Validation of Lagrangian Spray Formation for Use in Internal Combustion Engines

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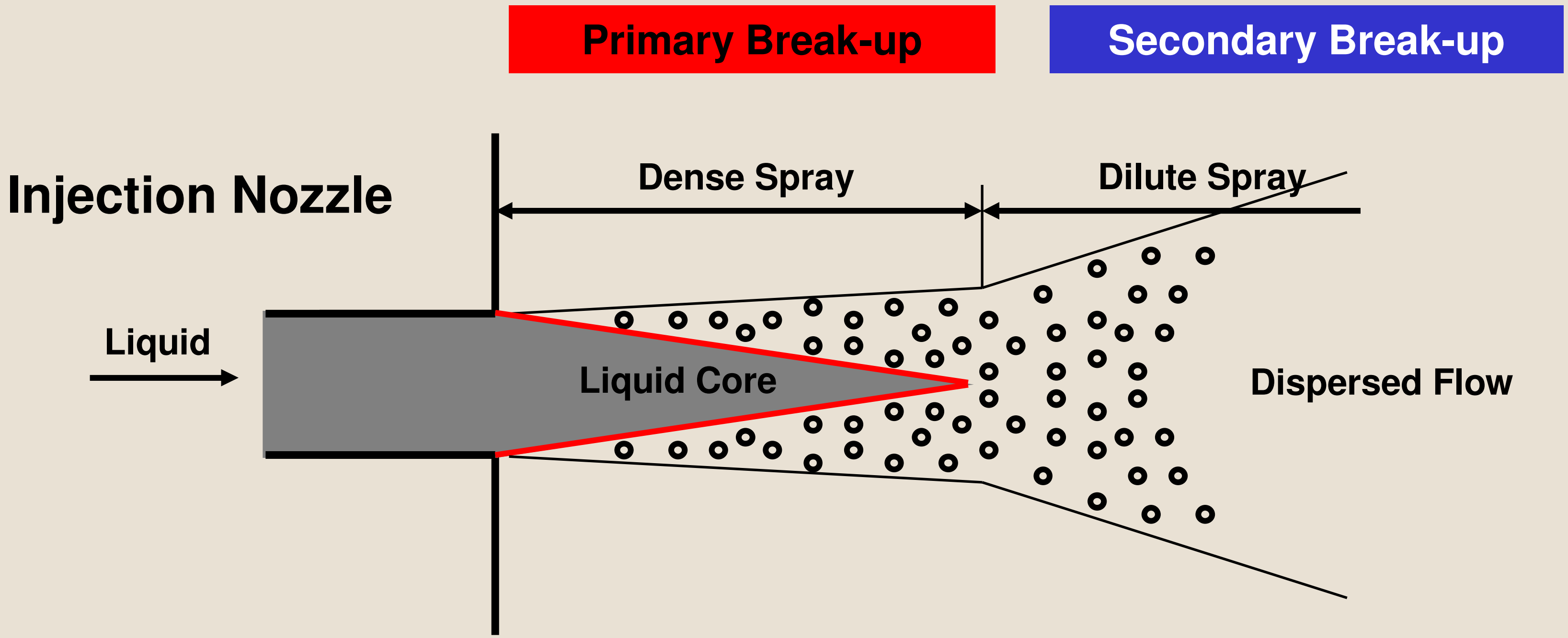
Overview

- Introduction
- Validation cases
  - Droplet in cross flow
  - Solid-cone injections
    - Non-evaporating sprays
    - Evaporating spray
  - Hollow-cone sprays
- Conclusions
- Outlook

Spray Formation



- Primary Break-up
  - In-nozzle effects (cavitation, turbulence induced disturbances)
  - Instabilities on liquid-gas interface lead to primary break-up
- Secondary Break-up
  - Droplets become unstable under the action of forces induced by their motion relative to the continuous phase

Secondary Droplet Break-up Models in CFX-11

In CFX-11 the following secondary break-up models are available

- **Reitz & Diwakar Model**(1987)
  - Wave instability on the surface of the drop leads to its breakup – “wave” breakup model
  - Bag and stripping regimes are taken into account
- **Schmehl Model** (2000)
  - Two stages of deformation are considered: first droplet undergoes deformation to a disc shape; later on the final destruction takes place
  - Experimental correlations are used for the breakup times

Secondary Droplet Break-up Models in CFX-11 (2)

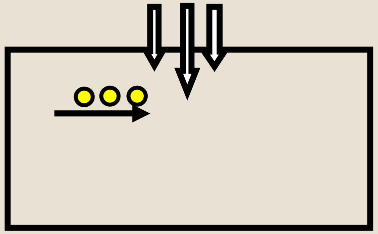
- **TAB Model** (O'Rourke, 1987)
  - Droplet is considered as a spring-mass system
  - Solve deformation equation for droplet
  - Droplet breaks up after maximum deformation
- **ETAB & CAB Model** (Tanner, 1997&2003)
  - Both models are based on the TAB model
  - Modification of the predicted child droplet sizes
  - Delay initial droplet breakup to mimic primary breakup

Note: Important input parameters for these models
(to be set up or defined from the primary breakup model)

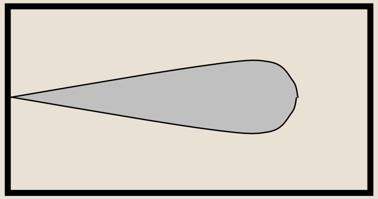
- Injection velocity
- Initial droplet diameter
- Initial spray angle

Overview about the Test Cases

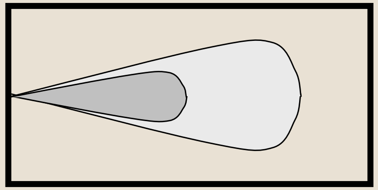
- **Droplet in a cross flow**
  - Liu et al. SAE Technical Paper, 930072 (1993).



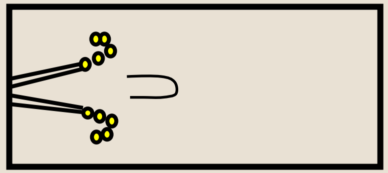
- **Non-evaporating spray into stagnant conditions**
  - Hiroyasu & Kadota. SAE paper 740715 (1974)
  - Schneider. CIMAC Congress (1995)
  - Lee & Park. Fuel, Volume 81, 2417-2423 (2002)
  - Confidential cases (Bosch)



- **Evaporating spray into stagnant surrounding**
  - Koss et al. IDEA periodic report, RWTH Aachen (1992)



- **Hollow-cone spray**
  - Schmidt et al. SAE paper, 1999-01-0496 (1999)

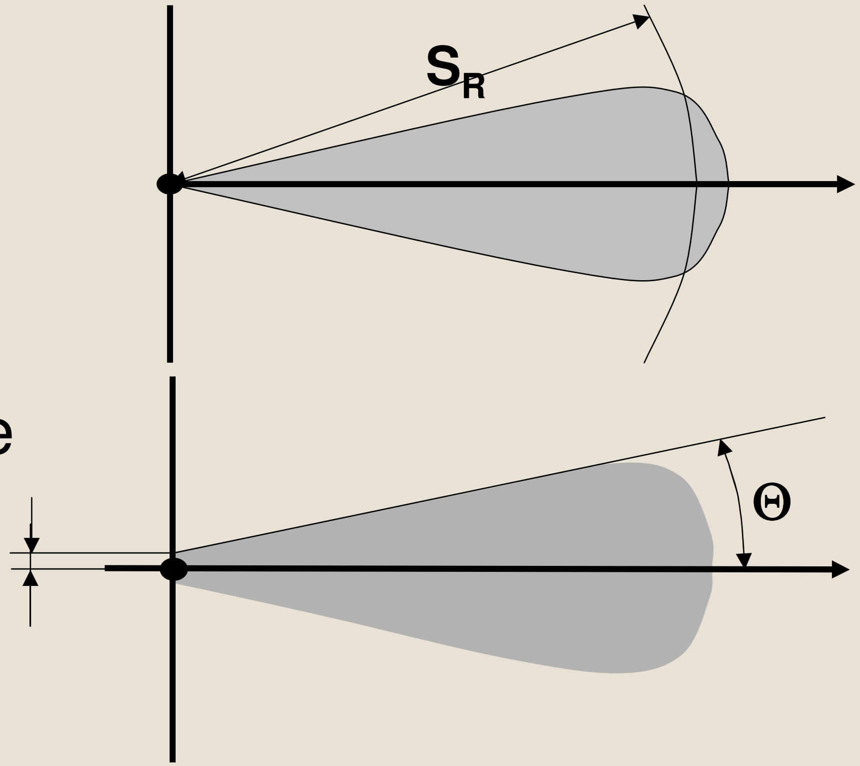


Sensitivity Studies

- Grid dependence
  - Grid size
  - Grid type (hex and prism elements)
  - Mesh movement
- Time step dependence
  - Eulerian time step
  - Lagrangian time step
- Dependence on number of computational particles
- Influence of initial turbulence flow field

Validation Criteria

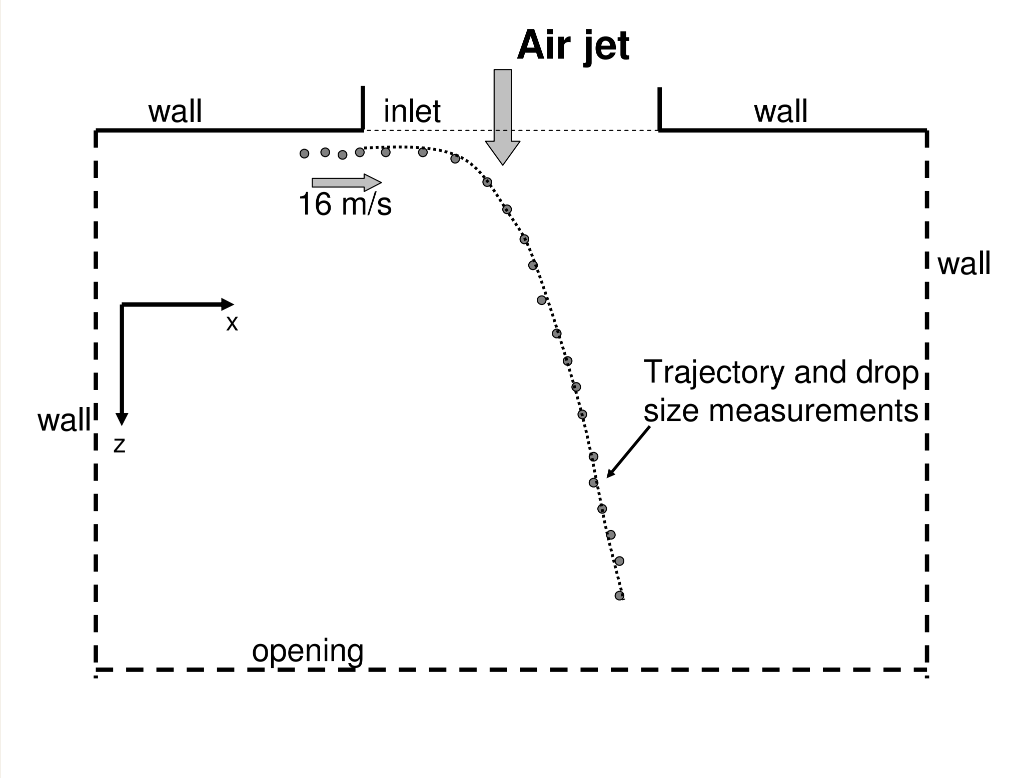
- Global criteria
  - Radial penetration depth (S_R)
  - Spray angle
  - User specified percentage of a total spray mass



- Local criteria
  - Droplet diameters
  - Droplet velocities
  - Droplet trajectories

Spray in Cross Flow: Set-Up

Liu, A.B, Mather, D. & Reitz, R.D. Modeling the Effects of Drop Drag and breakup on Fuel Sprays. SAE Technical Paper, 930072 (1993)



Case name	Air velocity (m/s)	Injected Weber Number
Case 2	59	37
Case 3	72	53
Case 4	100	102

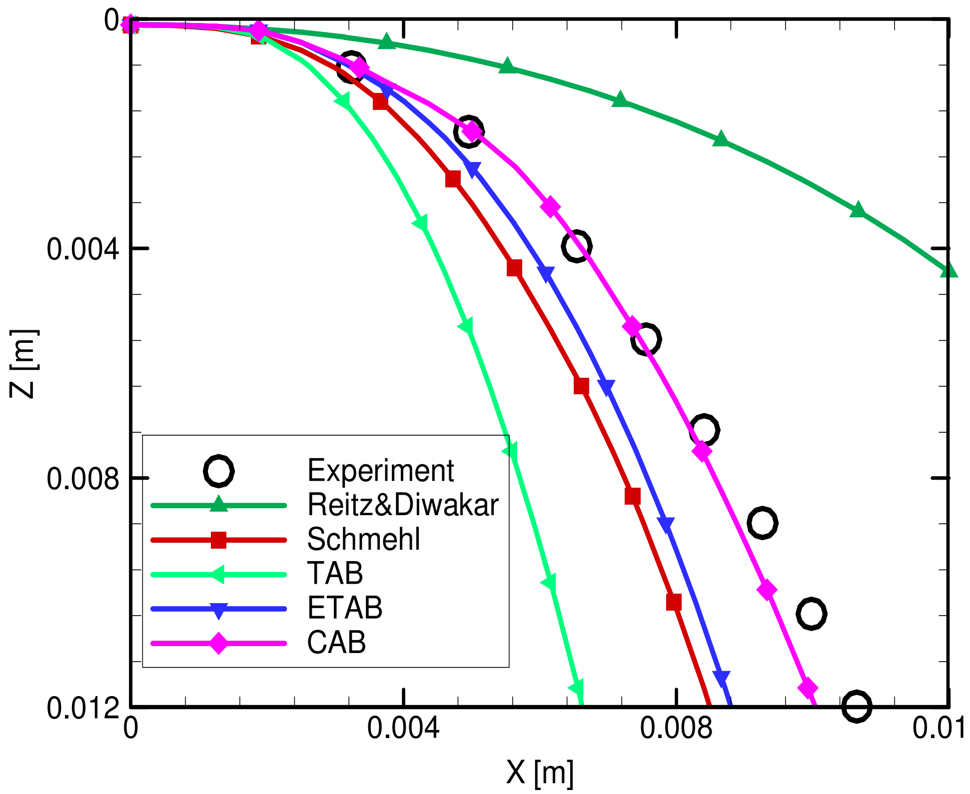
Liquid – **Benz UCF-I fuel**:
Density 824 kg/m^3

Steady state computations

Nozzle diameter =
Initial droplet diameter = 170 mkm

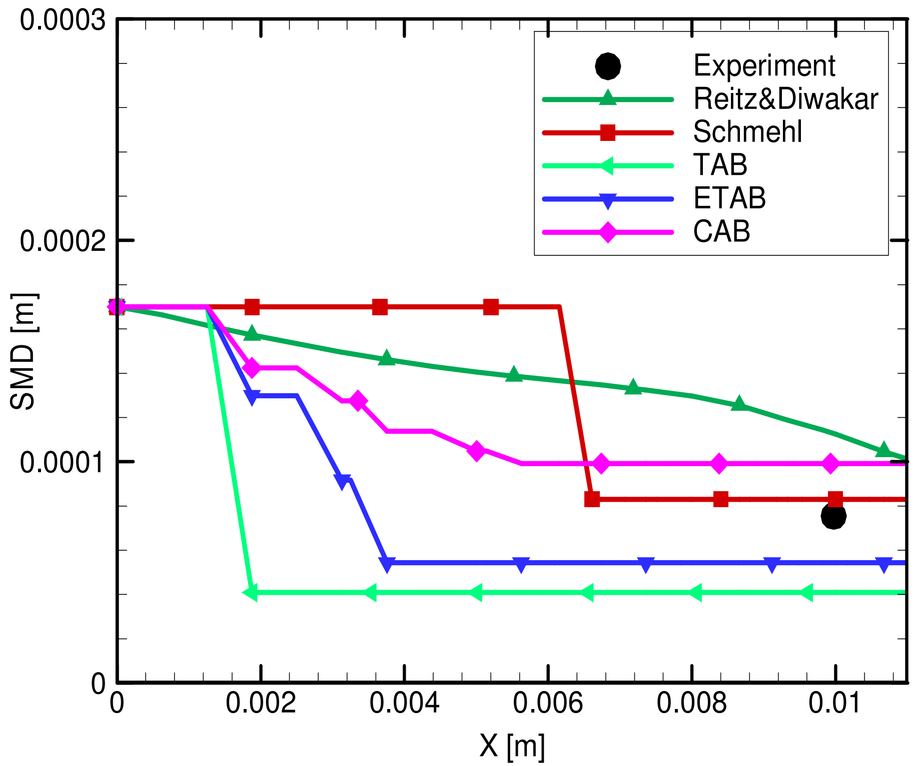
Spray in Cross Flow

We = 37



Droplet trajectories

SMD along trajectories

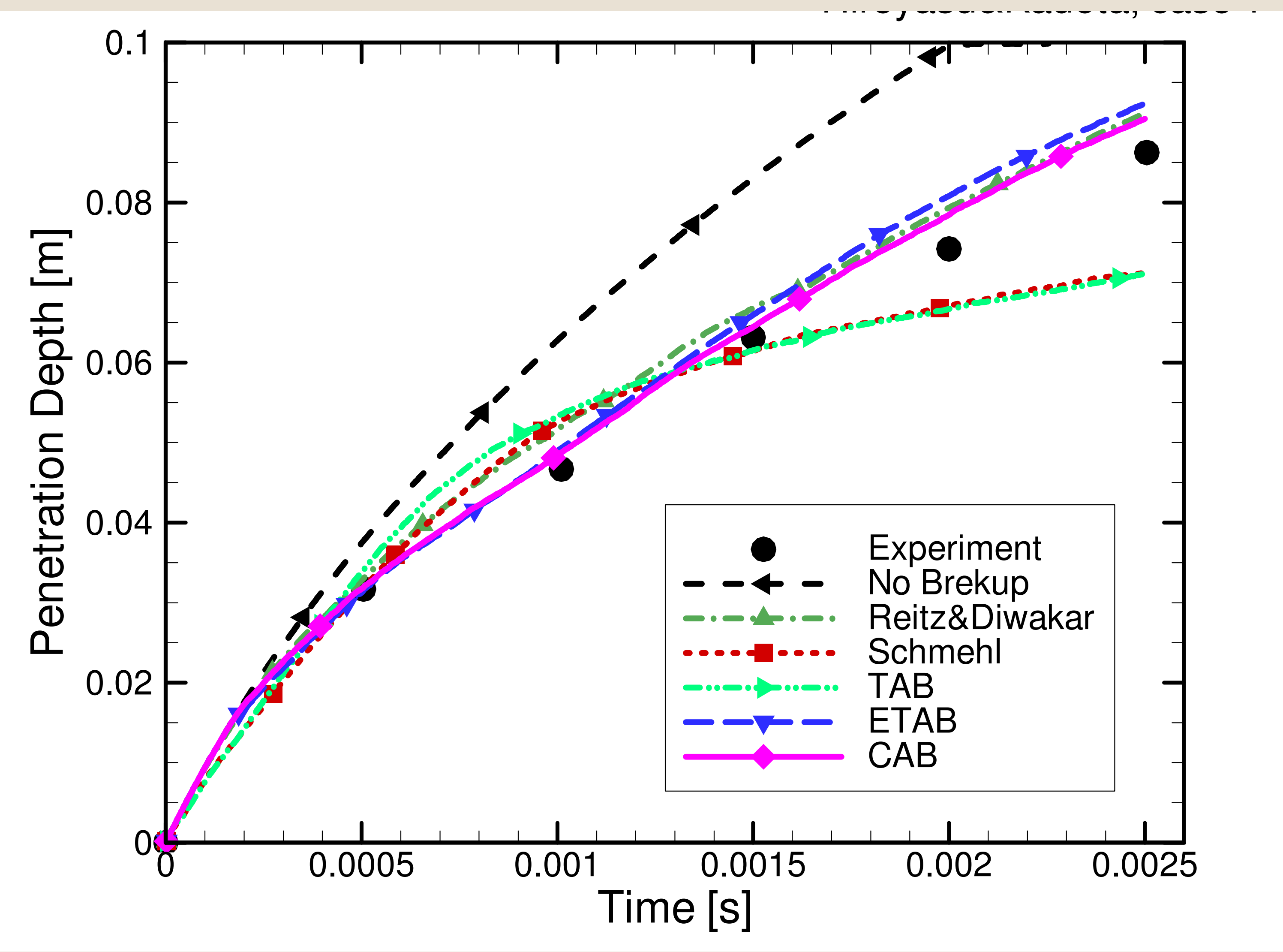


Conditions for Non-Evaporating Cases

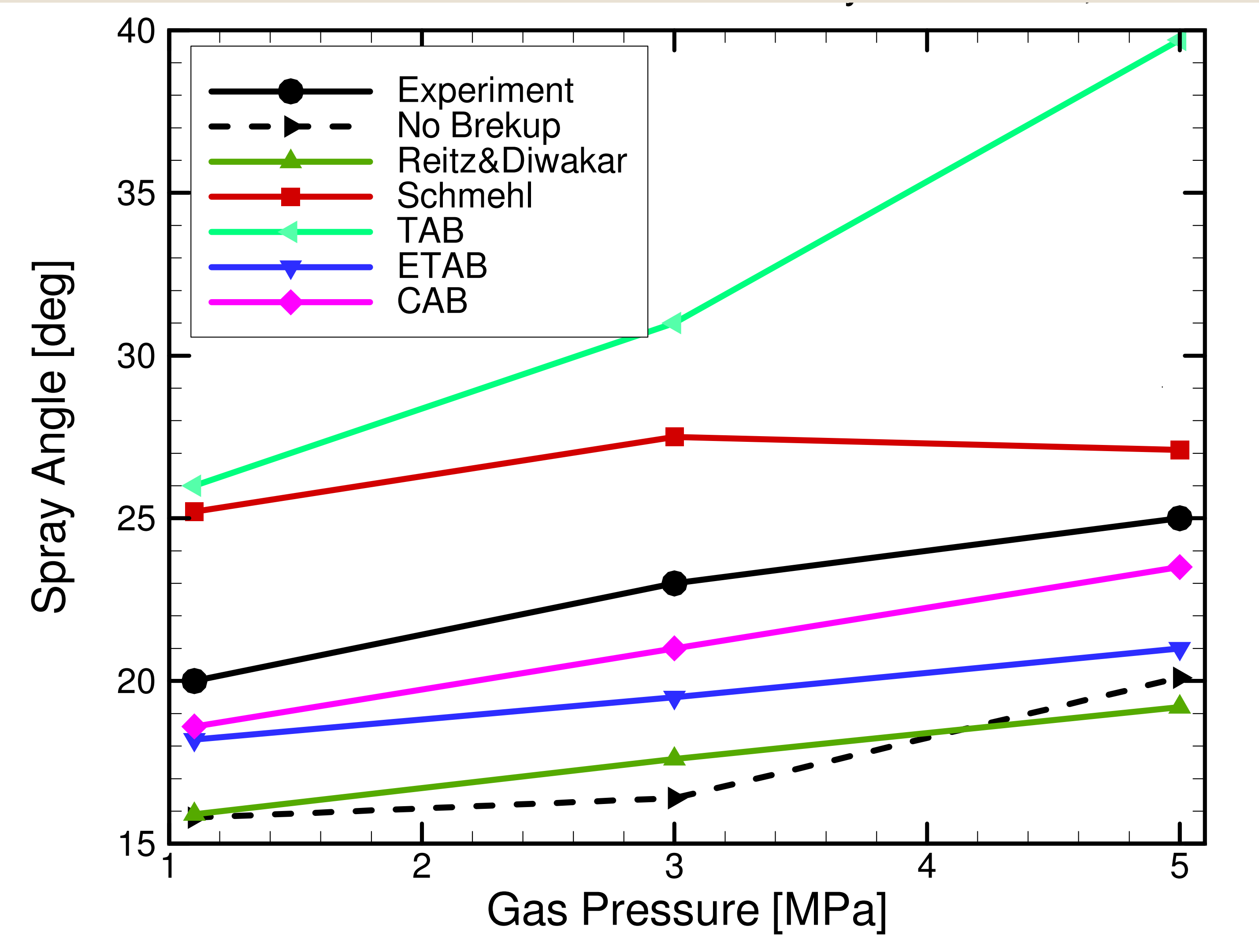
Case Reference	Hiroyasu & Kadota (1974)	Schneider (1995)	Lee&Park (2002)
Gas parameters			
Gas Type	N_2	N_2	Air
Temperature, K	300	395	300
Pressure, MPa	1.1, 3.0, 5.0	1.5	0.1
Fuel properties			
Fuel type	$C_{12}H_{26}$	$C_{12}H_{26}$	Diesel
Density, kg/m3	840	840	880
Spray parameters			
Injection velocity (m/s)	102, 90, 86	183	241.8, 266.2
Particle mass flow rate (g/s)	6.05, 5.36, 5.13	2.7	11.79, 14.4
Nozzle diameter (mm)	0.3	0.15	0.3
Injection Weber number	**1800, 4000, 6100**	**4100**	**1000, 1200**

Breakup Model Validation: Hiroyasu and Kadota, Case 1

We = 1800

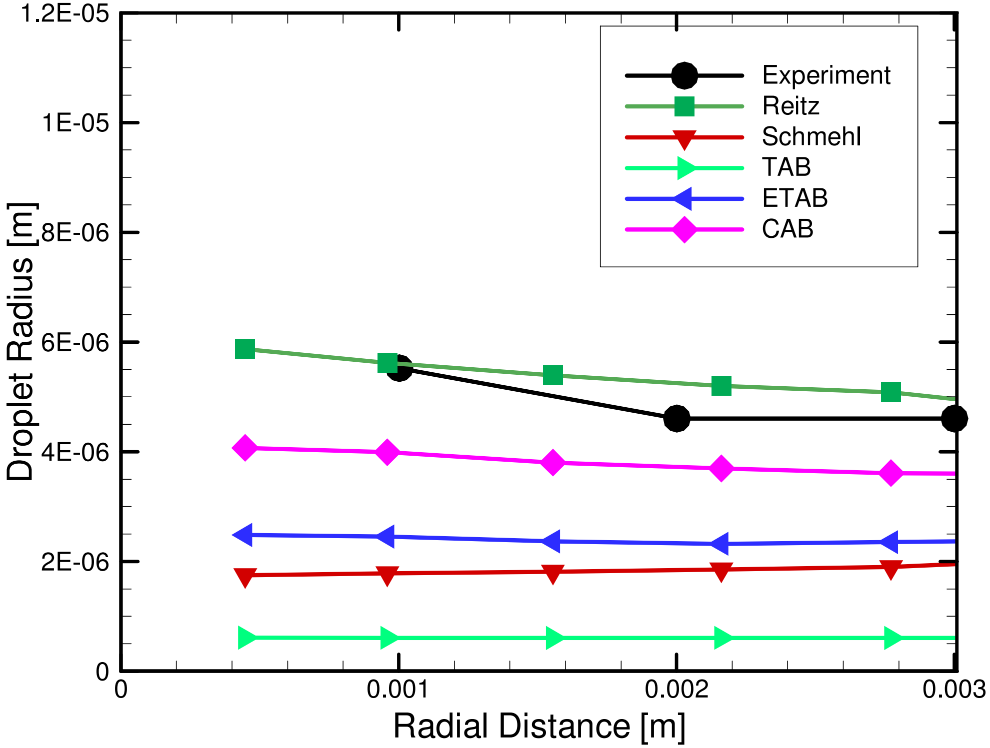


Breakup Model Validation: Hiroyasu and Kadota, Cases 1-3



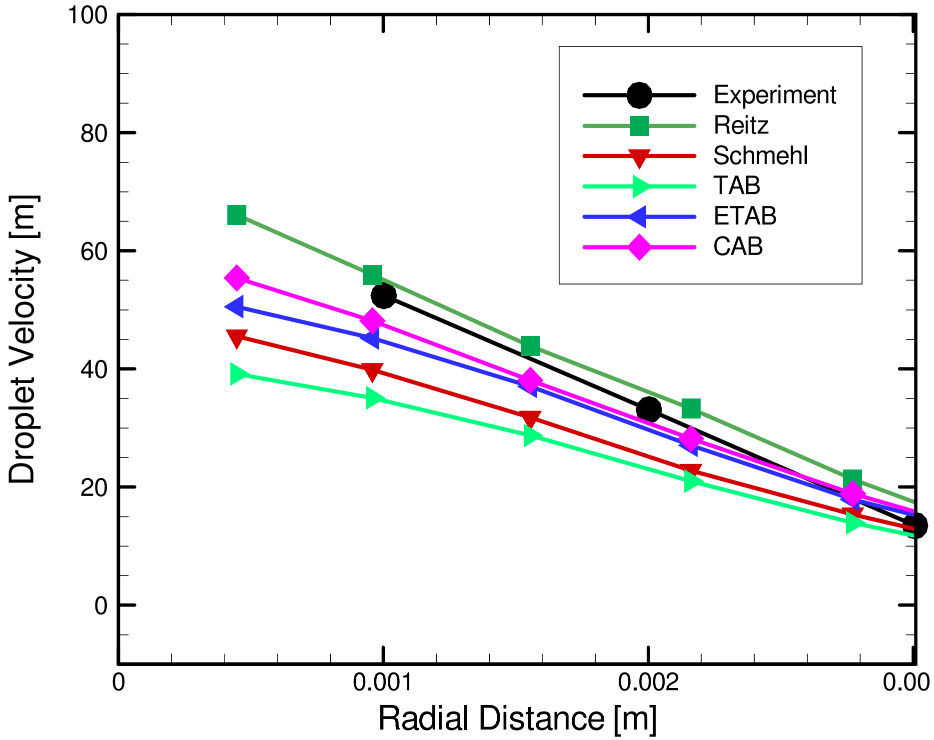
Case 1 **Case 2** **Case 3**

Breakup Model Validation: Schneider Experiment

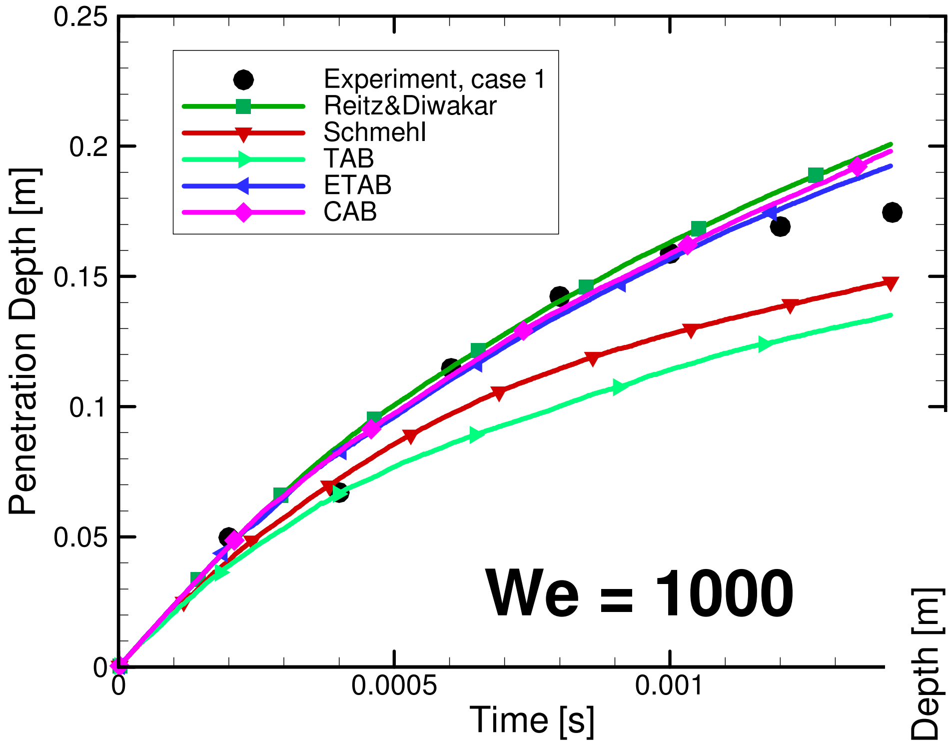


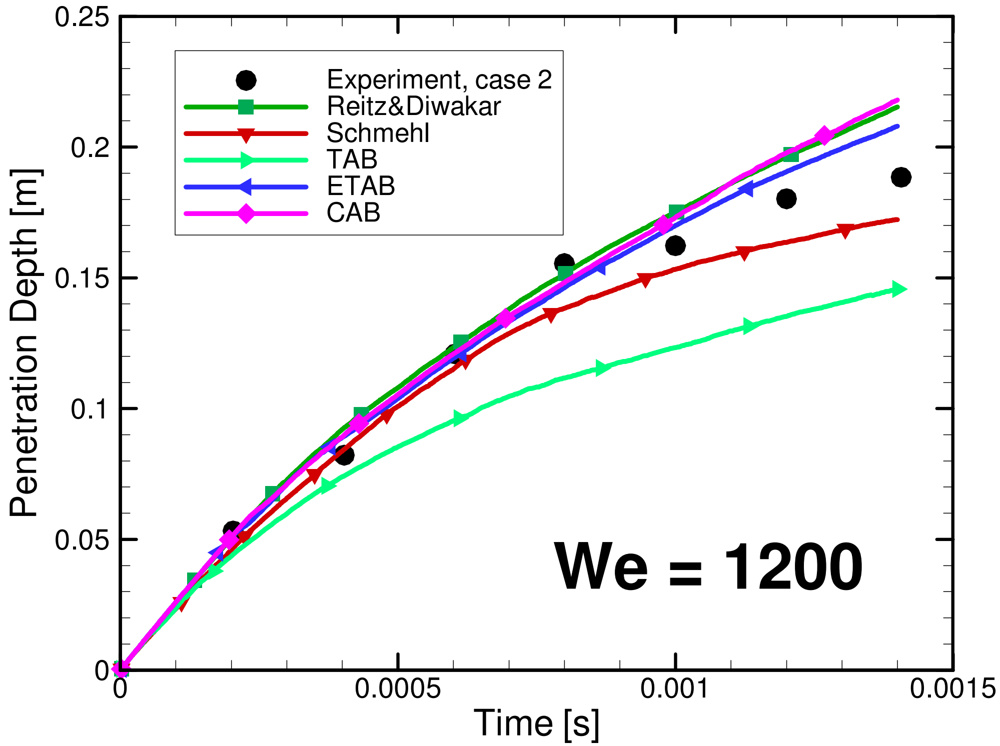
The mean droplet size @ 166d_0=25mm

The mean droplet velocity @ 166d_0=25mm



Breakup Model Validation: Lee & Park Experiment

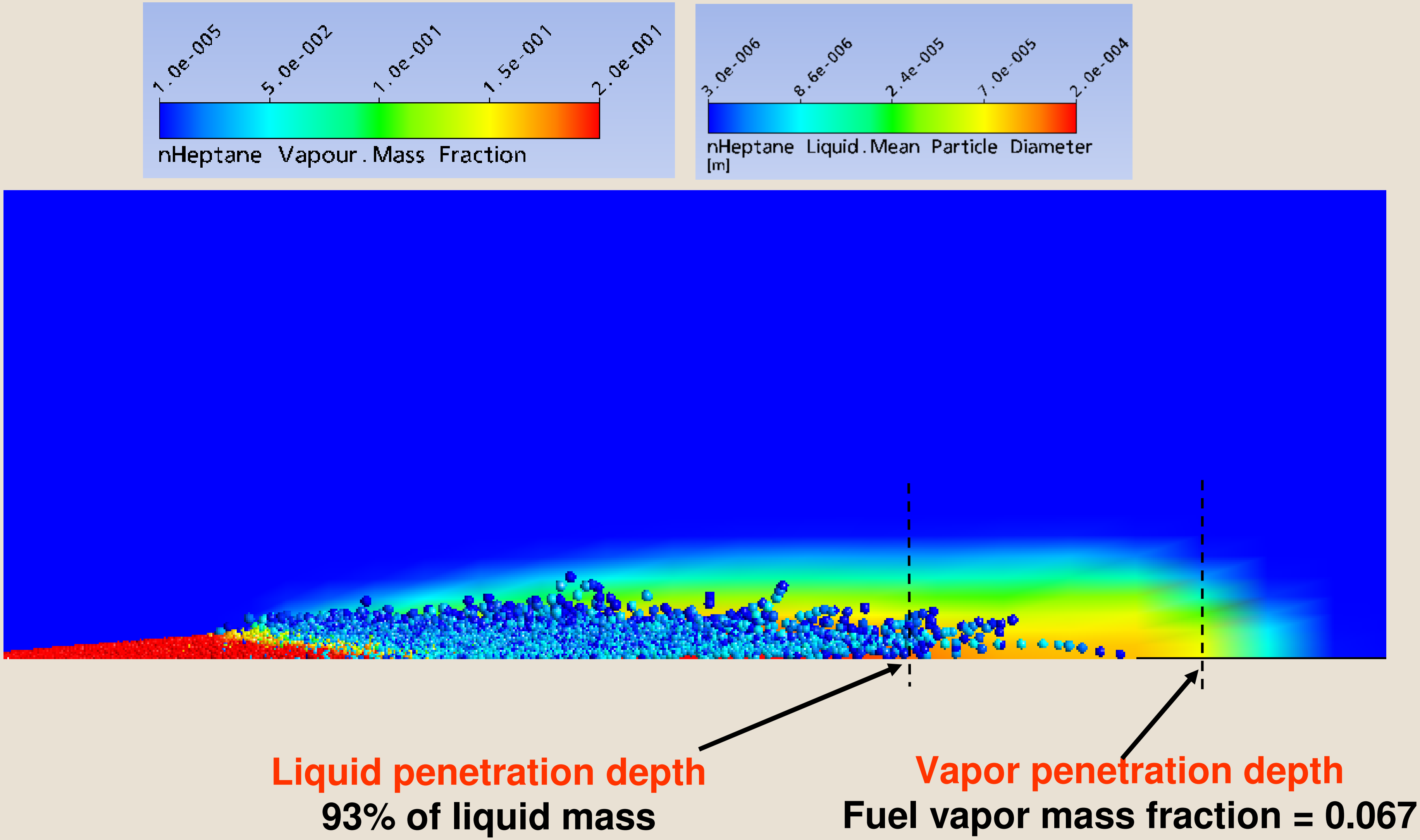




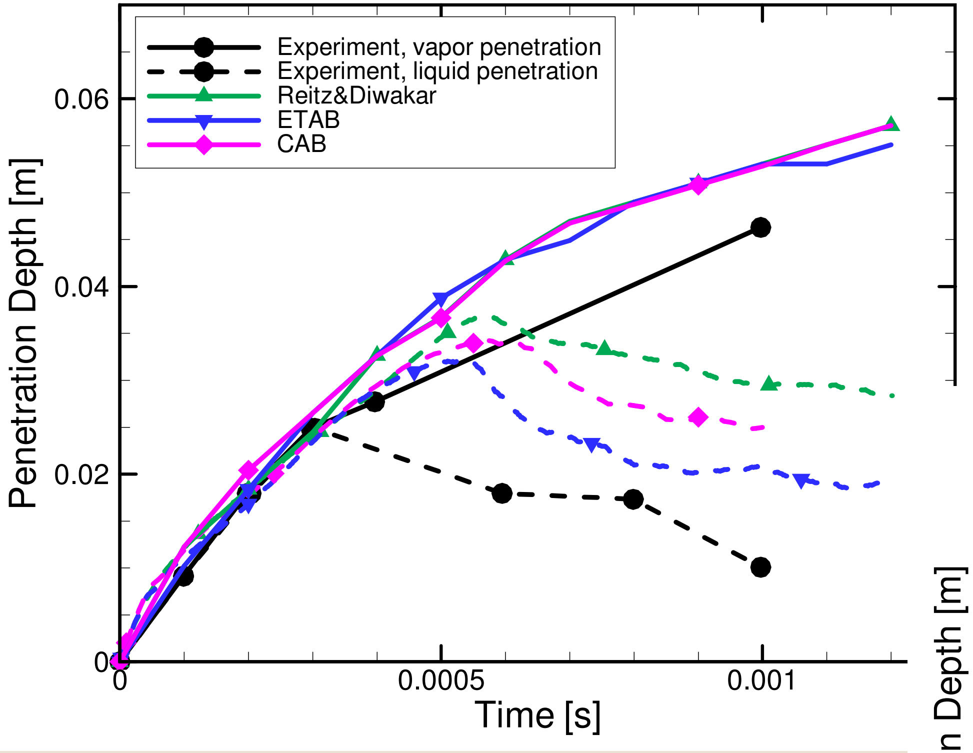
Conditions for Evaporating Spray

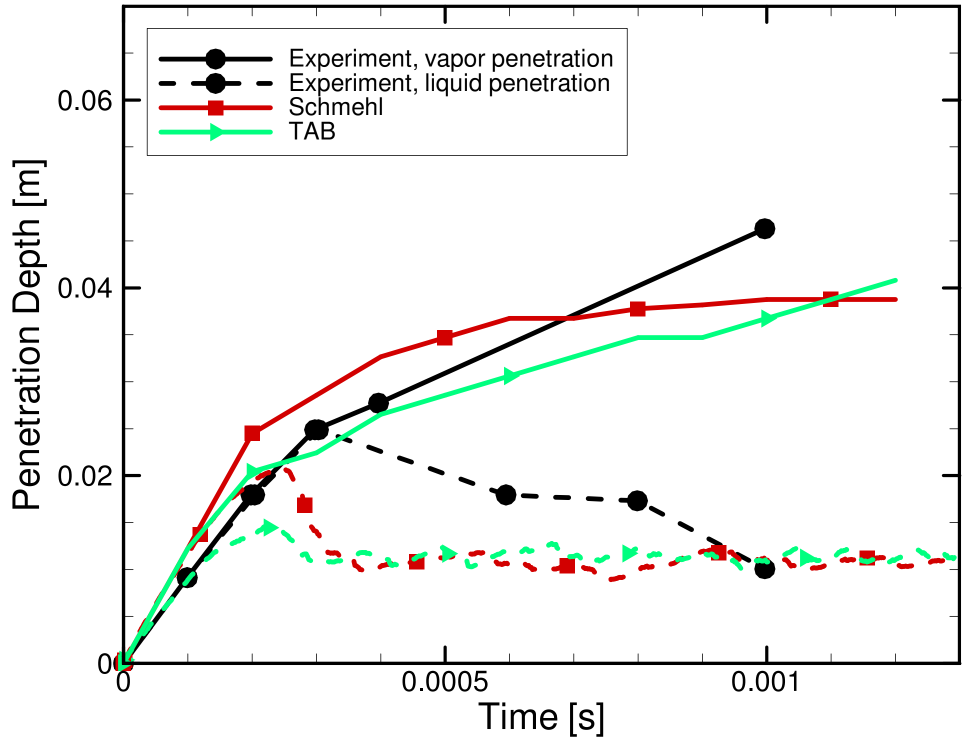
Gas Temperature [K]	800
Gas Pressure [MPa]	5
Gas Type	N_2
Particle Mass Flow Rate [g/s]	4.62
Droplets type	nHeptane (C7H16)
Density [kg/m^3]	684
Surface tension [N/m^2]	0.02
Nozzle diameter [mm]	0.2
Injection rate [ms]	1.3
Droplet diameter [mm]	0.2
Injection Velocity [m/s]	215
Injected Weber number	10000

Structure of Evaporating Spray



Breakup Model Validation: Evaporating Spray





Higher sensitivity of the liquid spray penetration depth wrt. droplet size distribution

LISA – Atomization Model

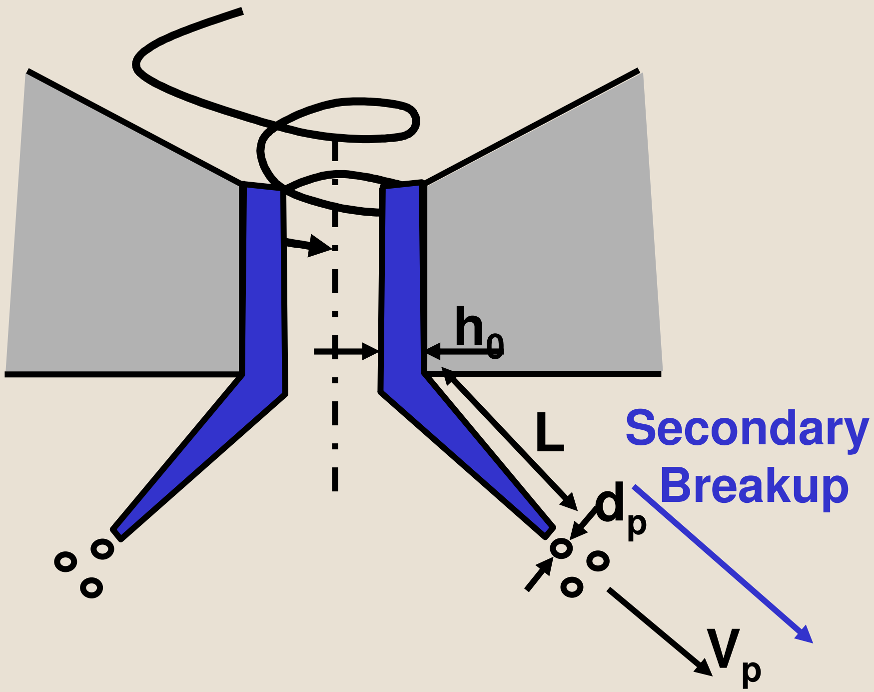
Linearized Instability Sheet Atomization

Use: Simulation of pressure swirl atomizers

Atomization processes is broken up into the following steps:

- Film formation
- Sheet breakup
- Atomization

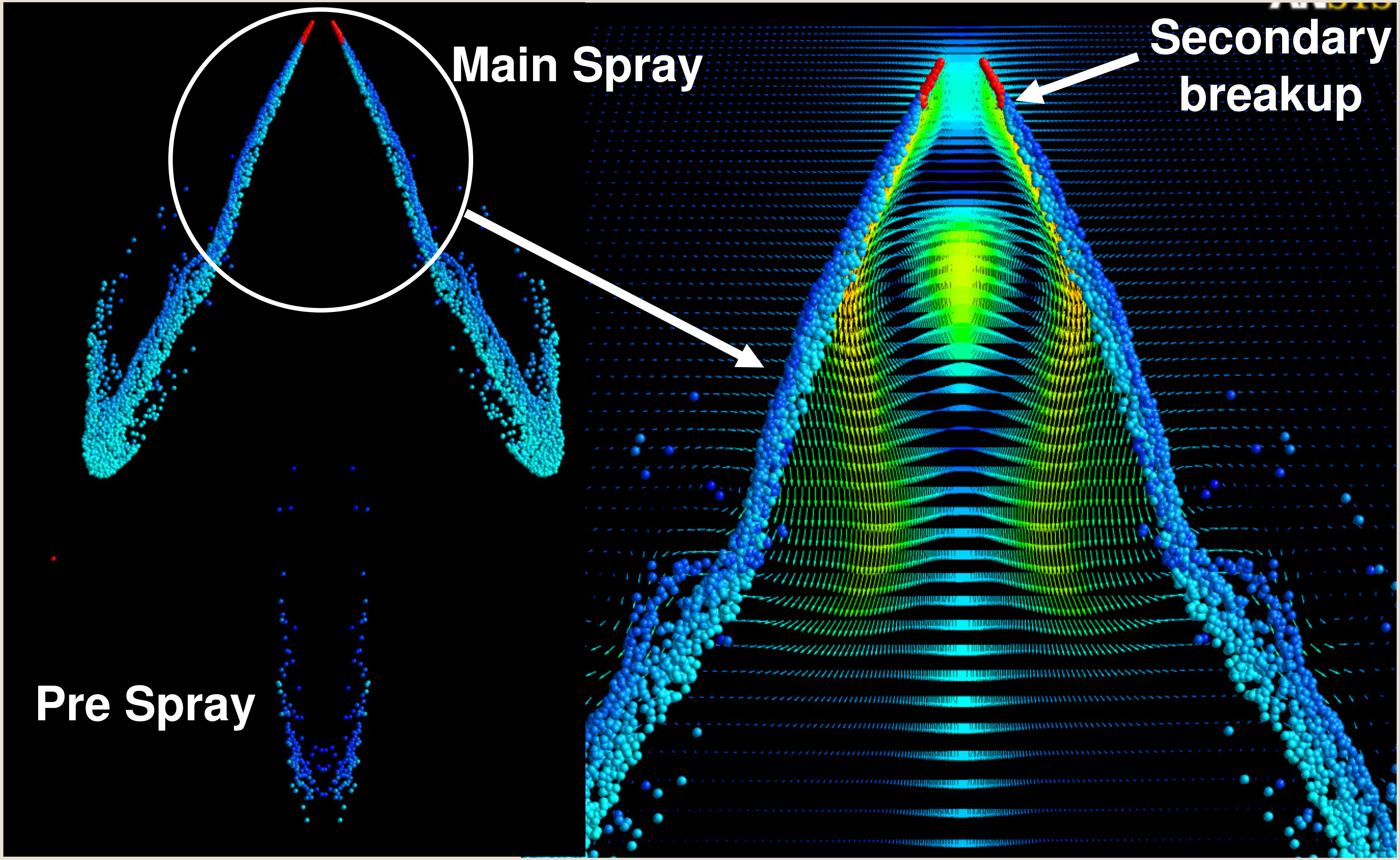
- Film formation → h_0
- Sheet breakup → L
- Atomization → d_p, V_p



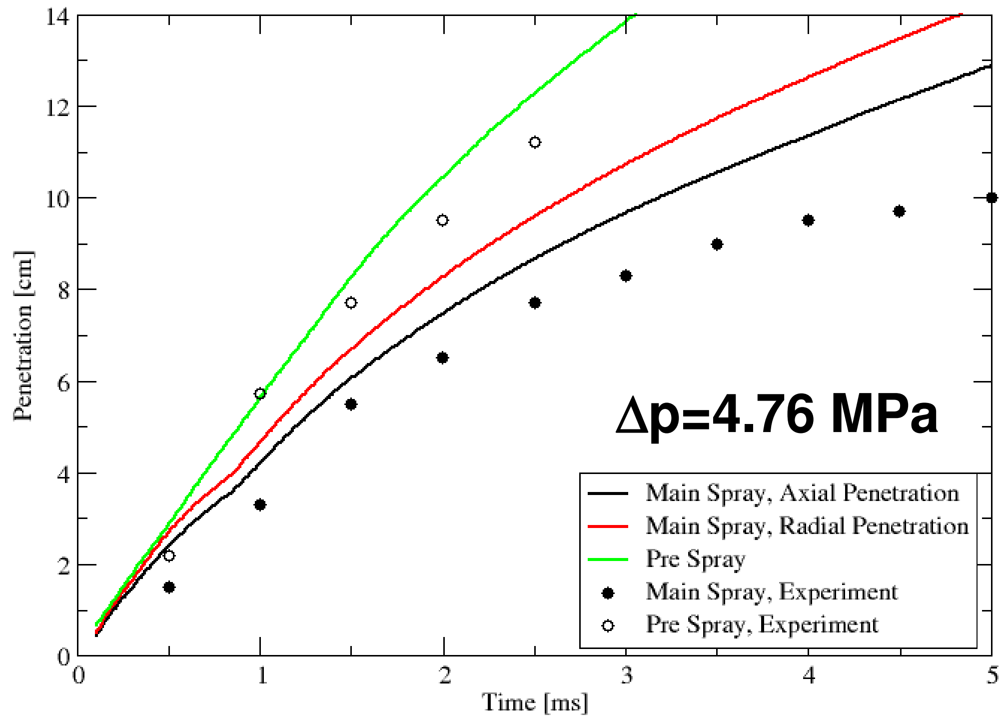
Validation of LISA: Test Case Data

Injector	A		B	
Nozzle Diameter [μm]	560		458	
Injection Pressure [MPa]	**4.76**	**6.12**	6.80	6.80
Mass flow [g/s]	11.33	12.86	13.75	13.28
Injection duration [ms]	3.86	3.4	**1.12**	**4.0**
Spray cone angle (deg)	46	46	54	54
Liquid density [kg/m^3]	770	770	770	770

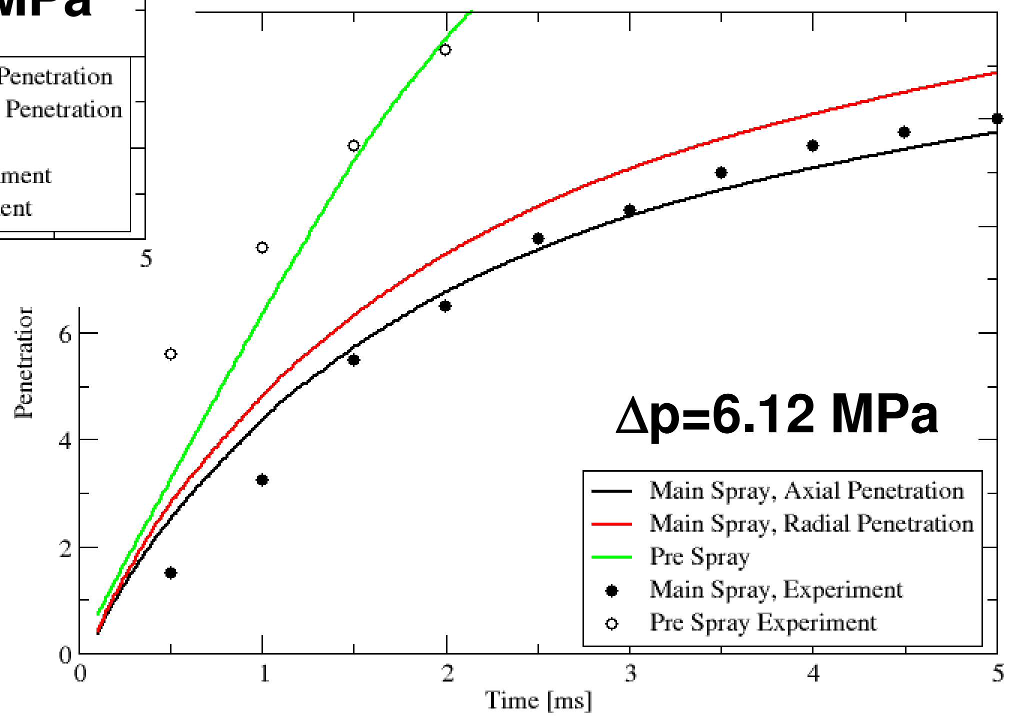
Spray Structures for Hollow-Cone Injection



Validation of LISA : Spray Penetration, Injector A

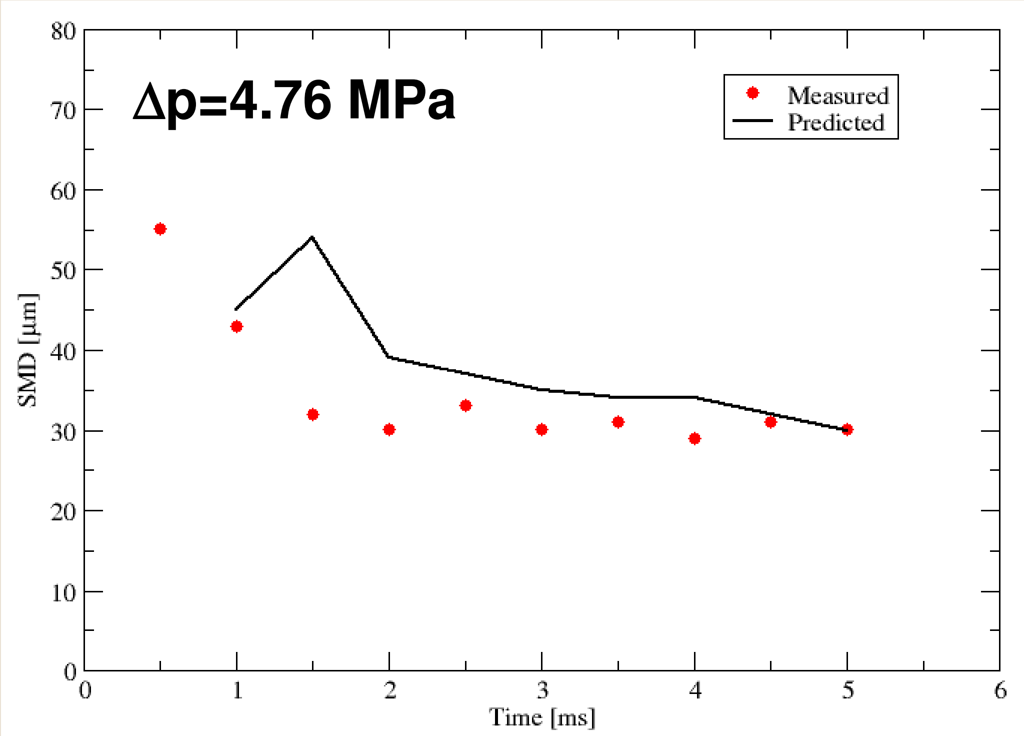


Pre and Main Spray tip penetrations

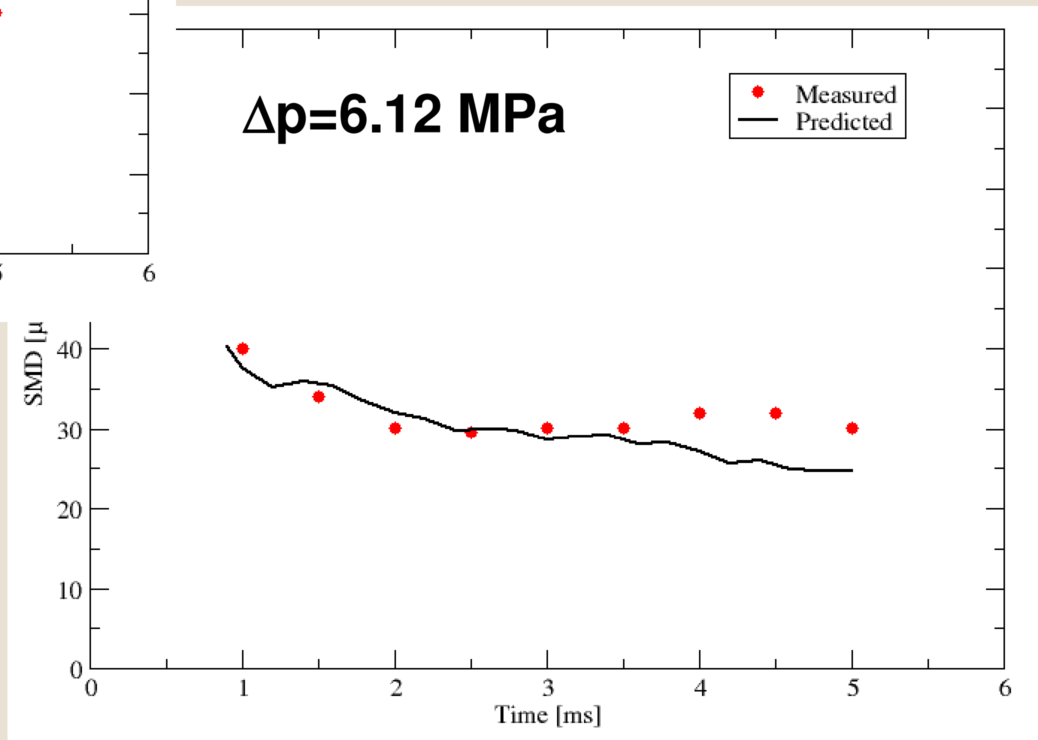


<u>Note</u>: Pre spray mass flow rate was assumed to be the same as for the main spray

Validation of LISA: Droplet Atomization, Injector A

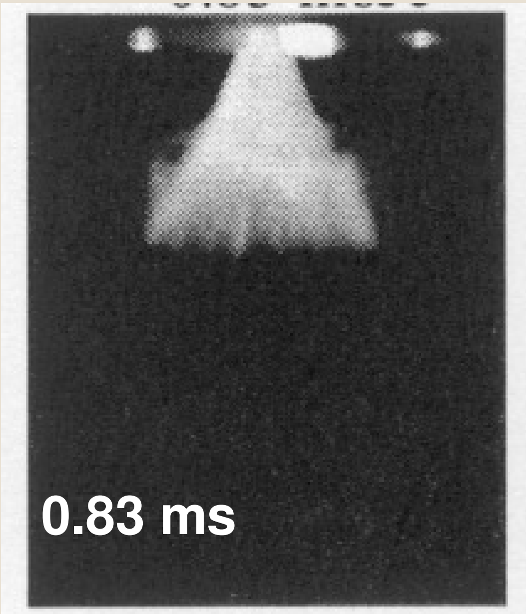


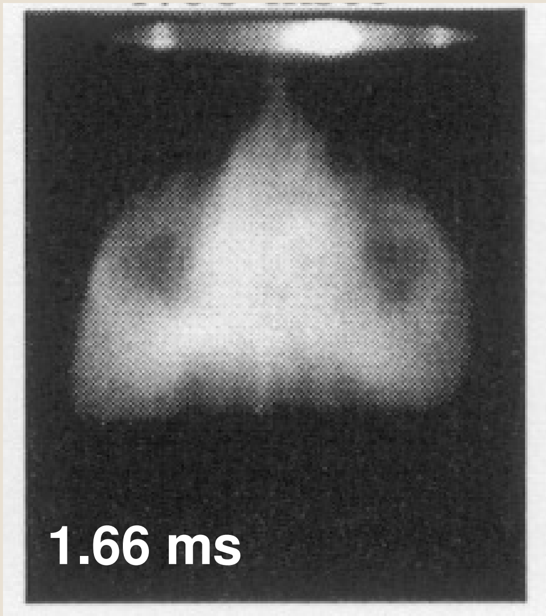
Sauter Mean Diameter @ Plane 39 mm downstream of Injector A

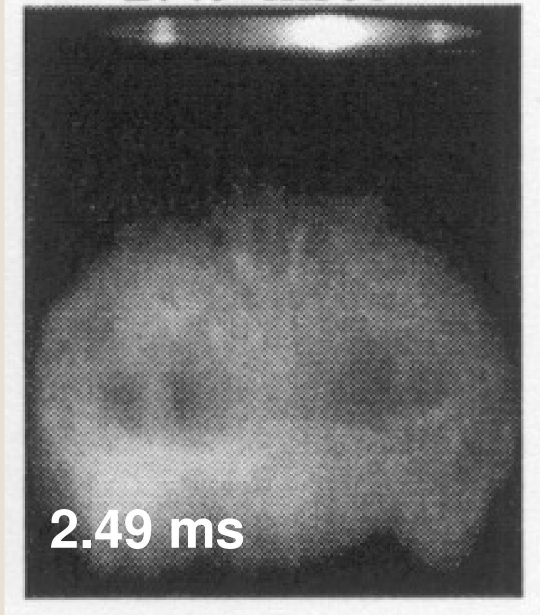


<u>Note</u>: Predicted SMD values are the result of atomization and secondary droplet breakup

Validation of LISA: Spray Formation, Injector B, Case 1







0.80 ms

1.70 ms

2.50 ms

Conclusions

- Numerous validation cases for spray simulations were set up and discussed. The considered validation cases cover a wide range of Weber numbers.
  - Droplet in a cross flow - from We>30
  - High pressure direct injection up to We<10000.
  - Comprehensive Validation Report available!
- The comparisons showed that none of the models provides excellent agreement with the experiments for whole range of the considered Weber numbers.
  - Low Weber number cases (We ~ 100): all models except the Reitz&Diwakar model give reasonable results.
  - High Weber numbers (We ~ 1000): the ETAB, the CAB and the Reitz&Diwakar models provide good comparison with the experiment.
- Evaporating spray structure is reasonably reproduced by the simulations.
  - Although large uncertainties in determination of liquid mass densities

Outlook

- Further comparison of local spray properties for validation of the existing breakup models for non-evaporating and evaporating sprays.
- Simulating reacting sprays.
- Investigation of spray-wall interaction
- Investigation of sprays in complex situations including all the above mentioned processes in a moving geometry (ICE).

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Thank You!