

FOSSEE Summer Fellowship

Tumbling of Elliptical Particle in Shear Flow

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Abstract

An elliptical particle tumbling under the influence of and hydrodynamic forces due to shear flow in a square channel is explored in this study. Two-dimensional transient simulations were performed under laminar flow conditions, with rigid-body motion in a Newtonian fluid. The study focused on the tumbling motion in the low-Reynolds-number regime using overset meshing and overPimpleDyMFoam in OpenFOAM.

1 Introduction

The tumbling motion of a particle is characterised by the particle rotating while moving along a trajectory under the influence of forces. Numerous naturally occurring situations and industrial applications involve transportation of inertial solid particles in a fluid of concern, like blood flow, slurries and colloids, as mentioned by Xia et al. [1]. The rotational motion of particles suspended in viscous fluids has attracted considerable attention for its relevance to particulate transport, suspension rheology, microfluidics studies, sedimentation, biomedical systems, and chemical processing. Unlike spherical particles, elliptical particles experience anisotropic hydrodynamic and gravitational forces and torques that result in periodic tumbling and orientation-dependent motion. These motion regimes strongly influence particle movement, mixing efficiency and fluid–particle interaction, particularly in confinement where wall blockage effects substantially alter the surrounding flow field.

The pioneering analytical solution for the rotation of an ellipsoidal particle in creeping shear flow was proposed by Jeffery [2], establishing the widely known Jeffery orbits. Since then, several researchers have investigated deviations from this idealised behaviour by considering fluid inertia,

particle inertia and confinement. Xia et al. [1], and Cai et al. [3] examined the effects of confinement, shear flow and particle geometry on the rotational behaviour of elliptical particles. In the present work, the tumbling behaviour of a rigid elliptical particle suspended in a confined simple shear flow is numerically investigated using OpenFOAM v2312, demonstrating use of overset meshes to simulate moving meshes.

The fluid flow is solved using the overPimpleDyMFoam solver coupled with the six-degree-of-freedom rigid body motion model. A two-component overset mesh comprising a stationary background mesh and a moving body-fitted mesh is employed for smooth interpolation to avoid mesh distortions due to large particle rotations. The predicted angular velocity and orientation are compared with Jeffery's analytical solution to evaluate the capability of the overset methodology in simulating confined particle dynamics.

2 Problem Statement

Tumbling motion of an elliptical particle with semi-axes a and b is studied in a square channel under the influence of hydrodynamic forces due to the shear flow of the fluid. The aspect ratio of the ellipse is taken as $\alpha = \frac{a}{b} = 2$ and the channel confinement ratio is taken as $\beta = \frac{H}{a} = 20$. The path is determined by Jeffery's orbit, as used for validation in Cai et al.[3]. Additionally, the ellipse is initially at a rotated position by an angle of 15° . A Reynolds number of 0.01 was taken to simulate a laminar regime. The shear flow is generated by two parallel walls moving in opposite directions at a constant velocity $u_0 = 0.10$, and the flow direction has periodic boundaries with shear rate $\dot{\gamma} = \frac{2u_0}{H} = 0.01$.

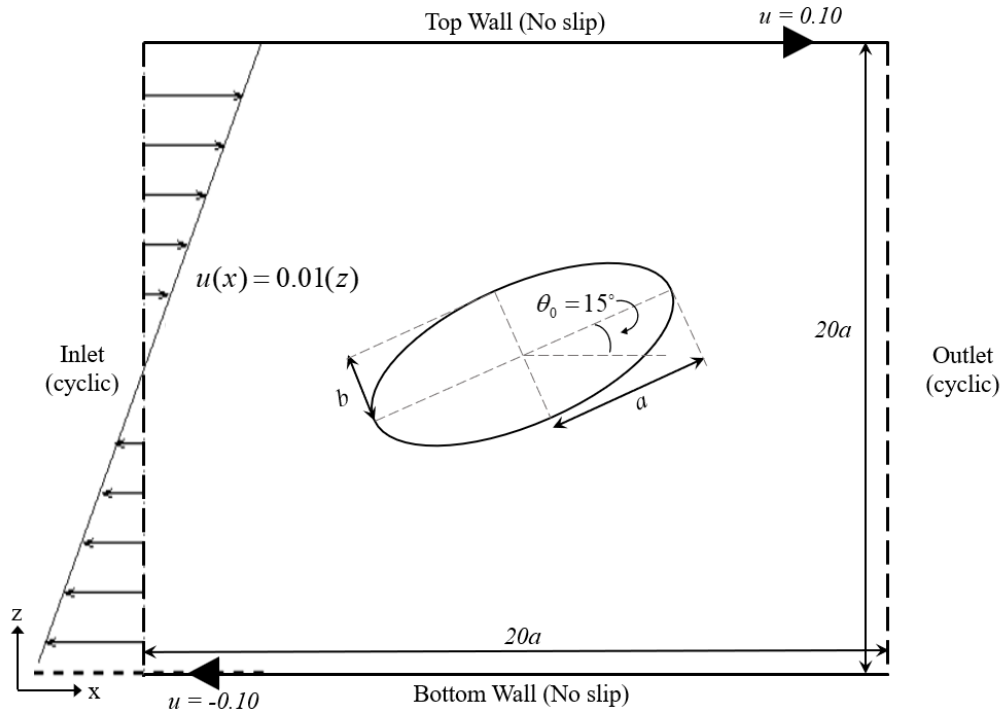


Figure 1: Computational Domain

3 Governing Equations and Models

The continuity equation and Navier-Stokes equation for a two dimensional, transient, laminar, incompressible fluid are given as:

$$\nabla \cdot \mathbf{U} = 0 \quad (1)$$

two-dimensional

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{g} \quad (2)$$

where u is the fluid velocity imparted because of the particle, ρ is the fluid density, ν is the fluid kinematic viscosity, p is the fluid pressure and g is the gravitational acceleration.

The rigid body dynamical equations governing the motion of the ellipse are:

- For translation of the cylinder

$$\mathbf{m}_p \frac{d\mathbf{u}_p}{dt} = \mathbf{F}_f + \mathbf{m}_p \mathbf{g} \quad (3)$$

- For rotational motion of the cylinder

$$\mathbf{I}_p \frac{d\omega_p}{dt} = \mathbf{T} \quad (4)$$

where F_f , T are the hydrodynamic force and torque on the particle and u_p , m_p , I_p and ω_p are the velocity, mass, moment of inertia and angular velocity of the particle.

Moment of Inertia for ellipse in z-x plane protruded in the positive y direction,

$$I_{xx} = \frac{1}{12} m(l^2 + 3b^2) \quad (5)$$

$$I_{zz} = \frac{1}{12} m(l^2 + 3a^2) \quad (6)$$

$$I_{yy} = \frac{1}{4} m(a^2 + b^2) \quad (7)$$

Velocity of the flow in the domain is given as:

$$u = \dot{\gamma} z \quad (8)$$

As stated earlier, an elliptical particle suspended in shear flow is expected to rotate with a periodic angular velocity as given by Jeffery Orbits as given below:

Angle traversed by the ellipse:

$$\theta = \tan^{-1} \left[\frac{a}{b} \tan \left\{ \frac{ab\dot{\gamma}t}{a^2 + b^2} + \tan^{-1} \left(\frac{b}{a} \tan \theta_0 \right) \right\} \right] \quad (9)$$

Angular velocity is given by:

$$\omega = \frac{\dot{\gamma}}{a^2 + b^2} (a^2 \cos^2 \theta + b^2 \sin^2 \theta) \quad (10)$$

For validating the mesh for a rotating ellipse, the case of an ellipse rotating in shear flow is considered, where the ellipse is said to undergo Jeffery's Orbits. The parameters used in this study:

- Reynolds number, $Re = \frac{u_f a}{\nu}$, where ρ is the density of the fluid, u_f is the velocity imparted to the fluid, a is the semi-major axis length of the ellipse. Here, Re is taken as 0.01.
- Normalized Force Magnitude $F^* = \frac{|F|}{\mu u_f a}$, where F is the total force acting on the ellipse, μ is the dynamic viscosity of the fluid, and a is the semi-major axis length of the ellipse.

4 Numerical Validation

4.1 Case-1: Circular Cylinder with Prescribed Rotation

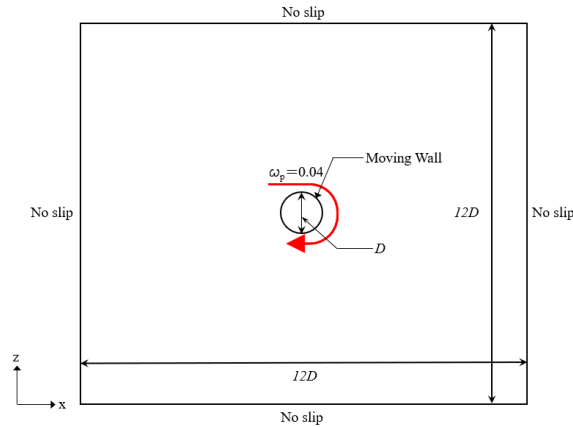


Figure 2: Computational Domain Case-1

For validating the results of the rotating circular cylinder, the Taylor-Couette Equation is employed:

$$\omega(r) = \frac{1}{r^2} \left(\frac{\omega_1 - \omega_2}{\frac{1}{r_1^2} - \frac{1}{r_2^2}} \right) + \left(\frac{\frac{\omega_2}{r_1^2} - \frac{\omega_1}{r_2^2}}{\frac{1}{r_1^2} - \frac{1}{r_2^2}} \right) \quad (11)$$

where, $\omega(r)$ is the angular velocity at a radius r in the annular region of the cylinder, ω_1 is the angular velocity of the inner cylinder, ω_2 is the angular velocity of the outer cylinder, r_1 is the inner cylinder radius and r_2 is outer cylinder radius.

For our case, the outer cylinder is a square shaped confinement, hence $r_2 = \infty$ and $r_1 = r_p$. The confinement is stationary, hence $\omega_2 = 0$ and $\omega_1 = \omega_p$. Hence the equation becomes:

$$\omega(r) = \frac{1}{r^2} \left(\frac{\omega_p}{\frac{1}{r_p}} \right) \quad (12)$$

or,

$$\omega(r) = \frac{\omega_p r_p}{r^2} \quad (13)$$

The cylinder rotating with a constant angular velocity ω_p of 0.01. When the results of the simulation are compared with the analytical solution, the simulation solution diverges from the analytical solution as the analytical plot gives zero at infinity, and since this is physically not feasible, hence the simulation solution diverges at the confinement walls.

The radial and tangential velocity are plotted accordingly:

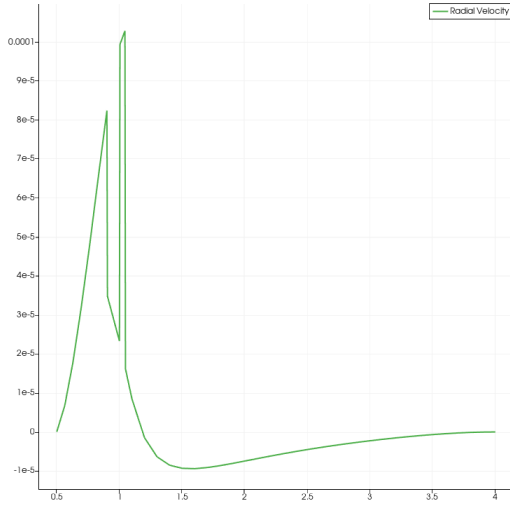


Figure 3: Radial Velocity

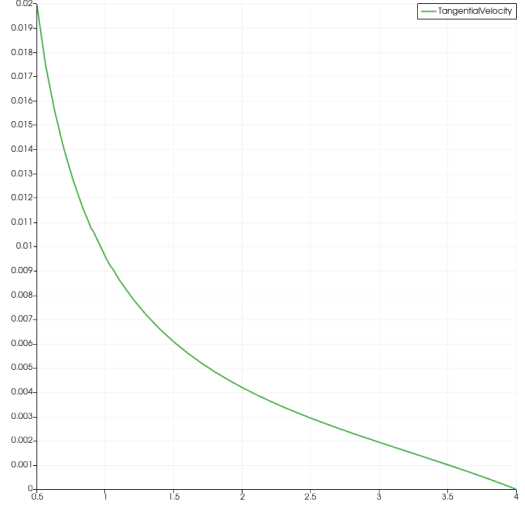


Figure 4: Tangential Velocity

The disturbances in radial velocity as shown in Fig. 4, are quite magnified by ParaView for visualisation. Tangential Velocity contributes the most part to the velocity magnitude, whereas radial velocity remains negligible.

4.2 Case-2: Circular Cylinder with Prescribed Translation

Rotational symmetry is crucial for a particle inside confinement hence, stringent checks were employed in this case i.e. the normalised force on the cylinder was compared for translation, plotted against normalised time, along +x, -x, +z and -z.

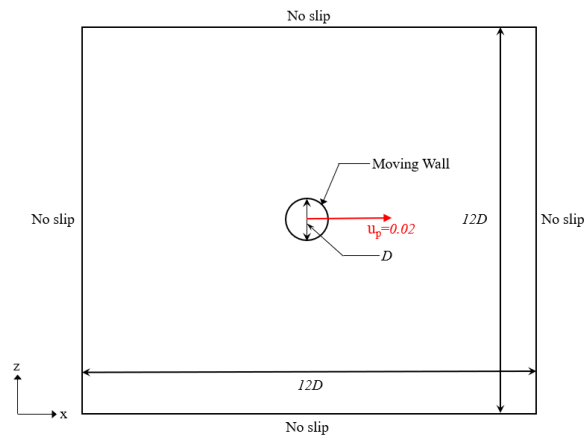


Figure 5: Computational Domain Case-2

The findings are listed as below:

- `overSetInterpolation` Scheme as specified in the `fvSchemes` was set to `inverseDistance`, which was showing an obvious bias in the $+x$ direction. The bias shown in different directions can be attributed to the stencil chosen by the solver as the cylinder translates. The interpolated value is computed as a weighted average of surrounding donor cells, where the weights are inversely proportional to the distance from the interpolation point.
- In order to reduce the heavy dependency of the `overSetInterpolation` method on the stencil being chosen by the solver, `leastSquares` scheme was chosen, whose algorithm uses a linear polynomial fit to the neighbouring donor-cell values.

`inverseDistance` and `leastSquares` were compared by plotting $\frac{|F|}{\mu u_p r_p}$ versus $\frac{tu_p}{r_p}$:

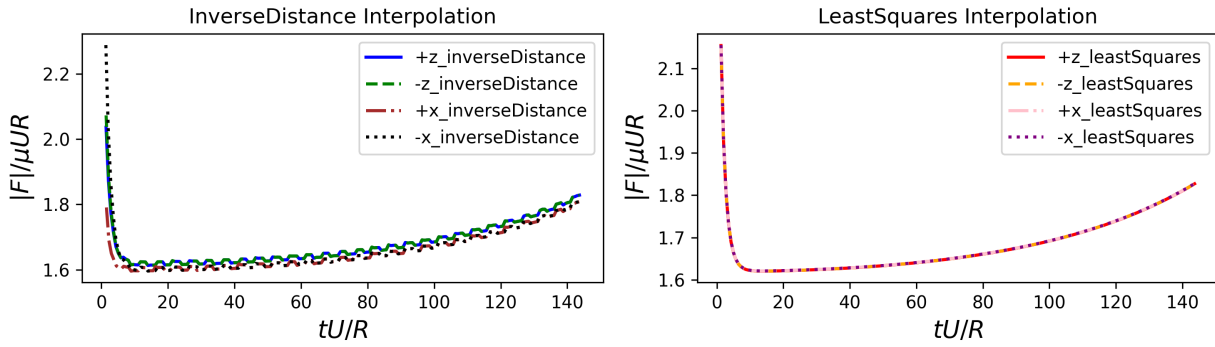


Figure 6: Interpolation Schemes Comparison

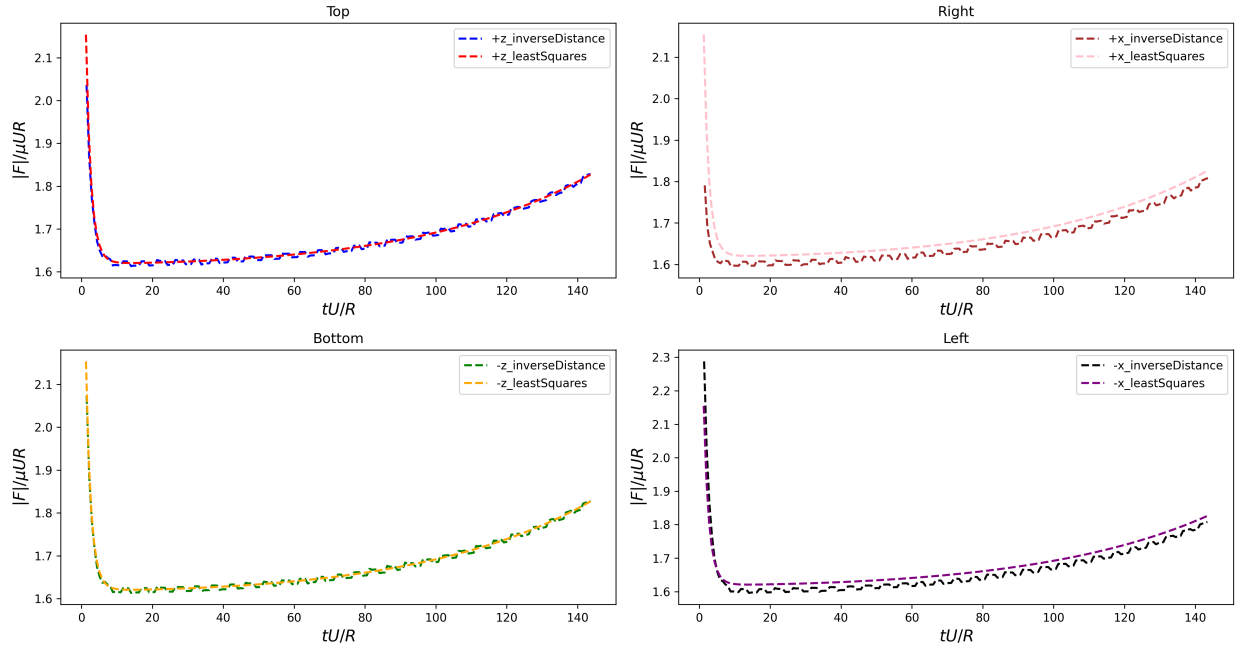


Figure 7: Interpolation Schemes Comparison according to Direction

The interpolation scheme, `inverseDistance`, shows directional bias in the $+x$ direction due to heavy dependence on differences in donor cell selection as the cylinder translates. Whereas `leastSquares` shows more symmetry in all four directions because it assumes the interpolated field at the receptor cell is a linear fit to the donor cell field values.

4.3 Case-3: Ellipse Particle with prescribed Rotation

Upon establishing the rotational and translational motion of the cylinder, the cylinder is replaced with the ellipse geometry made in the same way, but rotated by 15° and given a constant angular velocity, $\omega = 0.01$ as Reynolds number remains constant as 0.01.

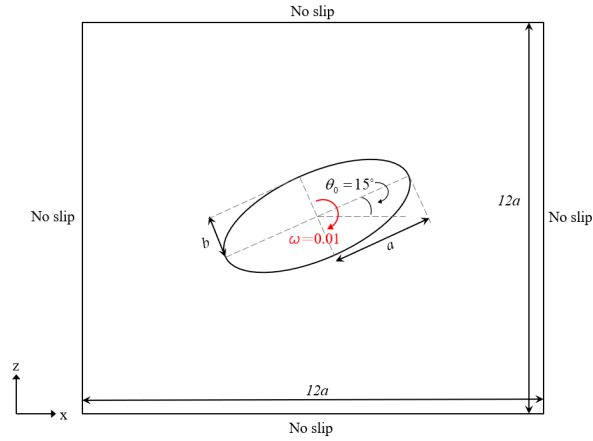


Figure 8: Computational Domain Case-3

4.4 Case-4: Cylinder in Shear Flow

Before onto the final case of ellipse in shear flow, a simplified case of cylinder in shear flow is studied.

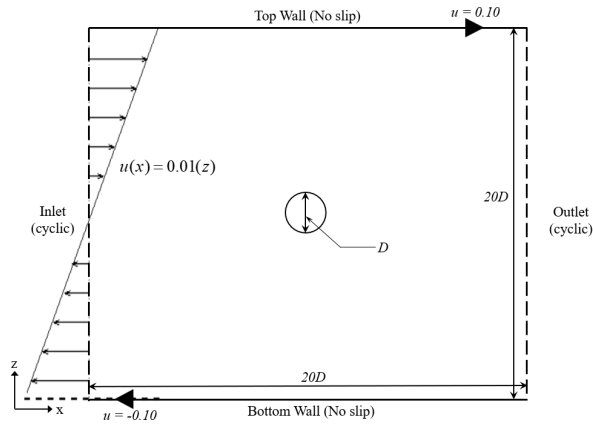


Figure 9: Computational Domain Case-4

Keeping the shear rate same velocity is given as:

$$u = \dot{\gamma}z \quad (14)$$

The Jeffery Orbits simplify for the cylinder as following,
Angle traversed:

$$\theta = \frac{\dot{\gamma}t}{2} + \theta_0 \quad (15)$$

Angular Velocity:

$$\omega = \frac{\dot{\gamma}}{2} \quad (16)$$

The angular velocity when compared started to coincide with the ideal graph after the simulation became steady,

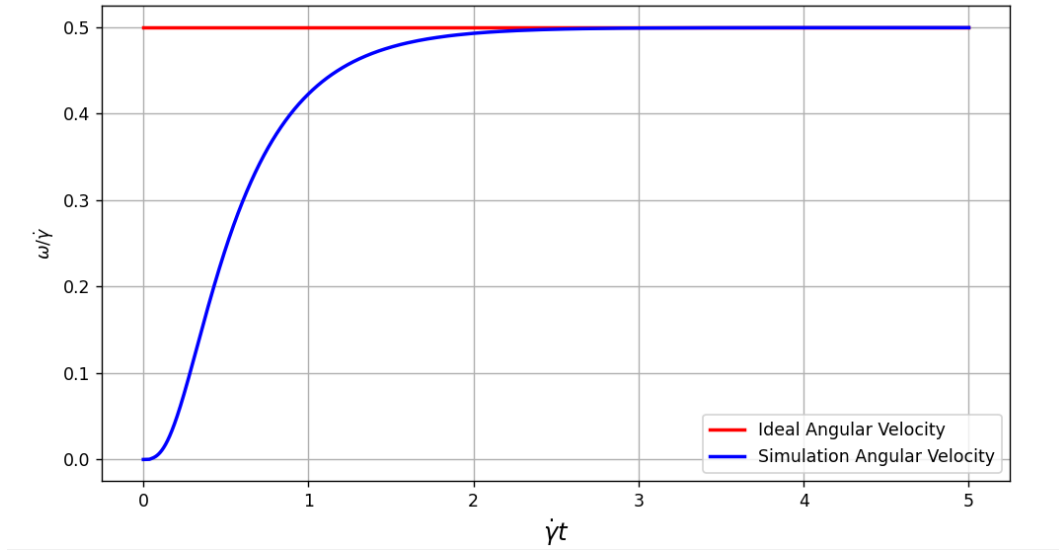


Figure 10: Angular Velocity Comparison

5 Simulation Procedure

5.1 Geometry and Mesh - Circular Cylinder

A three-component mesh strategy was implemented for this problem. The first component mesh, a body-fitted overset mesh surrounding the circular surface was generated using Gmsh with 90 faces present laterally. The surface is exported from Gmsh as VTK with Dataset Unstructured Grid Data and then converted into VTK Version 4.2 Dataset PolyData using Python library vtk to ensure compatibility with surfaceMeshReader as used in extrudeMesh. The patches are named using createPatch utility.

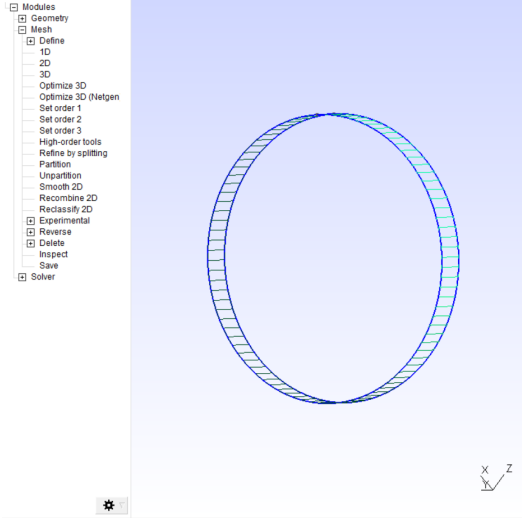


Figure 11: Circular Cylinder Surface Generation in Gmsh

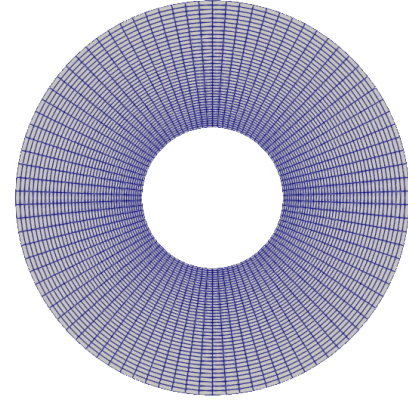


Figure 12: Circular Cylinder Body-Fitted Mesh

The second component refinement, a square cartesian grid was meshed using `blockMesh` utility of OpenFOAM with its boundary patches as `overset`, and `frontAndBack` as empty. The background is a coarser square cartesian grid meshed using the `blockMesh` utility. The other two meshes were merged into the background mesh using the `mergeMeshes` utility, one by one.

All simulations were run in the background directory named `cylinderAndBackground`. After `mergeMeshes`, the `checkMesh` utility was used to evaluate the mesh quality. Also, `checkMesh` automatically assigns every subpart of the mesh into regions, which are used for naming the parts to be given prescribed motion, which were named as `cylinderZone` and refinement using the `topoSet` utility. The `setFields` utility was used to assign `zoneIDs` to each region for deciding the priority while hole-cutting.

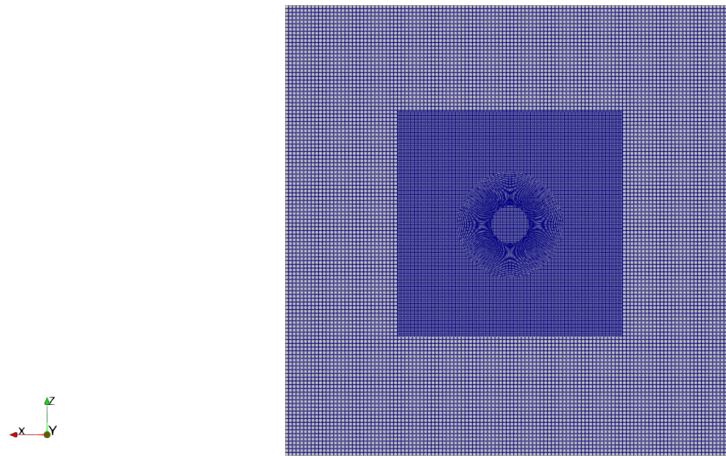


Figure 13: Merged Mesh-Circular Cylinder

5.2 Geometry and Mesh - Elliptical Cylinder

A three-component mesh strategy was implemented for this problem as well. Replacing the ellipse geometry with an elliptical geometry, the rest remains the same.

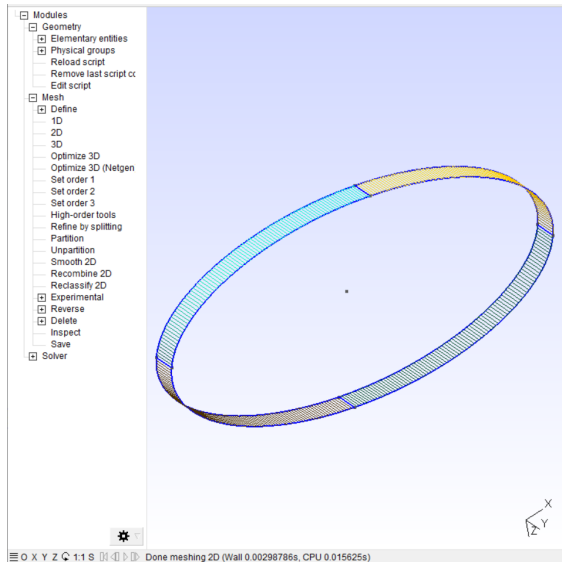


Figure 14: Ellipse Surface Generation

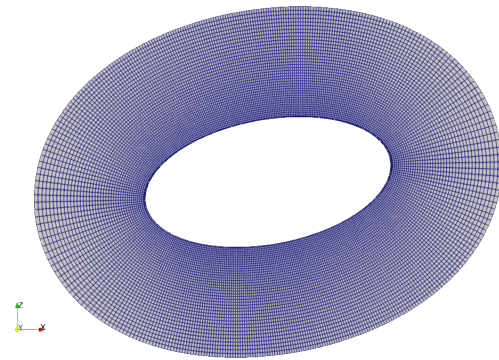


Figure 15: Body-Fitted Mesh; First Component Mesh

A similar approach was taken from here to generate the three-component mesh for the elliptical cylinder, for running the simulations, as shown below:

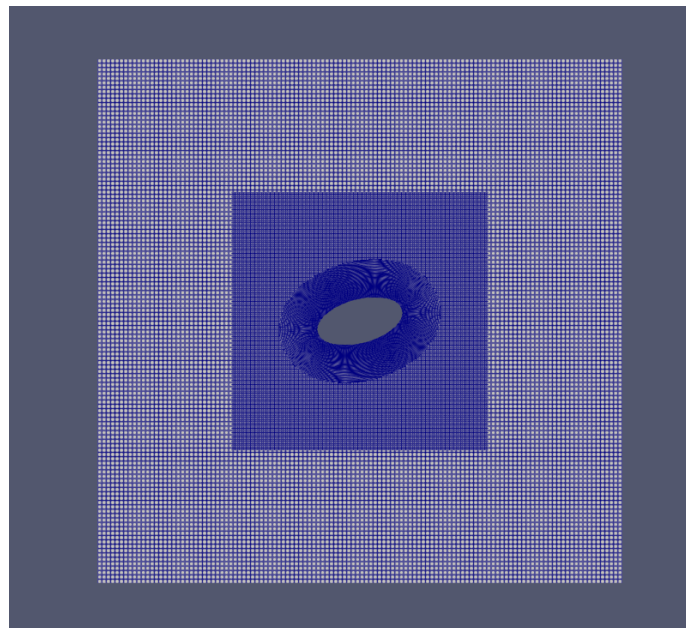


Figure 16: Merged Mesh

Although this three-component approach proved fruitful for the ellipse particle with prescribed

rotation, in the more complex case of ellipse particle in shear flow, due to limitations of the system being used, the refinement zone was dropped. Along with a much coarser background mesh, body-fitted mesh was adjusted to have the last layer cell size the same as the background. To ensure uniformity over versions of OpenFOAM being used, createPatch utility is used again to ensure all overset patches from different component meshes aren't tagged separately while using mergeMeshes.

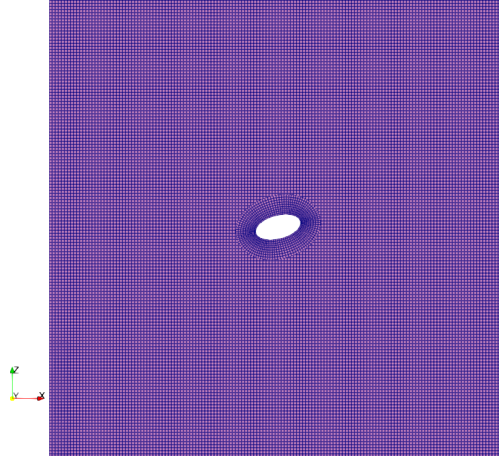


Figure 17: Merged Mesh for Ellipse Particle in SHear Flow

5.3 Initial and Boundary Conditions

The cylinder wall is given a prescribed motion as specified in the dynamicMeshDict file in constant directory.

5.3.1 Cylinder with Prescribed Rotational Motion and Translation

In case of rotation the cylinder is given a constant angular velocity, pinned at the origin, in case of translation, the cylinder wall is given a constant velocity in one particular direction. Front and Back are empty.

Patch Name	Condition Type	Value
overset	overset	—
walls	zeroGradient	—
inlet	zeroGradient	—
outlet	zeroGradient	—
,	zeroGradient	—

Table 1: Boundary Conditions for Pressure (p)

Patch Name	Condition Type	Value
overset	overset	–
walls	movingWallVelocity	uniform (0 0 0)
inlet	uniformFixedValue	(0 0 0)
outlet	uniformFixedValue	(0 0 0)
topAndBottom	uniformFixedValue	(0 0 0)
.	empty	–

Table 2: Boundary Conditions for Velocity (u)

Patch Name	Condition Type	Value
overset	overset (type zeroGradient)	–
walls	zeroGradient	–
”.*”	uniformFixedValue	(0 0 0)

Table 3: Boundary Conditions for Point Displacement

Patch Name	Condition Type	Value
overset	overset (type zeroGradient)	–
walls	cellMotion	uniform (0 0 0)
”.*”	cellMotion	uniform (0 0 0)

Table 4: Boundary Conditions for Cell Displacement

5.3.2 Elliptical Particle with Prescribed Rotation

The elliptical Particle with its centre of mass fixed is rotated with a constant angular velocity. Front and Back are empty.

Patch Name	Condition Type	Value
overset	overset	–
walls	zeroGradient	–
inlet	zeroGradient	–
outlet	zeroGradient	–
.	zeroGradient	–

Table 5: Boundary Conditions for Pressure (p)

Patch Name	Condition Type	Value
overset	overset	—
walls	movingWallVelocity	uniform (0 0 0)
inlet	uniformFixedValue	(0 0 0)
outlet	uniformFixedValue	(0 0 0)
topAndBottom	uniformFixedValue	(0 0 0)
.	empty	—

Table 6: Boundary Conditions for Velocity (u)

Patch Name	Condition Type	Value
overset	overset (type zeroGradient)	—
walls	zeroGradient	—
”.*	uniformFixedValue	(0 0 0)

Table 7: Boundary Conditions for Point Displacement

Patch Name	Condition Type	Value
overset	overset (type zeroGradient)	—
walls	cellMotion	uniform (0 0 0)
”.*	cellMotion	uniform (0 0 0)

Table 8: Boundary Conditions for Cell Displacement

5.3.3 Elliptical Particle Suspended in Shear Flow

The elliptical particle is suspended with its centre pinned to the origin, the inlet and outlet are cyclic patches with their neighbouring patches being each other. The top and bottom walls moving with velocities along x and -x of the same magnitude, respectively. Front and back are empty.

Patch Name	Condition Type	Value
overset	overset	—
walls	zeroGradient	—
inlet	cyclic	—
outlet	cyclic	—
.	zeroGradient	—

Table 9: Boundary Conditions for Pressure (p)

Patch Name	Condition Type	Value
overset	overset	–
walls	movingWallVelocity	uniform (0 0 0)
inlet	fixedValue	uniform (0.10 0 0)
outlet	fixedValue	(0 0 0)
topAndBottom	uniformFixedValue	uniform (-0.10 0 0)
.	empty	–

Table 10: Boundary Conditions for Velocity (u)

Patch Name	Condition Type	Value
overset	overset (type zeroGradient)	–
walls	calculated	–
.	uniformFixedValue	(0 0 0)

Table 11: Boundary Conditions for Point Displacement

Patch Name	Condition Type	Value
overset	overset (type zeroGradient)	–
walls	calculated	uniform (0 0 0)
.	cellMotion	uniform (0 0 0)

Table 12: Boundary Conditions for Cell Displacement

5.4 Solver

5.4.1 overPimpleDyMFoam

The solver used is overPimpleDyMFoam, which is a pressure-based solver for transient simulations of incompressible flow (for this case), implementing the PIMPLE algorithm, which is the combination of two classical algorithms used in Computational Fluid Dynamics: PISO (Pressure-Implicit with Splitting of Operator) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm for pressure-velocity coupling. This solver was chosen due to its applicability in dynamic meshes, with mesh motion and overset meshing capabilities.

The PIMPLE algorithm can be summarised as follows:

1. Create time object, mesh object, and initialise fields.
2. Execute function objects, calculate Courant Number and `delT`, update `runTime` object.
3. Categorize the cells into hole, interpolated and calculated cells.
4. Solve the discretised momentum equation to compute velocity field, with a guess value for pressure.
5. Calculate velocity with pressure and flux.
6. Solve pressure Equation.
7. Update explicit non-orthogonal correction till the number specified in `nNonOrthogonalCorrectors`.
8. Correct phi or flux.
9. Correct velocity explicitly.
10. Make fluxes relative to the overset mesh motion.
11. Repeat from Step 4 till the number specified in `nCorrectors`.
12. Repeat from Step 2 till the number specified in `nOuterCorrectors`.

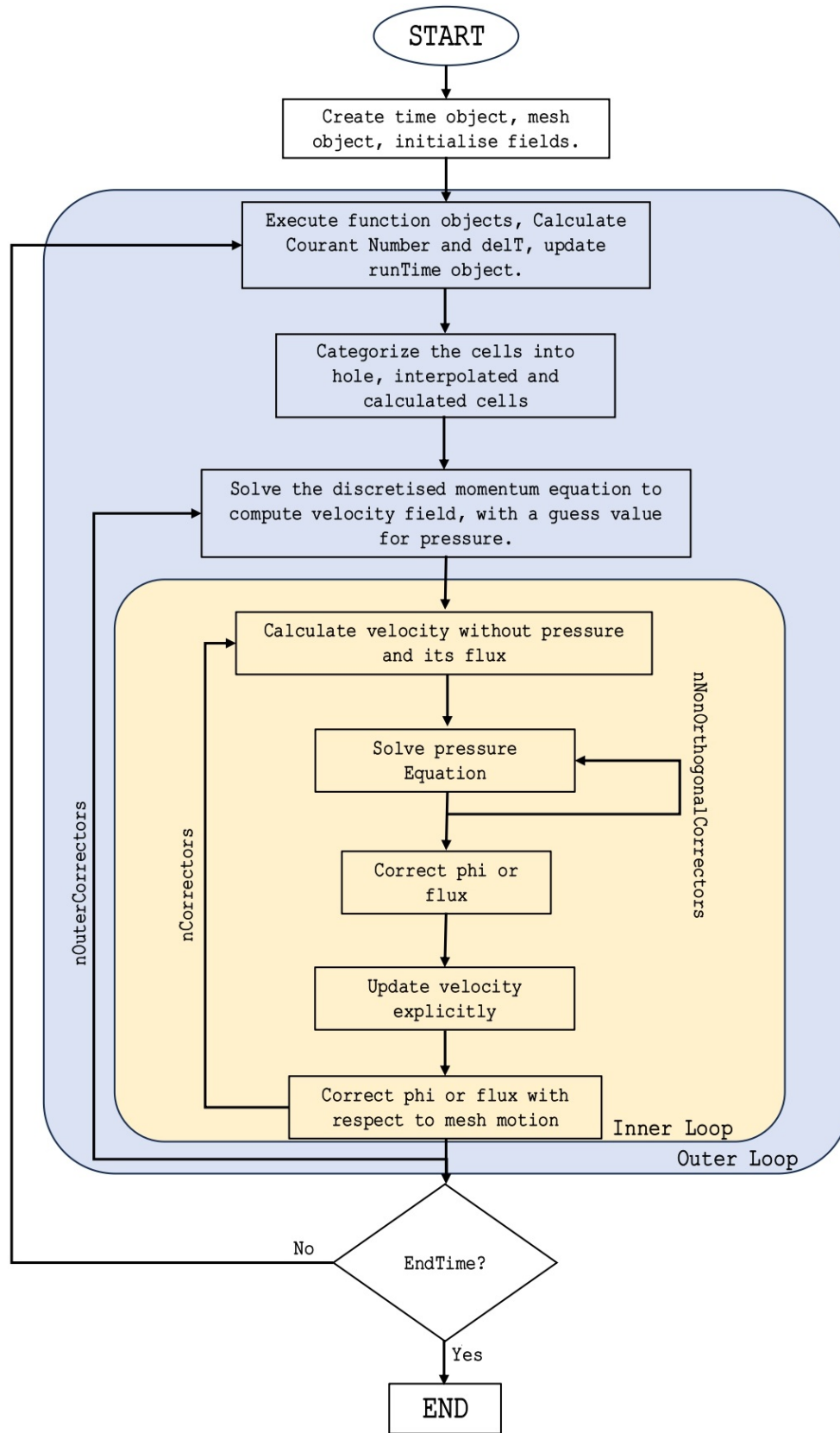


Figure 18: Algorithm Visualization

5.4.2 Fluid Properties

The fluid was modelled as an incompressible Newtonian fluid with constant properties, as specified in the transportProperties dictionary, are summarized below:

Parameter	Value	Description
Transport model	Newtonian	Incompressible Newtonian fluid
ν	$1 \text{ m}^2/\text{s}$	Kinematic viscosity
ρ	$1 \text{ kg}/\text{m}^3$	Fluid density

Table 13: Fluid properties

The selected fluid properties correspond to a viscous liquid medium suitable for simulation in the low Reynolds number regime.

5.4.3 Motion Properties

The rigid-body motion of the freely falling disks was modelled using the `sixDoFRigidBodyMotion` solver coupled with the dynamic overset mesh framework. The principal motion properties used in the simulations are summarised below,

Parameter	Value	Description
Motion solver	<code>sixDoFRigidBodyMotion</code>	Rigid-body motion solver
Dynamic mesh	<code>dynamicOversetFvMesh</code>	Overset mesh motion handling
Moving wall	walls	Ellipse particle boundary
Mass	0.1571 kg	Body mass
Moment of inertia	(0.00995 0.04909 0.03941)	Moment of inertia of ellipse
Centre of mass	(0 0.05 0)	Body center location
Fluid density	$1 \text{ kg}/\text{m}^3$	Reference fluid density
Acceleration relaxation	0.95	Motion stabilization parameter
Acceleration damping	0.05	Numerical damping parameter
Time integration scheme	Newmark	Time integration solver

Table 14: motion properties used in the simulation

The body motion was driven by hydrodynamic forces obtained from the shear flow of fluid through the domain. The Newmark integration scheme was used for temporal integration of the rigid-body equations of motion.

5.5 Numerical Schemes

The simulations were performed using the finite-volume framework in OpenFOAMv2312. `overPimpleDyMFoam` is a transient solver and solves for each time step until the end time specified in `controlDict` is reached. It does not support residual control. The Courant number must be less than 1 for a physical solution, and the solver terminates the case automatically if the Courant number is very large. The time step is suitably reduced so that the Courant number does not exceed 1.

Temporal discretisation was performed using the first-order implicit Euler scheme to ensure stable transient integration during overset mesh motion:

```
ddtSchemes
{
    default          Euler;
}
```

Spatial convection terms were discretised using bounded limited-linear schemes:

```
div(phi,U)          Gauss limitedLinearV 1;
```

Diffusion terms were discretised using the corrected Gauss linear scheme:

```
laplacianSchemes
{
    default          Gauss linear corrected;
}
```

Overset interpolation between the stationary background mesh and moving body mesh was performed using the `cellVolumeWeights` interpolation method, with 2 `holeLayers`, using layer 1 for interpolation:

```
oversetInterpolation
{
    method          cellVolumeWeight;

    holeLayers 2;
    useLayer 1;
}
```

PIMPLE scheme is used by the solver for velocity-pressure coupling, anchoring pressure to a particular point because as all the patches are `zeroGradient`:

```
PIMPLE
{
    momentumPredictor    true;
    oversetAdjustPhi      true;

    nOuterCorrectors      3;
    nCorrectors            2;
    nNonOrthogonalCorrectors 2;

    massFluxInterpolation true;
    ddtCorr                false;

    turbOnFinalIterOnly  false;

    moveMeshOuterCorrectors yes;

    pRefPoint (-7.900 0.06 7.900);
    pRefValue 0;
}
```

The pressure equation and velocity was solved using the PBiCGStab solver with DILU preconditioning:

```
p
{
    solver          PBiCGStab;
    preconditioner   DILU;
    tolerance        1e-6;
    relTol           0;

    maxIter          200;
    cacheAgglomeration off;
}

U
{
    solver          PBiCGStab;
    preconditioner   DILU;
    tolerance        1e-8;
    relTol           0;

    maxIter          200;
    cacheAgglomeration off;
}
```

6 Results and Discussions

6.1 Comparison with Analytical Solution

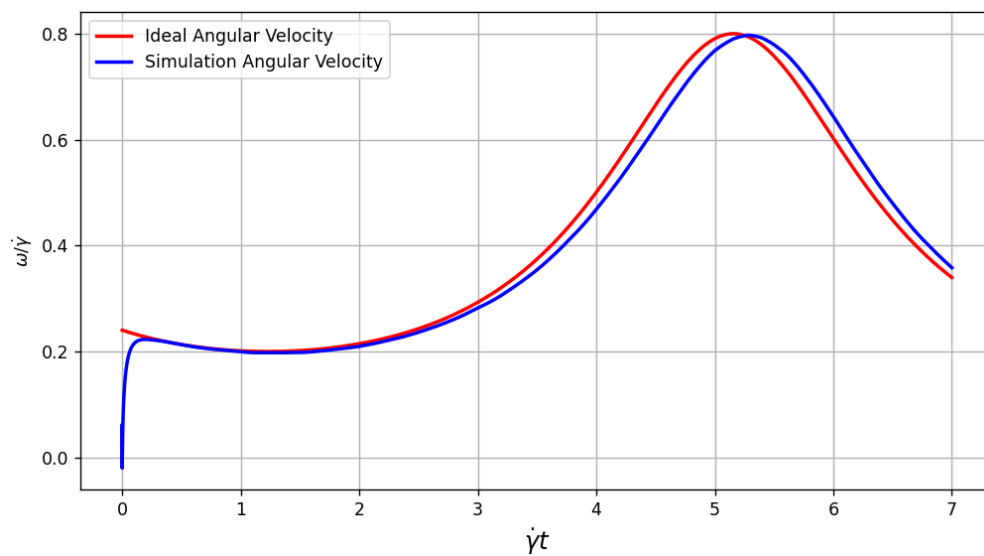


Figure 19: Angular Velocity Comparison

The numerical results closely follow the analytical prediction throughout the tumbling cycle, demonstrating that the overset mesh methodology accurately captures the rotational dynamics of the elliptical particle. A small transient is observed at the beginning of the simulation due to the rigid body initially being at rest, whereas Jeffery's solution assumes instantaneous equilibrium or a steady solution. Minor deviations near the peak angular velocity are attributed to confinement effects, finite rigid-body inertia, and overset interpolation errors, which are not considered in the analytical model. Overall, the numerical results show good agreement with the theoretical solution.

6.2 Flow visualisation

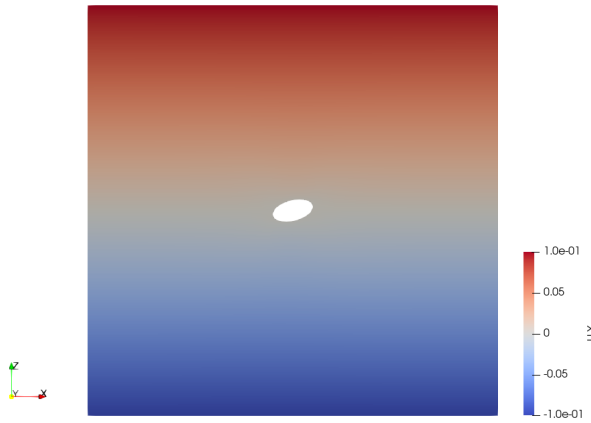


Figure 20: Establishment of Shear Flow

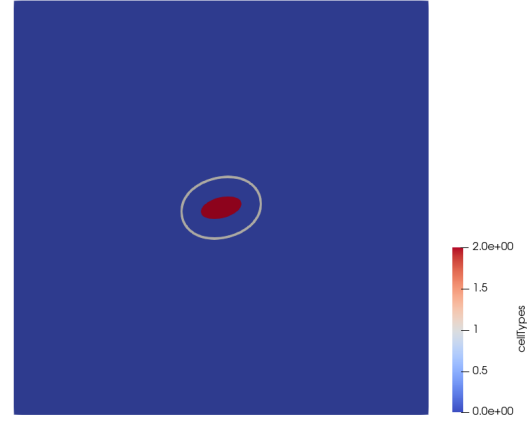


Figure 21: CellType Allocation by Solver

Disappearance of the interpolation boundary points towards a seamless interpolation between the body-fitted mesh and the background mesh through the overset patch.

Figure 20 shows the velocity distribution in the computational domain after the application of the boundary conditions. The linear variation of velocity across the channel height confirms the successful establishment of the desired simple shear flow, providing the background flow field required for the tumbling motion of the elliptical particle.

Figure 21 illustrates the overset cell-type classification generated by the solver. The body-fitted overset mesh surrounding the ellipse is identified as the active computational region, while the interpolation fringe facilitates information exchange between the moving overset mesh and the stationary background mesh. The absence of visible cells at the interpolation boundary indicates proper overset connectivity and successful communication between the two component meshes.

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