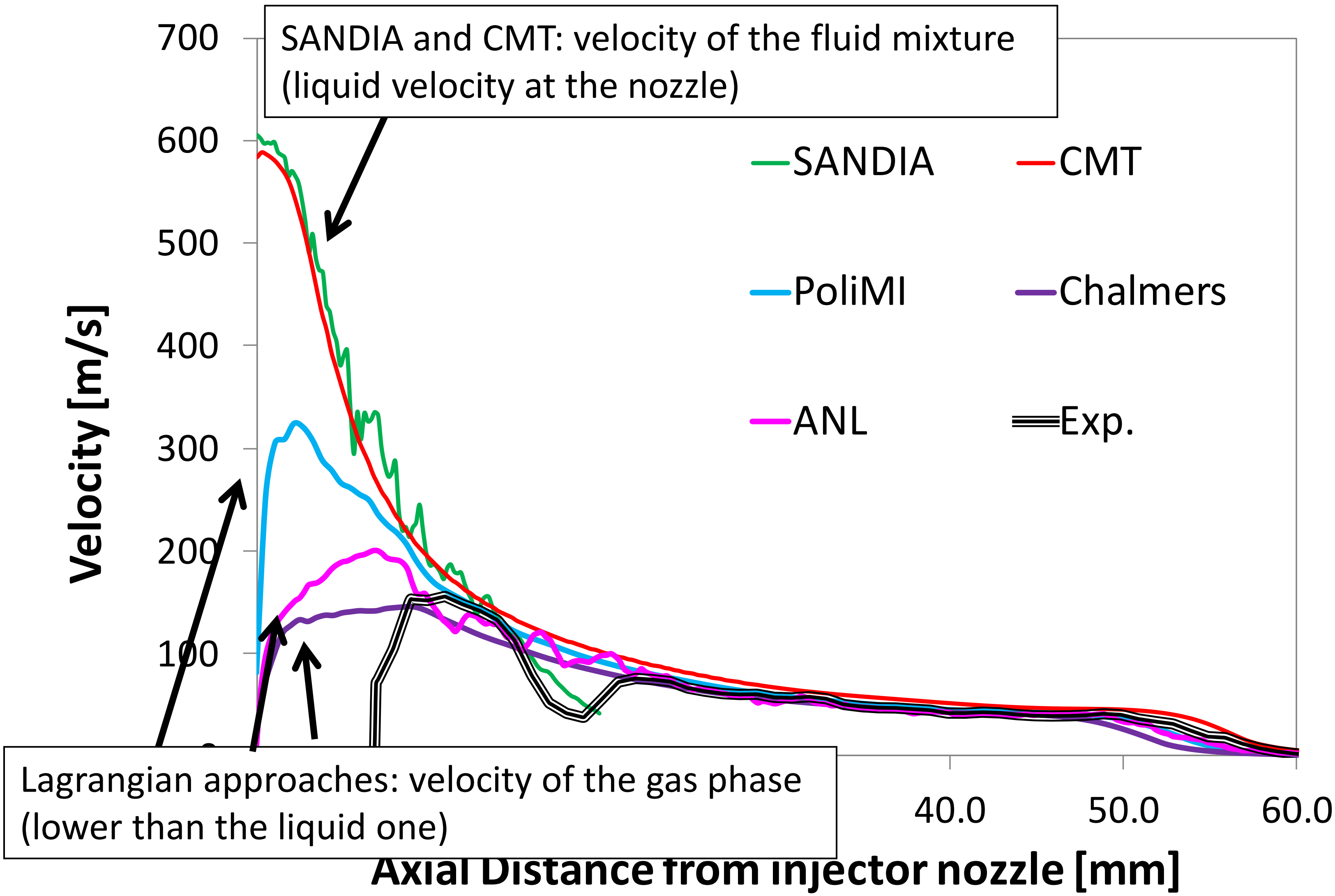


Baseline condition: radial mixture fraction at 1.5 ms

- Validation: radial distributions at 25 mm distances from injector

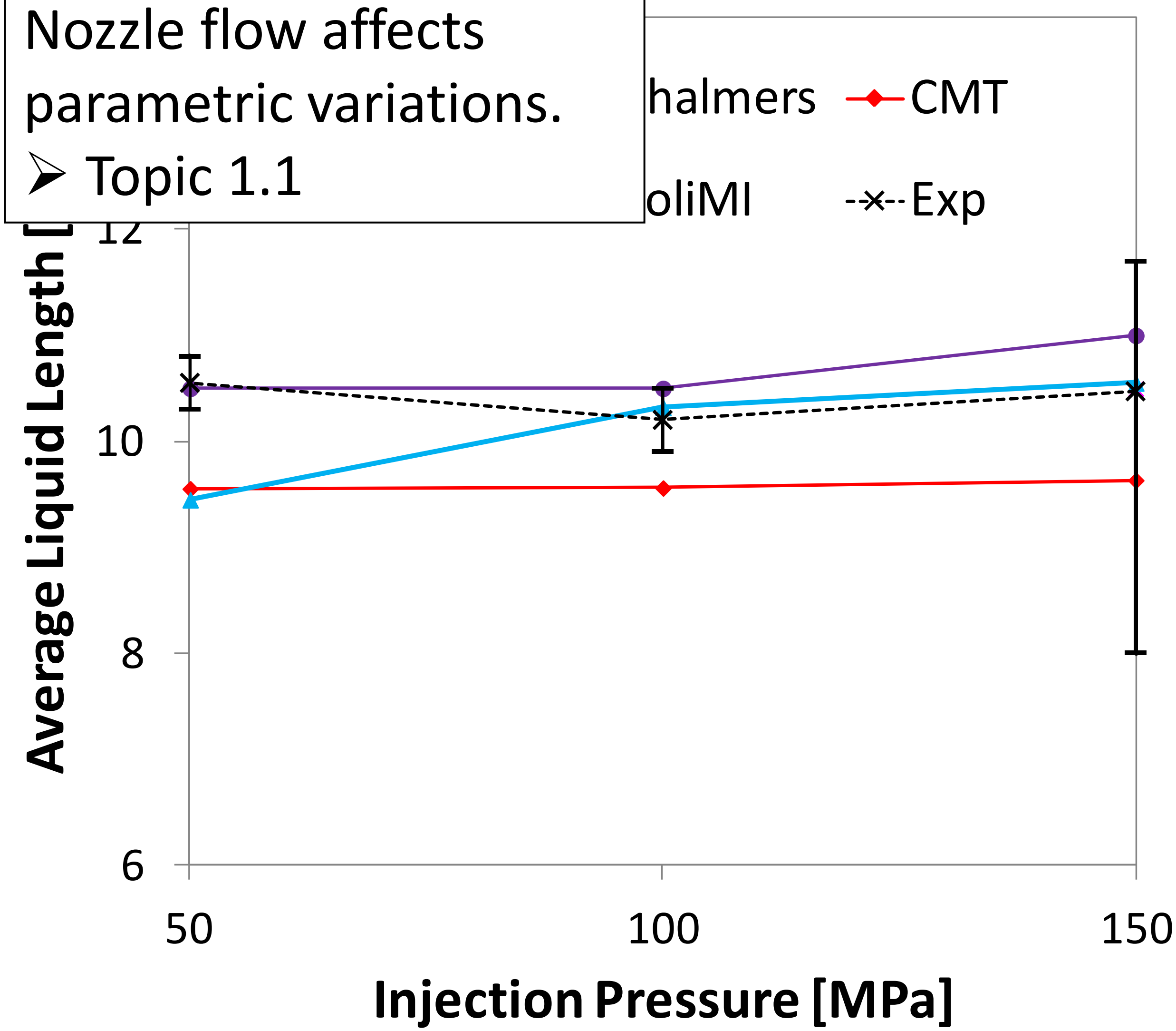


Baseline condition: axial velocity along injector axis at 1.5 ms



Parametric variations : Liquid length

Nozzle flow affects parametric variations.
➢ Topic 1.1



Injection pressure

#	T [K]	ρ [kg/m³]	p_{inj} [Mpa]
1	900	22.8	150
2	900	22.8	100
3	900	22.8	50

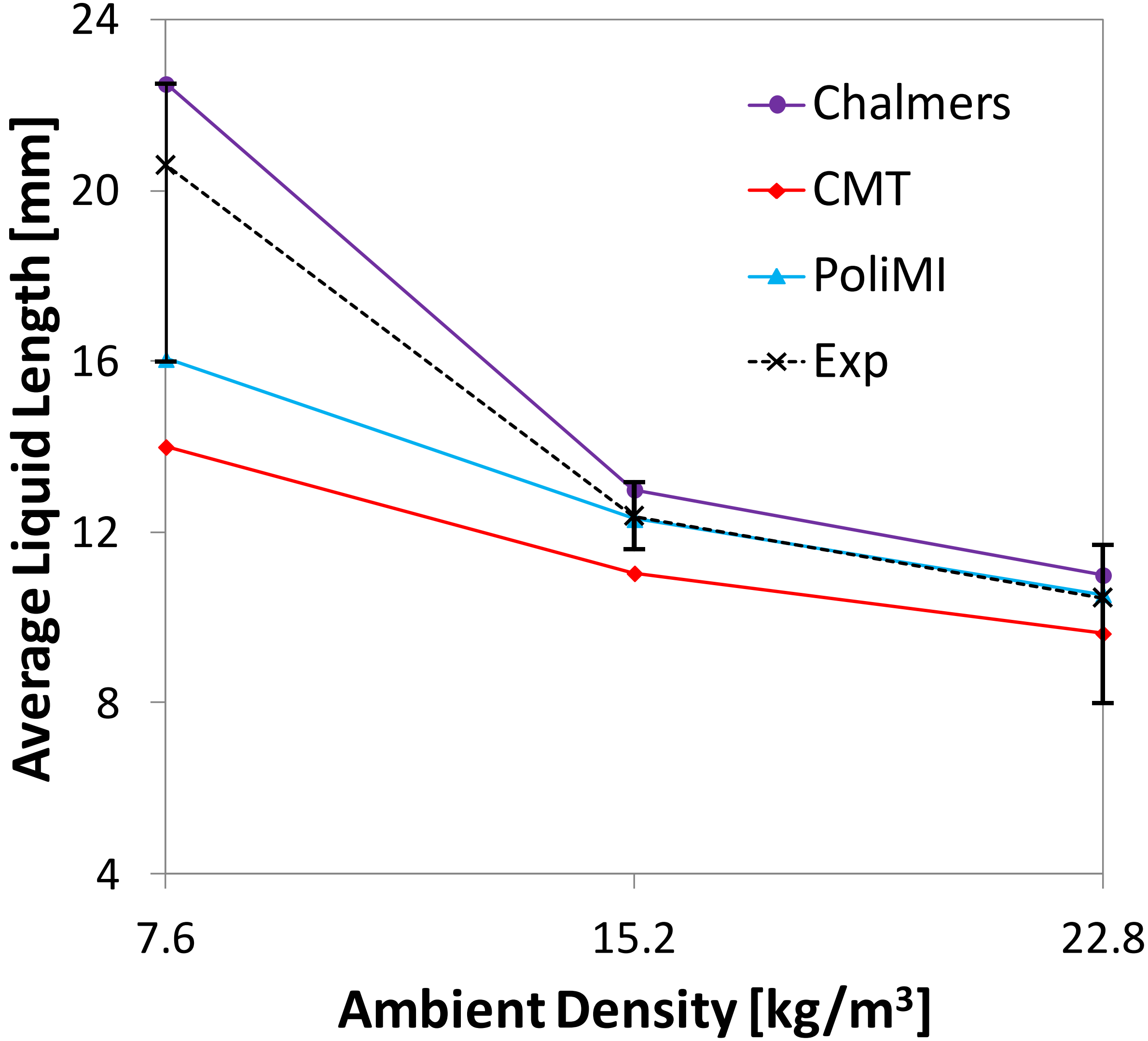
Momentum transfer and breakup affecting steady-state spray penetration.

CHALMERS results always within the expected experimental values;

POLIMI : good agreement at 100 and 150 MPa. Breakup model resposable for bad behavior at 50 MPa.

CMT: underestimation. Atomization model?

Parametric variations : Liquid length



Ambient density

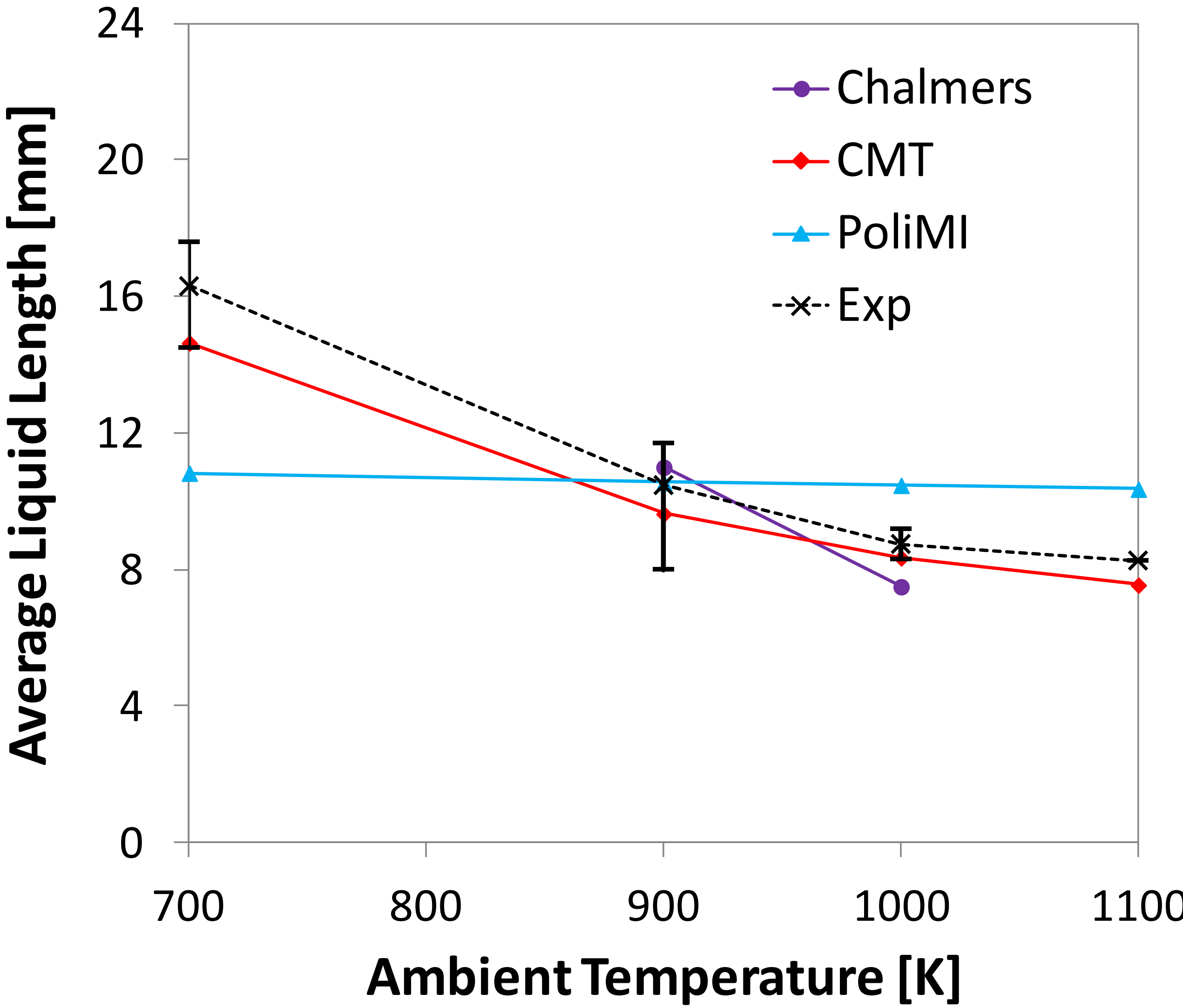
#	T [K]	ρ [kg/m³]	p_{inj} [Mpa]
1	900	22.8	150
4	900	7.6	150
5	900	15.2	150

Drag and breakup affect variation of liquid length with ambient density. Nozzle flow is not expected to play a big influence.

All models reproducing properly experimental trends.

Parametric variations : Liquid length

Ambient temperature



#	T [K]	ρ [kg/m³]	p_{inj} [Mpa]
1	900	22.8	150
6	700	22.8	150
7	1000	22.8	150
8	1100	22.8	150

Droplet diameter evolution (breakup) affects evaporation rate and, consequently, the steady state liquid length.

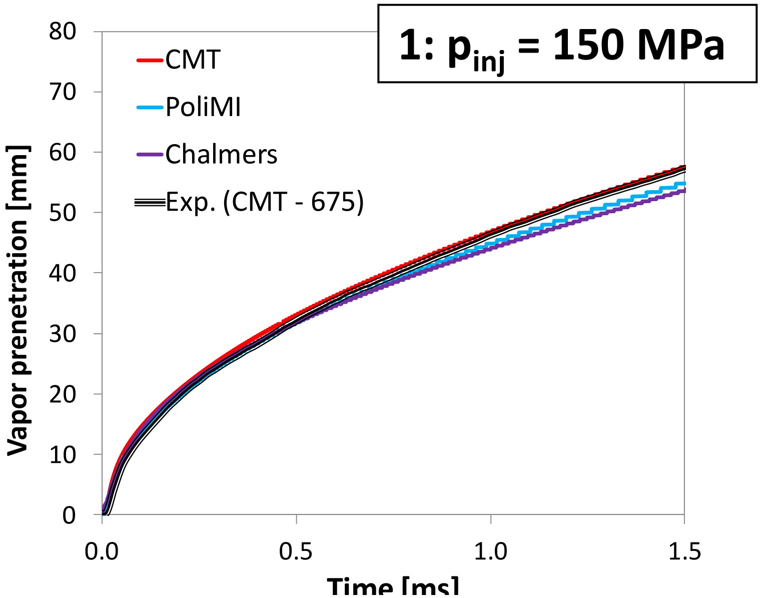
CMT: agreement is very good.

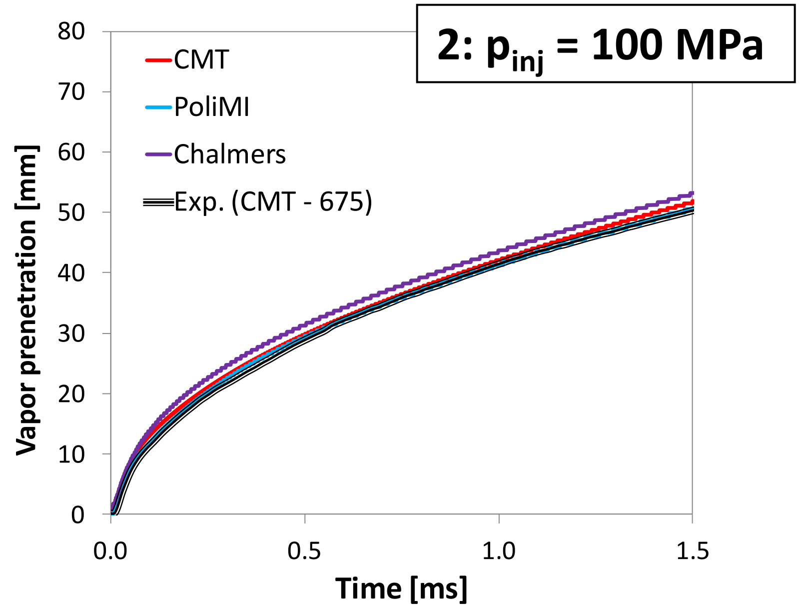
CHALMERS: trend reproduced

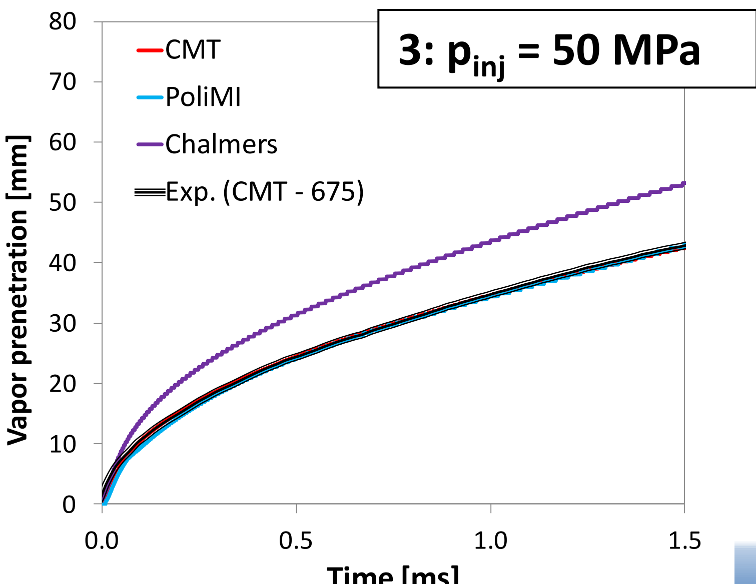
POLIMI: breakup model not suitable to reproduce such variation.

1/2/3	T = 900 K	ρ = 22.8 kg/m³

Injection pressure effect: vapor penetration





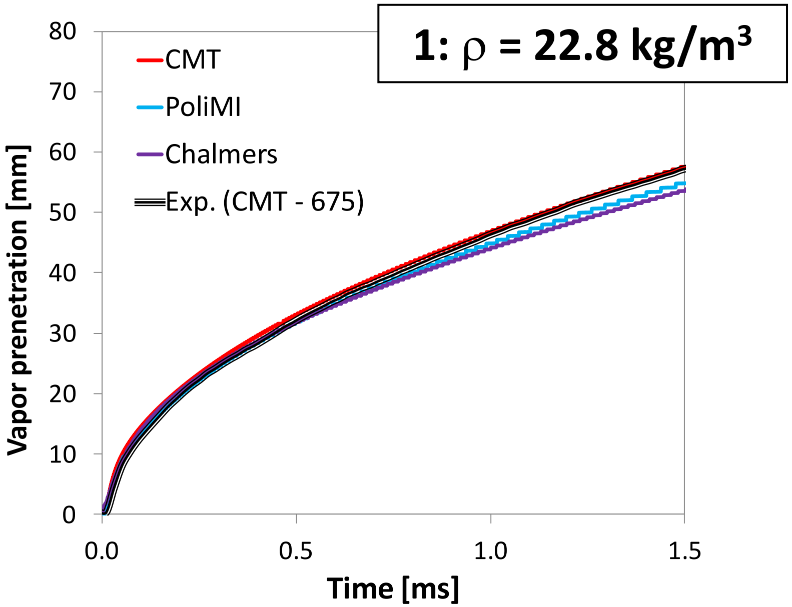


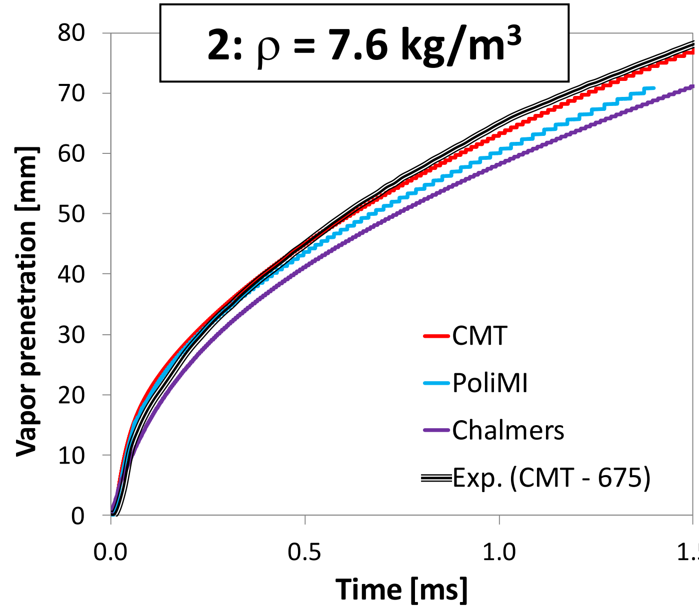
Vapor penetration mainly affected by momentum transfer to the gas phase and is reduced consistently with injection pressure.

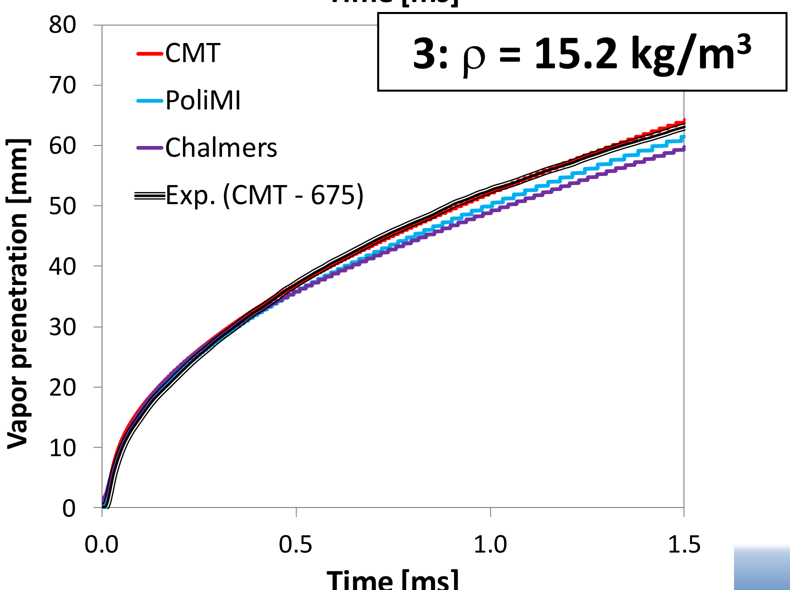
- CMT and POLIMI following rather well the experimental trend;
- Momentum transfer in VSB2 model?
- Steady state liquid penetration prediction not an issue for reproducing vapor evolution.

1/4/5	T = 900 K	p_{inj} = 150 MPa

Ambient density: vapor penetration





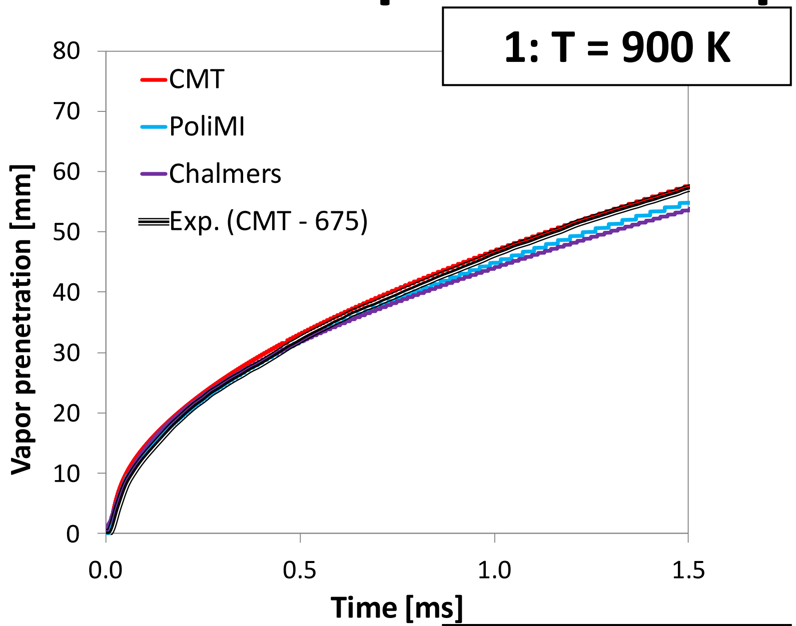


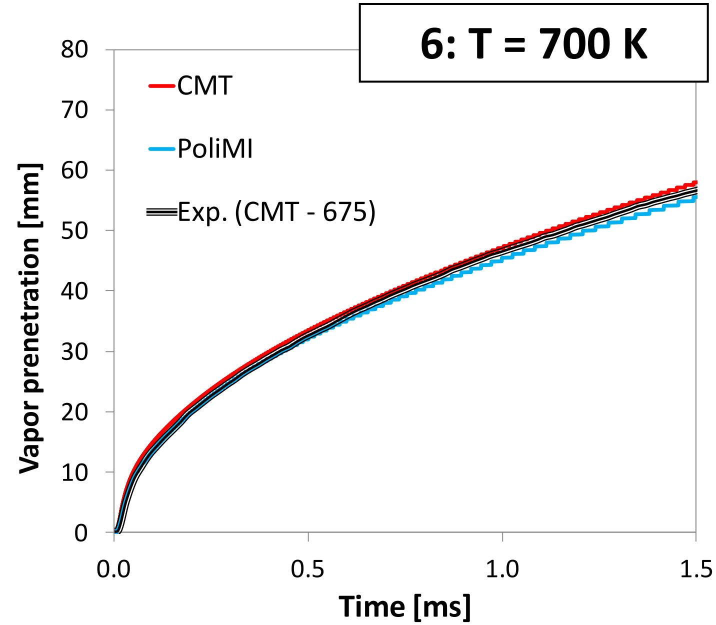
Spray dynamics (drag force) affects vapor penetration.

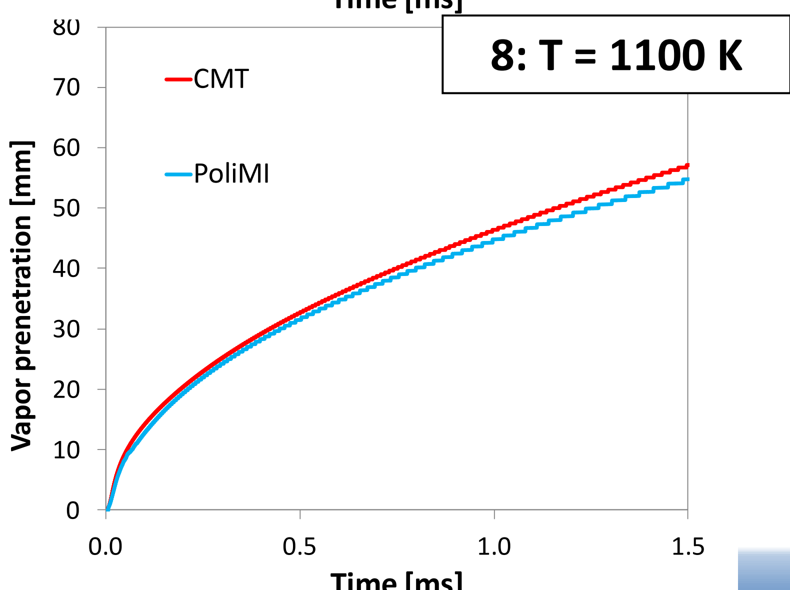
- Rather good agreement achieved by all the approaches.
- Consistent results by different institutions for the three different conditions (trends persist).

1/6/8	$\rho = 22.8\ kg/m^3$	$p_{inj} = 150$ MPa

Ambient Temperature: vapor penetration



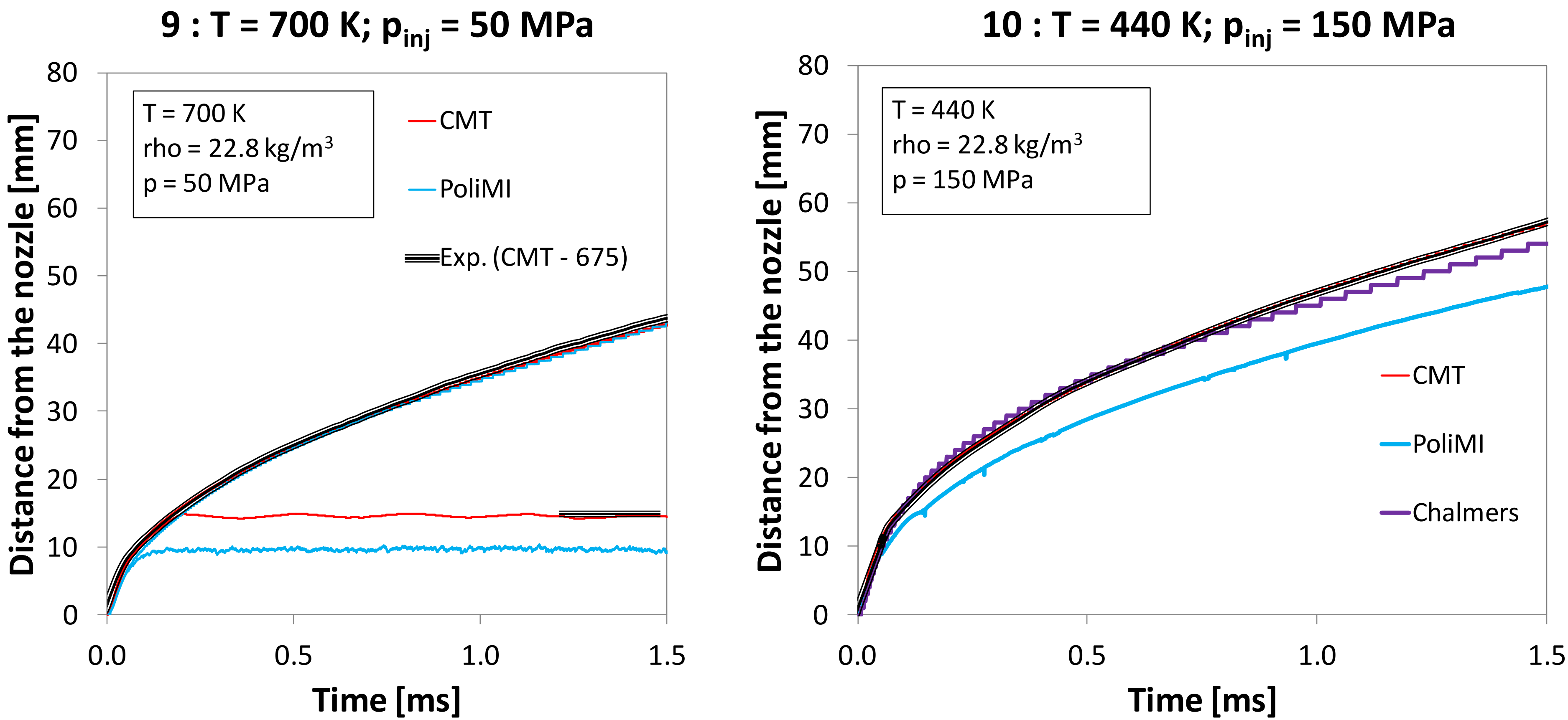




Vapor penetration cannot be drastically affected by spray breakup for constant injection pressure and density.

- Experimental trend properly reproduced at 700 and 900 K; consistent results at 1100 K

Low temperature; low pressure condition



- Still breakup model being an issue for liquid spray evolution for POLIMI
- Rather good results from Chalmers and CMT

Conclusions

- Results summary:
  - Capability of all the tested models to reproduce both vapor penetration and fuel air mixing in the far field.
  - Steady-state liquid penetration: rather good agreement from CMT and Chalmers.
- Suggested methodology for fuel-air mixing modeling:
  - Eulerian CMT in the near field + Lagrangian after liquid core atomization. ELSA model?
- Where to improve lagrangian models: Atomization needs a better description, accounting for nozzle flow conditions.
- New measurements: baseline mixture fraction and velocity closer to the liquid
- What if spray A was supercritical?