1D Sedimentation of a sphere

1. Introduction

In this work, we simulate the sedimentation of a single sphere using the sedFoam multiphase solver in OpenFOAM. The setup uses overset meshes and six-degree-of-freedom (6DoF) dynamics to fully resolve motion without mesh distortion, enabling clean particle descent and interaction with the fluid.

2. Objective

To replicate and validate the experimental findings of ten Cate et al. (2002) regarding the settling of a sphere in a viscous fluid using high-fidelity CFD tools, and to analyze the fluid-particle interactions under gravity using dynamic mesh and multiphase Modeling. (Settling Sphere by Michael Alletto).

3. Simulation Setup

3.1. Geometry:

- The computational domain consists of a static **background mesh** and a moving **overset mesh** enclosing the sphere.
- Background mesh size: **cube of length ~133.3 mm**
- Overset mesh: smaller cube moving with the sphere.

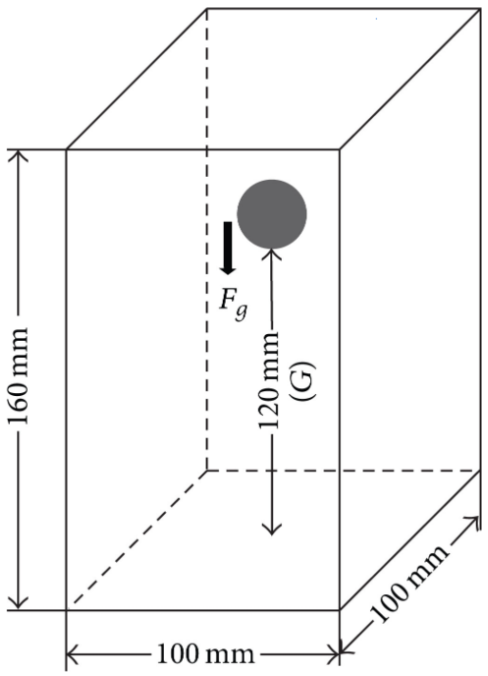

Figure 1:Simulation geometry setup used for simulating the single sphere settling due to the gravitational force

3.2. Domain Dimensions

- A 3D box: **100 mm x 100 mm x 160 mm**
- Sphere diameter: **15 mm (0.015 m)**

3.3. Initial Condition

- The sphere is initially located at **120 mm height** in the domain.
- Fluid is at rest.

3.4. Meshing:

- blockMesh + snappyHexMesh used to define sphere and background domains.
- transformPoints used to scale geometry to physical size.
- topoSet assigns zone IDs (0 for background, 1 for overset).

3.5. Physics:

- **Solver used:** overSedDymFoam_rbgh (includes 6DoF motion).
- **Motion model:** sixDoFRigidBodyMotionSedFoam
- The sphere's motion is governed by the balance of buoyancy and drag, with gravity acting downward.
- The simulation tracks free fall from rest to near-wall interaction.

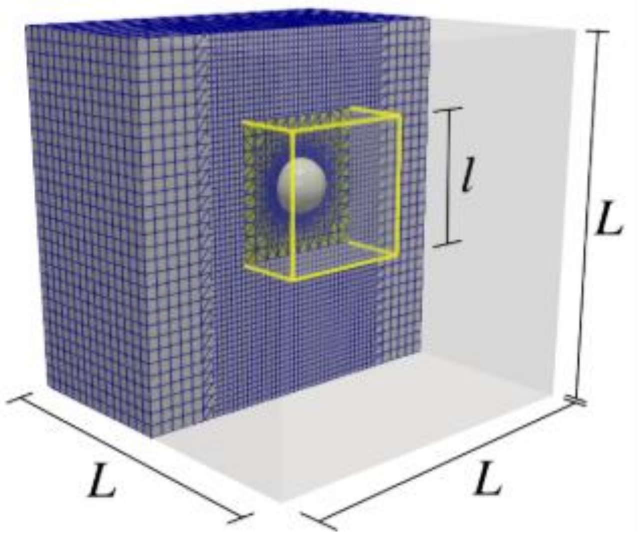

Figure 2: Geometrical domain for the falling sphere using an overset mesh

4. Solver and Physics Model

4.1. sedFoam Overview

`sedFoam` is a two-phase, Eulerian-Eulerian solver based on OpenFOAM. It supports multiphase, turbulent, and particle-laden flows. Key features include:

- Multiphase momentum coupling
- Granular rheology
- Dynamic mesh motion (overset, rigidBody)

4.2. SixDoFRigidBodyMotion

This library enables rigid body motion with six degrees of freedom. It updates the particle's position and orientation based on hydrodynamic forces, gravity, and collisions.

In this case:

- The **sphere** is governed by sixDoF motion

- Mass and inertia tensors are defined in `constant/dynamicMeshDict`
- The movement is solved implicitly and coupled with the flow field

4.3. Overset Mesh (Chimera Grid)

Overset meshes allow moving bodies (like the sphere) to have a separate, finely resolved mesh that moves over a static background mesh. Benefits:

- Avoids mesh distortion
- Allows large translations and rotations
- Ensures accurate interface interpolation

Files:

- `constant/oversetMesh` defines donor and receiver zones
- `constant/dynamicMeshDict` handles interpolation and motion strategy

5. Simulation Setup

5.1. Domain and Mesh

- **Domain**: Rectangular tank, background mesh
- **Sphere**: Separate mesh (refined), embedded using overset
- **Mesh Creation**:
  - `blockMesh` creates the tank mesh
  - `snappyHexMesh` is used for sphere (as per `sphereMesh` dir)
  - `mergeMeshes` and `createPatch` used to combine and prepare overset interpolation

5.2. Mesh Statistics and Grid Size

- **Total cells (Grid Size)**: 70,472
- **Cell types**:
  - Hexahedra: 53,656
  - prisms: 312
  - Polyhedra: 16,504
- **Point count**: 86,083
- **Regions**: 2 (background + sphere)
- **Patches**: 7 (including overset and sphere surface)

5.3. Initial and Boundary Conditions

- Velocity `U`: Initially zero
- Pressure `p_rgh`: Hydrostatic equilibrium
- Phase fraction `alpha`: Defined for both fluid and solid
- Gravity vector defined in `constant/g`

5.4. Material Properties (constant/transportProperties)

- Two-phase system: fluid (silicon oil analog) and solid.

- Fluid viscosity and density match experimental values:
  - Viscosity: Case dependent (e.g. 373 mPa·s for Re ≈ 1.5)
  - Density: 970–960 kg/m³ for fluid, 1120 kg/m³ for sphere

5.5. Time Control and Numerical Schemes

- Time stepping: Fixed (small dt (1E-05) to capture transients).
- Schemes: Upwind for convection, central differencing for diffusion.

6. Results and Validation

6.1. Trajectory and Velocity

- The simulation tracks sphere position using `xcenter.txt`, `zcenter.txt`, etc.
- Velocity data in `vx.txt`, `vy.txt`, `vz.txt`
- The sphere accelerates under gravity, reaches terminal velocity, and decelerates near the bottom.

6.2. Simulation Time:

The complete simulation took 82236 sec (approx. 23 hrs).

6.3. Comparison with Reference Data

Experimental Reference:
ten Cate et al. measured the trajectory and fluid field using PIV for Re = 1.5

Simulation Images:

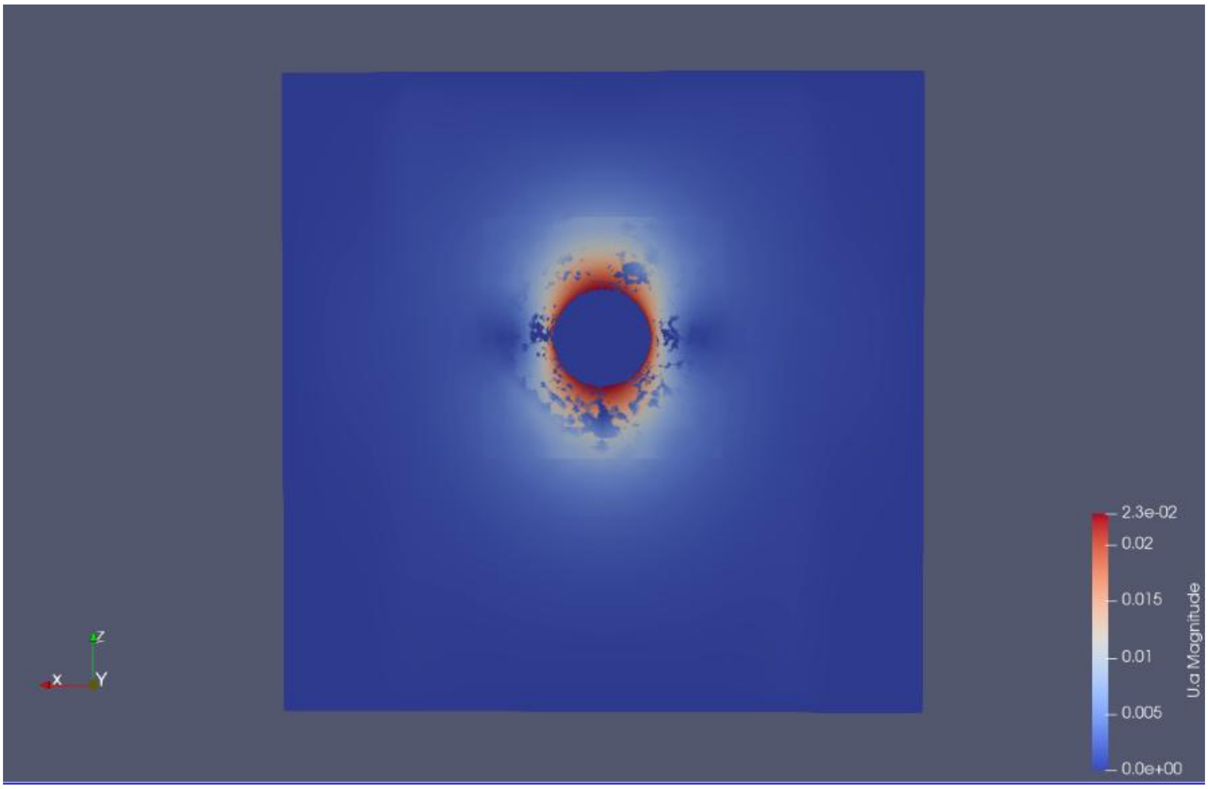

Figure 3: Initial position of the sphere and the fluid interaction

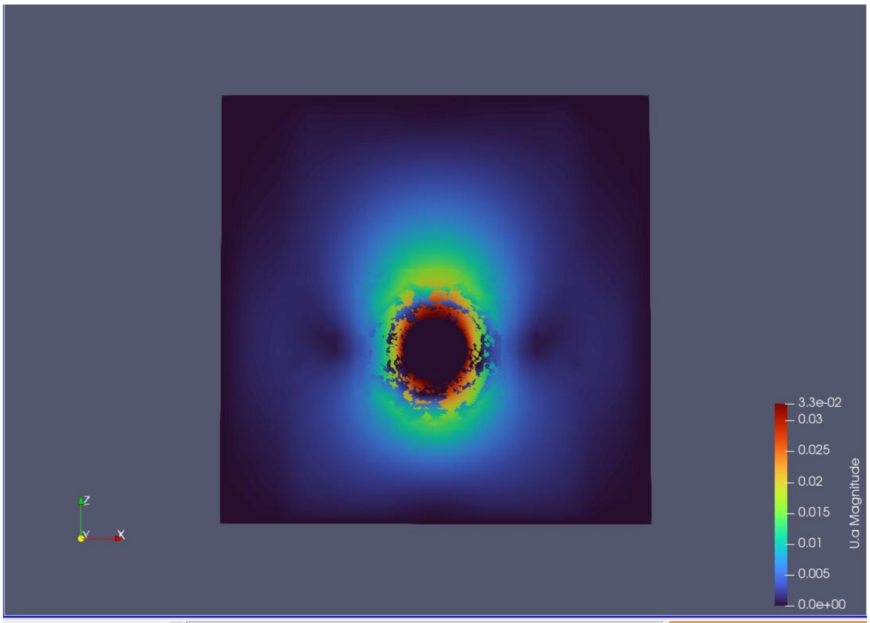

Figure 4: Final position of the sphere and the fluid interaction

Contour Plot (Flow Field) generated by the Sphere during sedimentation at Re 1.5:

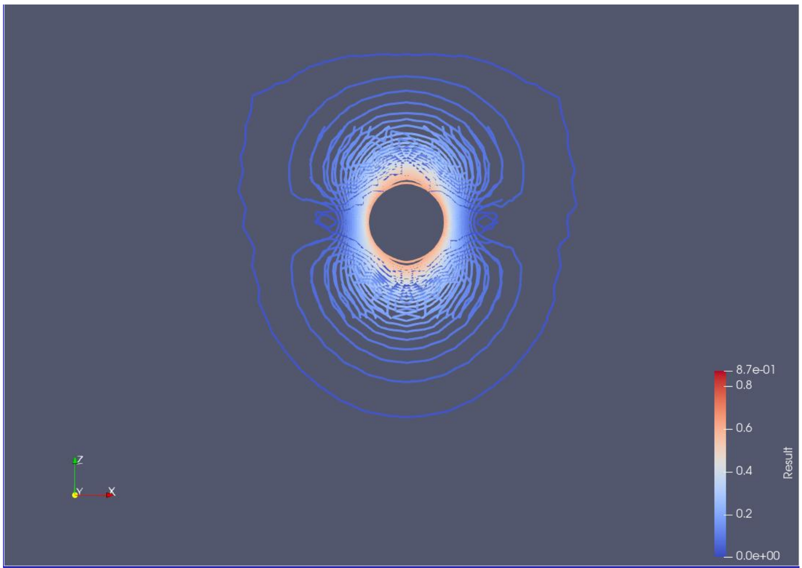

Figure 5: Contours generated by the sphere at tie instance 0.1 sec

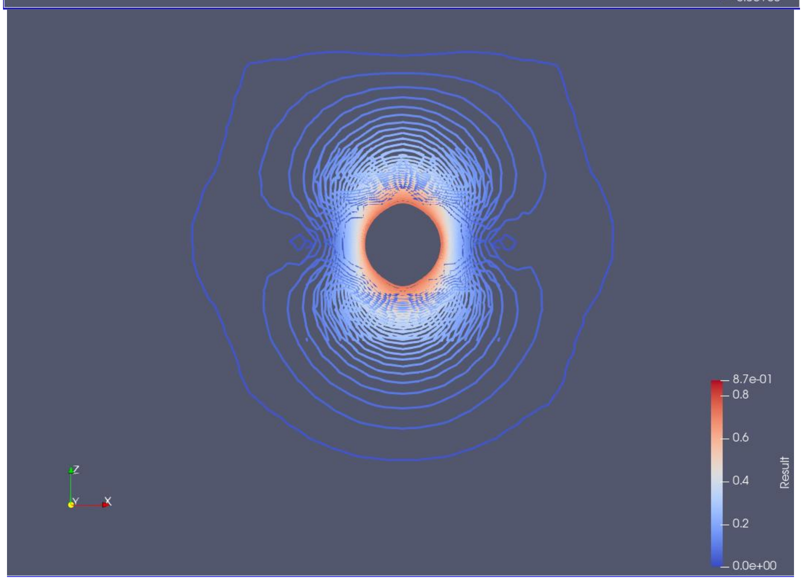

Figure 6: Contours generated by the sphere at tie instance 0.2 sec

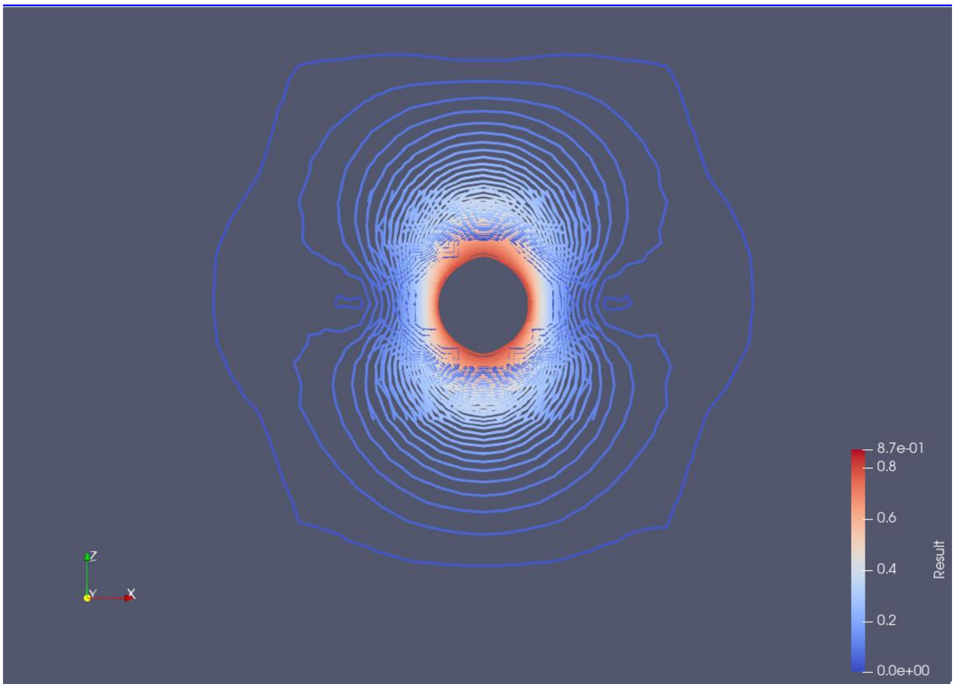

Figure 7: Contours generated by the sphere at tie instance 0.3 sec

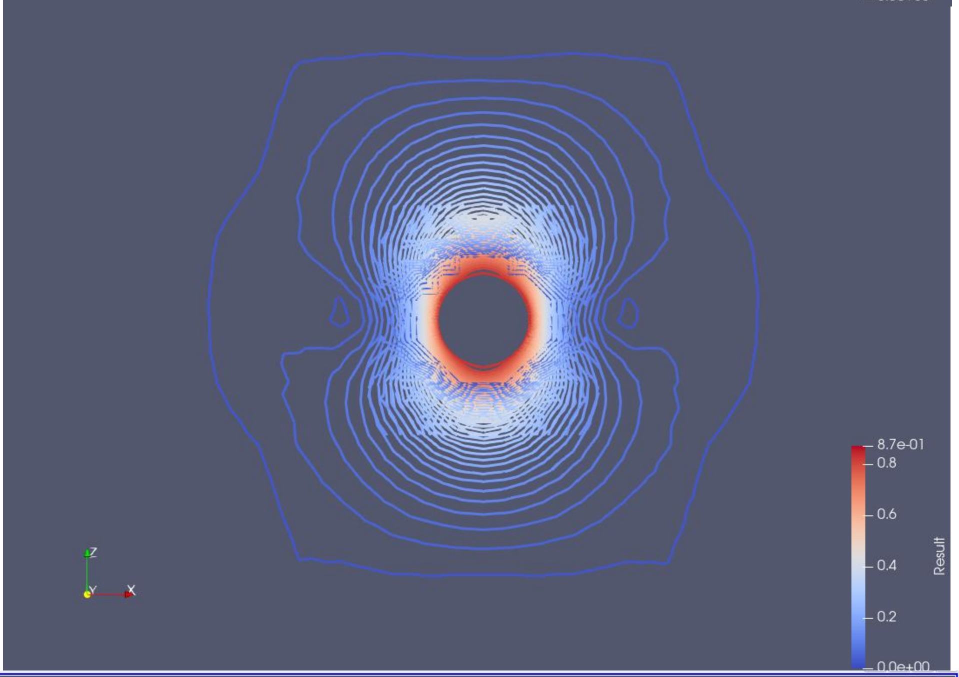

Figure 8: Contours generated by the sphere at tie instance 0.4 sec

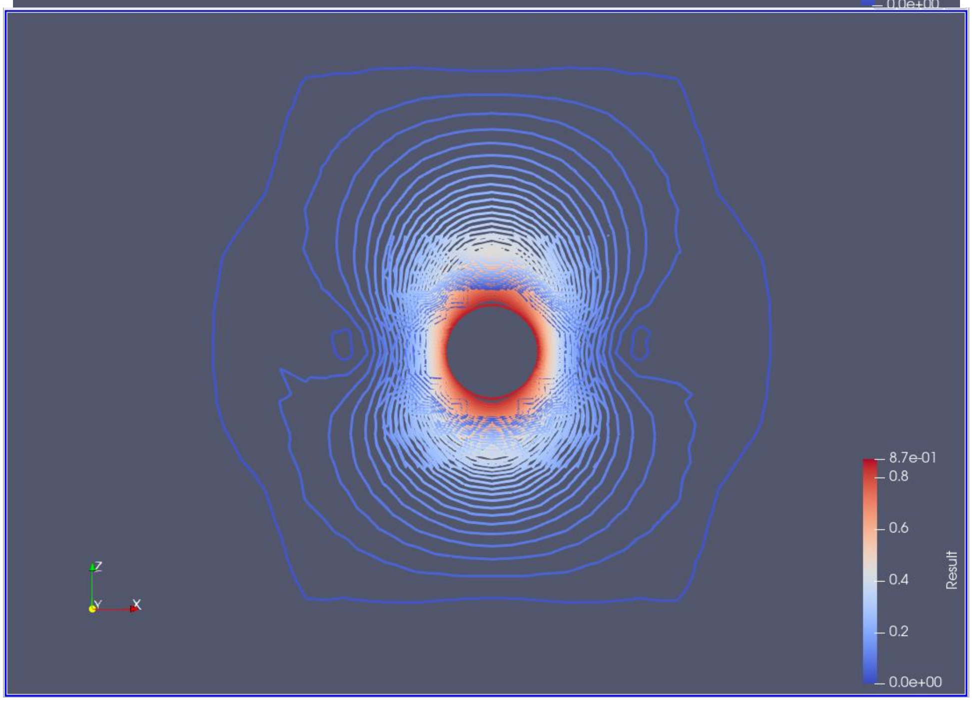

Figure 9: Contours generated by the sphere at tie instance 0.5 sec

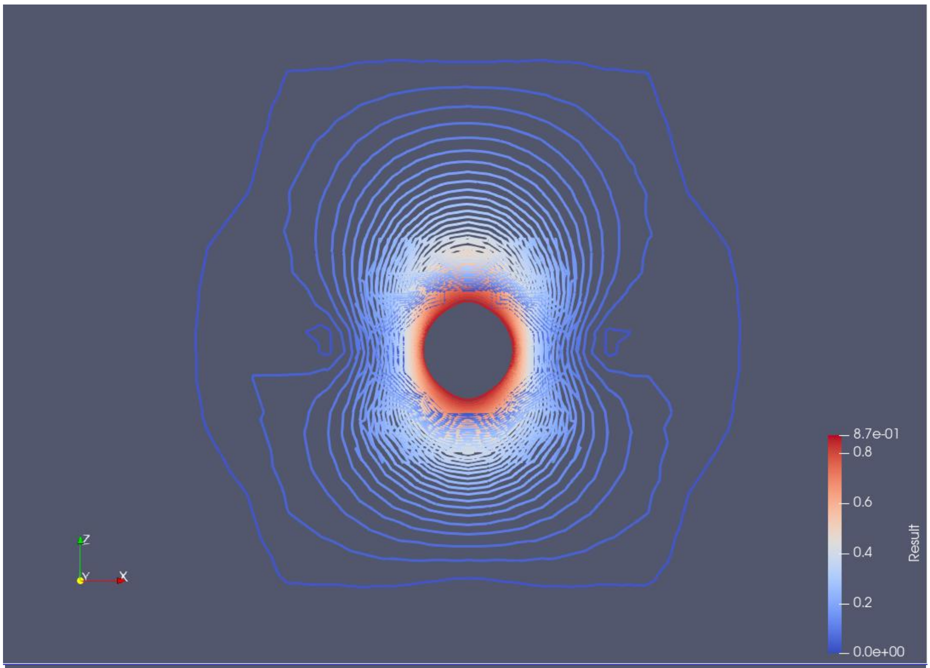

Figure 10: Contours generated by the sphere at tie instance 0.6 sec

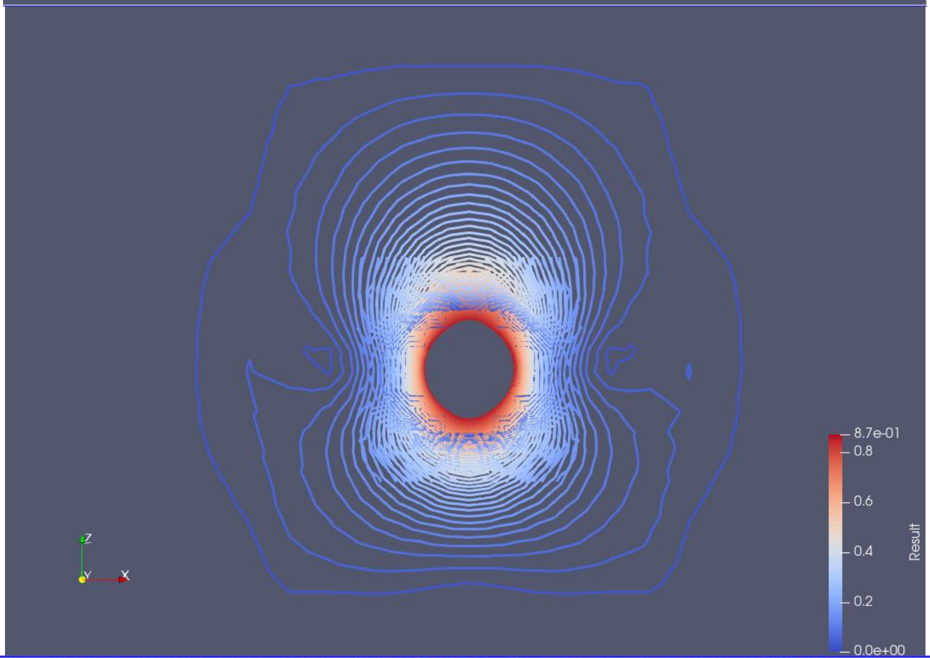

Figure 11: Contours generated by the sphere at tie instance 0.7 sec

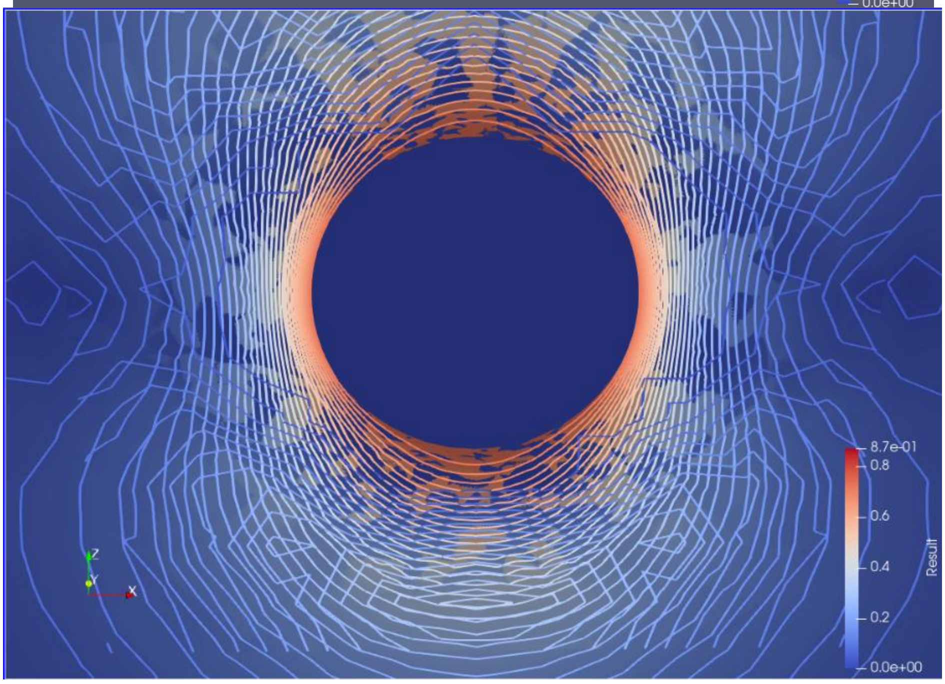

Figure 12: Zoomed in at the contour plot focused at the sphere center

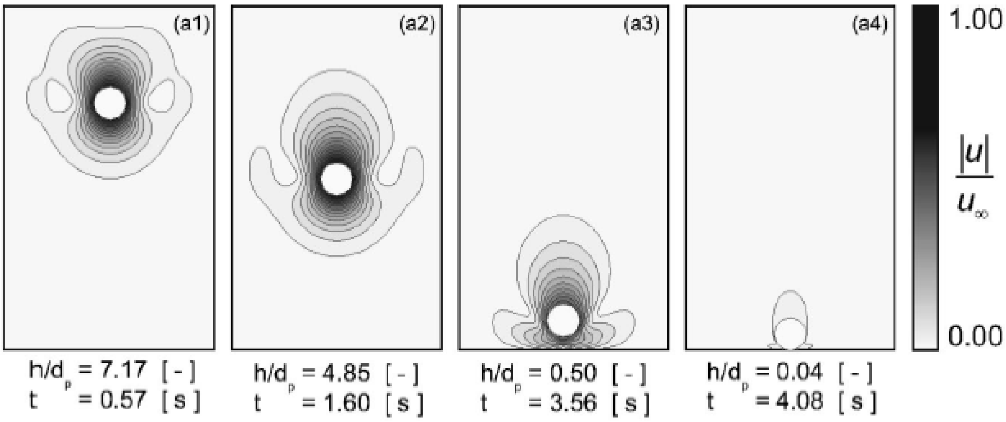

Figure 13: Contour from the reference Paper for comparison at Re 1.5

- Show clear vortex formation and wake at higher Reynolds numbers.
- Contour plots (e.g., `FallingSphereComparison.png`) align closely with the experimental velocity fields and wake patterns.
- Sphere settles with **no rebound**, as expected at low Stokes numbers (St < 10).

Quantitative Comparison:

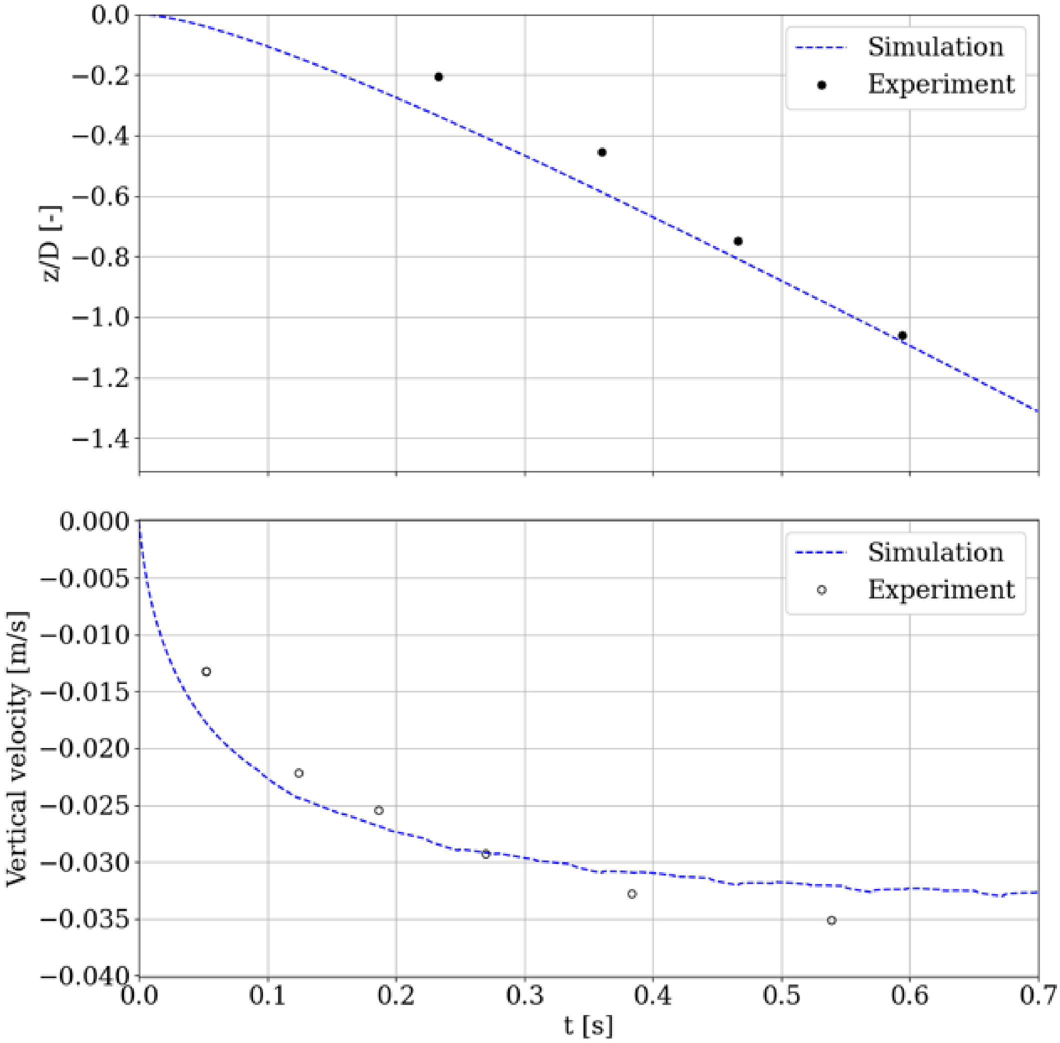

Figure 14: Sphere a) trajectory and b) velocity evolution using an overset mesh till time instance 0.7 sec.

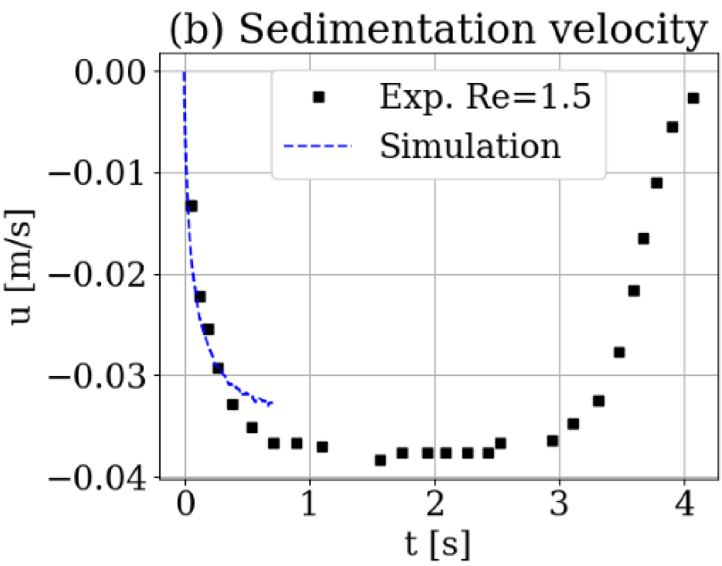

Figure 15: Sphere velocity evolution using an overset mesh for whole sedimentation in experimental and till 0.7-time instance in simulation.

6.4. Observations

- The **sphere starts from rest** (Vz=0) and accelerates due to gravity.
- **Velocity increases rapidly at first** but quickly reaches a plateau around −0.028m/s, suggesting the approach to terminal velocity.
- The **position curve (z/D)** is smooth and convex, typical of a body accelerating and then entering a steady-fall regime.
- The simulation shows **no significant rebound or oscillation**, consistent with expectations at Reynolds number ≈ 1.5 (as in ten Cate et al., 2002).
- Steady-state appears to be reached around **0.5 seconds**, after which velocity stabilizes, validating the dynamic mesh and 6DoF setup.

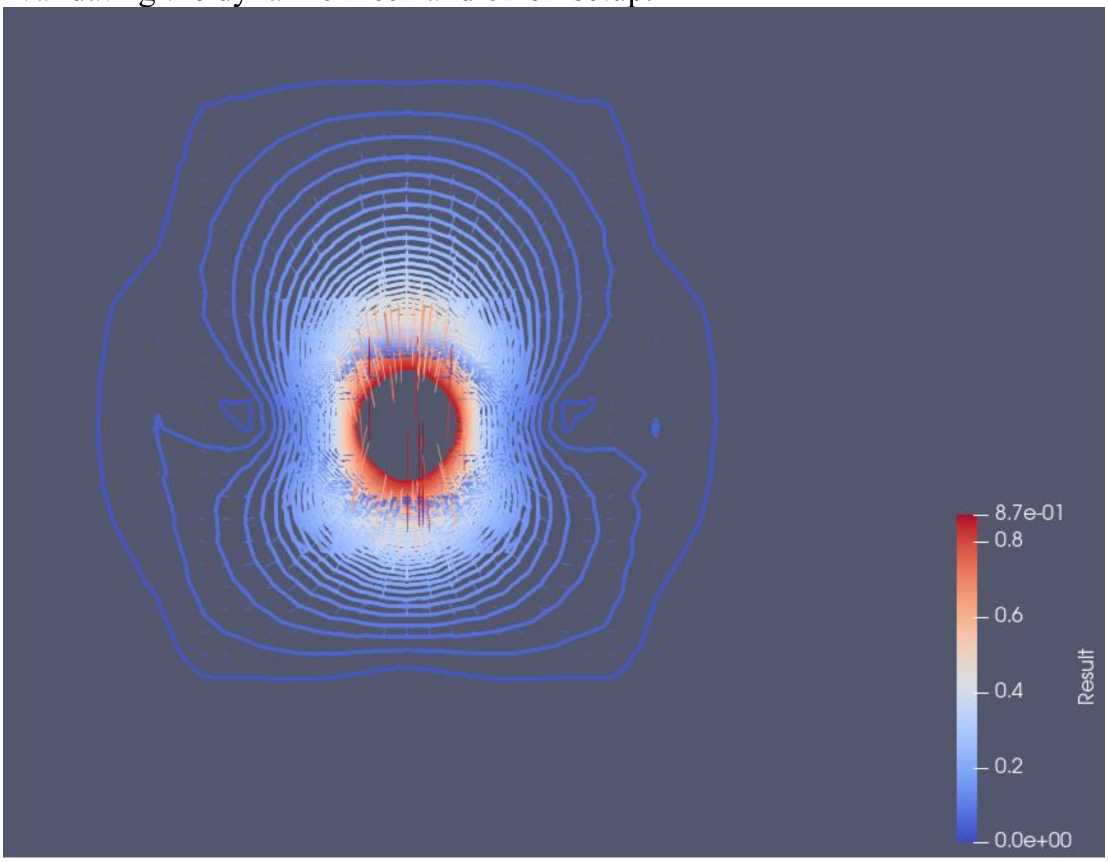

Figure 16: flow field of the sphere at a dimensionless gap height of z/*d = 1.2*

7. Discussion

7.1. Accuracy and Robustness

- Overset mesh ensures smooth descent without remeshing
- sixDoF library realistically captures inertia and torque
- Minor discrepancies near bottom approach due to unmodeled lubrication forces (can be added analytically)
- **Errors:**
  - `Velocity (Vz):  Mean % Error = 14.12%, Max % Error = 34.32%`
  - `Simulated z/D at given times:`
    - `Time: 0.084430391 s -> Sim z/D: -0.08324`
    - `Time: 0.232789799 s -> Sim z/D: -0.33577 Error = 62.81%`
    - `Time: 0.360096720 s -> Sim z/D: -0.58736 Error = 28.93%`
    - `Time: 0.466406266 s -> Sim z/D: -0.80865 Error = 8.2%`
    - `Time: 0.593878521 s -> Sim z/D: -1.08151 Error = 2.1%`
    - `Time: 0.742403263 s -> Sim z/D: -1.40435 Error = 4.04%`

7.2. Numerical Challenges

- Interpolation across overset interfaces can introduce errors
- Small time steps required to maintain coupling stability
- Solver settings need fine-tuning for low Re cases

8. Conclusion

This study successfully reproduces the classic sedimentation benchmark using modern CFD tools:

- The `sedFoam` solver with sixDoF motion and overset mesh accurately captures the full sedimentation dynamics.
- Comparisons with experimental data from ten Cate et al. validate the physical and numerical Modeling.
- This approach is extensible to multiple particles and turbulent flows with minimal modifications.