Droplet aerobreakup in high-speed gas flow using a multiscale two-fluid approach

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Abstract

- Multiscale complexities are realised in numerous multiphase flow fields of both industrial and more theoretical interest, e.g. in fuel spray injection, in droplet breakup occurring in all type of liquid-fuel combustors and in the Rayleigh-Taylor instability.
- A novel numerical methodology is proposed to deal with the coexistent segregated and dispersed flow regions; it concerns a compressible Σ-Y two-fluid model with dynamic interface sharpening based on an advanced topology detection algorithm.
- The advantages of the proposed methodology have been evaluated against the challenging case of an aerodynamic-induced droplet breakup, where a vast spectrum of scales and different flow regimes are involved.

Motivation & Novelty

- The development of a new numerical framework for compressible multiphase flows, where both segregated and dispersed flow regions co-exist and form as part of the flow evolution due to the widespread liquid fragmentation.
- The new dynamic switching algorithm calculates on-the-fly the local flow topology, estimates the appropriate closure source terms for the system of governing equations and allows for the highly transient and co-existing scales to be simulated.

Numerical Model

The governing equations of the compressible Σ-Y two-fluid model [1] consist of:

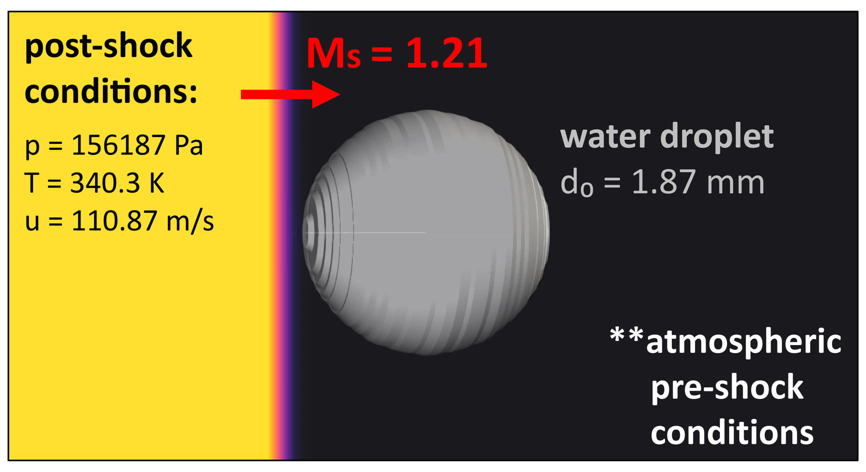
- a set of mass, momentum and energy conservation equations for each phase [2]
- a transport equation for the liquid volume fraction
- a transport equation for the interface surface area density (Σ) [3]

The multiscale numerical framework is introduced with a dual operation of the solver using both a sharp [4] and a diffuse interface approach within the same fully Eulerian framework. On-the-fly criteria based on an advanced flow topology detection algorithm allow for a dynamic switching between the two interface approaches. The new methodology has been implemented in OpenFOAM®.

Discussion & Conclusions

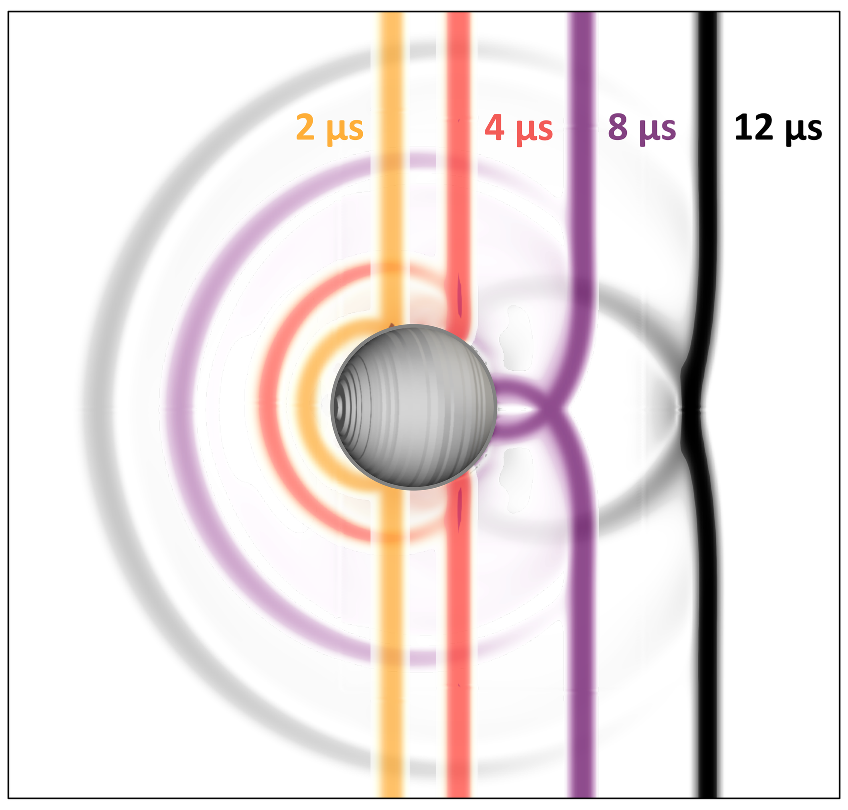
- The shock wave induced aerobreakup of a water droplet under various breakup regimes and different dominant interfacial instabilities has been studied before in the literature at the early stages in the experimental work of Theofanous et al. [5], [6].
- Additional information regarding the later stages of droplet aerobreakup are presented here, using the proposed numerical method.
- The new methodology provides an insight into the later stages of droplet aerobreakup evolution for the first time.
- Significant information regarding the produced secondary flow structures dimensions are provided, which is not available from the experiment due to limitations in diagnostic methods.

Problem Set-up

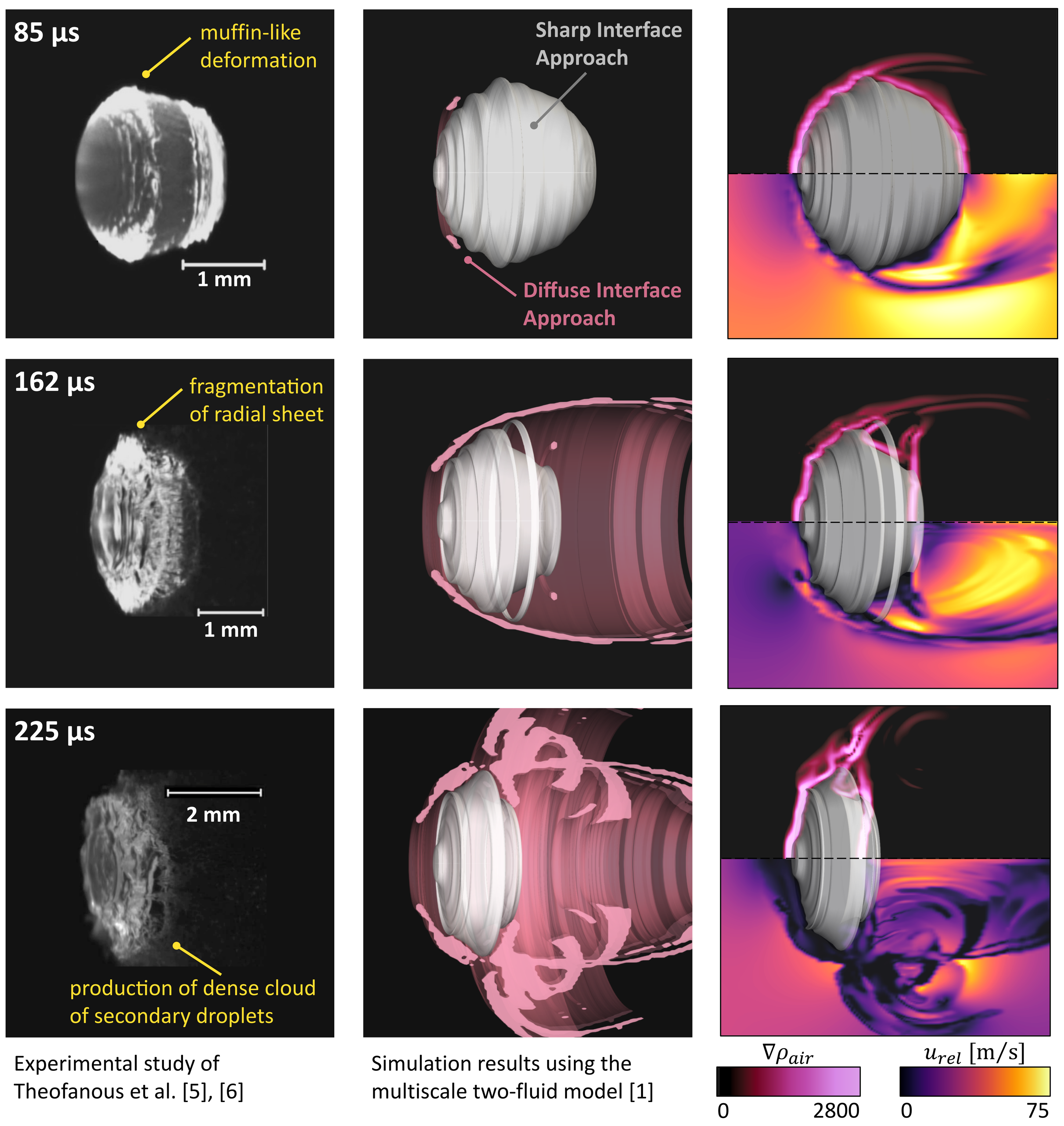


Key dimensionless numbers of the impact:
$We = 1.6 \times 10^3$, $Oh = 1.8 \times 10^{-2}$, $Re_g = 1.6 \times 10^4$

Shock Wave Propagation



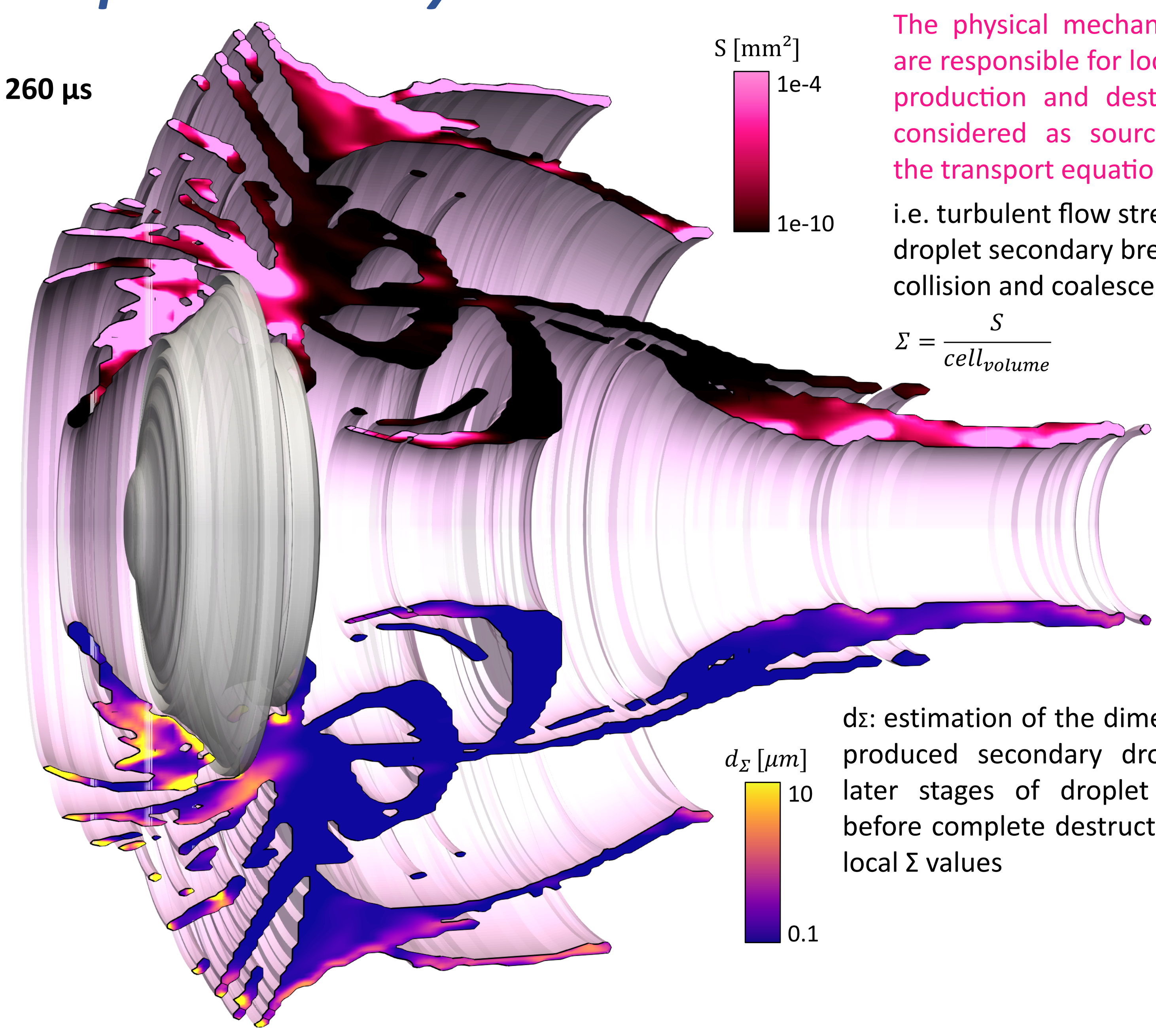
Physics of Aerobreakup



Experimental study of Theofanous et al. [5], [6]

Simulation results using the multiscale two-fluid model [1]

Droplet Cloud Dynamics



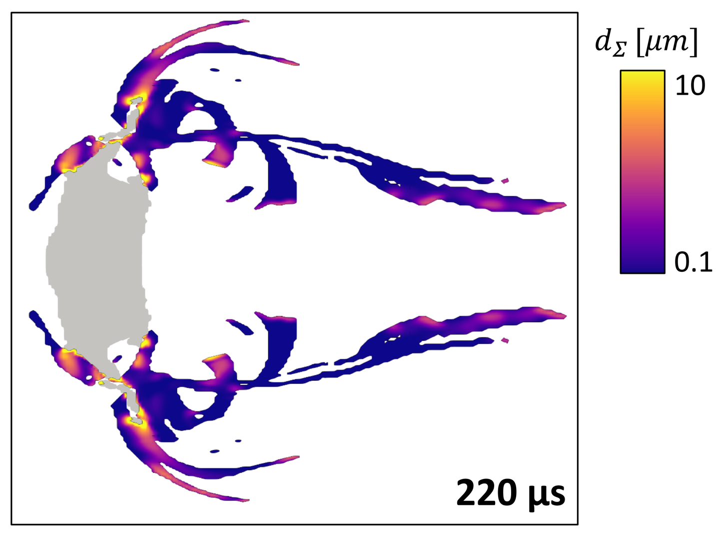
The physical mechanisms which are responsible for local interface production and destruction are considered as source terms in the transport equation for Σ.

i.e. turbulent flow stretching, droplet secondary breakup, collision and coalescence effects

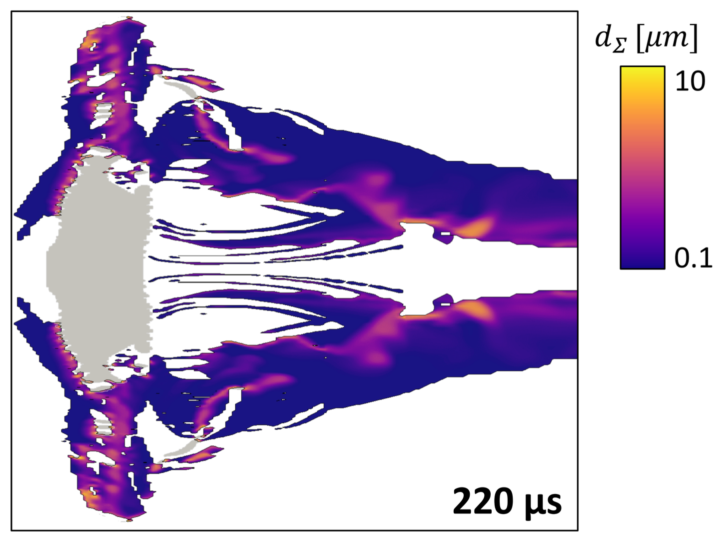
$$\Sigma = \frac{S}{cell_{volume}}$$

dΣ: estimation of the dimensions of the produced secondary droplets at the later stages of droplet aerobreakup before complete destruction, based on local Σ values

Coarse Mesh ~100 cells/ diameter



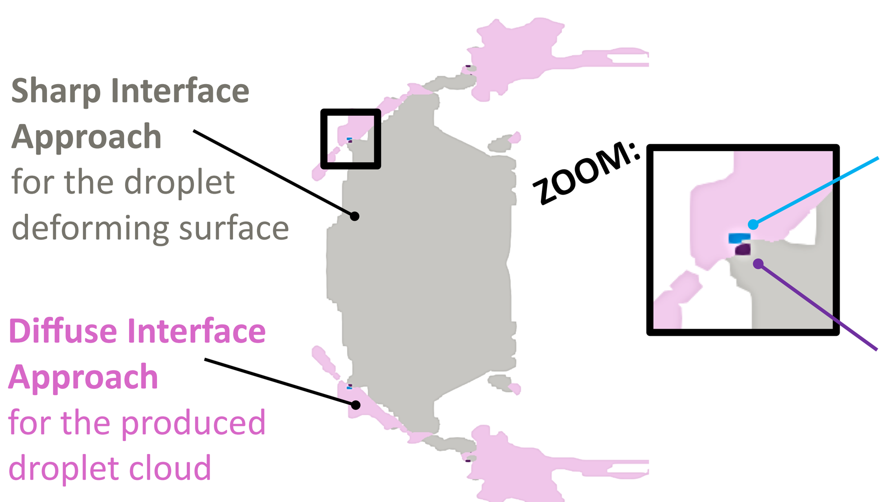
Fine Mesh ~200 cells/ diameter



- The increased resolution of the computational domain results in the prediction of a significantly extended cloud of secondary droplets, which meets the experimental observations of a very dense cloud after the radial water sheet breakup.

Holistic Multiscale Methodology

- implementation of a novel flow topology detection algorithm within the fully Eulerian framework
- flexible two-way switching between a sharp and a diffuse interface approach based on advanced local topological criteria
- evaluation of the most appropriate numerical approach for local interfaces for each computational cell in the interfacial region



SWITCH 1: *diffuse cell -> sharp cell*

single geometric criterion:

$$d_\Sigma > min(d_{cell})$$

- No further examination of the surrounding topology due to direct dependency of the SGS modelling on mesh resolution.

SWITCH 2: *sharp cell -> diffuse cell*

1st stage: geometric criterion
indication for potential change

$$d_{curv} < 3max(d_{cell})$$

2nd stage: topological criterion
examination of neighbour cells

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