Dynamics of bubbles across scales

Niklas Hidman

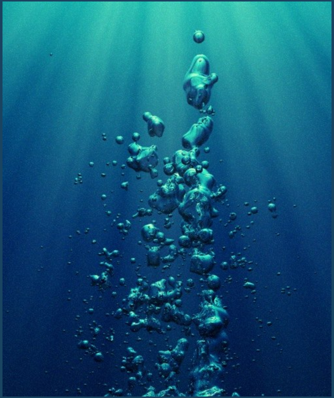
Division of Fluid Dynamics, Multiphase Flow Group

ERCOFTAC Da Vinci Competition 2023-10-12

CHALMERS

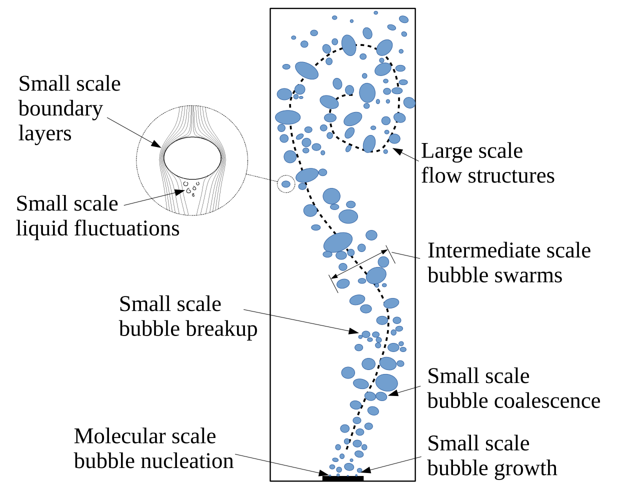
Bubbly flows

- Dispersed bubbles in a liquid.
- Industrial and natural processes:
  Bubble columns, froth flotation tanks, nuclear reactors, heat exchangers, marine vessel drag reduction, oil and gas transport, atmosphere-ocean exchanges etc.
- Good heat and mass transfer characteristics without need for moving parts.



Wide range of scales

- Illustrative example: Saturated pool boiling
- Bubbles form ($\sim 1\ nm$), grow, interact with other bubbles and liquid, form structures ($\sim 10\ m$)



Predicting bubbly flows - Multiphase DNS

- Direct Numerical Simulation - Resolves all scales relevant to fluid dynamics.
- High computational cost. Not feasible for industrial systems.
- Common to model phenomena at small scales to predict phenomena at larger scales.
- Many phenomena not fully understood and available models not always reliable.

→ Improved models and better understanding needed to facilitate accurate predictions.

Project outline

- Aim: To increase our understanding of bubbly flows and to facilitate improved numerical predictions across wide range of spatiotemporal scales.
- 3 main parts with increasing characteristic length scales:
  - 1: Cavitating microbubbles (Papers A and B)
  - 2: Dynamics of a rising bubble (Papers C and D)
  - 3: Mixing properties of bubbly suspensions (Paper E)
- For each part: Challenges - Solution - Examples

Challenges

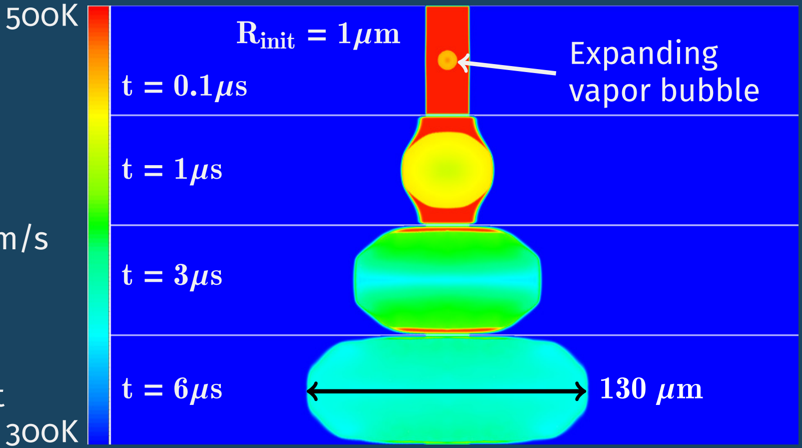
- Focus on laser-induced thermocavitation method (crystallization) - challenges from boiling and cavitation events.
  - Dynamics governed by rapid phase change across bubble interface.
  - Complex physics and extreme fluid conditions, theoretical models not yet complete.
- Predict evolution process of vapour bubble and fluid conditions around the bubble.

Solutions

- 2 numerical frameworks developed:
- Paper A: Multiphase Volume of Fluid DNS framework with phase change.
  - Major challenge: implement phase change model at the interface.
  - Detailed information in complex geometries, high cost.
- Paper B: 1D numerical framework.
  - Spherical symmetry. Conditions resolved in gas and liquid phases. Phase change and surface tension at bubble interface.
  - Low cost, extensive parameter investigations.

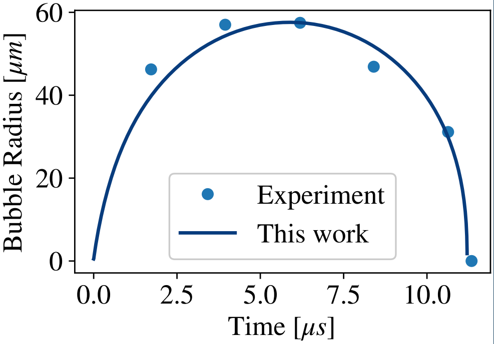
Examples - Multiphase DNS results

- laser pulse heat liquid to 500 K
- Focus on bubble growth period
- Rapid growth > 20 m/s
- Thermal boundary layers ~$0.1\ \mu m$
- Computational cost



Example: 1D results

- Experimental laser-induced thermocavitation bubble with $4\ \mu J$ laser pulse.
  (Quinto-Su et al. 2009)
- Good agreement, 1D framework predicts realistic dynamics.
- Computational cost negligible compared to DNS -> a large number of simulations possible!



CHALMERS

Presentation overview

- ☑ 1, Cavitating microbubbles:
  - Challenges - Solution - Examples
- ☐ 2, Dynamics of a rising bubble:
  - Challenges - Solution - Examples
- ☐ 3, Mixing properties of bubbly suspensions:
  - Challenges - Solution - Examples
- Summary

Challenges

- Focus on individual bubble rising in laminar or turbulent flow.
- Not all phenomena fully understood:
  interfacial forces, breakup, coalescence...
- Phenomena can be studied using multiphase DNS but with prohibitive computational cost.

→ Efficient numerical frameworks needed to study these phenomena and to improve models.

Solutions

- Identified challenges and proposed solutions:

1. Dynamics may develop over large distances (a priori unknown).

→ Develop numerical framework with a Moving Reference Frame (MRF) following the bubble (Paper C).

2. Turbulent flow often includes length scales much larger than the bubble size (costly to resolve).

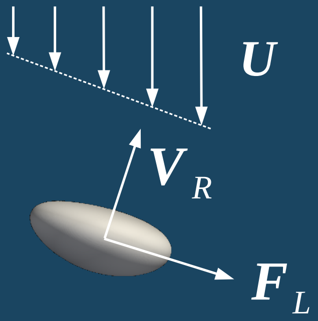
→ Couple solver for turbulent flow (with $\eta \gtrsim D$) with multiphase DNS for bubble dynamics (Paper C).

Examples - Lift force study (Paper D)

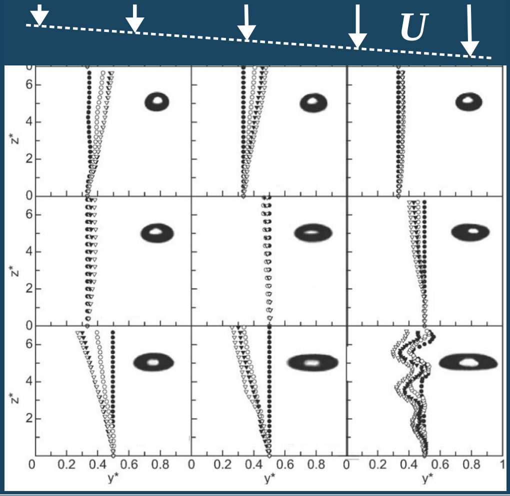
- Numerical framework developed in Paper C reduces high computational cost. Makes this study possible.
- Liquid exerts the lift force on a bubble in shear flow perpendicular to its relative motion.

$$\boldsymbol{F}_L = -C_L \Omega_g \rho_l \boldsymbol{V}_R \times \boldsymbol{\omega}_U$$

- Common assumption: $C_L = 0.5$.
  Ok or not?



Examples - Lift force study

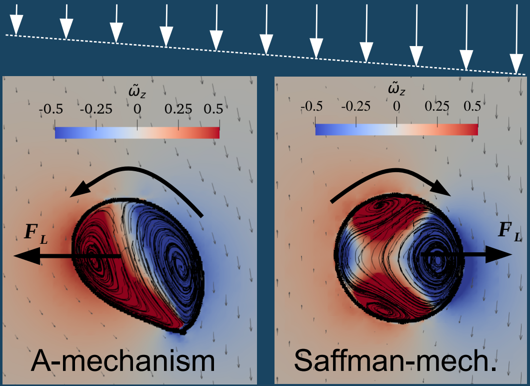


- Deformable bubbles – lift force sign reversal.
  (Tomiyama et al. 2002)
- Why?

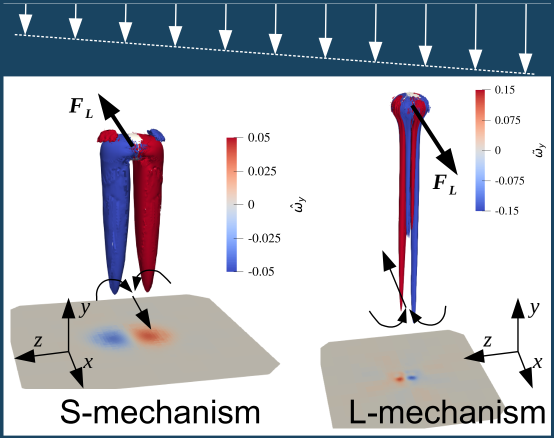
Examples - Lift force study

- 4 lift force mechanisms distinguished:
  Asymmetric (A), Saffman, Surface (S), Lighthill (L)
- Common feature: Asymmetric vorticity.
- Aim: Provide comprehensive explanation for all mechanisms based on the bubble-induced vorticity.
- We provide theoretical framework supported by multiphase DNS with the MRF-technique.

Examples - Governing lift force mechanisms



Highly viscous flow



Weakly viscous flows

Presentation overview

- ☑ 1, Cavitating microbubbles:
  - Challenges - Solution - Examples
- ☑ 2, Dynamics of a rising bubble:
  - Challenges - Solution - Examples
- ☐ 3, Mixing properties of bubbly suspensions:
  - Challenges - Solution - Examples
- Summary

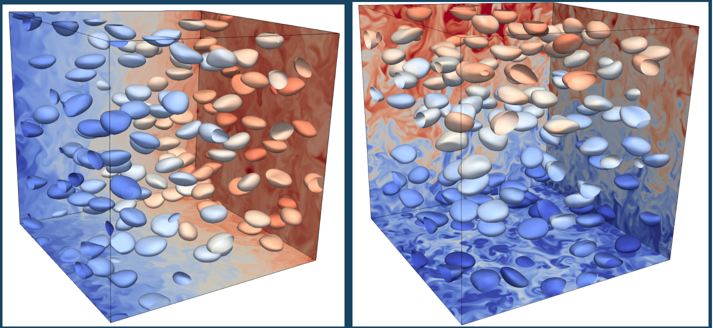
Challenges

- Focus on scalar transport (chemical species, temperature) in large-scale turbulent bubbly flows.
- Transport and mixing properties important for heat exchangers, chemical reactors etc.
- Bubbles influence scalar mixing but how much, why, significant parameters?

→ Need for more studies to elucidate bubble effects on scalar dynamics, mixing mechanisms, influence of governing parameters.

Solution (Paper E)

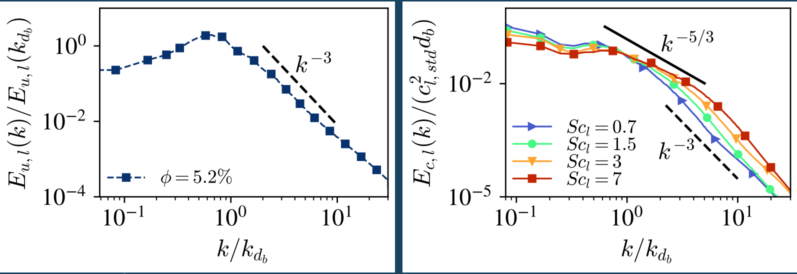
- Simulate monodisperse bubbly flow in cubic periodic domain using multiphase DNS.
- Impose linear scalar field and study scalar disturbances generated by the bubbles.
- Resolves all relevant scales, accurate statistics.



Total scalar field, $\phi = 5.2\%$.

Examples - Turbulent statistics 2.5 mm air bubbles in water (Paper E)

- Four interacting scalar mixing mechanisms identified.
- Spectra different from single-phase turbulence with -5/3 scaling.
- Show influence of governing parameters on scalar statistics.



Velocity and scalar spectra. $\phi = 5.2\%$, $\nabla^v \langle c \rangle$, $\mathrm{Sc}_l = \nu / D_{\mathrm{mol}}$

Presentation overview

- ☑ 1, Cavitating microbubbles:
  - Challenges - Solution - Examples
- ☑ 2, Dynamics of a rising bubble:
  - Challenges - Solution - Examples
- ☑ 3, Mixing properties of bubbly suspensions:
  - Challenges - Solution - Examples
- Summary

Summary

- A comprehensive modelling and numerical framework for understanding the dynamics of bubbly flows across scales.

Paper A: N. Hidman et al. Laser-induced vapour bubble as a means for crystal nucleation in supersaturated solutions - Formulation of a numerical framework. *Experimental and Computational Multiphase Flow* 1.4 (2019), 242–254.
Paper B: N. Hidman et al. Numerical Frameworks for Laser-Induced Cavitation: Is Interface Supersaturation a Plausible Primary Nucleation Mechanism? *Crystal Growth & Design* 20.11 (2020), 7276–7290.
Paper C: N. Hidman et al. A multiscale methodology for small-scale bubble dynamics in turbulence. *International Journal of Multiphase Flow* 150 (2022), 103976.
Paper D: N. Hidman et al. The lift force on deformable and freely moving bubbles in linear shear flows. *Journal of Fluid Mechanics* 952 (2022), A34.
Paper E: N. Hidman et al. Assessing passive scalar dynamics in bubble-induced turbulence using direct numerical simulations. *Journal of Fluid Mechanics* 962 (2023), A32.