Development of a high order resolved CFD-DEM solver

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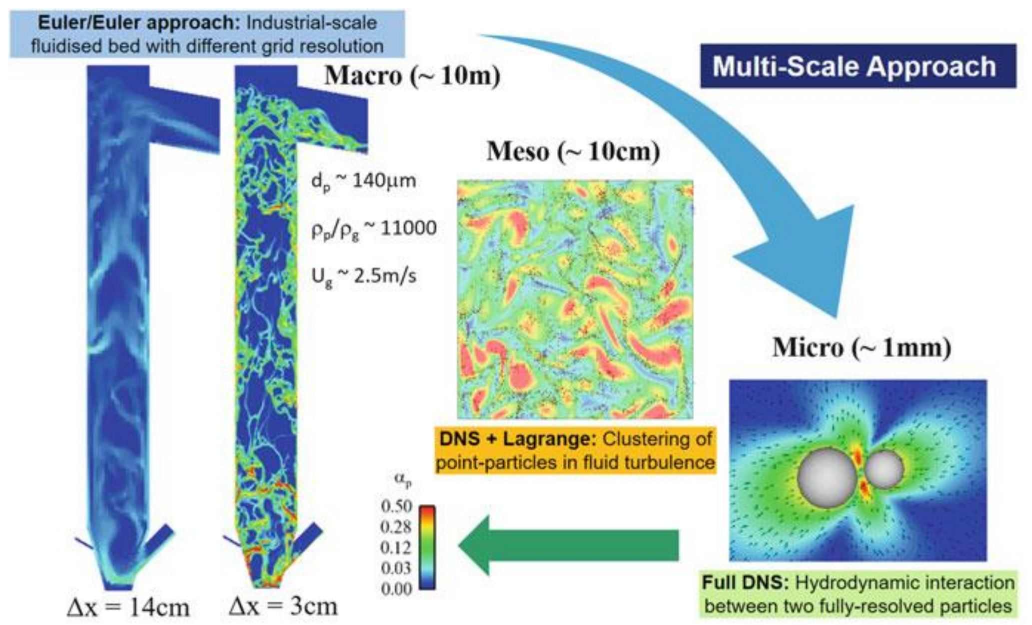
MOTIVATION

- Resolved CFD-DEM is a useful tool to understand particles' interactions. It allows for:
  - Closure model for unresolved CFD-DEM
  - Fundamental analysis of particle clusters dynamics
  - Extremely accurate resutls
  - Applicablity to many chemical engineering fields
  - Support for high order which can give more accurate results in less time



Link between the different scale of the solid-fluid resolution [1]

CFD-DEM THEORIES

Computational fluid dynamics (CFD): The Navier-Stokes equations are discretized using the finite element method.

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\, \boldsymbol{u} = -\nabla p^* + \nabla \cdot \boldsymbol{\tau} + \boldsymbol{f}$$

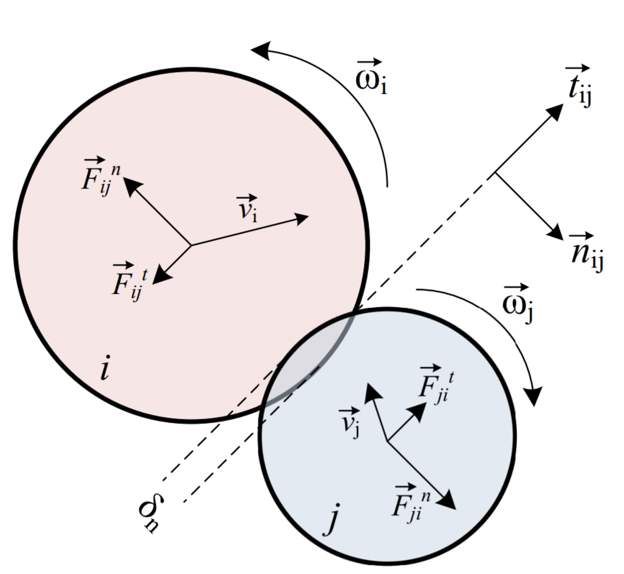
$$\boldsymbol{\tau} = \nu \left((\nabla \boldsymbol{u}) + (\nabla \boldsymbol{u})^T \right)$$

Discrete Element Method (DEM): Track each particle individually using a Lagrangian approach (Newton's second law).

$$\frac{d\boldsymbol{v_i}}{dt} = \frac{1}{m_i} \sum_{j=0}^{nb_p} \boldsymbol{F^c_{ij}} + \boldsymbol{F^w_i} + \boldsymbol{F^f_i} + \boldsymbol{g} m_i + \boldsymbol{F^{ext}_i}$$

$$\frac{d\boldsymbol{\omega_i}}{dt} = \frac{1}{I_i} \sum_{j=0}^{nb_p} \boldsymbol{T^c_{ij}} + \boldsymbol{T^w_i} + \boldsymbol{T^f_i} + \boldsymbol{T^{ext}_i}$$

- **Contact between particles :** Soft sphere approach.



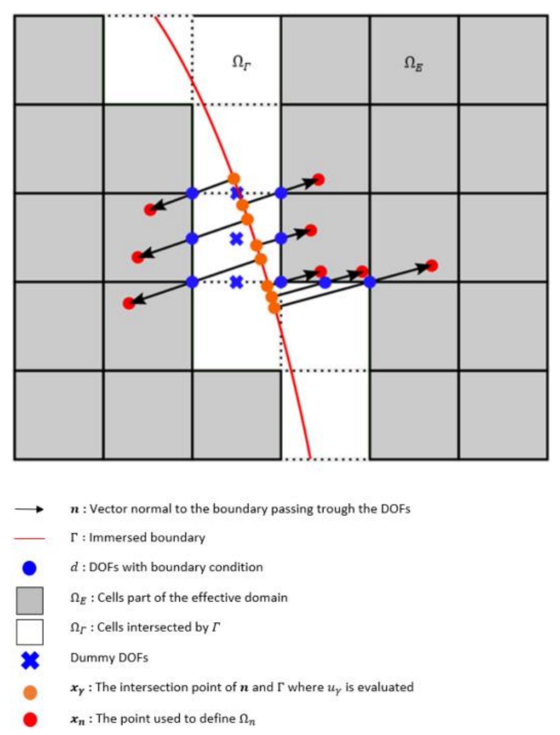
Typical particle-particle contact in the framework of soft-sphere DEM [2]

OBJECTIVES

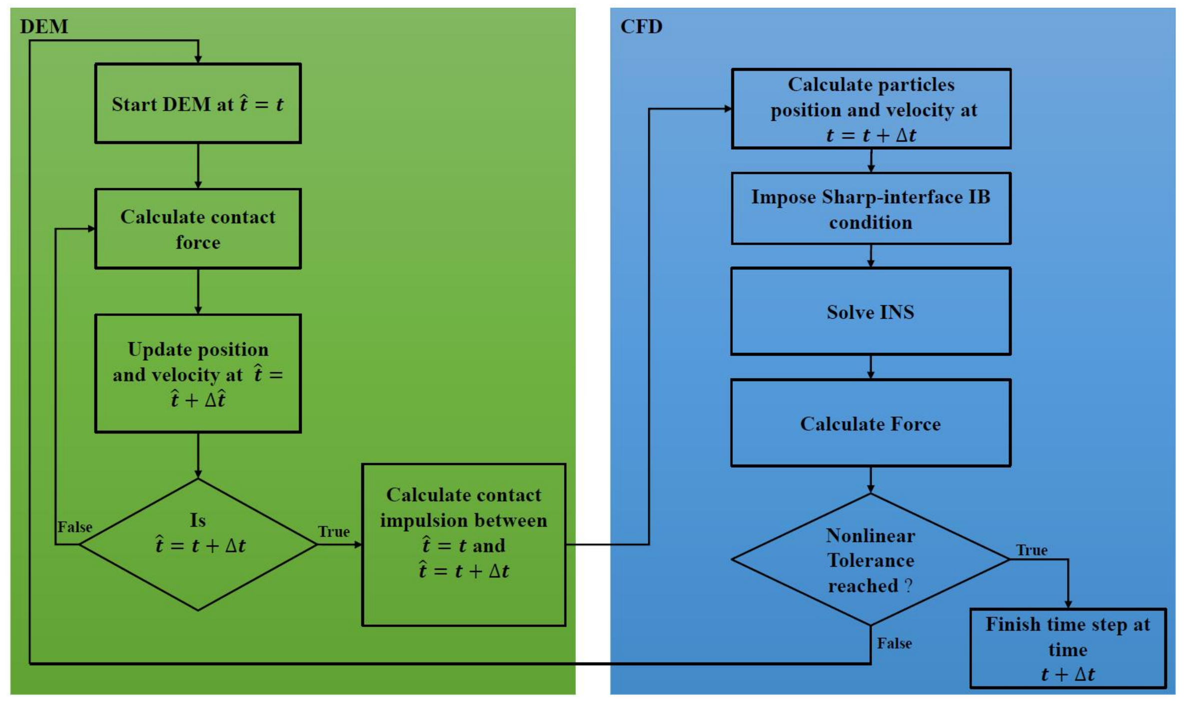
- Develop a high order Immersed Boundary Method (IBM) in FEM
- Couple the CFD and DEM with the hydrodynamic forces
- Verify and validate the solver

METHODOLOGY

- Develop a Sharp interface IBM in the context of FEM
- Integrate the existing DEM solver within *Lethe*
- Couple the CFD and the DEM solvers using an implicit scheme.
- Use a relaxed fixpoint approach to solve the implicit coupled system of equations.



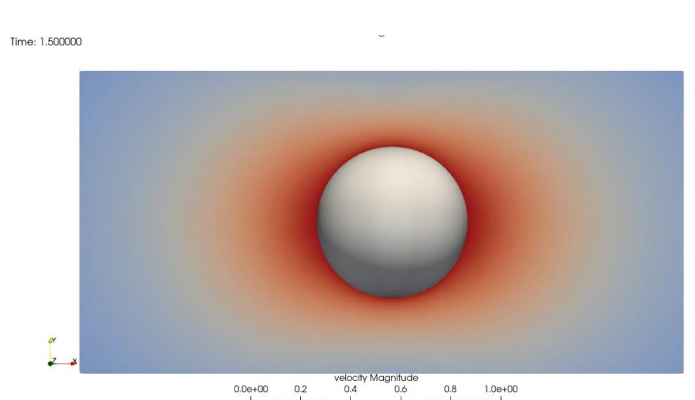
Imposition of sharp interface IBM [3]



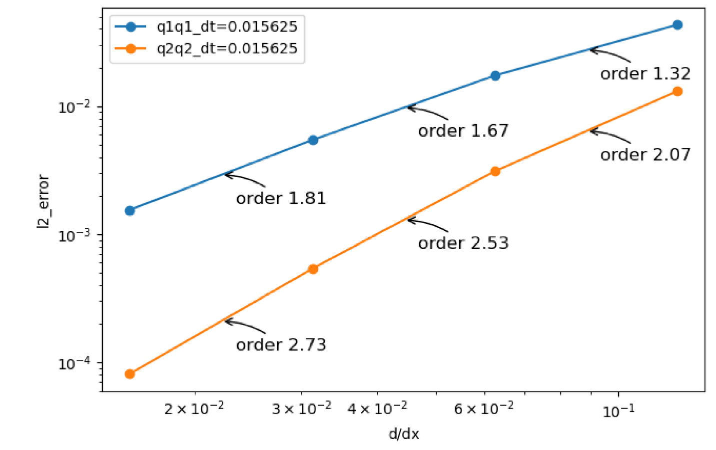
Implicit resolved CFD-DEM coupling

VERIFICATION

- The method of manufactured solution (MMS) of an oscillating Stokes's flow:
  - Stokes's flow around a sphere in the reference frame of an external observer with: $u_\infty = -sin(t)$



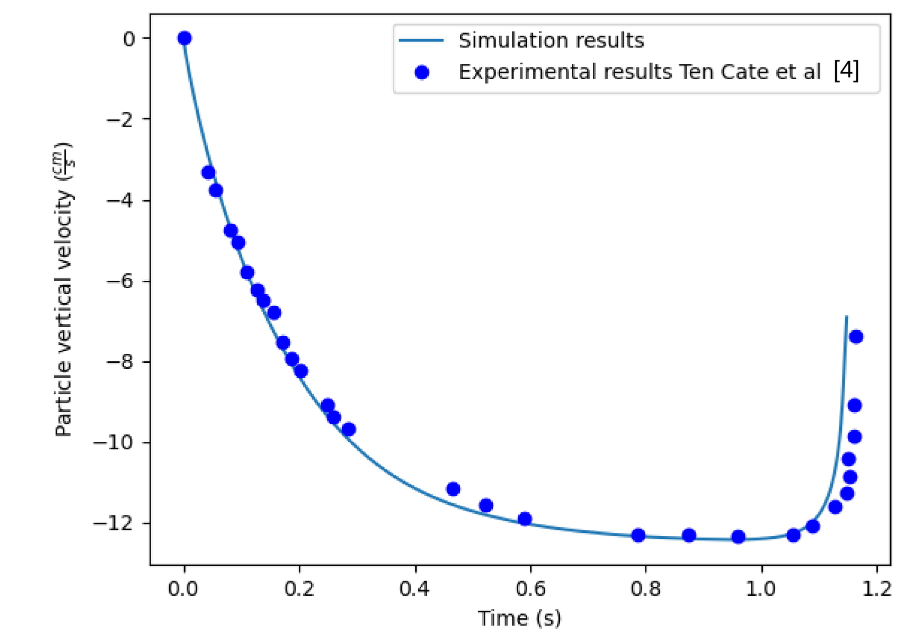
Velocity field norm for Oscillating Stoke's flow



Convergence of the error on the velocity field with the size of the space discretization

Validation

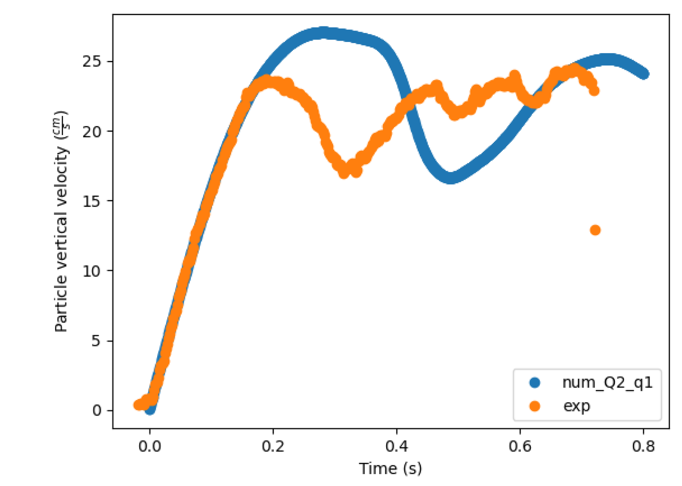
- Sedimentation case of a lone particle at a Reynolds number of 32



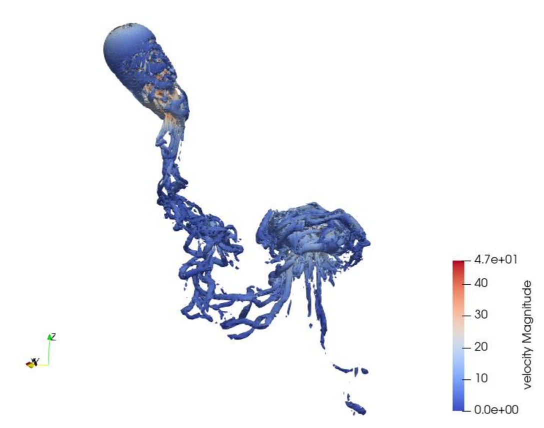
Sedimentation of a lone particle at Reynolds =32 [4]

Validation elements:
- Same acceleration
- Same terminal velocity
- Same deceleration

- One particle floating at a Reynolds number of 2500



Floating particle at a Reynolds number of 2500 vertical velocity

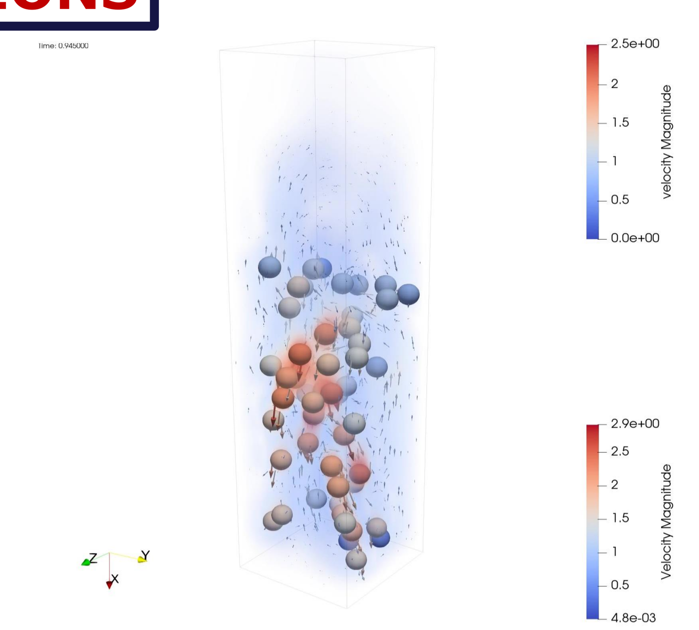


Floating particle at a Reynolds number of 2500, isosurface of Q criterion = 100

Validation elements:
- Same acceleration
- Same velocity after the first vortex release
- Same terminal velocity

CONCLUSIONS

- We develop a new high order resolved CFD-DEM solver through:
  - A new high order IBM in FEM
  - A new coupling scheme between CFD-DEM
  - A new verification case
  - New validation cases



Sedimentation of 50 particles in a small rectangular box at a Reynolds number of 20

REFERENCES

1. M. Sommerfeld, "Numerical methods for dispersed multiphase flows," dans *Particles in Flows*. Springer, 2017, p. 327–396.
2. Golshan S, Munch P, Gassmoller R, Kronbichler M, Blais B. Lethe-DEM: An open-source parallel discrete element solver with load balancing. arXiv preprint arXiv:2106.09576. 2021 Jun 4
3. Barbeau L, Étienne S, Béguin C, Blais B. Development of a high-order continuous Galerkin sharp-interface immersed boundary method and its application to incompressible flow problems. Computers & Fluids. 2022 May 15;239:105415.
4. A. Ten Cate et al., "Particle imaging velocimetry experiments and lattice-Boltzmann simulations on a single sphere settling under gravity," Physics of Fluids, vol. 14, no. 11, p. 4012–4025, 2002.

ACKNOWLEDGMENTS

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