High-fidelity simulations of three-phase flows in photobioreactors for space application

Angelo Raimondo Favero - 41st Cycle

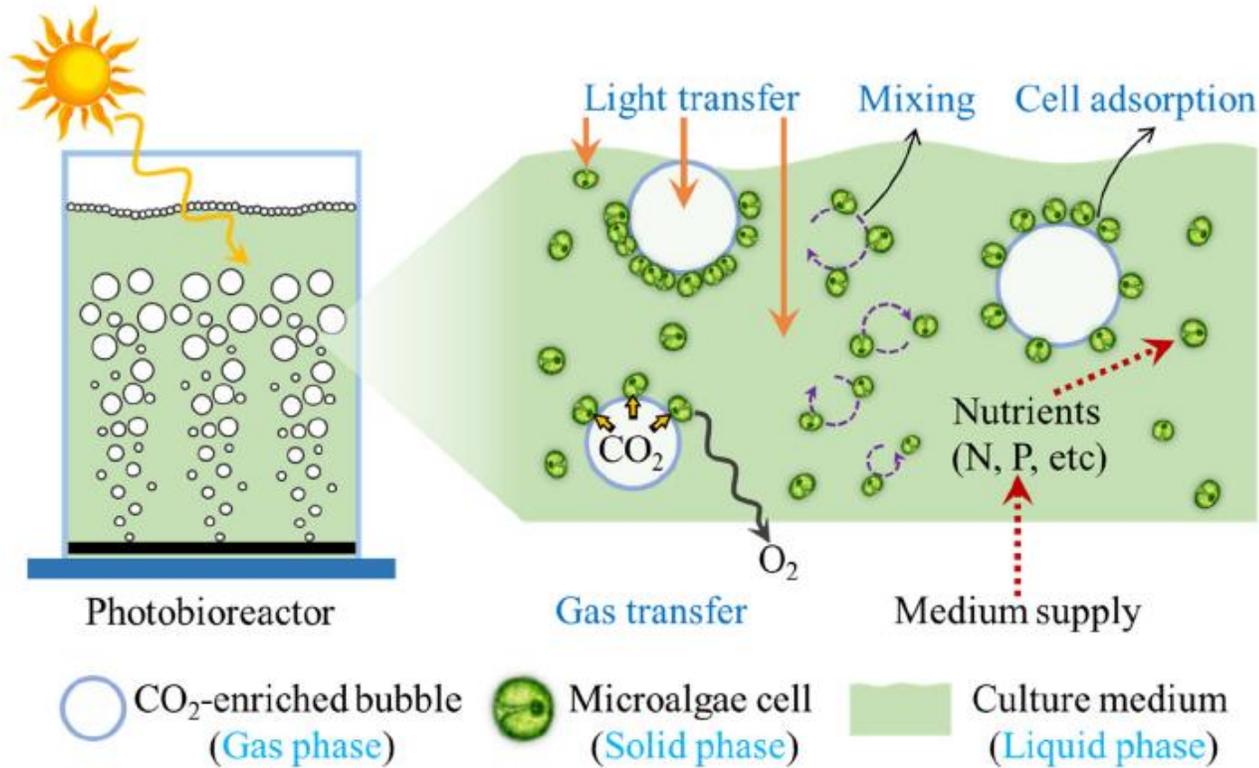Admission to the first year - 12/11/2025

- Long-term space missions are becoming feasible.

- It is necessary to reduce the cost of the transportation of resources.

- In situ resource utilization becomes fundamental.

Photobioreactors

Schematic diagram of the operation of a photobioreactor (Fu et al. 2019)

$$CO_2 + H_2O + \text{nutrients} + \textit{light energy}$$

$$O_2 + Biomass$$

- Simulation modeling for practical applications continues to rely on semi-empirical models that lack sufficient accuracy

- The main aim of this project is twofold:

    1. Develop a high-fidelity software based on first principles in order to solve the problem at lab scale exploiting the most recent GPU architecture

    2. Use the software to study three-phase systems at lab scale in order to develop the next generation of multiphase models
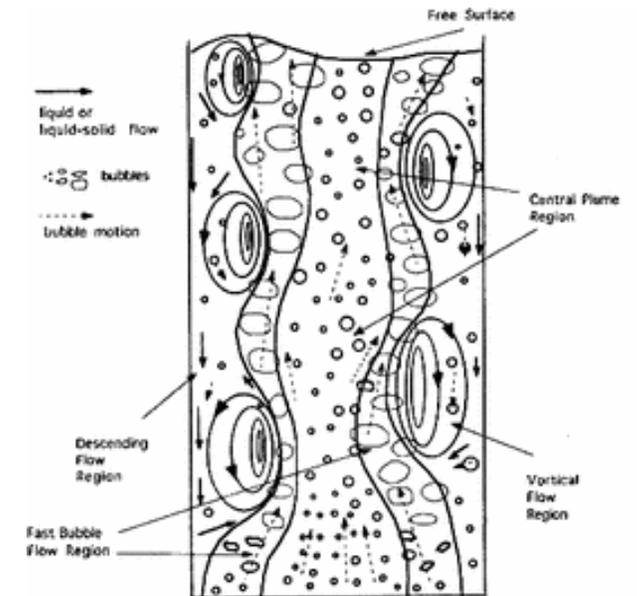
Turbulent mixing generated by rising bubbles
(Jakobsen 2014)

# A complex multiphase system

Moving deformable interface (bubble)

- Description with front capturing/tracking methods

Solid particles

- Immersed boundary method (IBM) to solve boundary conditions on the surface of the particle

- Inter-particle forces (e.g. collisions, subgrid lubrication forces)

Contact lines

- Need to model molecular interactions between phases

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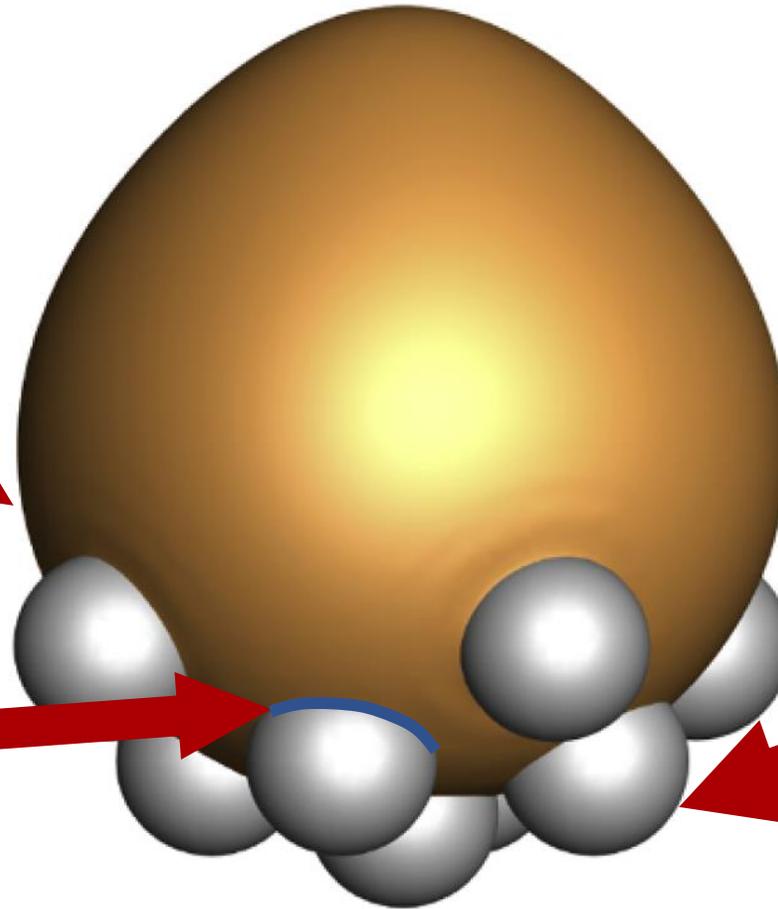
- DNS of a flow with a large number of fully resolved particles and bubbles has been achieved only recently (Zeng et al. 2025), using Lagrangian points to describe the interfaces

- This remains a major challenge, with numerous methods actively under investigation
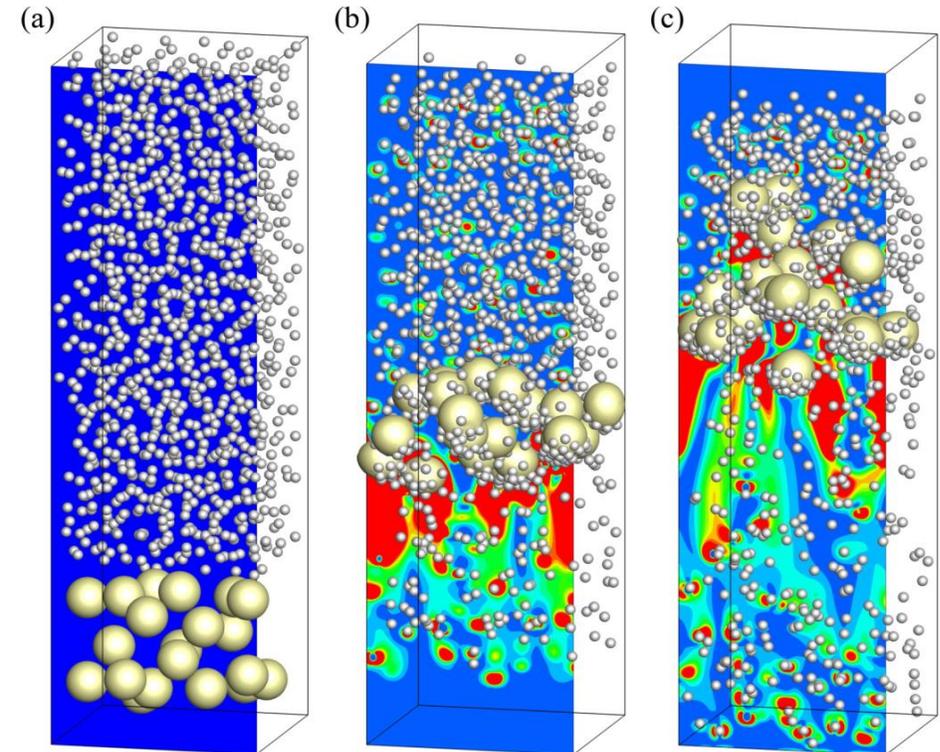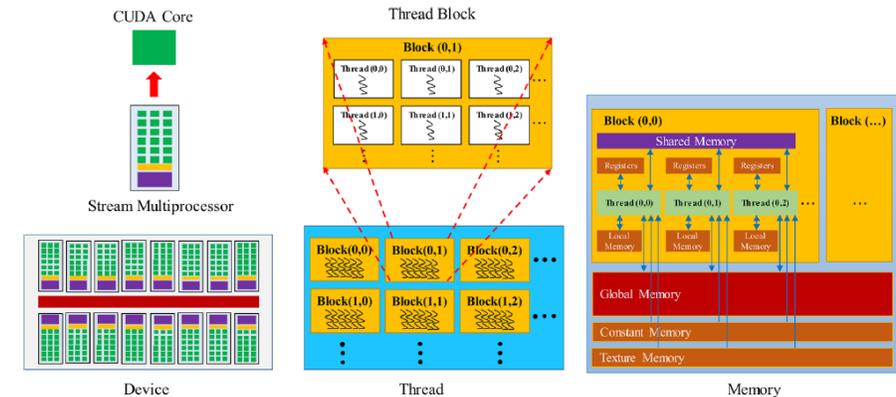

Bubbles rising through a suspension of hydrophobic particles (Zeng et al. 2025)

Study formulations for both particles and bubbles

suitable for a three-phase DNS and

computationally efficient (easy to parallelize and

suitable for GPU computations)
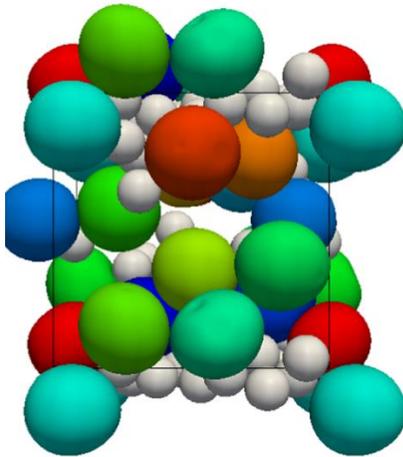
Three phase flow (Baltussen et al. 2013)

Organization of CUDA threads for NVIDIA's GPU (Ye et al. 2022)

Development of a method to model contact line dynamics to describe accurately particle-bubble interactions.
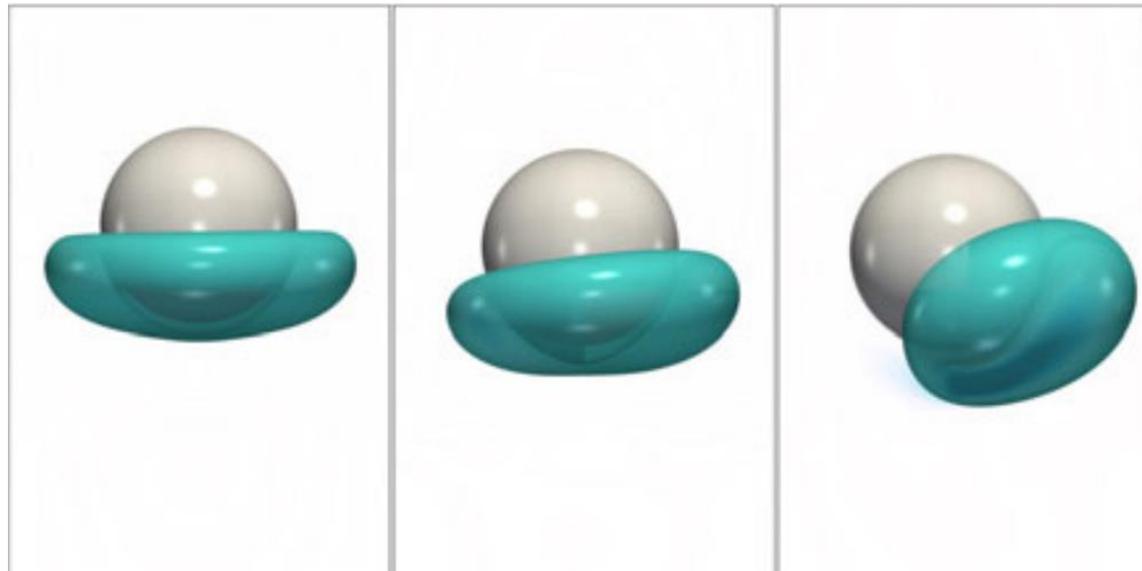
Interaction between a deformable bubble and a rigid particle (Abdal et al. 2024)

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Numerical simulation and parametric analysis of a bubble-column photobioreactor under realistic operating conditions.

DNS with different Bond numbers and solid particle number (Zeng et al. 2025)

Gantt chart

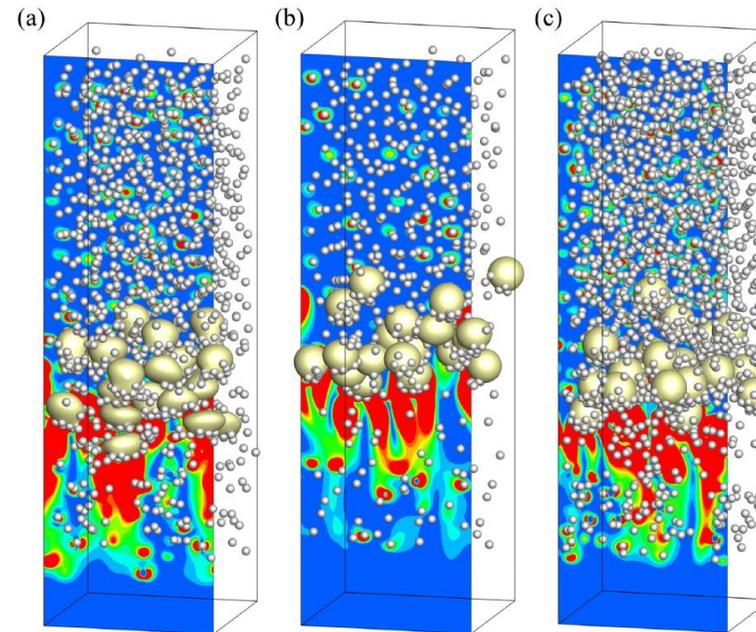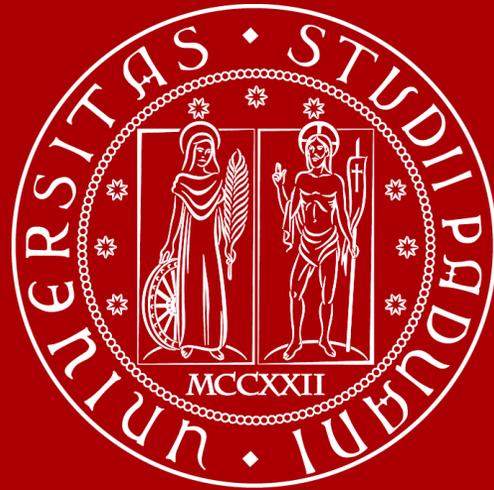| WBS NUMBER	TASK TITLE	% OF TASK COMPLETE
1	Three-phase flows	
1,1	Analysis of the state of the art for particle resolved DNS	0%
1.2	Analysis of the state of the art for multiphase DNS	0%
1.3	Delineation of an efficient method to couple solid-gas phases	0%
2	Contact lines dynamics	
2.1	Analysis of the state of the art	0%
2.2	Implementation of contact lines in the code	0%
3	CFD simulations for photobioreactor	
3.1	Numerical simulations in realistic conditions	0%
3.2	Effect of varying simulations parameters	0%
4	Writing thesis and reports	
4.1	Writing report for the admission to the next year	0%
4.2	Writing PhD thesis	0%

Timeline columns: FIRST YEAR (T1, T2, T3, T4 — O N D J F M A M J J A S), SECOND YEAR (T1, T2, T3, T4 — O N D J F M A M J J A S), THIRD YEAR (T1, T2, T3, T4 — O N D J F M A M J J A S)

Thanks for the attention

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