Simulation of fluid–structure interaction with moving contact line

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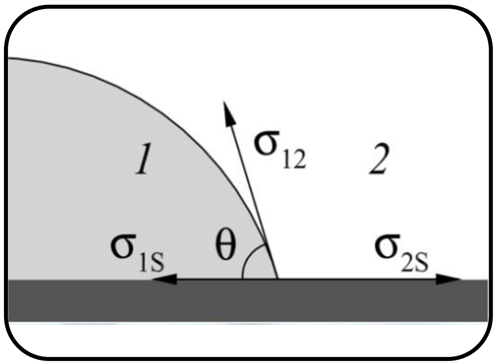
Outline

- Background
- Numerical Methods
  - Diffuse-Interface Immersed Boundary Method
  - Diffuse-Interface for ternary fluids
- Verification
- Conclusion

Background

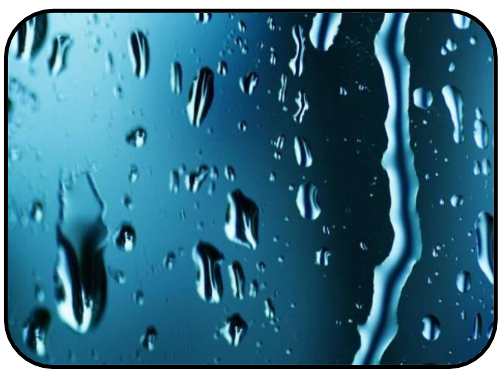
Multiphase flows with Moving Contact Lines



❖ Moving contact line

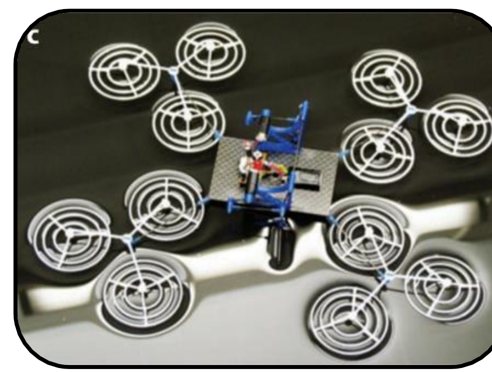
❖ Water strider on water

❖ Lotus self-cleaning



❖ Raindrops on window

❖ Ink printing



❖ Aquatic robot

Numerical Methods

Diffuse-Interface Immersed-Boundary method

- Diffuse Interface method

  ---- Interface Capturing

- Immersed Boundary method

  ---- Fluid-Structure Interaction

- Characteristic Contact Line Model

  ---- Wetting Condition

Liu & Ding, J. Comput. Phys. 2015

Liu et al., J. Comput. Phys. 2017

Numerical Methods

Governing Equations

- Cahn-Hilliard Equation

$$\frac{\partial C}{\partial t} + \nabla \cdot (\boldsymbol{u} C) = \frac{1}{Pe} \nabla^2 \Psi$$

- Navier-Stokes Equation

Immersed-Boundary Force

$$\begin{cases} \rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \frac{1}{Re} \nabla \cdot [\mu(\nabla \mathbf{u} + \nabla \mathbf{u}^T)] + \frac{f_s}{We} - \frac{\rho}{Fr} \mathbf{j} + f_{IB} \\ \nabla \cdot \mathbf{u} = 0 \end{cases}$$

Ding et al., J. Comput. Phys., 2007

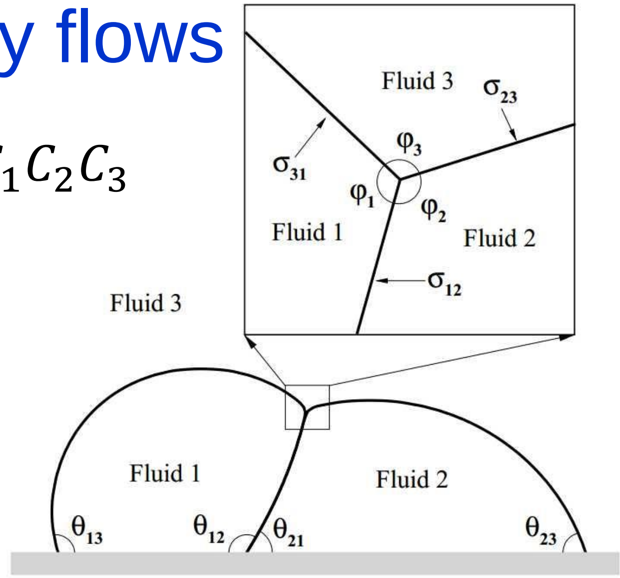
Liu & Ding, J. Comput. Phys. 2015

Numerical Methods

Diffuse-interface for ternary flows

$$\frac{\partial \mathbf{C}}{\partial t} + \nabla \cdot (\boldsymbol{u}\mathbf{C}) = \frac{1}{Pe}\nabla^2(\boldsymbol{\Psi} - \boldsymbol{\beta}) \qquad \beta_i = C_1 C_2 C_3$$

$$\mathbf{C} = (C_1, C_2, C_3)$$

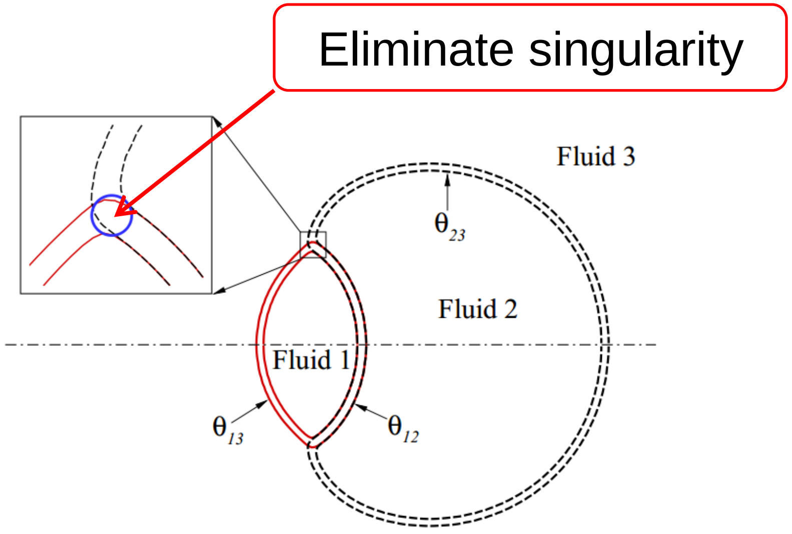


$$\boldsymbol{sin\varphi_2 cos\theta_{13} - sin\varphi_3 cos\theta_{12} - sin\varphi_1 cos\theta_{23} = 0}$$

- Diffuse interface model

$$\boldsymbol{\theta_1} = \frac{C_3}{C_3 + C_2}\boldsymbol{\theta_{13}} + \frac{C_2}{C_3 + C_2}\boldsymbol{\theta_{12}}$$

$$\boldsymbol{\theta_2} = \frac{C_3}{C_3 + C_1}\boldsymbol{\theta_{23}} + \frac{C_2}{C_2 + C_1}\boldsymbol{\theta_{21}}$$



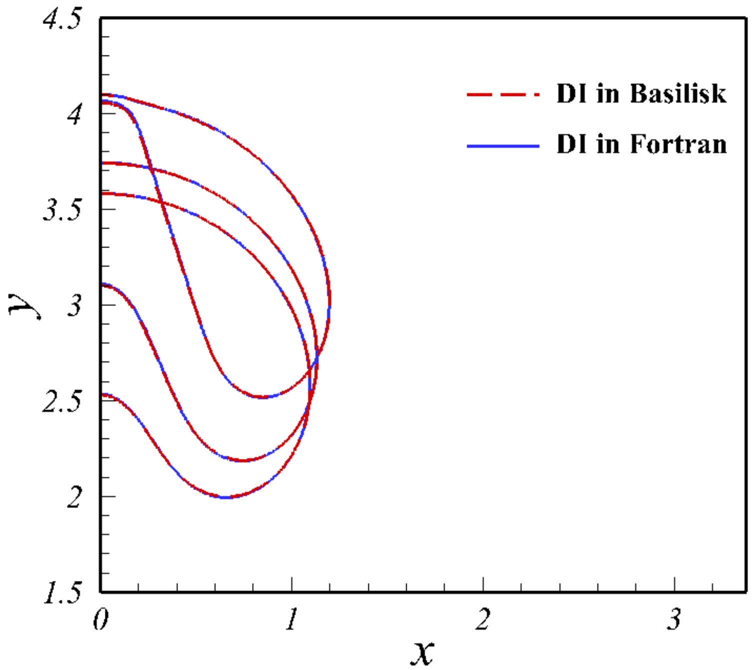
Kim, Comput. Methods Appl. Mech. Eng. 2007

Zhang et al., J. Comput. Phys. 2016

Verification

Axisymmetric Bubble Rising

	Break up time	Break up position
Sussman et al., 1997	1.61	4.05R
Ding et al., 2007	1.60	4.09R
Present	1.62	4.1R

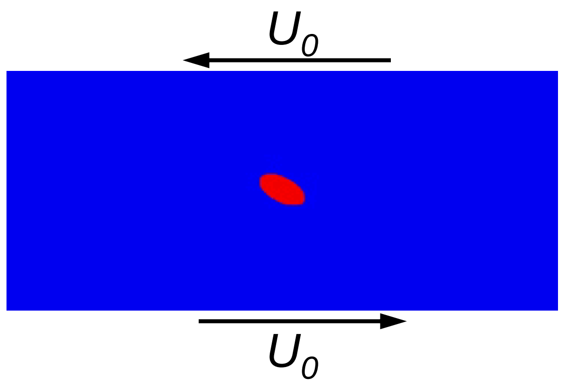


❖ Numerical results of DI in Basilisk are in good agreement with benchmark solutions.

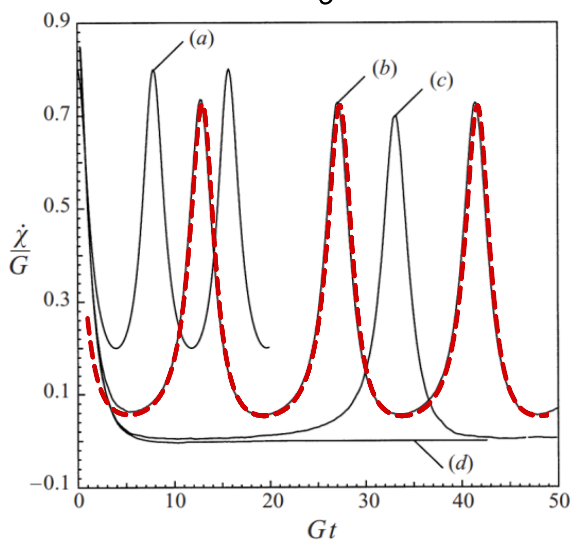
Sussman & Smereka, J. Fluid Mech., 1997
Ding et al., J. Comput. Phys., 2007

Verification

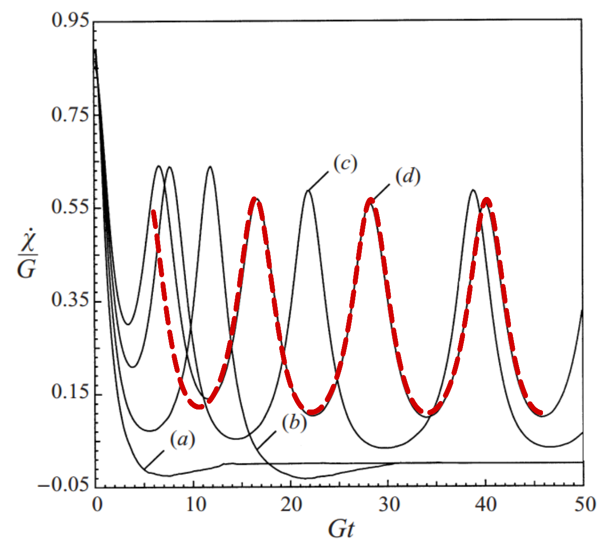
Rotating Elliptic Cylinder in Shear Flow



- Immersed Boundary method works well in Basilisk.



$(b)\ \mathrm{Re}=15, \alpha=1$

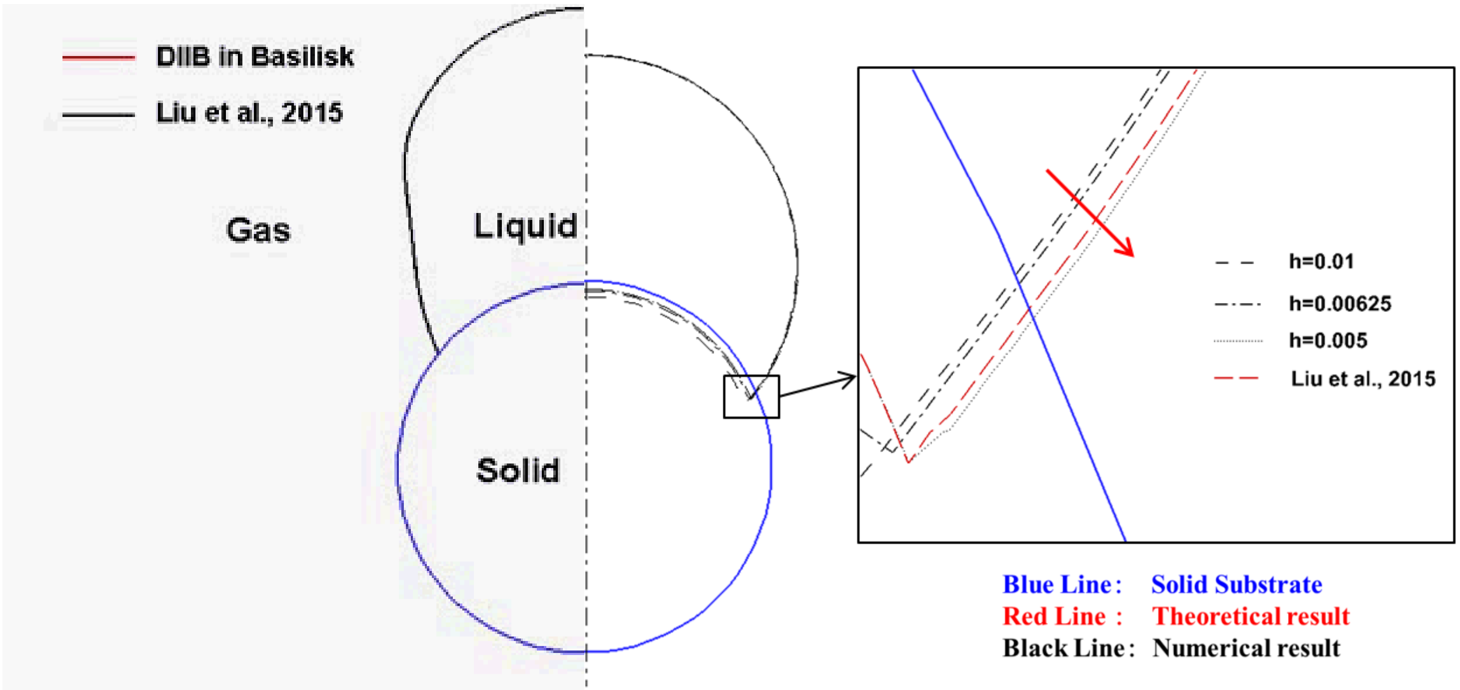


$(d)\ \mathrm{Re}=50, \alpha=4$

Ding & Aidun, J. Fluid Mech., 2000

Verification

2D Droplet Spreading on a Cylinder



Blue Line: Solid Substrate
Red Line : Theoretical result
Black Line: Numerical result

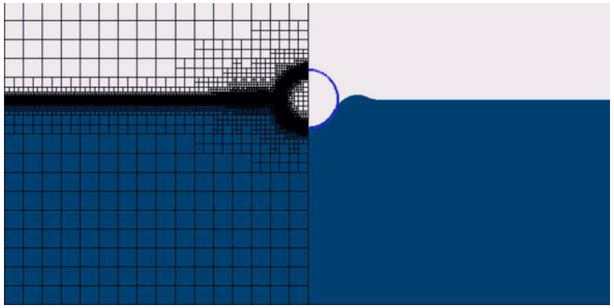
- The results of DIIB in Basilisk agree with theoretical prediction.
- Numerical results converge with mesh refinement.

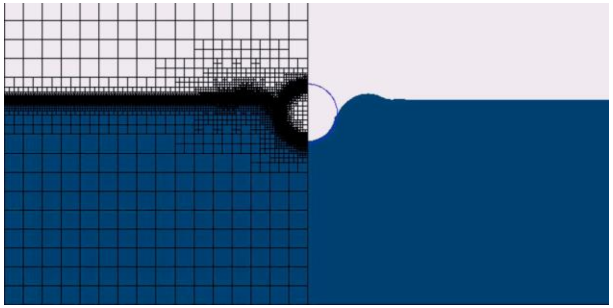
Liu & Ding, J. Comput. Phys. 2015

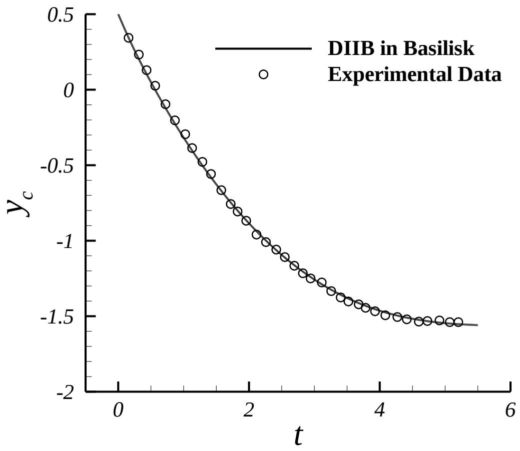
Verification

Particle Impacting Liquid-Gas Interface

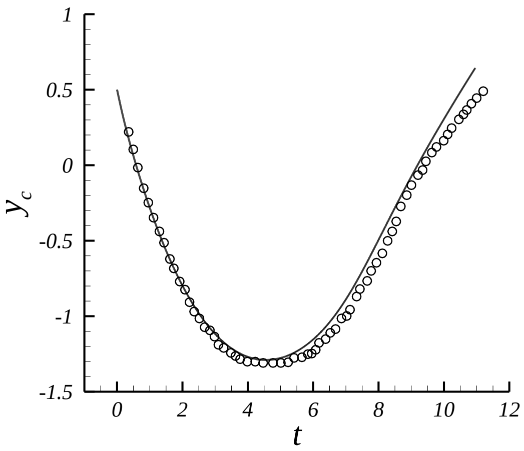
Super-hydrophobic: $\theta = 154^{\circ}$







Position of a sinking sphere



Position of a bouncing sphere

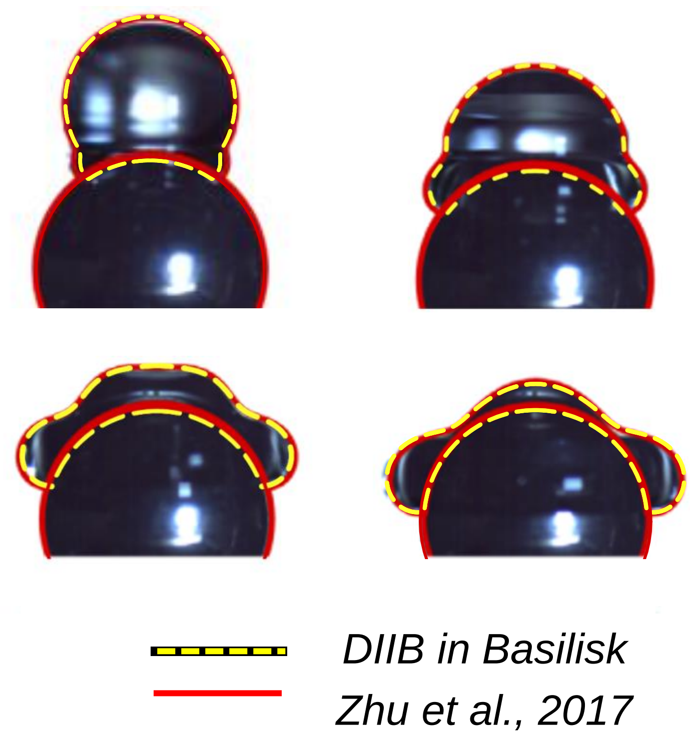
Quantitative agreement has been achieved with experimental data.

Lee & Kim, Langmuir, 2008

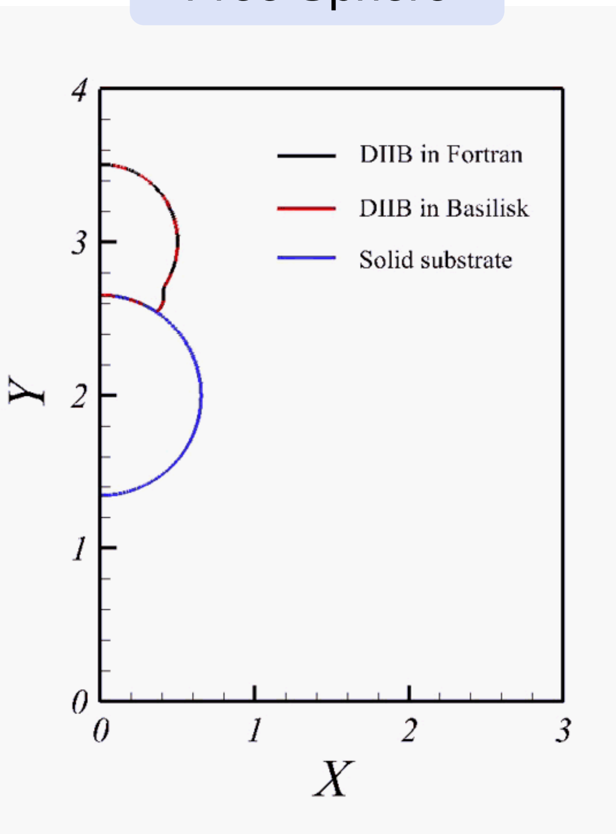
Verification

Drop Impacting a Solid Sphere

Fixed Sphere



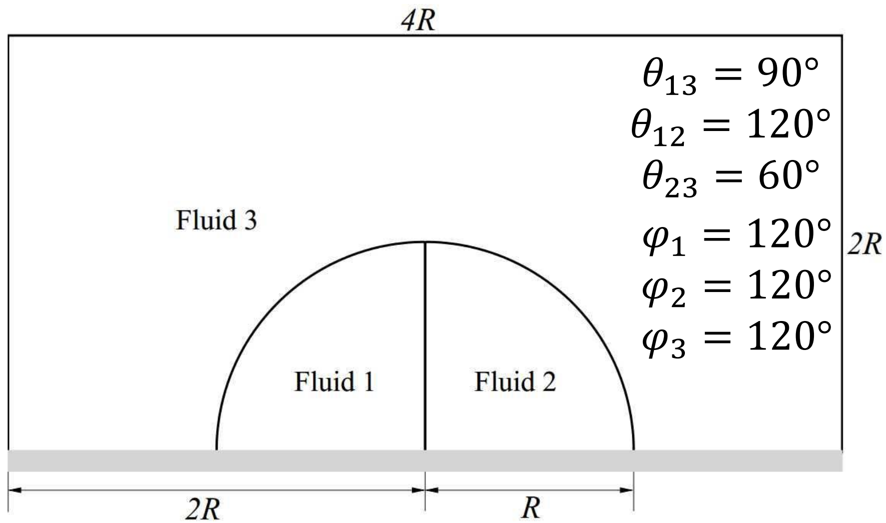
Free Sphere

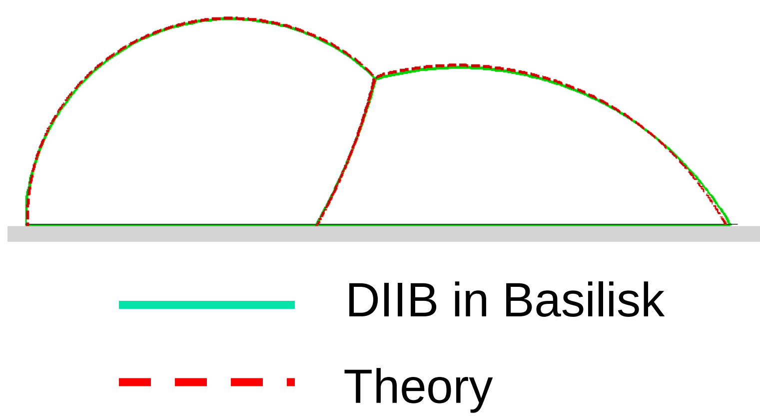


Zhu et al., J. Fluid Mech., 2017

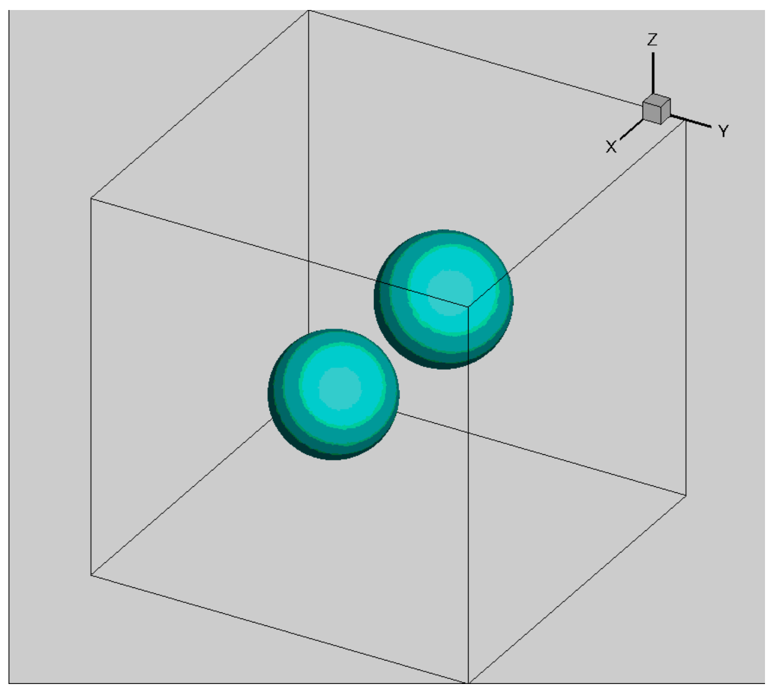
Verification

☐ Spreading of Compound Droplets on Plate





☐ 3D Ternary Flows



Challenges

Mesh stencil

- Stencil with AMR is not sufficiently large for high-order scheme, such as the 5th-order WENO.
- DIIB method needs to use the value of f[3,0], but the value is lost in MPI parallel computation.

Output in Tecplot

- It is difficult to write connectivity list when using adaptive mesh.

Conclusion

- DIIB method can be used in Basilisk to simulate FSI involving dynamic wetting.
- Ternary fluid flow with moving contact lines can be simulated in Basilisk.
- Parallel computation remains to be solved.

Reference

- H Ding et al., Diffuse interface model for incompressible two-phase flows with large density ratios, J. Comput. Phys. 2007
- HR Liu & H Ding., A diffuse-interface immersed-boundary method for two-dimensional simulation of flows with moving contact lines on curved substrate, J. Comput. Phys. 2015
- HR Liu et al., Fluid-structure interaction involving dynamic wetting: 2D modeling and simulation, J. Comput. Phys. 2017
- CY Zhang et al., Diffuse interface simulation of ternary fluids in contact with solid, J. Comput. Phys. 2016

THANK YOU !

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