Engine After Treatment: Atomization and Mixing of Urea Water Solution

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CCGEx Research Day

2016-10-28

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Outline

- Research questions
- Spray pre-study
- Numerical simulations
- Experimental measurements
- Research answers

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Research questions

1. How much do the initial spray characteristics affect evaporation and mixing? Why?
2. How much does the exhaust gas flow affect evaporation, mixing properties, and wall-film formation? Why?
3. Simulations offer better flexibility and cost efficiency but
   - How reliable are they? Can we achieve proper experimental validation?
   - How sensitive are they to the different models and necessary simplifications?
4. What is the potential of this particular topic? Strategic interest for industrial partners and CCGEx?

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Pre-study: Injection Strategies

- IS1: Constant injection duration + controlled frequency

	OP0	OP1	OP2
Exhaust gas temperature (°C)	228	304	340
Exhaust mass flow rate (kg/s)	0.0144	0.0306	0.0467
Mean Gas velocity (m/s)	6.18	15.04	24.41
SCR backpressure (rel) (Pa)	25	135	360
AdBlue mass flow rate (mg/s)	3.0	12.4	28.8
Injection duration (ms)	5	5	5
Injection mass flow rate (kg/s)	0.00110	0.00110	0.00110
Injection frequency (Hz)	0.548	2.260	5.243
Interval between injections (s)	1.821	0.438	0.186
Duty Cycle	0.27%	1.13%	2.62%

- IS2: Constant frequency + controlled injection duration

	OP1	OP2a	OP2b	OP2c	OP3a	OP3b	OP3c	OP4a	OP4b	OP4c
Exhaust mass flow rate (kg/h)	0	400	400	400	800	800	800	1600	1600	1600
Outlet temperature (°C)	ambient	200	300	400	200	300	400	200	300	400
Gas density (kg/m3)	1.210	0.747	0.616	0.576	0.747	0.616	0.576	0.747	0.616	0.576
Mean Gas velocity (m/s)	0.00	13.16	15.94	17.05	26.32	31.88	34.10	52.64	63.75	68.20

	INJ1	INJ2	INJ3	INJ4
Injection mass flow rate (kg/s)	0.083	0.417	1.667	3.25
Injection frequency (Hz)	1	1	1	1
Duty Cycle	3%	13%	51%	100%

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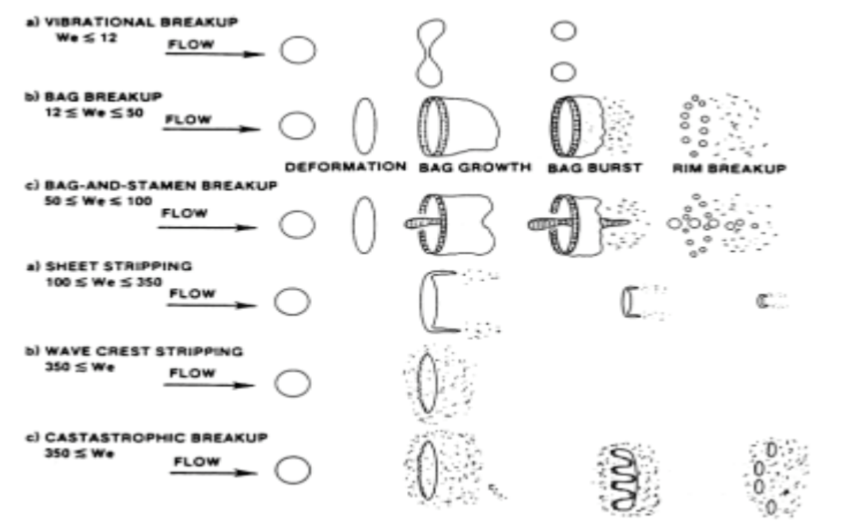
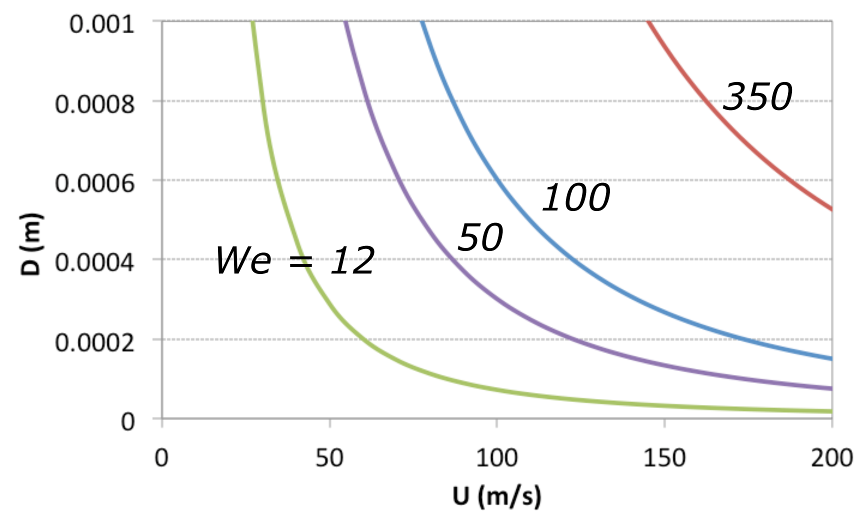
Pre-study: Spray behavior

- Droplet breakup

Regimes



Urea spray in hot air



D< 400μm + mean gas velocities = droplets will be subject to vibrational breakup

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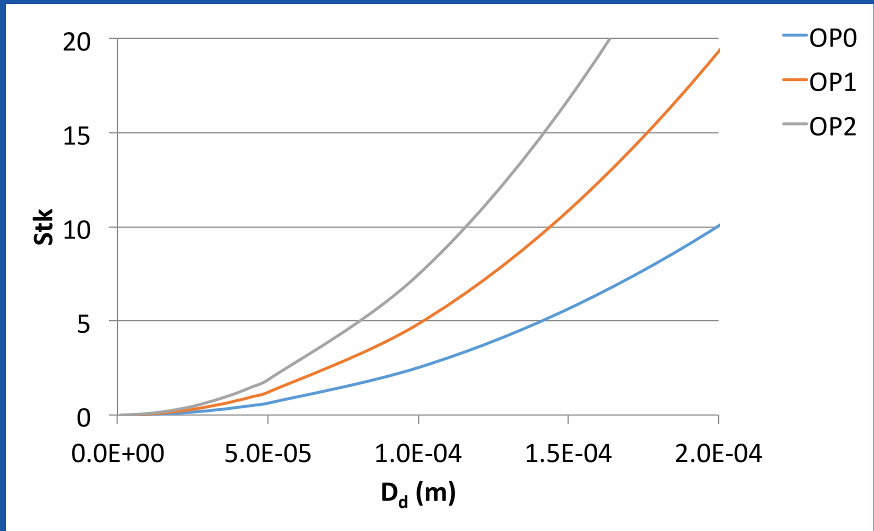
Pre-study: Spray behavior

- Droplet behavior

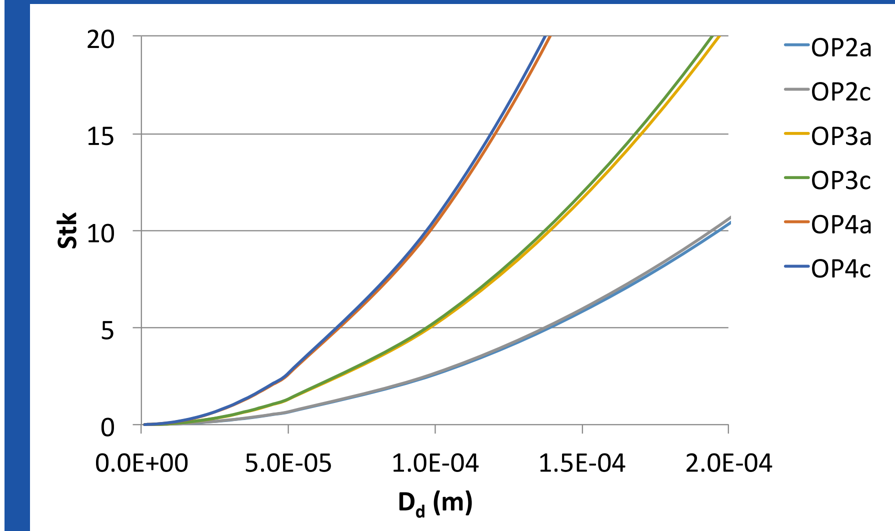
$$Stk = \frac{\rho_l D_d U_g}{18 \mu_g D}$$

>> 1 particles will detach from the flow
<< 1 particles follow fluid streamlines closely

IS1



IS2



Droplets > 30-40 μm will not follow the exhaust flow streamlines -especially in regions of acceleration or deceleration of the flow

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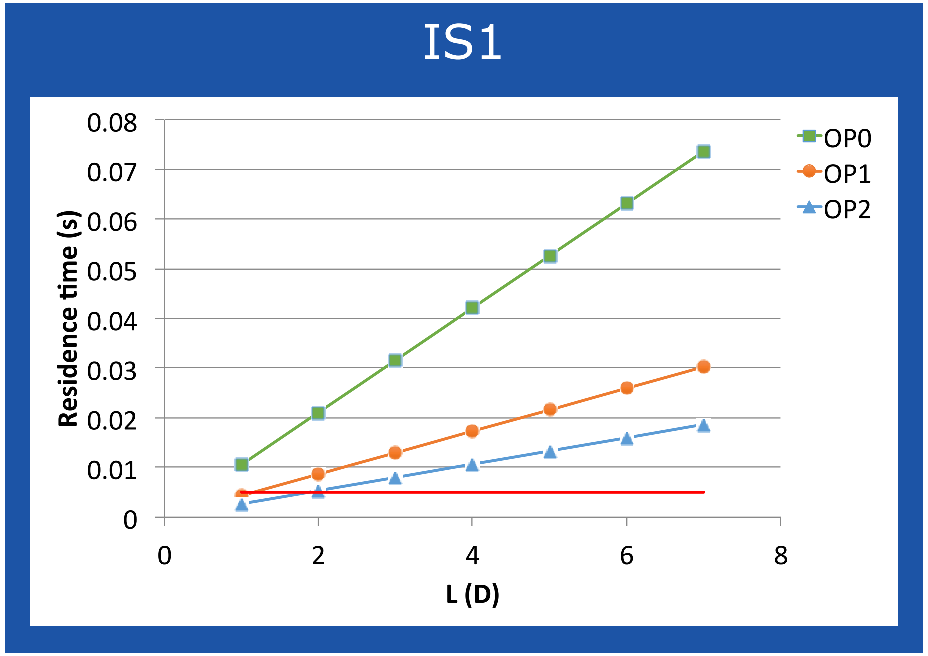
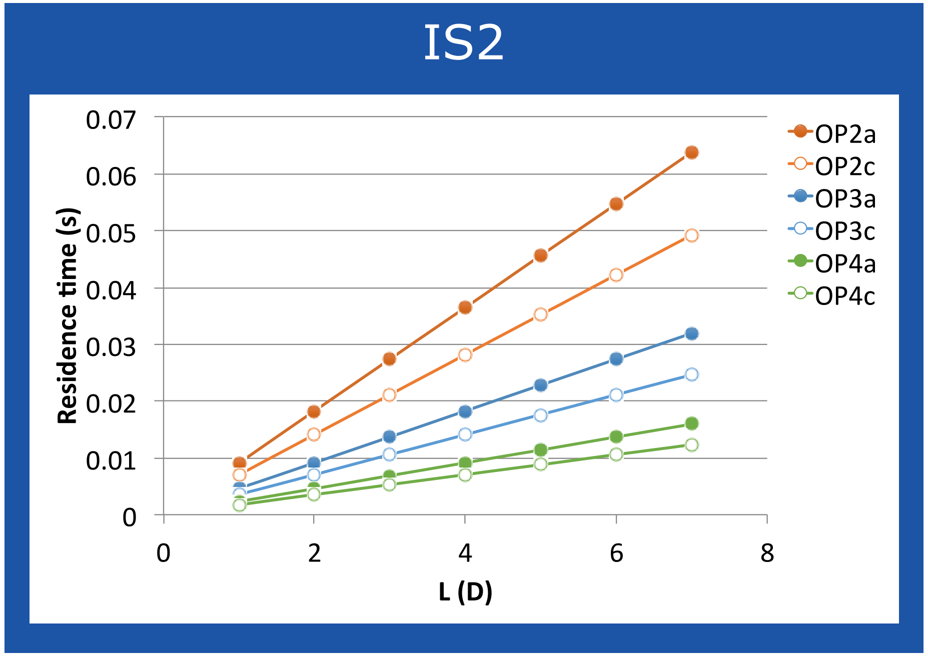
Pre-study: Spray behavior

- Droplet residence time





time UWS droplets have to evaporate as much water as possible, and get ready to react with the exhaust NOx

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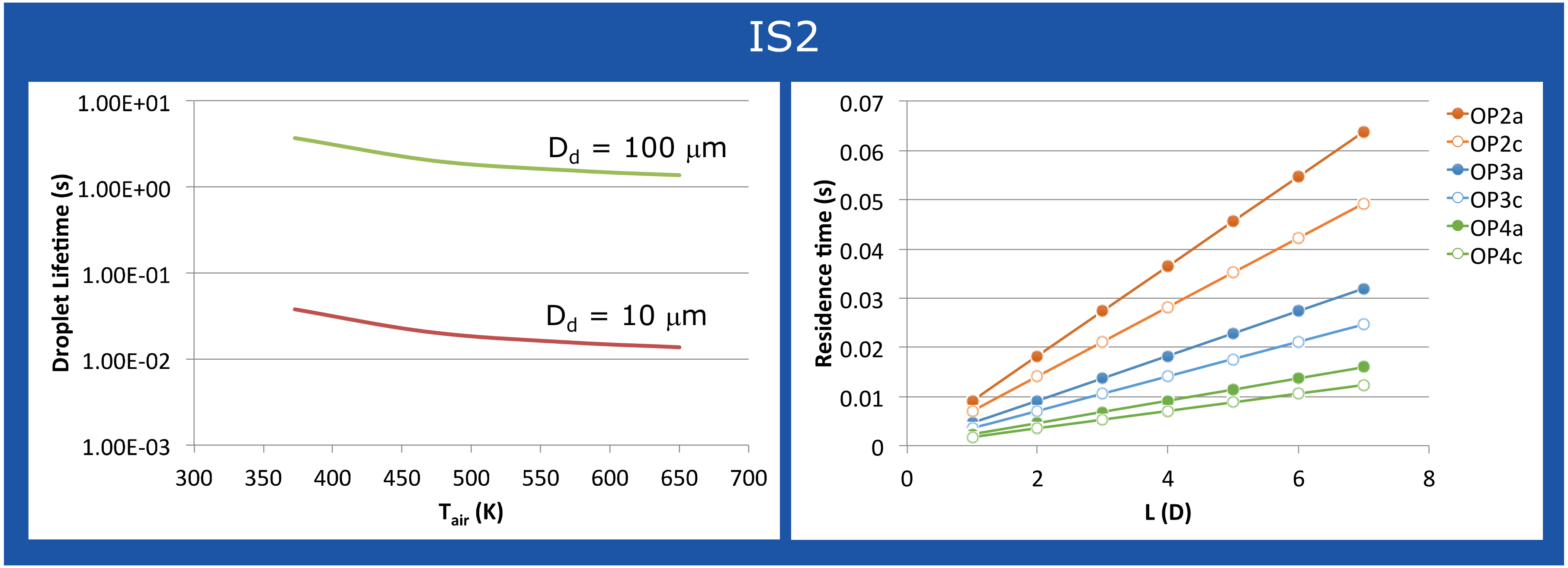
Pre-study: Spray behavior

- Droplet lifetime



time water droplets would need to evaporate

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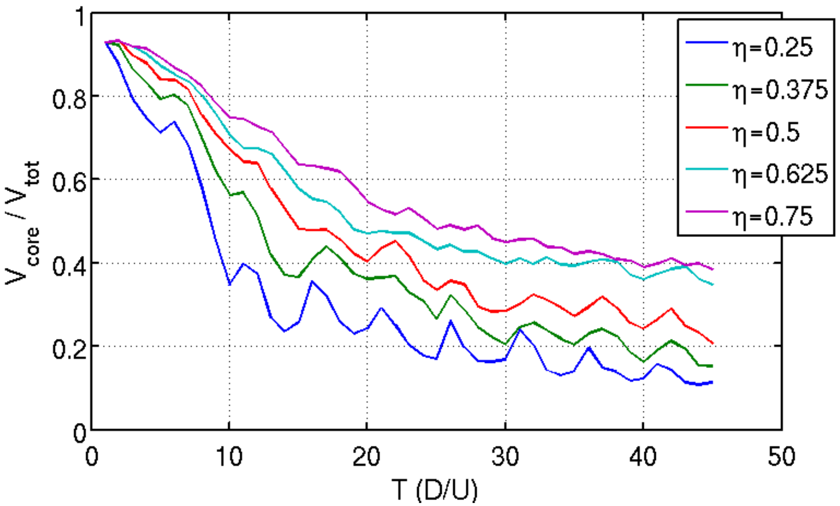
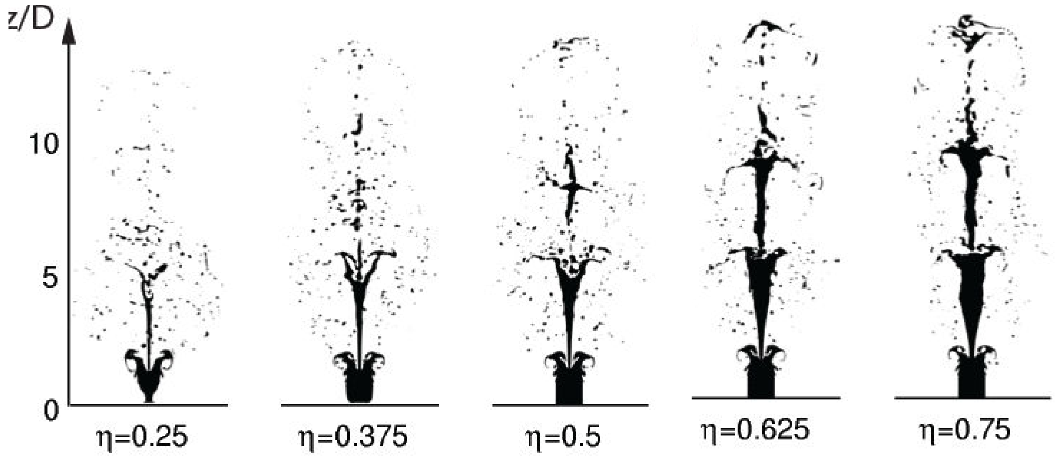
Pre-study: Injection strategy

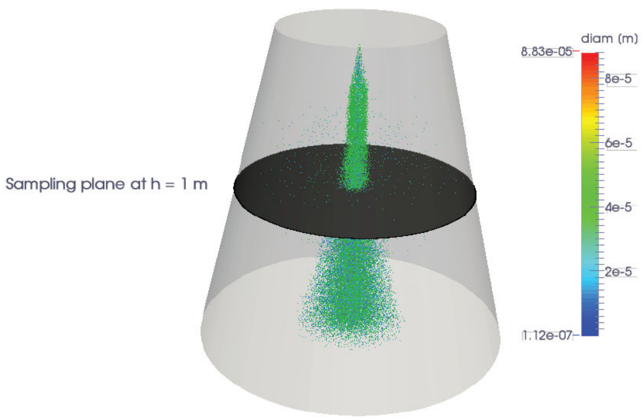
- Interaction between injection pulses
  - Duty cycle IS1 < 3%
  - Duty cycle IS2 = **3 -100%**

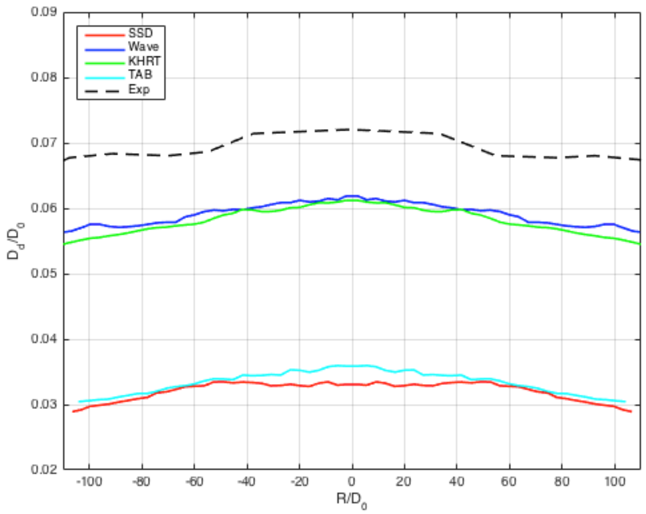


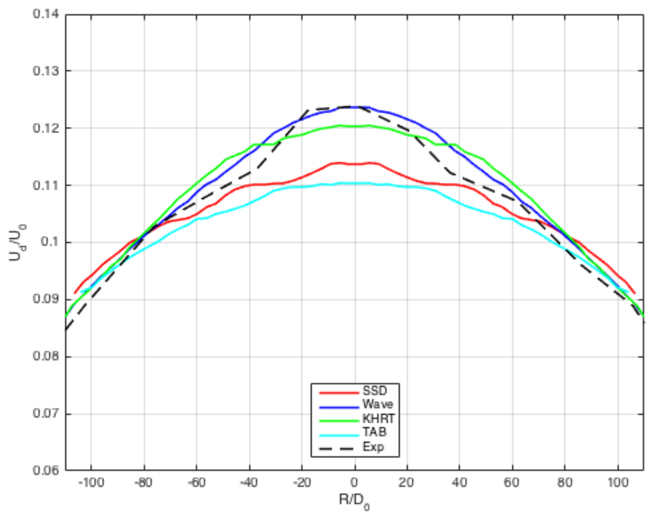


Pre-study: Sub-model sensitivity

Case	DPM-Turbulence		Evaporation		Droplet breakup			
	Yes	No	Diffusive	Convective/diffusive	SSD	Wave	KHRT	TAB
1	x		x					
2		x	x					
3	x		x		x			
4	x			x	x			
5	x			x		x		
6	x			x			x	
7	x			x				x

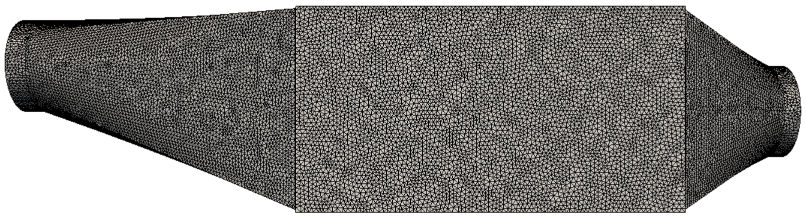


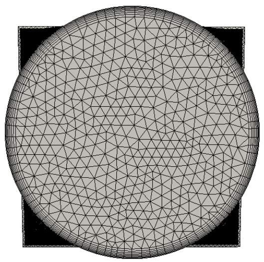




Numerical simulations

	Case	Mass flow [kg/h]	Temperature [C]
No cross flow	1a	0	20
Mild cross flow	2a	400	200
	2b	400	300
	2c	400	400
High cross flow	4a	1400	200
	4b	1400	300
	4c	1400	400





Mean diameter = 34 μm
Initial velocity 25 m/s
Cone angle = 50 degrees
Mass flow rate = 195 g/min
200 000 particle parcels/second

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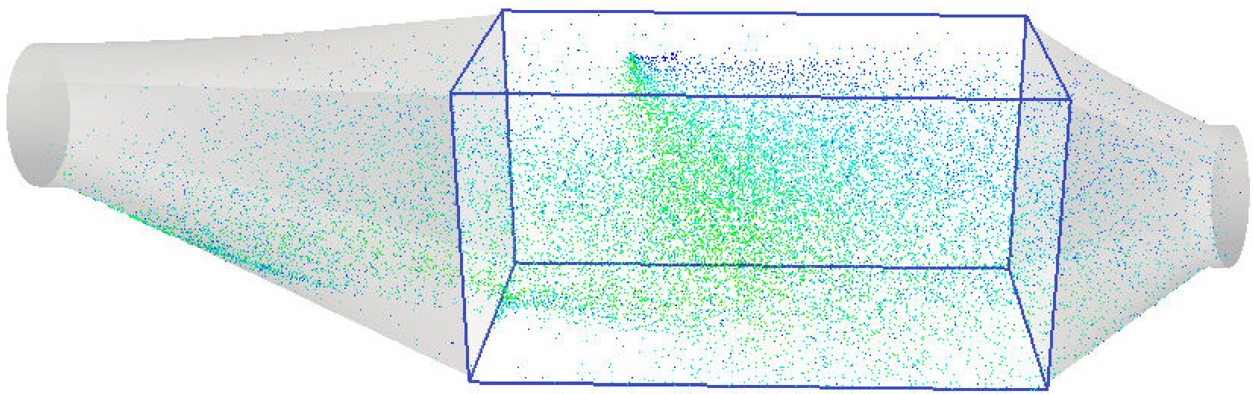
Numerical simulations

	Case	Mass flow [kg/h]	Temperature [C]
No cross flow	1a	0	20
Mild cross flow	2a	400	200
	2b	400	300
	2c	400	400
High cross flow	4a	1400	200
	4b	1400	300
	4c	1400	400



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Numerical simulations

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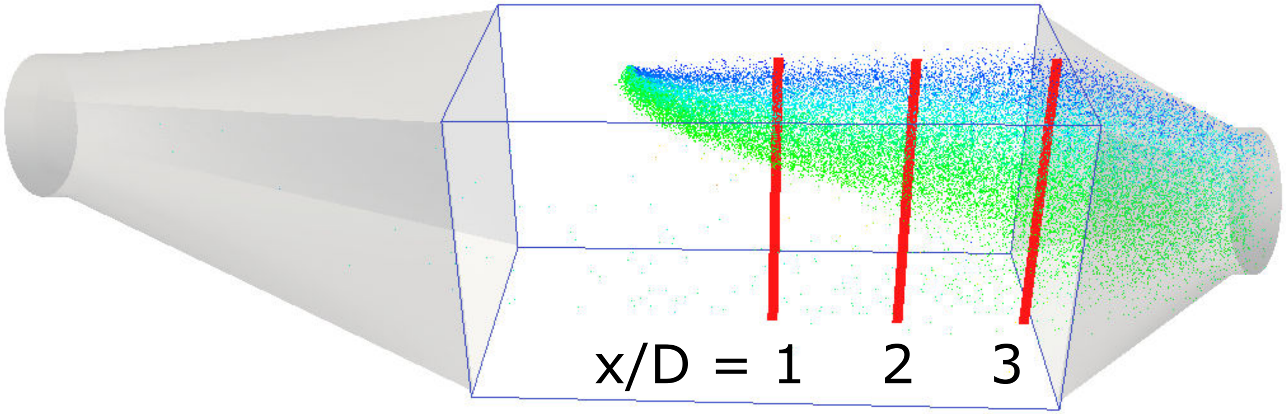
	4b	1400	300
	4c	1400	400



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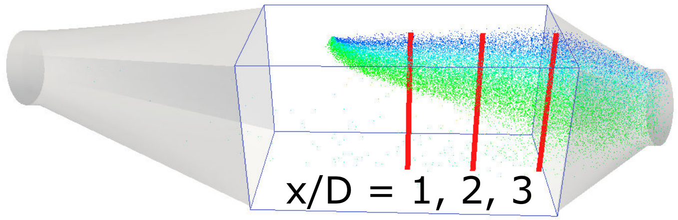
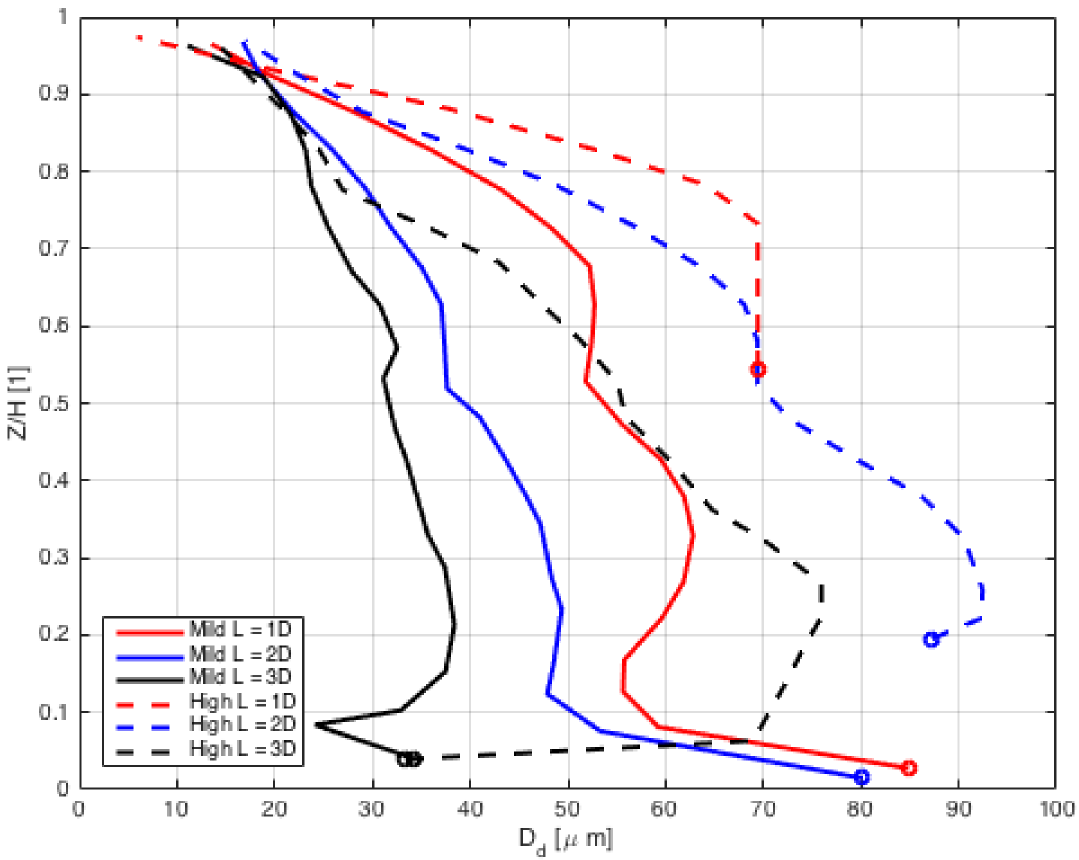
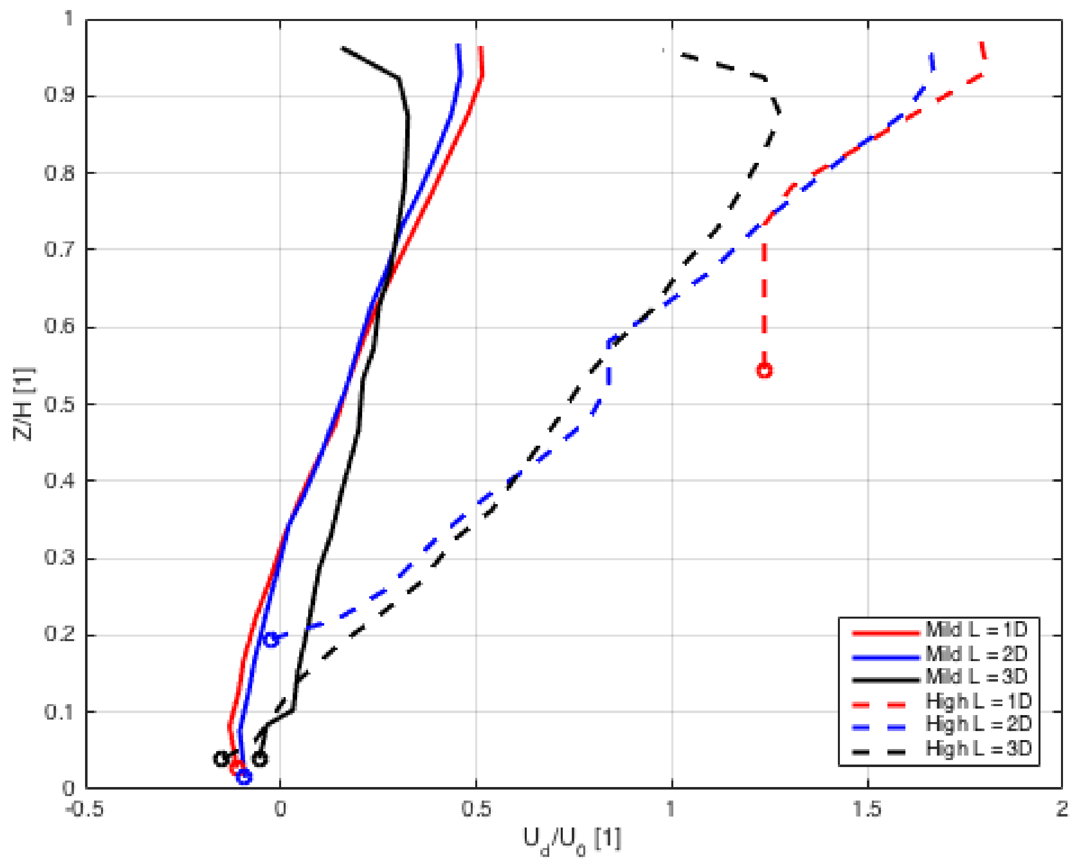
Numerical simulations: Crossflow effects



- Droplet size (left) and velocity (right) number averaged distribution along probe lines.





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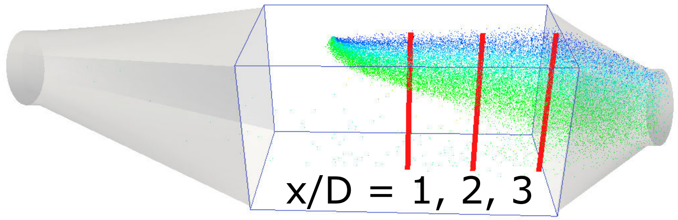
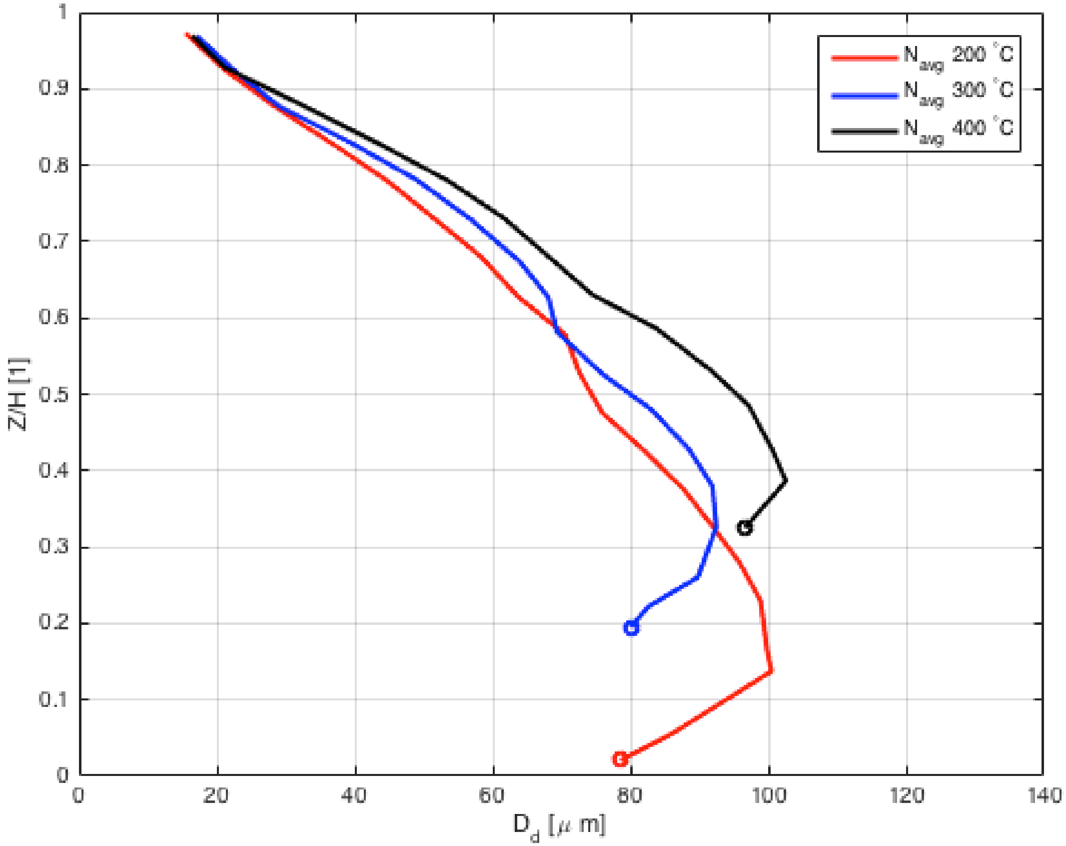
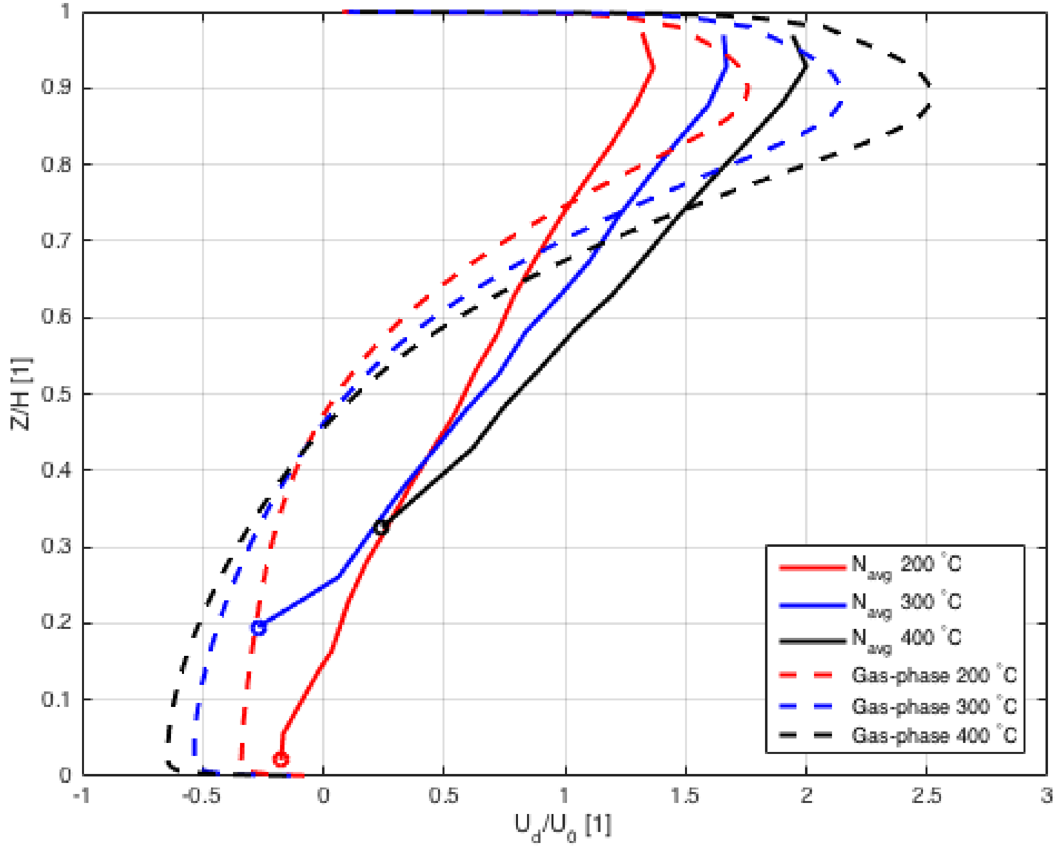
Numerical simulations: Temperature effects



- Droplet size (left) and velocity (right) number averaged distribution along x/D = 2.





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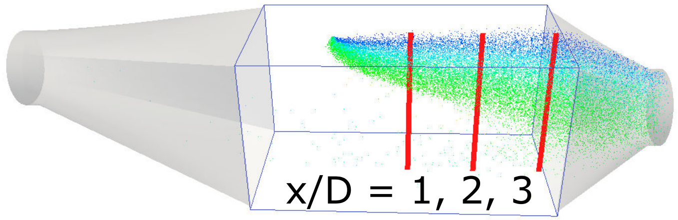
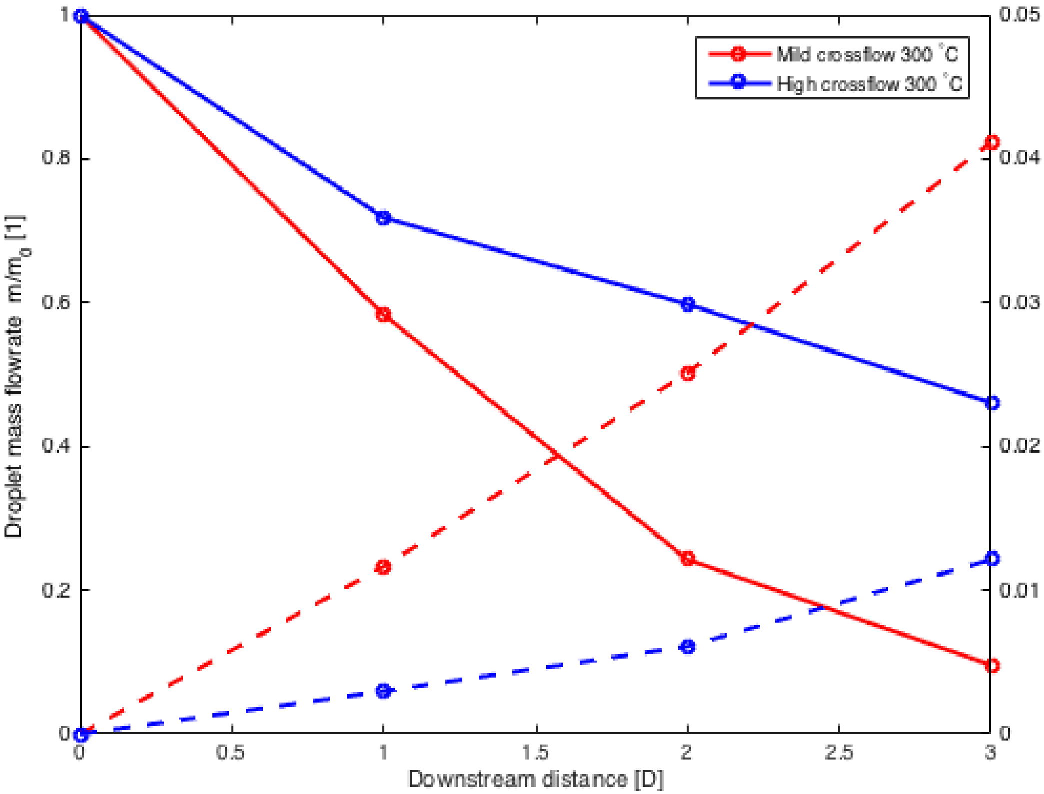
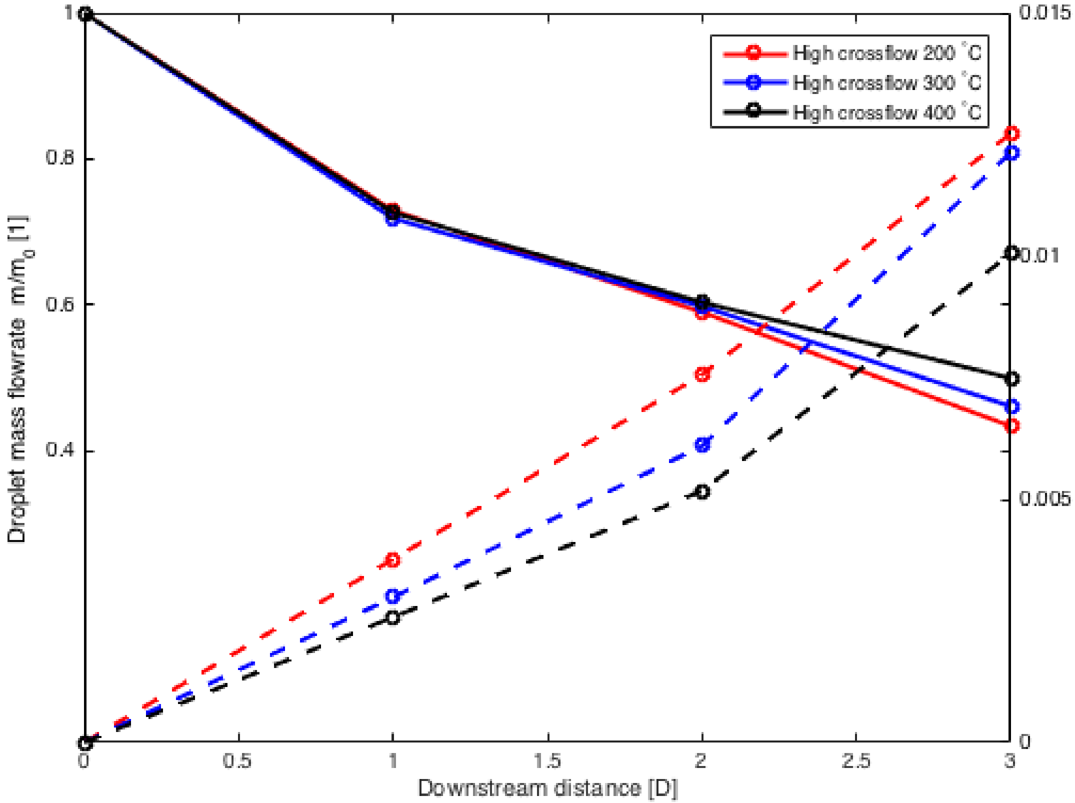
Numerical simulations: Evaporation



- Droplet mass flow rate through cross-planes (solid line) and residence time (dashed line). Sensitivity to crossflow (left) and gas temperature (right).





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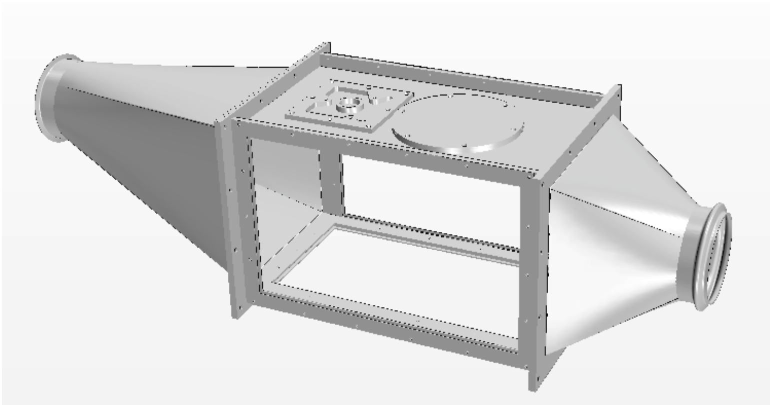
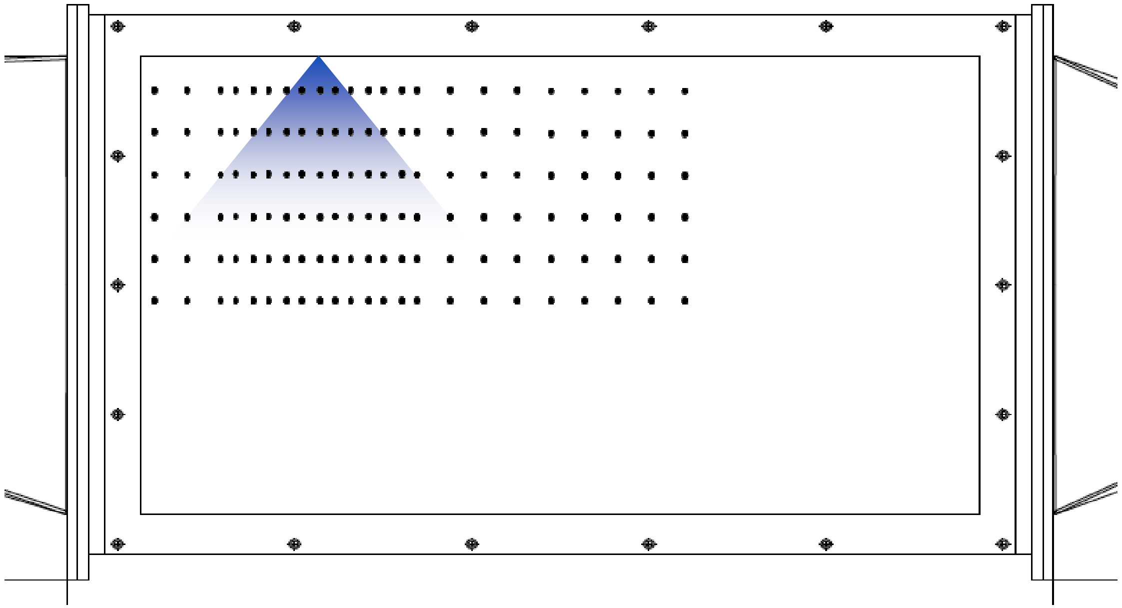
Experimental measurements



- Droplet size and velocity distribution
- Variation with injection distance



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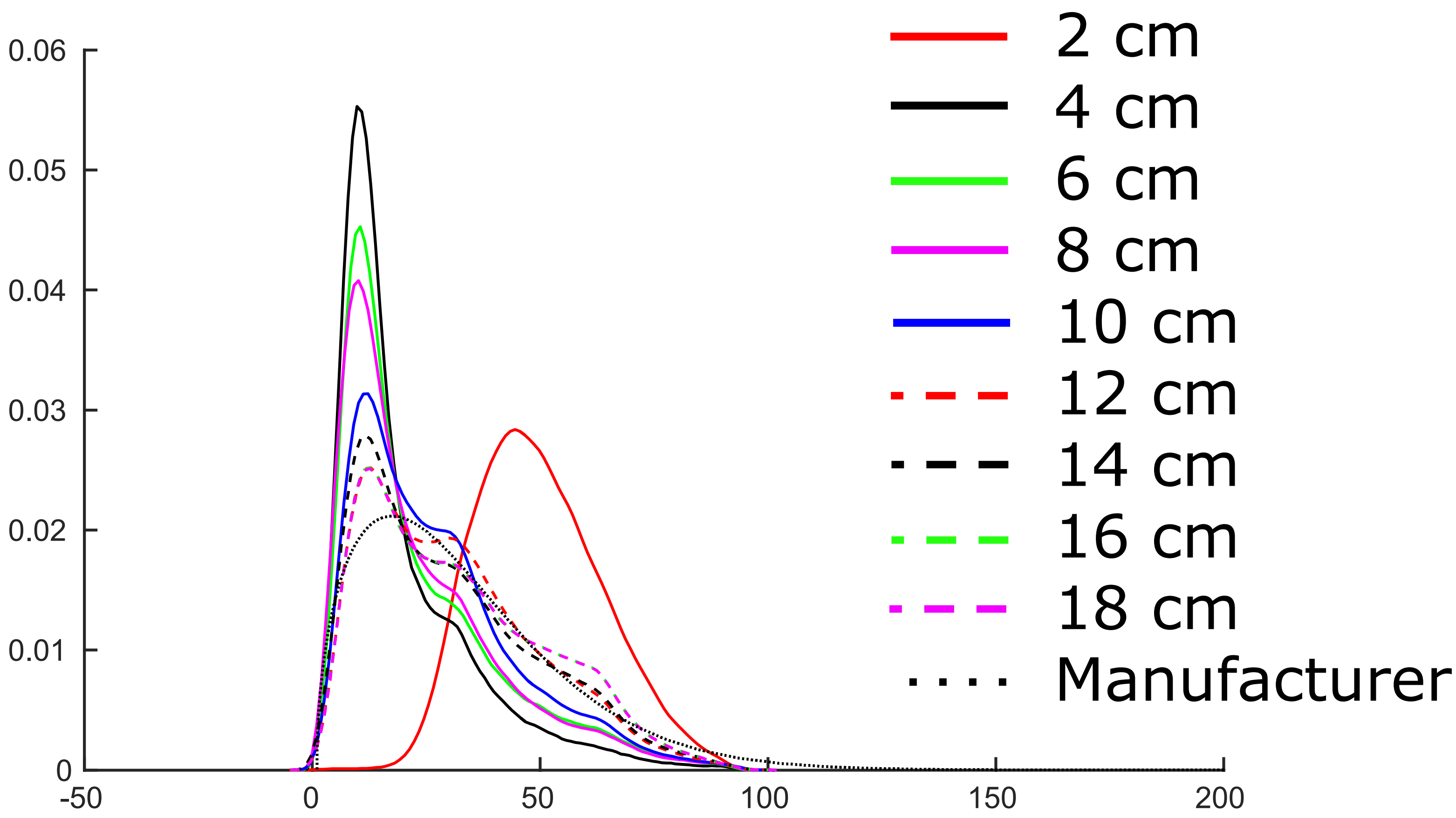
Experimental measurements

- Droplet size pdf (μm) – no crossflow



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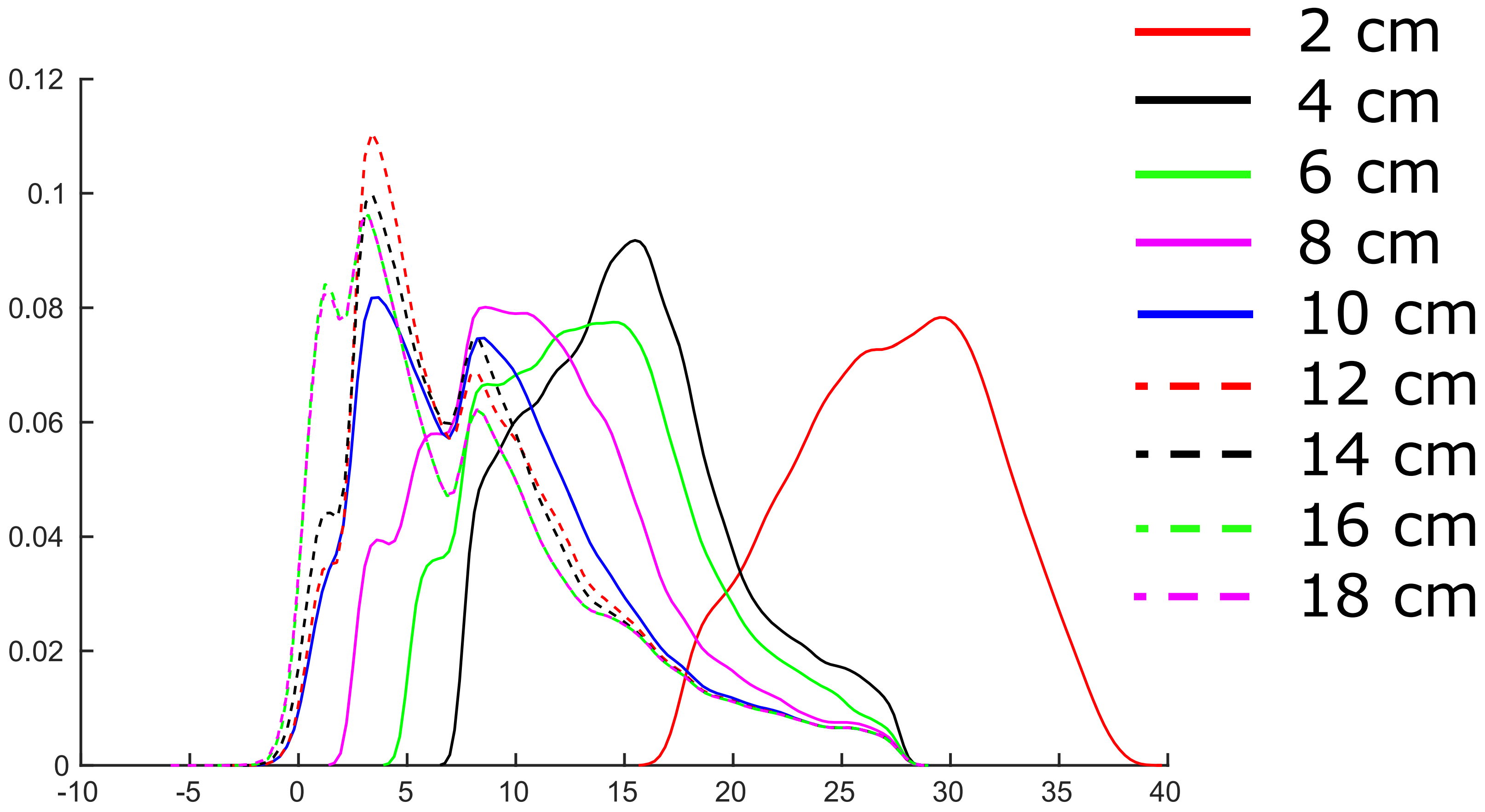
Experimental measurements

- Droplet velocity pdf (m/s) – no crossflow



Research answers #1, 2

- UWS droplets have a short time to evaporate as much water as possible, so **the smaller** the droplets**, the better**.
- Very **short injections** with **high instantaneous UWS flow rates** = Large number of droplets impacting on the **walls**.
- Pressure transients and **interaction between injection pulses** will have a strong impact on breakup, especially with a large **duty cycle**.
- At high operating temperatures, the evaporation rate slowly increases with temperature, but this benefit is cancelled by the increase in exhaust gas velocity.
- **Droplet residence time is more important than temperature, within the operating range considered.**

Research answers #3

- **Droplet velocity** is quite **insensitive** to the additional models adopted for breakup, evaporation and turbulence.
- Neither droplet size nor velocity are sensitive to the choice of model for evaporation.
- **Not** including a **DPM-turbulence** model **negatively affects** droplet size and velocity.
- The combination of models that provides better agreement with the experiments is: **WAVE breakup model, DPM-turbulence interaction, Convective evaporation**.
- **Use of realistic spray boundary conditions (size and velocity) is needed.**

Research answers #4

- Experimental side
  - **Unique possibility** to obtain this kind of measurements
  - Results database available for **validation** of numerical simulations
  - Creation of an **industrial standard for SCR experiments**

- Numerical side
  - **Deeper insight** into the breakup and mixing mechanisms
  - **Scientific relevance** through study of pulse interaction in cone sprays
  - **Potential for improvement** through novel CFD optimization packages

Thank you for your attention!

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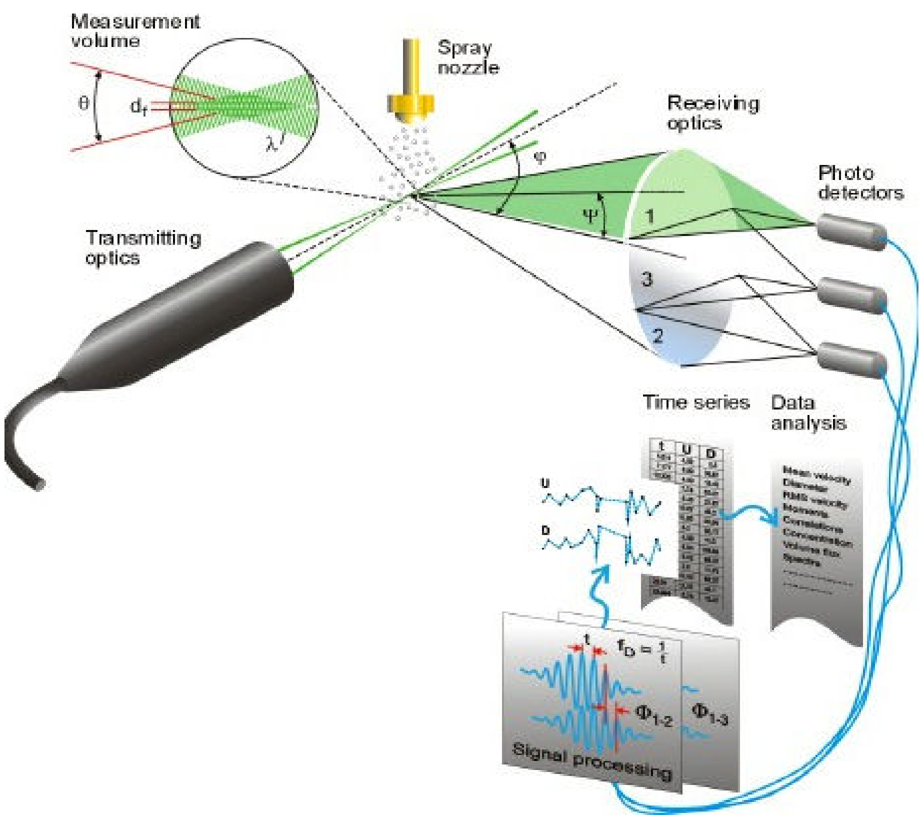
Experimental measurements: PDPA (Phase Doppler Particle Analyzer)



Dantecdynamics.com

- Simultaneous measurement of droplet size and velocities
- Principles
  - Particle scatters light from two laser beams
  - Scattered light received by a multi-detector probe
  - Phase shift between signals proportional to particle size
  - Doppler frequency dependent on particle velocity

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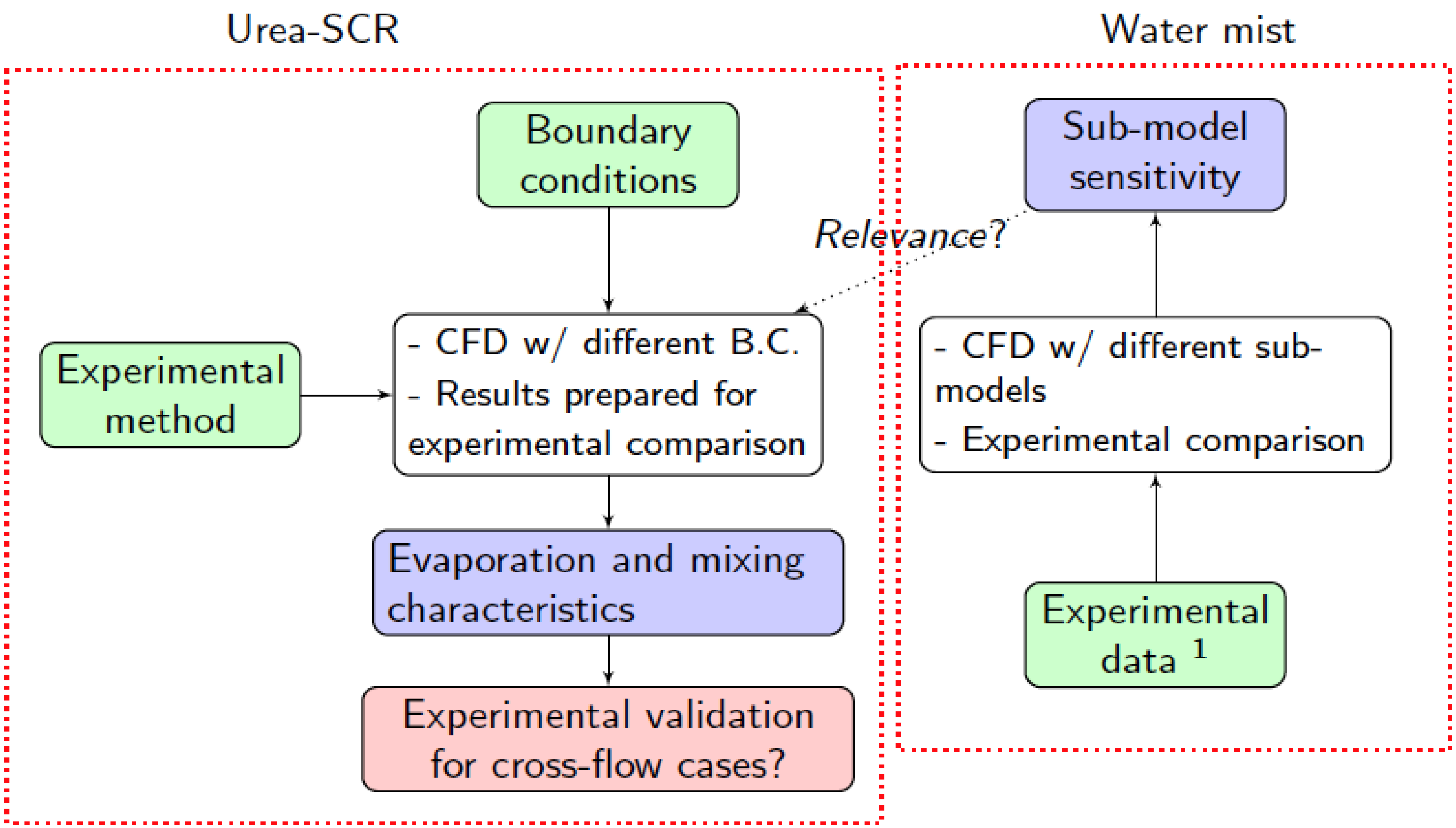
Pre-study: Sub-model sensitivity



[1]Iannantuoni, et al. (2013). "Validation and Assessment of Water Mist Multi-hole Nozzle Model for Fire Simulations"

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Experimental measurements: start up

- 04/28: test cell arrives at ICE lab
- 05/11: connection of the dosing unit
- 05/27: first PDPA measurements without gas flow

- 09/15: first run with exhaust gas crossflow
- 10/13: first PDPA measurements with gas crossflow