Large Eddy Simulation of air-blast atomization using ELSA-PDF

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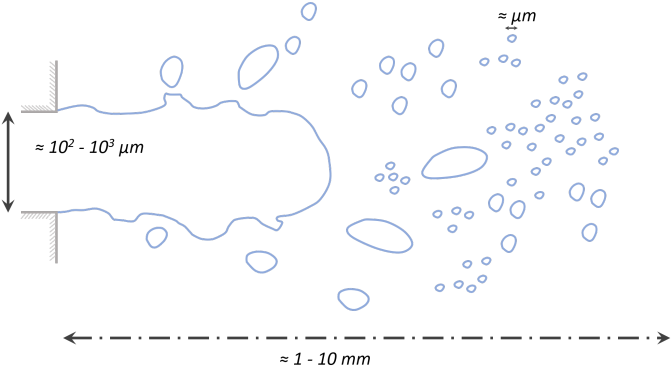
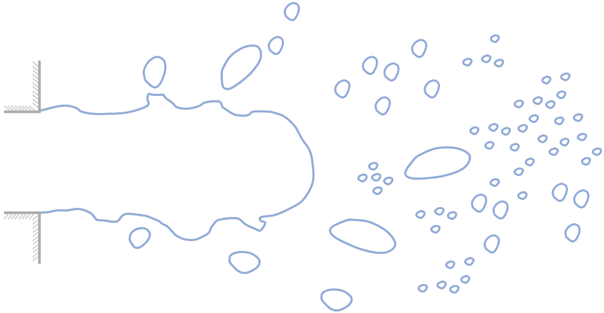
Sub–Grid Liquid Structures



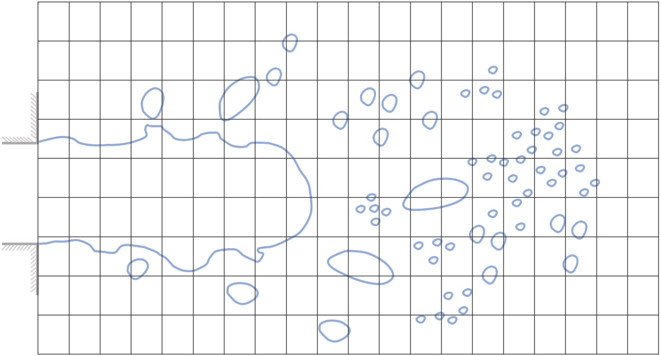
- High Velocity Spray: **wide range of length scales**

Sub–Grid Liquid Structures



- Numerical Simulation: **Discrete** representation of Multiphase Flow

Sub–Grid Liquid Structures



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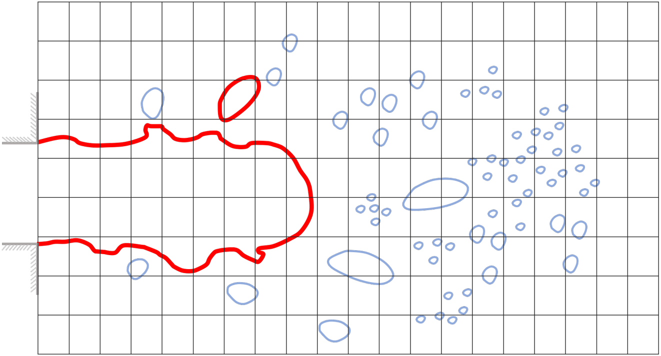
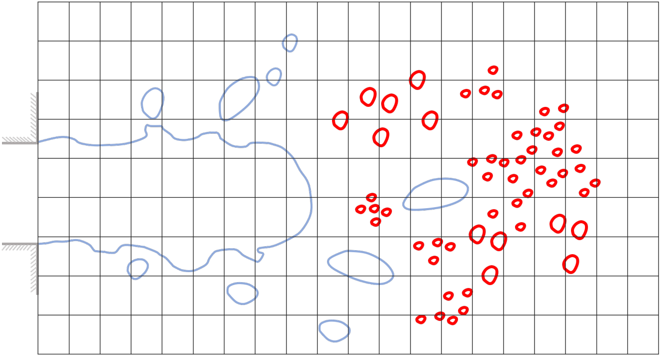


- Dense Region: **Interface Well Resolved**

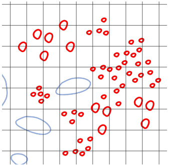
Sub–Grid Liquid Structures

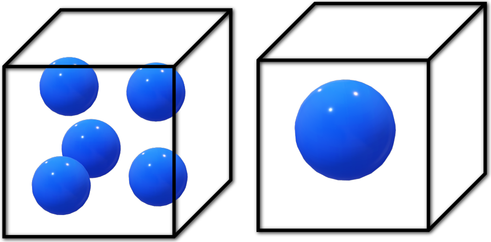


- Dilute Region: **Sub-Grid Structures**;

Sub–Grid Structures: Surface Density Concept

Two Cells: same **Volume** of liquid, different **Number** of droplets.





- Volume Fraction α **may not be enough**
- New variable: Interface Surface Density [1]

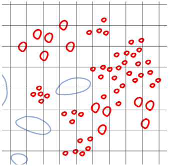
$$\Sigma = \frac{\text{Interface Amount}}{\text{Cell Volume}} = [m^{-1}]$$

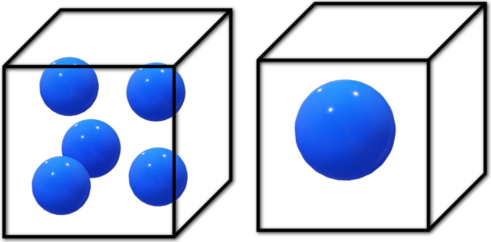
[1] Vallet et al., 2001, *Atomization and Sprays*, 11(6).

Sub–Grid Structures: Surface Density Concept

Imperial College London

Two Cells: same **Volume** of liquid, different **Number** of droplets.





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$\Sigma - Y$ model

$\Sigma - Y$ or ELSA model[1]

$$\text{Volume Fraction Eqn.} \ : \ \frac{\partial \bar{\alpha}}{\partial t} + \bar{u}_j \frac{\partial \bar{\alpha}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[D_{sgs} \frac{\partial \bar{\alpha}}{\partial x_j} \right]$$

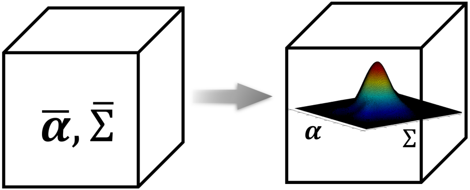
$$\text{Interface Density Eqn.} \ : \frac{\partial \bar{\Sigma}}{\partial t} + \bar{u}_j \frac{\partial \bar{\Sigma}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[D_{sgs} \frac{\partial \bar{\Sigma}}{\partial x_j} \right] + \overline{S_{gen}} - \overline{S_{des}}$$

- Source terms *not linear* $\left(\overline{S} = \overline{S_{gen}} - \overline{S_{des}} = a\overline{\Sigma} - b\overline{\Sigma}^2 \ , \ a, b = f(\alpha, \Sigma)\right)$;
- Single filtered/averaged value for each cell;

[1] Vallet et al., 2001, *Atomization and Sprays*, 11(6).

Statistical description: Σ-Y-PDF

From **Filtered** values to Cell **Joint Instantaneous PDF**

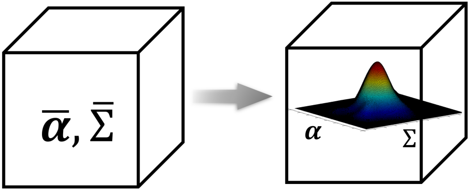


Joint Sub–Grid Probability Density Function (PDF) P_{sgs} of α and Σ.

$$\frac{\partial P_{sgs}}{\partial t} + \frac{\partial \bar{u}_j P_{sgs}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[D_{sgs}\frac{\partial P_{sgs}}{\partial x_j}\right] - \frac{\partial S(\boldsymbol{\theta})_k P_{sgs}}{\partial \theta_k}$$

Statistical description: Σ-Y-PDF

From **Filtered** values to Cell **Joint Instantaneous PDF**



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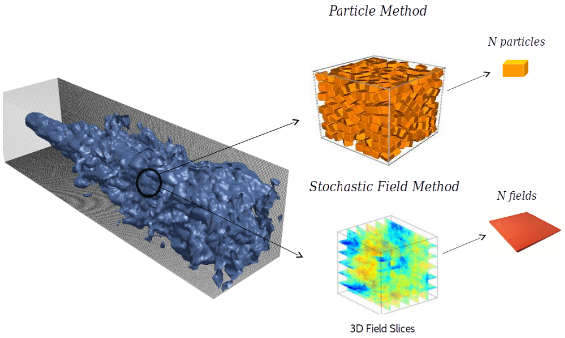
Statistical description: $\Sigma - Y - PDF$

System of N_ϕ **Stochastic Fields** or Particles **equivalent** to P_{sgs}



- N_ϕ *fields* to represent the average;
- Each *field* carries the state variables $\boldsymbol{\theta} = (\alpha, \Sigma)$;

Sub–Grid Formulation: $\Sigma - Y - PDF$

Final Set of SPDE [2]:

$$\frac{d\alpha^{\phi}}{dt} + \bar{u}_j \frac{\partial \alpha^{\phi}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[D_{sgs}\frac{\partial \alpha^{\phi}}{\partial x_j}\right] + \sqrt{2D_{sgs}}\frac{\partial \alpha^{\phi}}{\partial x_j}\frac{dW_j^{\phi}}{dt}$$

$$\frac{d\Sigma^{\phi}}{dt} + \bar{u}_j \frac{\partial \Sigma^{\phi}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[D_{sgs}\frac{\partial \Sigma^{\phi}}{\partial x_j}\right] + \sqrt{2D_{sgs}}\frac{\partial \Sigma^{\phi}}{\partial x_j}\frac{dW_j^{\phi}}{dt} + S^{\phi}$$

- First Moment (or Filtered Value) $\overline{\alpha} = \frac{1}{N_{\phi}} \sum_{\phi=1}^{N_{\phi}} \alpha^{\phi}$, $\overline{\Sigma} = \frac{1}{N_{\phi}} \sum_{\phi=1}^{N_{\phi}} \Sigma^{\phi}$
- Sub–Grid Diffusivity $D_{sgs} = \frac{\nu_{sgs}}{Sc_{sgs}}$
- Wiener Increment Term $d\mathbf{W}^{\phi}$ with mean 0 and variance $\sqrt{dt}$

[2] Navarro-Martinez , 2014, *Int. J. of Multiphase Flow*, 63:1122.

Test Case: Jet in Cross Flow

- Liquid Jet into Gaseous Cross Flow

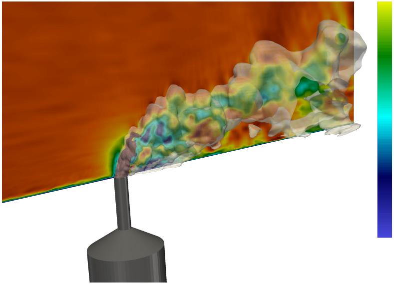


Fig. Jet into a Cross Flow.

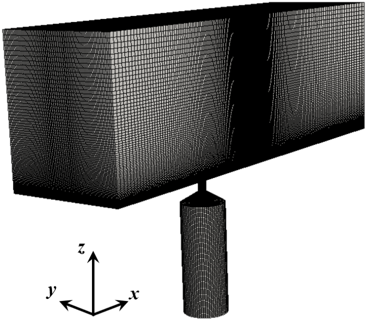
- Challenging configuration;
- Application of engineering interest;
- Configuration investigated numerically[3] and experimentally[4];

[3] Herrmann et al. , 2011, *Jo. of Eng. for Gas Turbines and Power*, 133(6), 061501.

[4] Brownand T and McDonell, 2006, *19th ILASS America*.

Test Case: Jet in Cross Flow

Numerical Set Up



$d_j [mm]$	1.3
We_j	2178
We_g	330
$Re_j [-]$	$1.4 \cdot 10^4$
$Re_g [-]$	$5.7 \cdot 10^5$
Q	6.6
Cells	$\approx 2.5 \cdot 10^6$

Same We, Re and Q, **different density ratio** ρ_j/ρ_∞

- $\rho_j/\rho_\infty = 10$: **DNS** density ratio [3];
- $\rho_j/\rho_\infty = 860$: **Experimental** density ratio [4];

Test Case: Jet in Cross Flow

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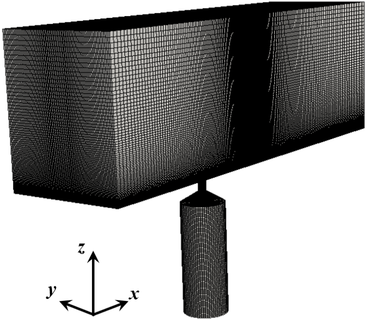
Numerical Set Up



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Test Case: Jet in Cross Flow

Liquid Jet Break–Up

- Increasing ρ_j/ρ_g reduce the bending;
- Agreement with empirical correlation for $\rho_j/\rho_\infty = 860$;

We et al. (1997)

$$\frac{y}{d_j} = 1.37 \left(q \frac{x}{d_j} \right)^{1/2}$$

Stenzler et al. (2006)

$$\frac{y}{d_j} = 2.63 q^{0.442} \left(\frac{x}{d_j} \right)^{0.391} We^{-0.088} \left(\frac{\mu_l}{\mu_{H_2O}} \right)^{-0.027}$$

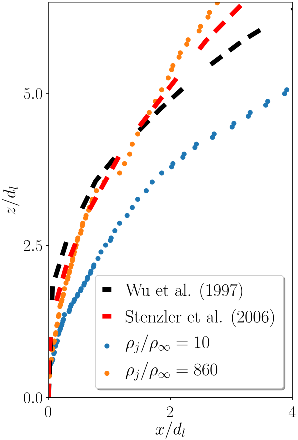

Fig. Jet boundary varying N_ϕ

Test Case: Jet in Cross Flow

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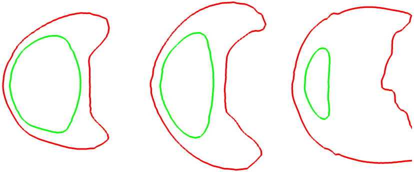
Liquid Jet Break–Up

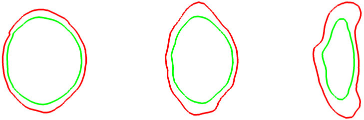
Time averaged α on **x-y** planes.
Red : $\langle\alpha\rangle = 0.1$;
Blue : $\langle\alpha\rangle = 0.5$;

$\rho_j/\rho_\infty = 10$: lateral deformation observed;

$\rho_j/\rho_\infty = 10$



$\rho_j/\rho_\infty = 860$

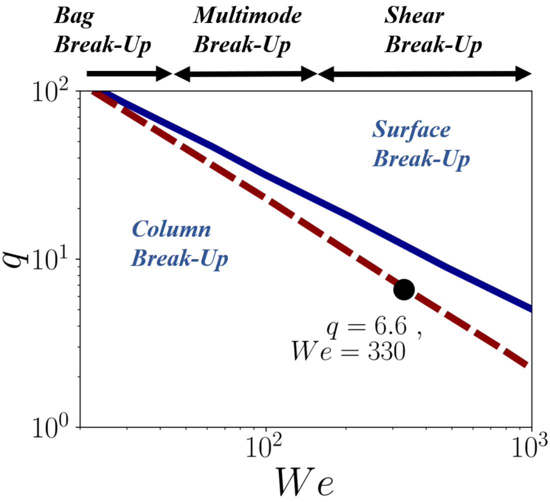


Test Case: Jet in Cross Flow

Liquid Jet Break–Up

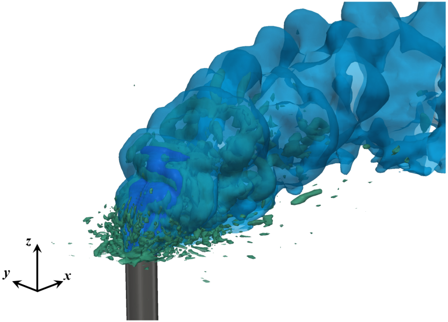
Primary breakup processes $We - q$ regime map;

- Column/Surface break–up threshold **not clear**;
- Influence of ρ_j/ρ_∞ on **lateral deformation**



Test Case: Jet in Cross Flow

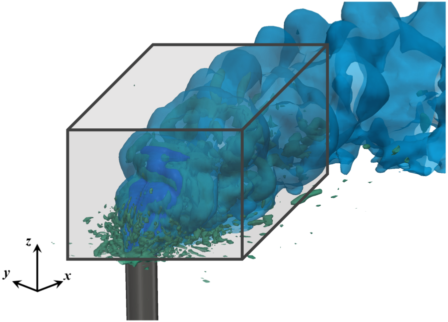
Droplet Size distribution: Primary Break–Up



- Influence of ρ_j/ρ_∞ on **droplets formation**;

Test Case: Jet in Cross Flow

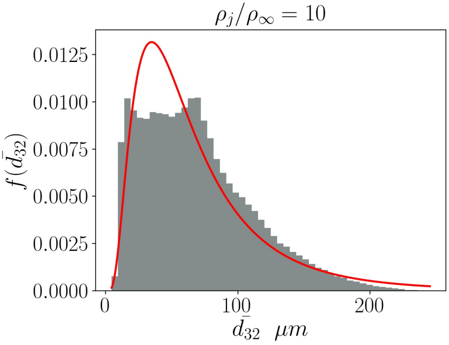
Droplet Size distribution: Primary Break–Up

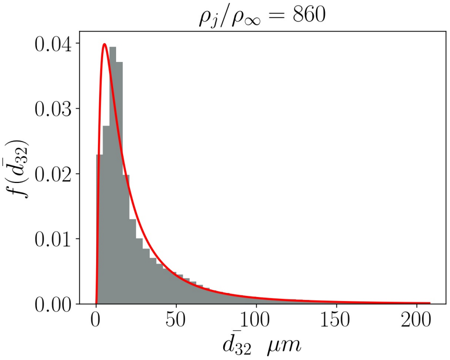


- Influence of ρ_j/ρ_∞ on droplets formation;
- Droplet Size d_{32} collected in the whole core volume

Test Case: Jet in Cross Flow

Droplet Size distribution: Primary Break–Up



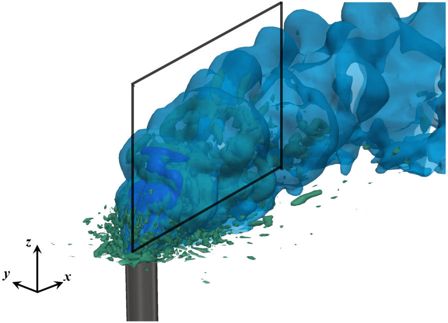


- **dichotomy** ;
- big scales more present ;

- log-normal distribution;
- mode $\approx 10\mu m$;

Test Case: Jet in Cross Flow

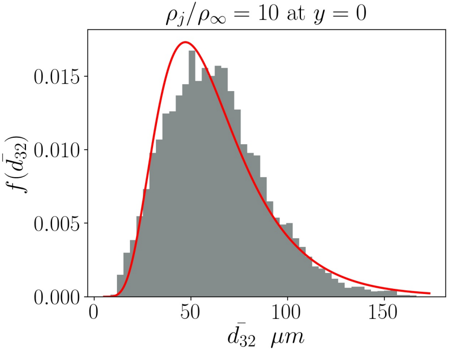
Droplet Size distribution: Primary Break–Up



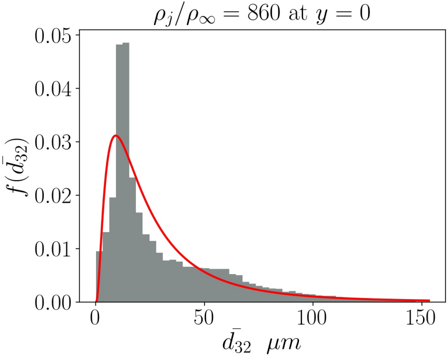
- Droplet Size d_{32} collected on $x-z$ plane at $y=0$

Test Case: Jet in Cross Flow

Droplet Size distribution: Primary Break–Up
Sampling on $x - z$ plane at $y = 0$



- dichotomy not present ;
- mode $\approx 70\mu m$ (bigger scales);



- Shape preserved ;
- mode $\approx 10\mu m$;

Concluding remarks

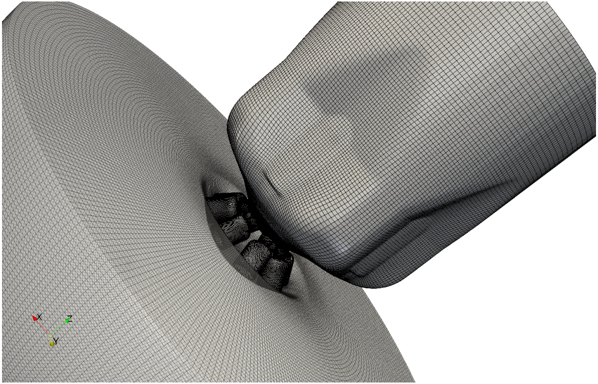
- Implementation of Stochastic Fields approach in OpenFOAM;
- Application of Stochastic Fields approach to Jet into Crossflow ;

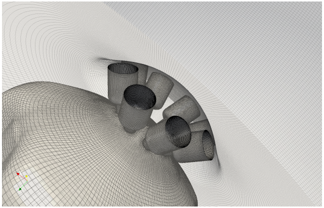
Influence of **density ratio**

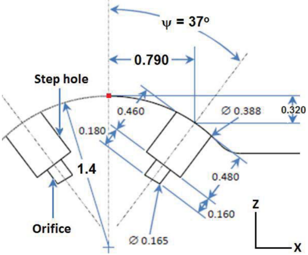
- Jet penetration: decreasing ρ_j/ρ_∞ decrease the bending;
- Break–up : increasing ρ_j/ρ_∞ no **surface break–up** ;
- Droplets formation: for small ρ_j/ρ_∞ bigger scale;

On-going Work

ECN Spray G: Gasoline Direct Injection

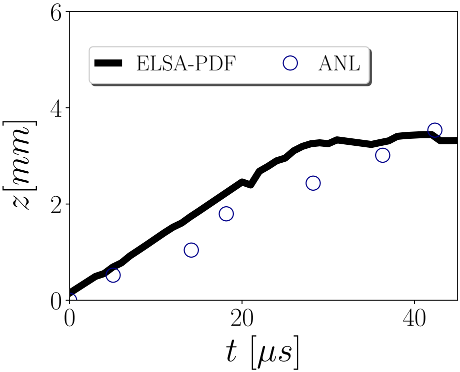


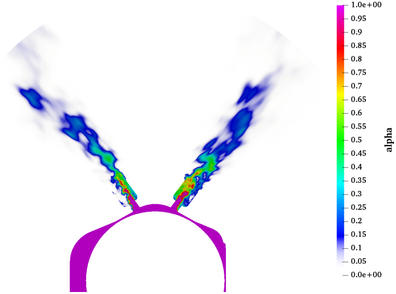




On-going Work

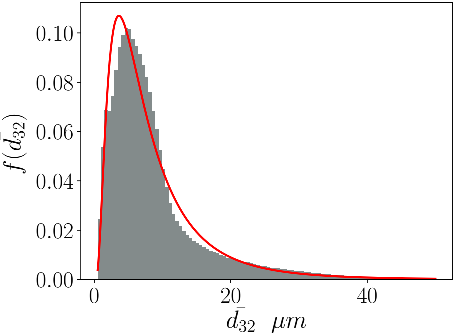
ECN Spray G: Gasoline Direct Injection
Liquid Penetration





On-going Work

ECN Spray G: Gasoline Direct Injection
Droplet size distribution



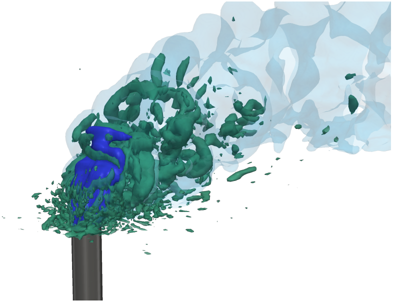
Near Field droplet size pdf

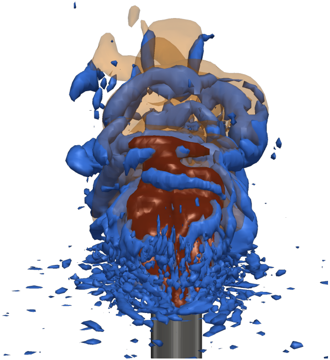
- Log-normal distribution
- Mode correctly predicted ($4.5\mu m$)

Acknowledgement

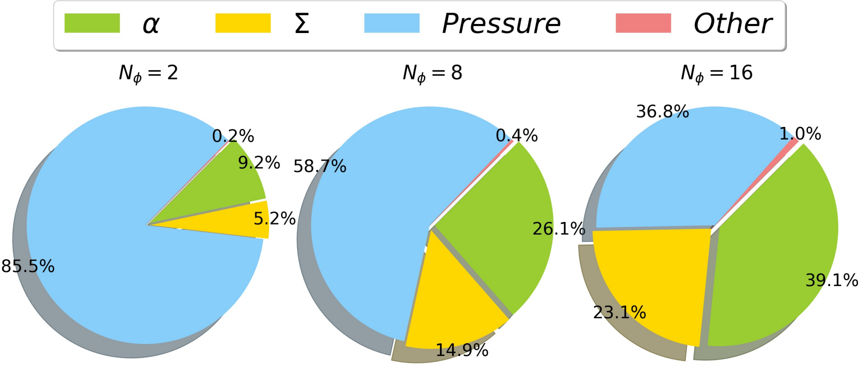
We gratefully acknowledge the support provided by the EU as part of the Horizon 2020 program, being this work part of the HAoS project.
We also acknowledge funding by the UKs Engineering and Physical Science Research Council support through the grant EP/P012744/1

Thank you very much





Appendix: Computational Time



Appendix: Computational Time