Implementing a hybrid immersed boundary/fictitious domain (HFD-IB) method coupled with the Discrete Element Method (DEM) to consider lubrication effects between the particles in the fluid domain

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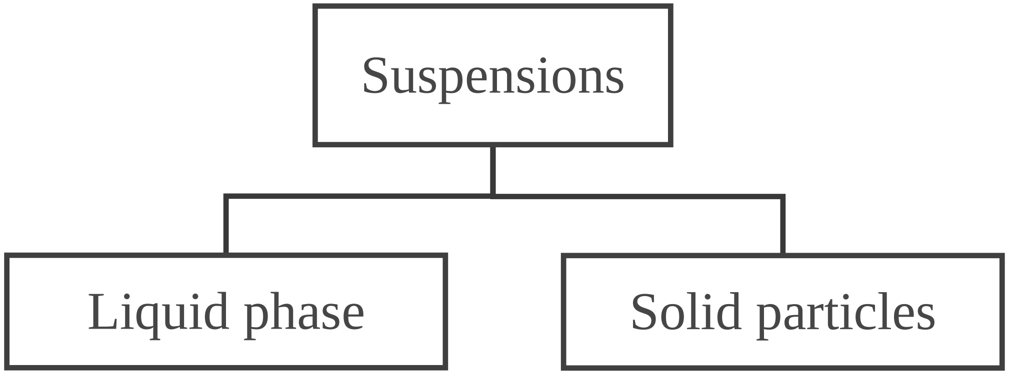
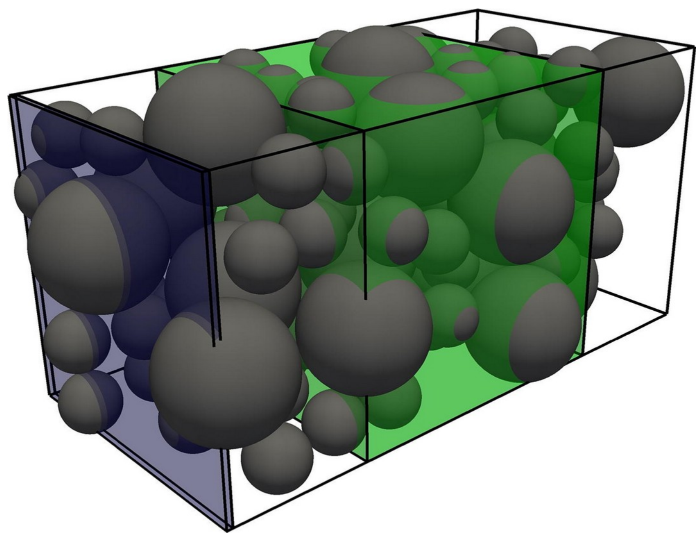
IUTAM symposium "From Stokesian suspension dynamics to particulate flows in turbulence"
Toulouse, France, from August, 29th to September, 2nd - 2022.

Introduction





Municchi, Federico, and Stefan Radl. "Consistent closures for Euler-Lagrange models of bi-disperse gas-particle suspensions derived from particle-resolved direct numerical simulations." International Journal of Heat and Mass Transfer 111 (2017): 171-190.

Coupled CFD-DEM Simulation:

Liquid phase	Solid particles
Eulerian Framework	Lagrangian Framework
Computational Fluid Dynamics	Discrete Element Method
OpenFOAM	XDEM code

Main forces faced by particles

Main forces faced by particles

- Hydrodynamic long-range interaction
- Collision between particles
- Lubrication forces

Treated with high accuracy in CFD-DEM simulations

less accurate in a small gap distance

Considering lubrication effects

Lubrication forces are less accurate in a small gap distance

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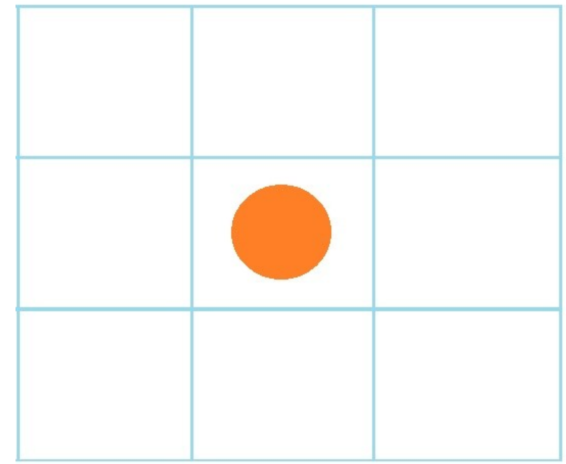
Grid resolution is not fine enough to capture the correct hydrodynamic interaction



One remedy for this problem

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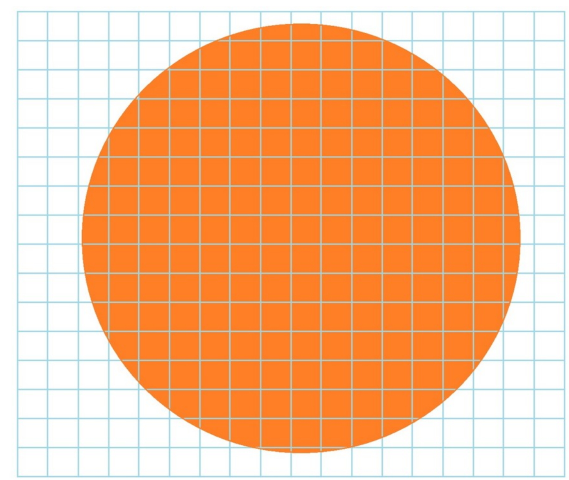
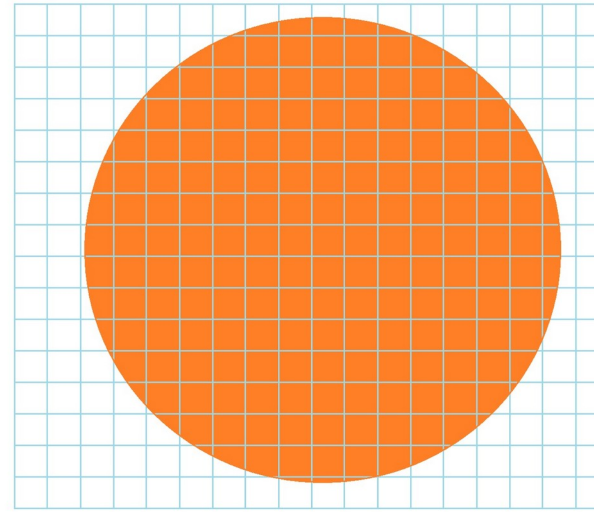
Using Immersed Boundary (IB) method in a CFD solver



Immersed Boundary Method



Fixed, continuous, and structured grids

Without regriding

Using the natural lubrication arising from the IBM

Considering the fully resolved simulation

Governing equations

Governing equations

Lagrangian framework

Eulerian framework

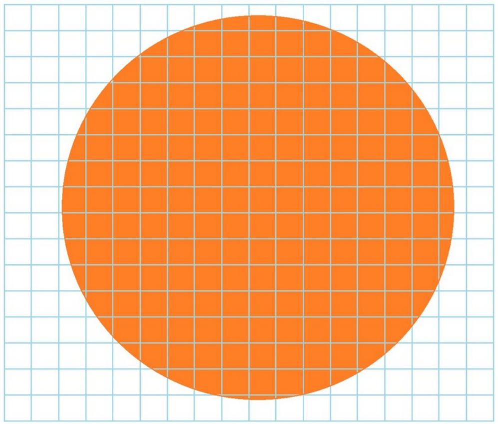
$$m_p \frac{du_p}{dt} = \int_\Gamma \tau . n \, dS \; + V_p(\rho_p - \rho_f) g$$

$$\frac{\partial u}{\partial t} = -\nabla.(u \otimes u) + \frac{1}{\rho_f} \nabla . \tau + f$$

Hydrodynamic stress tensor

Tschisgale, S., Kempe, T. and Fröhlich, J., 2018. A general implicit direct forcing immersed boundary method for rigid particles. Computers & Fluids, 170, pp.285-298.

Unkown part of the Lagrangian framework



$$\int_{\Gamma} \tau.n\, dS = \frac{d}{dt}\int_{\Omega^p} \rho_f u\, dV - \int_L \rho_f f\, dV$$

Immersed boundary force

$$I_p \frac{d\omega_p}{dt} + \omega_p \times I_p.\omega_p = \int_{\Gamma} r \times (\tau.n)\, dS$$

$$\int_{\Gamma} r \times (\tau.n)\, dS = \frac{d}{dt}\int_{\Omega^p} \rho_f r \times u\, dV - \int_L \rho_f r \times f\, dV$$

[1] Tschisgale, S., Kempe, T. and Fröhlich, J., 2018. A general implicit direct forcing immersed boundary method for rigid particles. Computers & Fluids, 170, pp.285-298.
[2] Kim, Y. and Peskin, C.S., 2016. A penalty immersed boundary method for a rigid body in fluid. Physics of Fluids, 28(3), p.033603.

Governing equations for Blais Method:

$$\nabla . u = 0$$

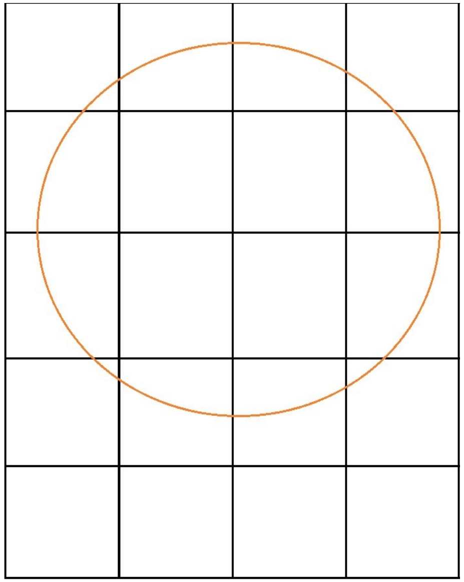
$$\frac{\partial u}{\partial t} = -\nabla . (u \otimes u) + \frac{1}{\rho_f} \nabla . \tau + f$$

Calculating the immersed boundary force:

$$f^n = f^{n-1} + \frac{\alpha \lambda_i}{\Delta t} (u_{ib,i} - u_i^n)$$

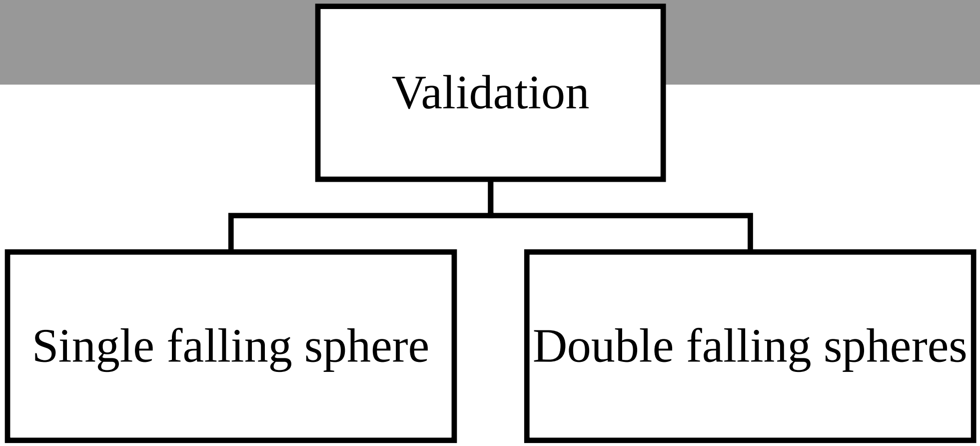
Calculating the lambda:

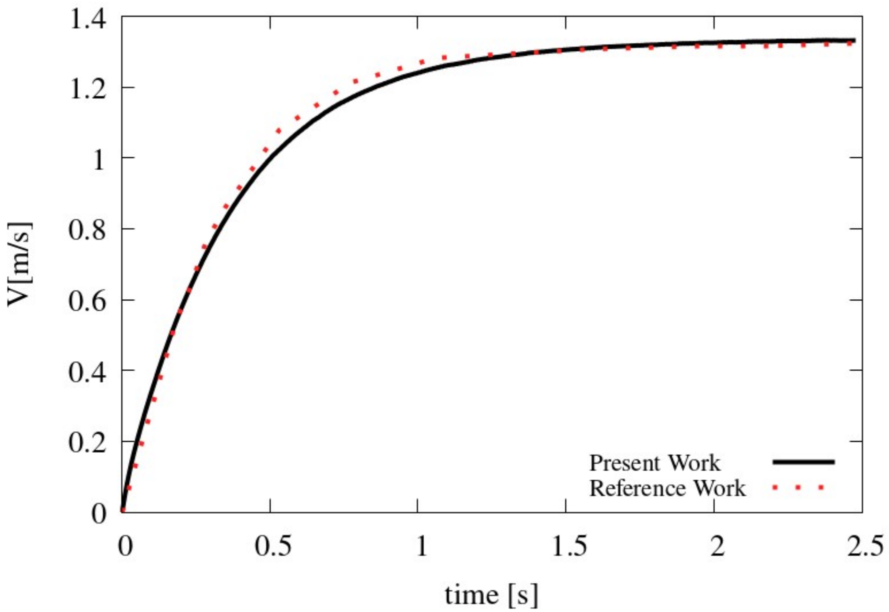
$$\lambda_i = \frac{N_{vc,i} + N_{cc,i} N_{v,i}}{2 N_{v,i}}$$

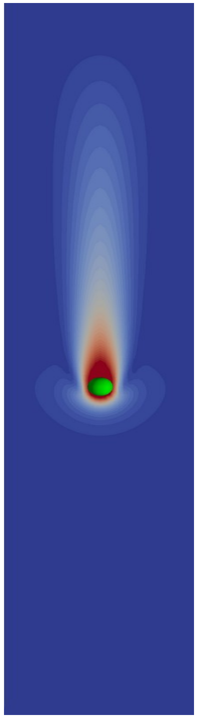


Blais, B., Lassaigne, M., Goniva, C., Fradette, L. and Bertrand, F., 2016. A semi-implicit immersed boundary method and its application to viscous mixing. Computers & Chemical Engineering, 85, pp.136-146.

Validation:

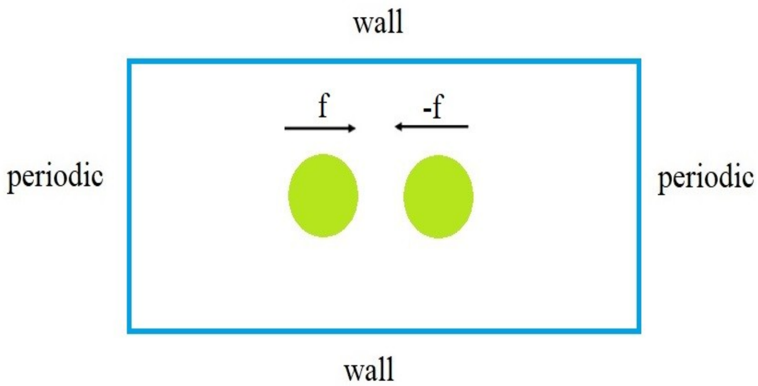






Wu, M., Peters, B., Rosemann, T. and Kruggel-Emden, H., 2020. A forcing fictitious domain method to simulate fluid-particle interaction of particles with super-quadric shape. Powder Technology, 360, pp.264-277.

Mesh resolution



$$C_{\Delta t} = \frac{6\mu^f \Delta t}{\rho^f \Delta^2},$$

Implementing the parameter introduced by Hori

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Using the natural lubrication arising from the IBM

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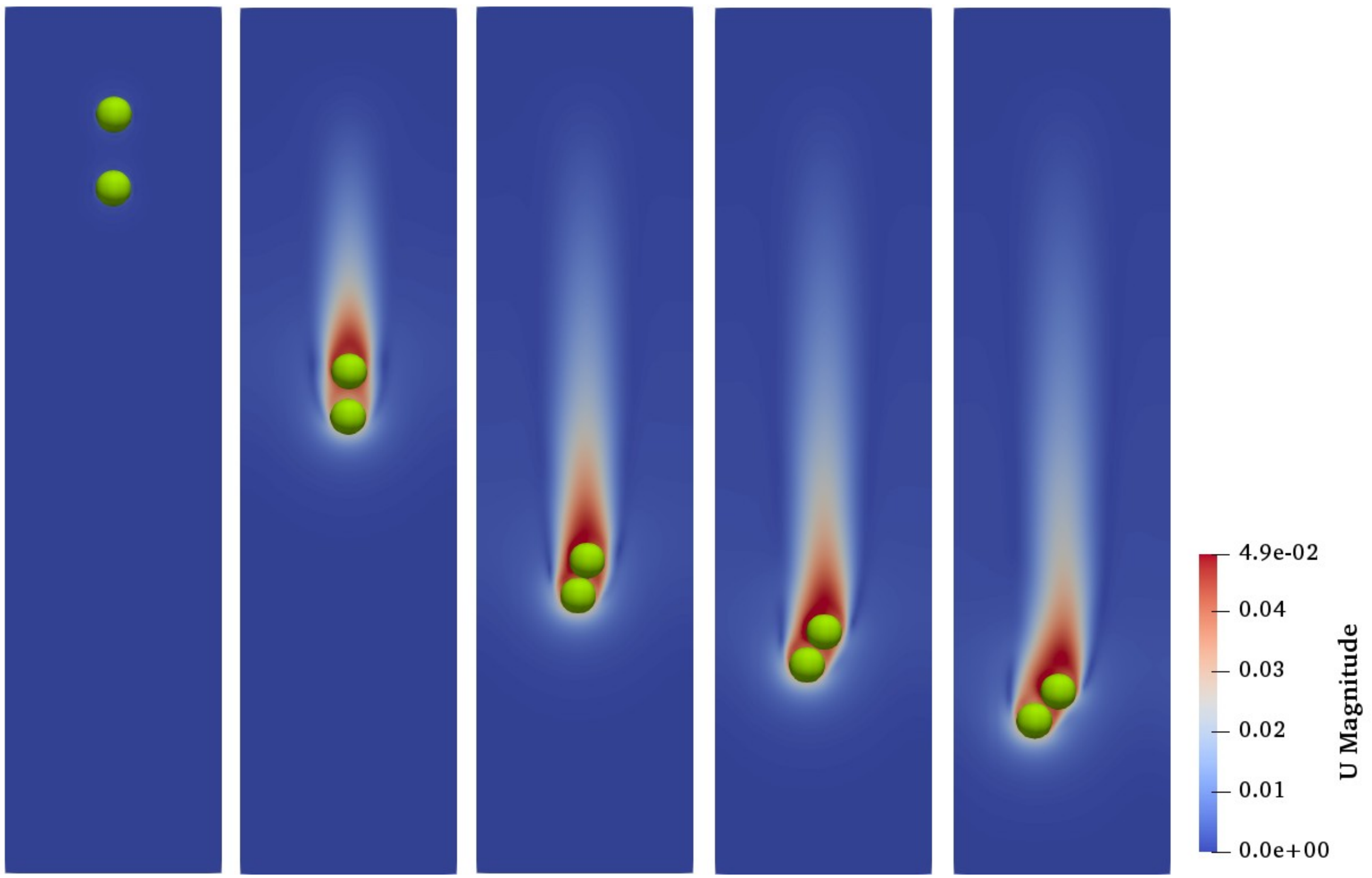
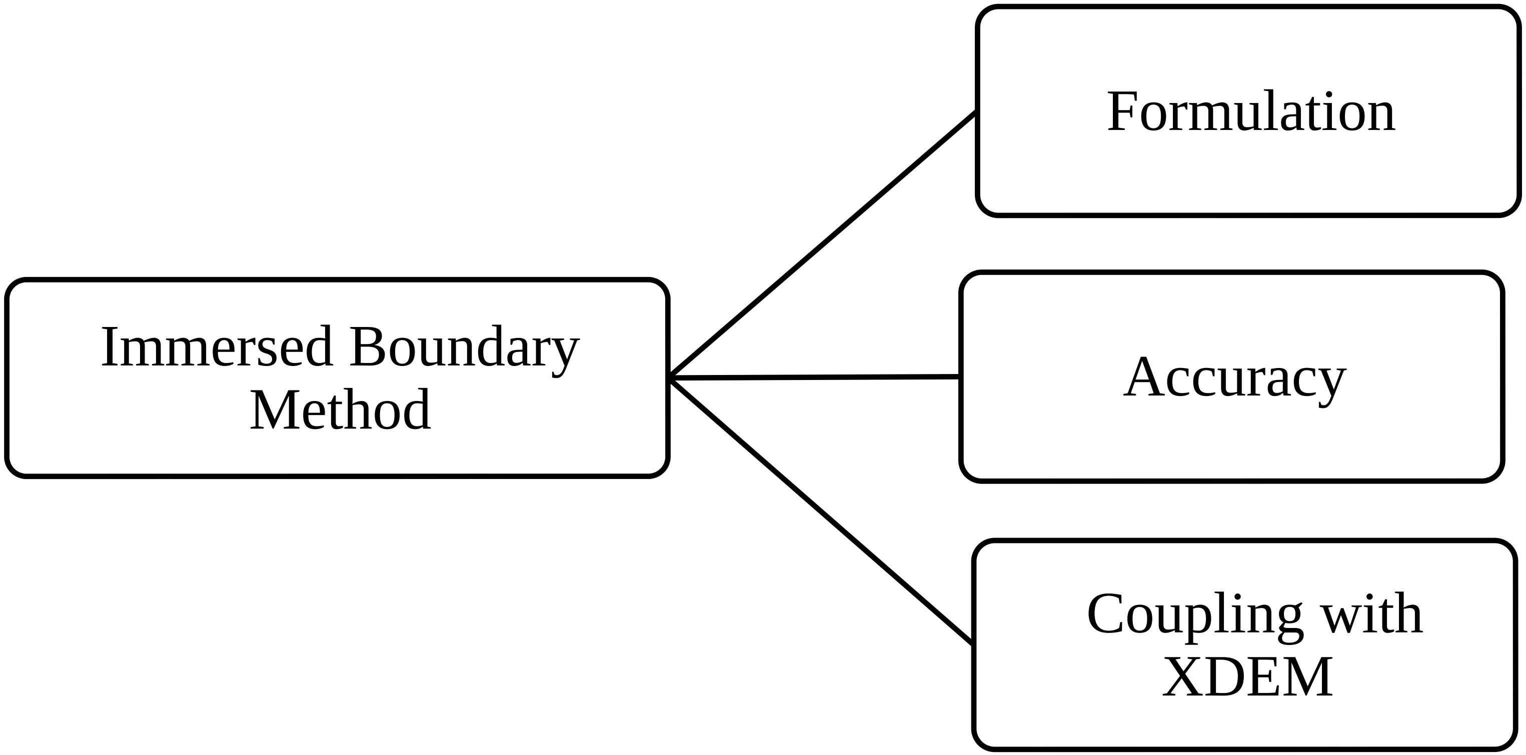
Without any lubrication correction

Hori, N., Rosti, M.E. and Takagi, S., 2022. An Eulerian-based immersed boundary method for particle suspensions with implicit lubrication model. Computers & Fluids, p.105278.

Two falling spheres



Summary of our work



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Reference

1. Municchi, Federico, and Stefan Radl. "Consistent closures for Euler-Lagrange models of bi-disperse gas-particle suspensions derived from particle-resolved direct numerical simulations." International Journal of Heat and Mass Transfer 111 (2017): 171-190.
2. Kroupa, M., Vonka, M., Soos, M. and Kosek, J., 2016. Utilizing the discrete element method for the modeling of viscosity in concentrated suspensions. Langmuir, 32(33), pp.8451-8460.
3. Tschisgale, S., Kempe, T. and Fröhlich, J., 2018. A general implicit direct forcing immersed boundary method for rigid particles. Computers & Fluids, 170, pp.285-298.
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5. Wu, M., Peters, B., Rosemann, T. and Kruggel-Emden, H., 2020. A forcing fictitious domain method to simulate fluid-particle interaction of particles with super-quadric shape. Powder Technology, 360, pp.264-277.
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