Simulation of two phase flow using a modified ACLS method

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Overview

Introduction & Motivation

Model problem & Solver description

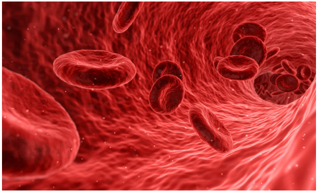
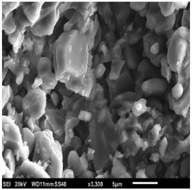
Numerical results

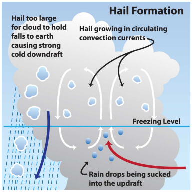
- Zalesak disk
- Vortex-in-a-box
- 3D FHIT of liquid-gas flow

Conclusions

General introduction

- Two-phase gas–liquid turbulent flows featuring phase changes are encountered in many natural and industrial processes

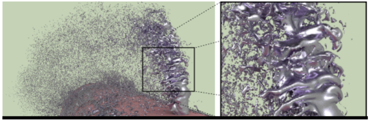


- Effectiveness depends on many parameters
  - Volume and residence time of discrete phase, bubble rise velocity, bubble size or bubble size distribution, and bubble deformability.
- Numerical simulations could be of significant use if adapted models and methods are carefully developed

Modeling two-phase flows is challenging

- Discontinuities in density across the interface
- Discrete conservation of:
  - mass of each fluid
  - total momentum
  - kinetic energy
- Dynamic creation of interfaces and complex topological changes
- Accurate modeling of surface tension effects

Drop deformation in shearing flow [a]

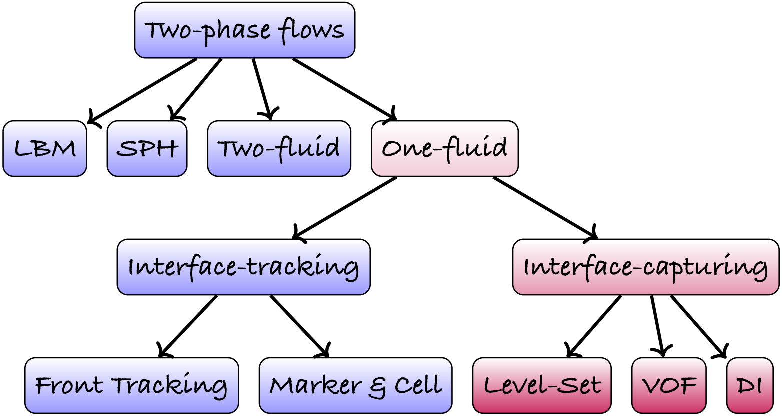


Liquid jet in a swirling gas crossflow [b]

[a] Enright, D. P. (2002). PhD Thesis. stanford university.
[b] Prakash, S. R., et al. (2019). Atomization & Sprays.

Classification of Methods

- Numerical methods employed for the description of the dispersed phase topology

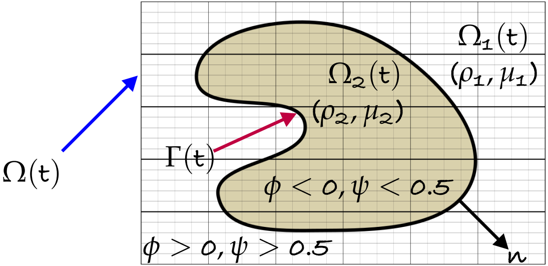


- LS is the state-of-art method for incompressible flows [1]

[1] Soligo G., Alessio R., and Alfredo S. (2021). Journal of Fluids Engineering.

Model problem

⇨ $\Omega \in \mathbb{R}^3$ a bounded domain such that $\overline{\Omega} = \overline{\Omega_1(t)} \cup \overline{\Omega_2(t)}$ and $\Omega_1 \cap \Omega_2 = \emptyset$ and $\Gamma(t) = \partial\Omega_1(t) \cup \partial\Omega_2(t)$ is the interface between two fluids.



⇨ Immiscible incompressible two-fluid system

$$\nabla \cdot u = 0, \frac{\partial u}{\partial t} + u \cdot \nabla u = \frac{1}{Re}\nabla \cdot (\mu(\nabla u + \nabla u^T)) - \nabla p + \frac{1}{Fr} g$$

with $[p]_\Gamma = \frac{1}{We}\kappa + \frac{2}{Re}[\mu]_\Gamma n^T \cdot \nabla u \cdot n$

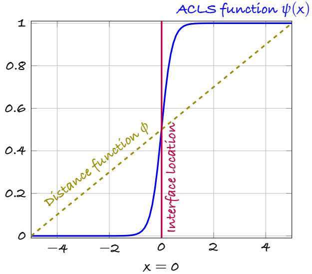
Level set method for two-fluid flows

- The interface is define as $\Gamma(t) = \{x \in \Omega; \phi(x,t) = 0\}$
- The interface movement is captured by solving the level-set equation:

$$\frac{\partial \phi}{\partial t} + u \cdot \nabla \phi = 0,$$

- The Accurate Conservative Level Set (ACLS) method uses

$$\psi(x,t) = \frac{1}{2}\left(\tanh\left(\frac{\phi(x,t)}{2\varepsilon}\right) + 1\right)$$



where the interface location is the $\psi(x,0) = 0.5$ isosurface and

$$\frac{\partial \psi}{\partial t} + \nabla \cdot (\psi u) = 0.$$

Level set method for two-fluid flows

- ϕ does not maintain the property $|\nabla \phi| = 1$ during transport.
- In the classical ACLS method, a relaxation step is added by solving in pseudo-time

$$\frac{\partial \psi}{\partial \tau} + \nabla \cdot (\psi(1-\psi)n) = \nabla \cdot (\epsilon \left(\nabla \psi \cdot n\right) n)$$

- The enhanced ACLS method, the re-initialization process is[2]

$$\frac{\partial \psi}{\partial \tau} = \nabla \cdot \left[\frac{1}{4\cosh^2\left(\frac{\phi_{map}}{2\epsilon}\right)} \left(\nabla \phi_{map} \cdot n_{FMM} - n_{FMM} \cdot n_{FMM}\right) n_{FMM} \right]$$

where $\phi_{map} = \epsilon \log\left(\frac{\psi}{1-\psi}\right)$ and n_{FMM} is obtained from a Fast Marching Method (FMM) according to $n_{FMM} = \nabla \phi_{FMM}$

[2] Desjardins O., Vincent M., and Heinz P. (2018). Journal of computational physics.

Some Numerical details

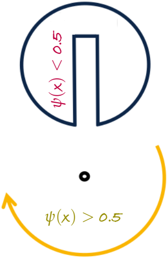
- IZEM is a low-Mach number code for the DNS and LES of reacting two-phase flows.
- Projection method based on fractional time steps developed by Chorin [3] and improved by Kim & Moin [4].
  - ✔ Fourth-order central scheme is used for the spatial integration
  - ✔ Third-order accurate semi-implicit Crank-Nicolson scheme is employed for time integration.
- Poison equation is solved using the Livermore's Hypre library with the PCG (pre-conditioned conjugate gradient) method [5].

[1] Chorin, A.J. (1968). Mathematics of computation.

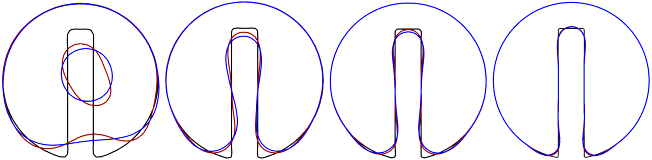
[2] Kim, J., & Moin, P. (1985). Journal of computational physics.

[3] Falgout, R. D., and Ulrike M. Y. (2002). Computational Science – ICCS 2002.

We consider a domain of unit size with the slotted disk with a constant velocity field defined by



$$\begin{cases} u_1 = -2\pi\cos(x_2 - 0.5) \\ u_2 = 2\pi\sin(x_1 - 0.5) \end{cases}$$

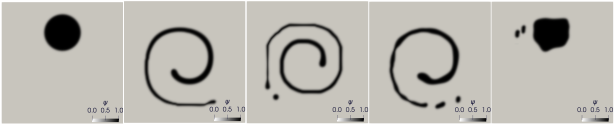


(a) $\mathcal{R}/\Delta x = 9.6$ (b) $\mathcal{R}/\Delta x = 19.2$ (c) $\mathcal{R}/\Delta x = 38.4$ (d) $\mathcal{R}/\Delta x = 76.8$

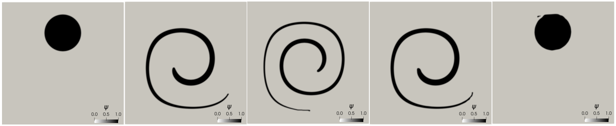
The red and blue the solutions after one and two full revolutions.

The velocity field is derived from the stream function

$$\Psi(x_1, x_2, t) = \pi \sin^2(\pi x_1) \sin^2(\pi x_2) \cos(\pi t / T)$$

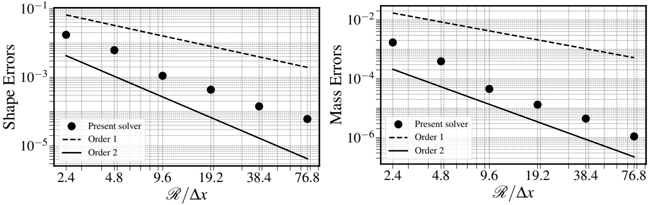


(a) $t = 0$ s (b) $t = 2$ s (c) $t = 4$ s (d) $t = 6$ s (e) $t = 8$ s

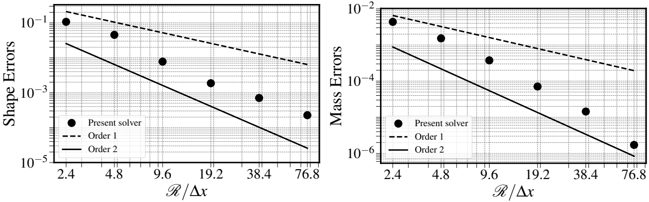


(f) $t = 0$ s (g) $t = 2$ s (h) $t = 4$ s (i) $t = 6$ s (j) $t = 8$ s

Temporal evolution of circle deformation in a box shape (serpentine) at different times with (top row) $R/\Delta x = 19.2$ and (bottom row) $R/\Delta x = 76.8$.



Mesh error convergence for the Zalesak's disk rotation



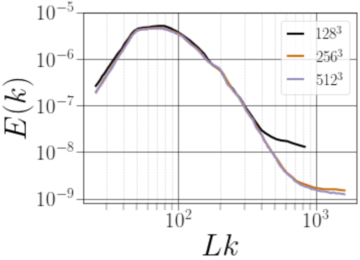
Mesh error convergence for the serpentine

Numerical results – 3D FHIT of liquid-gas flow

- 3D cubical domain with periodic boundaries.
- 8 droplets were confined whose sum is equal to the prescribed liquid volume fraction.
- The control-based linear forcing approach of Bassenne [6] is extended for the liquid-gas mixtures.

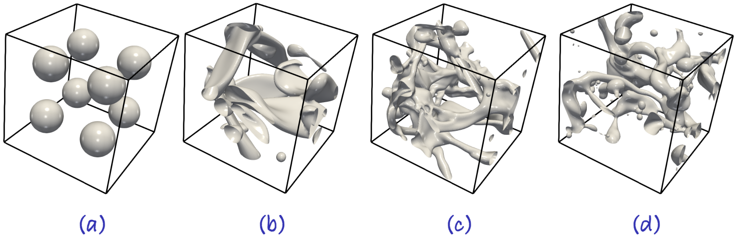
ρ_ℓ/ρ_g	μ_ℓ/μ_g	σ [N.m^{-1}]	L [m]	ϕ_ℓ	We_g	We_ℓ	Re_ℓ	Re_λ	Oh_ℓ	$\Delta x/\eta_g$	λ/η_g
30	30	0.0135	1.5×10^{-4}	0.10	2.0	60	620	31.25	0.0125	1.78	11.00

- Small-scale effects are resolved on the resolution mesh featuring 512^3 grid points.



[5] Bassenne M., et al. (2016). Physics of Fluids.

Numerical results – 3D FHIT of liquid-gas flow



The temporal evolution of the liquid/carrier interface

- The interface exhibits slight wrinkling.
- The interface becomes stretched and rolled up, and undergoes complex turbulent breakup and wrinkling

Conclusions

- Major findings
  - A novel solver for the simulation of incompressible two-phase flows is introduced.
  - The numerical method employed to capture the interface is based on the ACLS technique combined with a recently developed reinitialization technique.
  - The solver's accuracy is assessed.
- Perspectives
  - Multi-level adaptive mesh refinement method.
  - Parallel computing on unstructured grids.

Thanks for listening!

Acknowledgments

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Multiphysics & HPC of UM6P