CFD Simulation of the Control Rod Emergency Insertion in the MYRRHA Nuclear Facility

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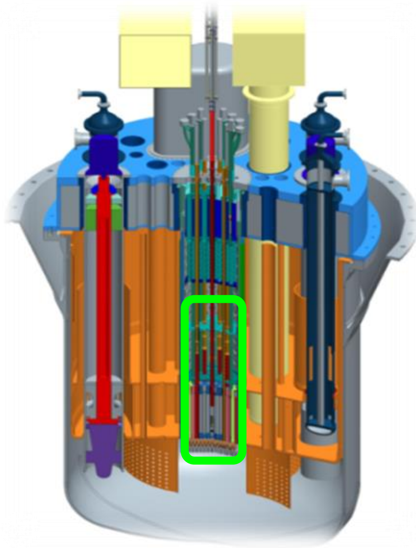
MYRRHA – Control Rod System

- MYRRHA = **M**ulti-purpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications
  - Critical and Accelerator Driven System (ADS) mode
  - Lead Bismuth Eutectic (LBE) coolant
  - Fast spectrum irradiation facility
  - Partition&Trasmutation demonstration in ADS



- Six Control Rods (CRs) in the MYRRHA critical reference core
- Normal operation: reactivity control function

Emergency operation: safety function (SCRAM)

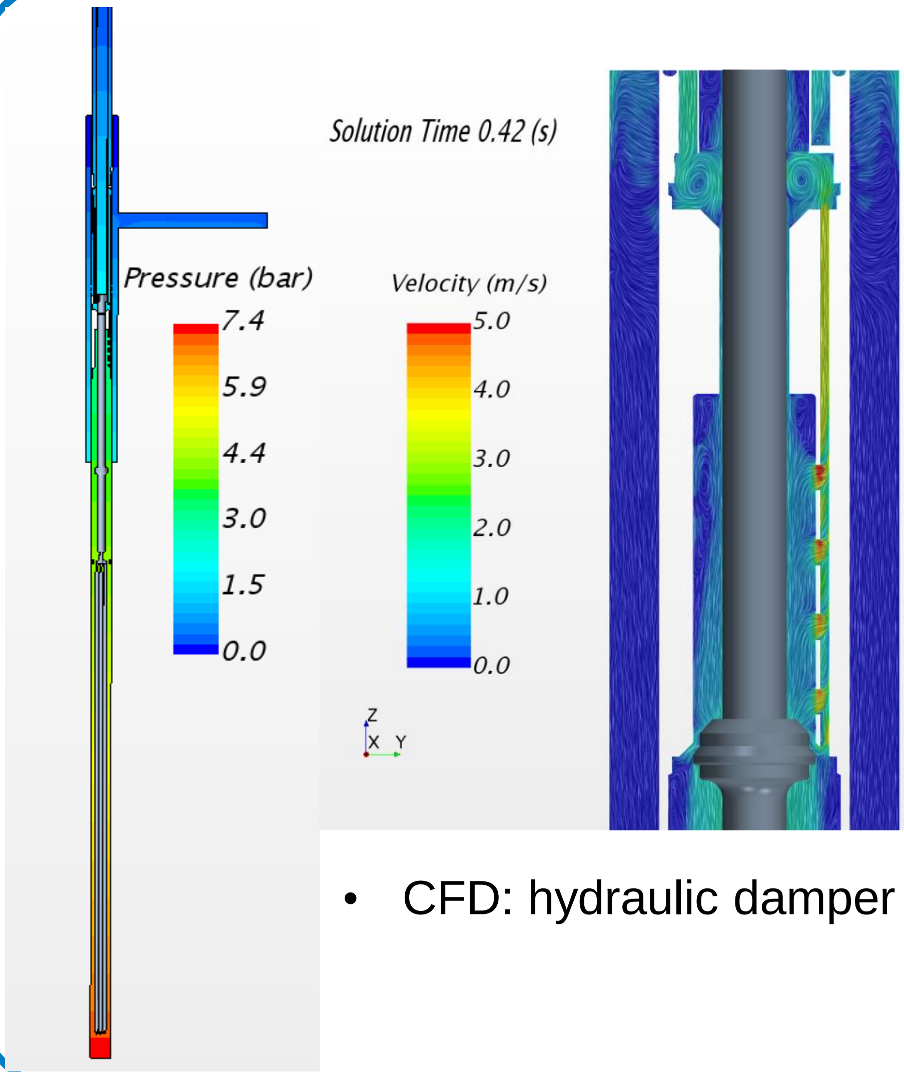
Diversification of safety devices

Insertion time < 1 s

Framework

- European project MAXSIMA
- **Methodology, Analysis and eXperiments for the "Safety In MYRRHA Assessment"**
- **CFD Numerical Simulation of Safety/Control Rod system dynamics (CRS4)** as in the COMPonentLOopTesting facility (SCK•CEN)
- **CFD methodology and results will be validated against experimental results in COMPLOT**
- Simulate the control rod displacement in the MYRRHA primary loop configuration. Input for the safety analyses

Control Rod Test Section in COMPLOT facility



COMPLOT full-scale experimental facility at SCK

- Complex geometry and physics: different roles components
- High density driving fluid
- CFD: support for the on-going experimental facility
- CFD: design exploration and optimization

- CFD: hydraulic damper effect must be captured.

Damper Operating Principle

- The 19-pin absorber bundle is roller guided within the guide tube filled with LBE and is mechanically linked with a piston that links to a hollow tube which continues through the reactor cover to the reactor exterior.

- After a steep acceleration the CR assembly is reaches quickly its terminal velocity.

- To stop it at full insertion, a damper is foreseen to smoothly slow it down.

- The piston gets into the damper, pushing the LBE through a series of outlet discharge holes. The damper keeps it strength when nearing the rest position at low speed.

Built CFD Geometry-challenging Task

- STAR-CCM+
- Version 8.02 to version 10.06
- Modular construction
- Easy handling and substitution, useful in case of size variations

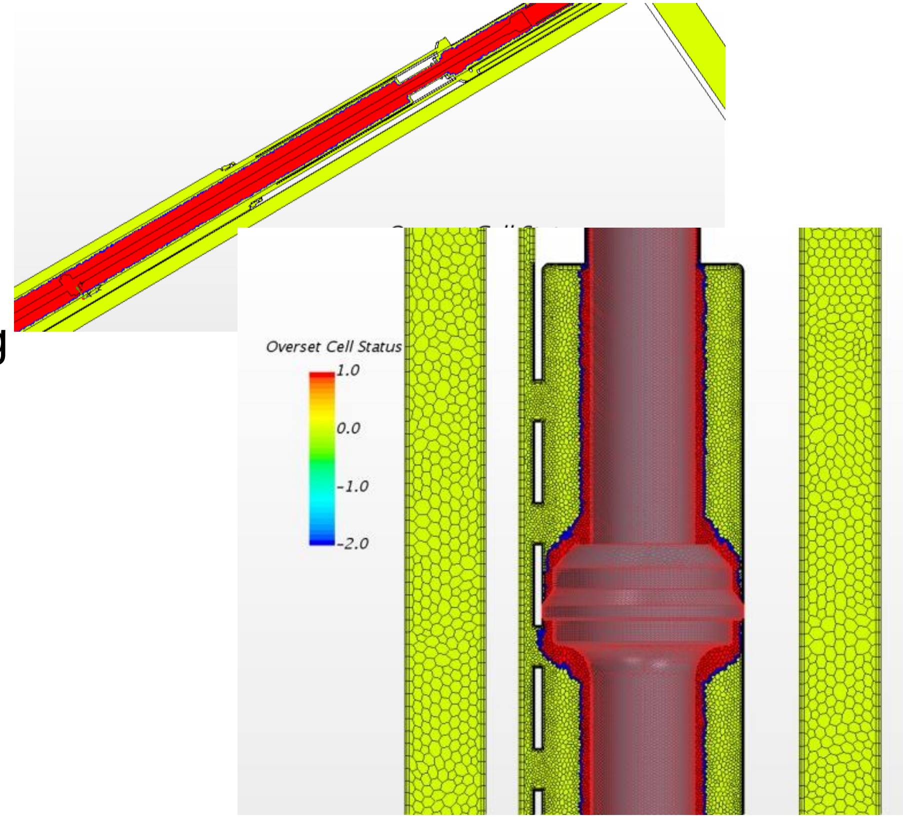
- Delay in experiment due to manufacturing issues
- Delay in numerical simulation due to geometrical complexity

Roadmap to Control Rod dynamic simulation

- Steady state simulation with MFR in Inlet
  - Determine MFR to get prescribed pressure drop
- Transient simulation- **stationary** CR
  - Impose ΔP at BC
    Stagnation Inlet and pressure outlet
  - Include cover gas
- Transient simulation- **moving** CR
  - Preliminary imposed motion from theoretical model
  - Two-way coupling motion from force balance
  - Include cover gas

Overset Mesh Methodology in STAR-CCM+

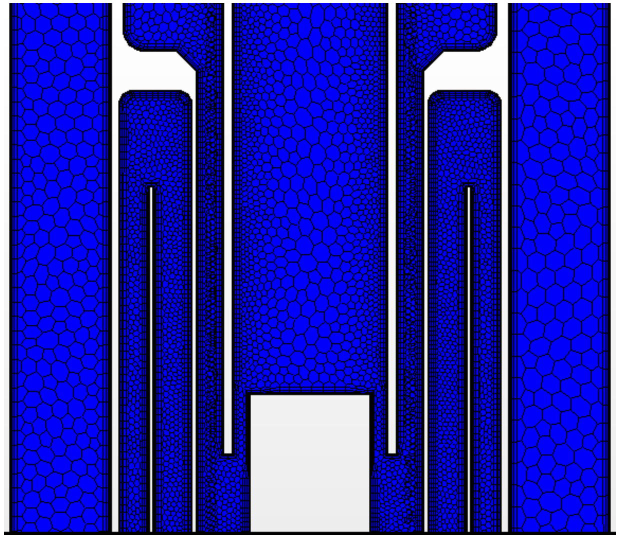
- **Background region**
  - Containing the flow domain
- **Overset region**
  - Separate region enclosing the moving body
- **Overset Mesh Interface**
  - "Volume" interface for information exchange
  - **Overset Mesh Zero Gap**
- **Conditions for a successful coupling**
  - 1-2 layers of cells attached to the moving body boundary
  - Same mesh size in both regions in the overlapping zone.

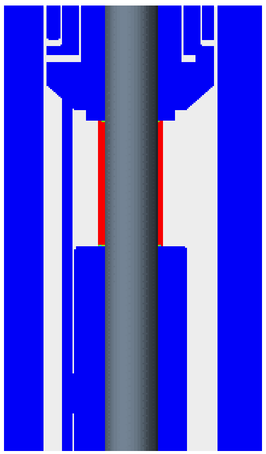


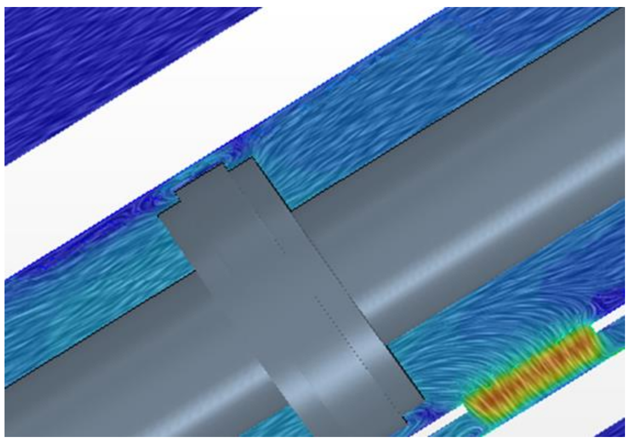
- **Yellow-active cells** in background region
- **Red-inactive cells** in overset region
- **Blue-acceptor cells**: couple solutions on the two overlapping grids

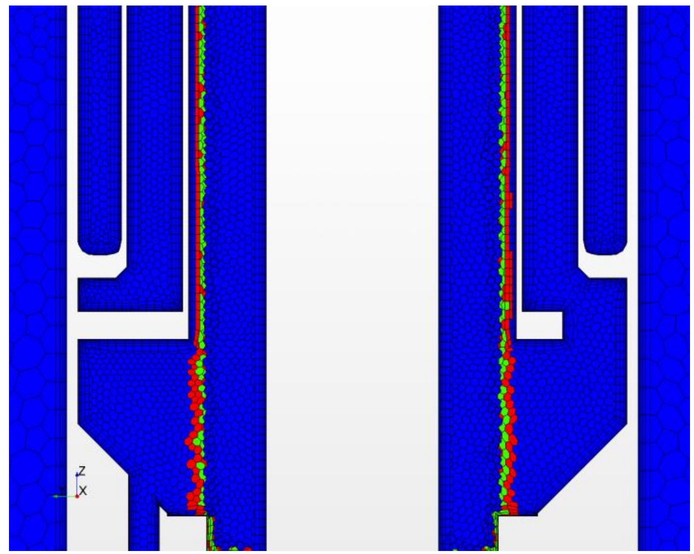
Challenges of the Overset Mesh Method

- Reduce interpolation errors in overlapping zones
  - Generate suitable meshes – non trivial task
  - Flow path and moving component with different and complex geometries
- Treatement of the narrow gaps in the flow path
  - Acceptable compromise mesh density vs. geometrical accuracy
  - Near zero leakage at seal passage in the damper and above the damper





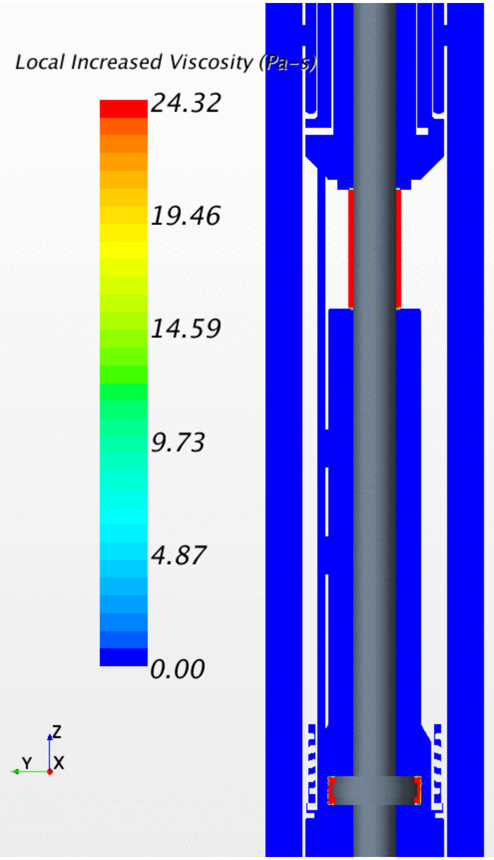


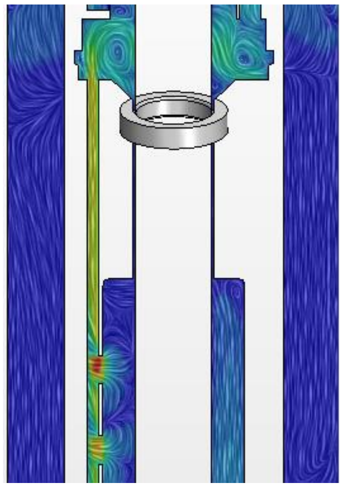


Reduced Geometrical Accuracy integrated with an Increased Dynamic Viscosity

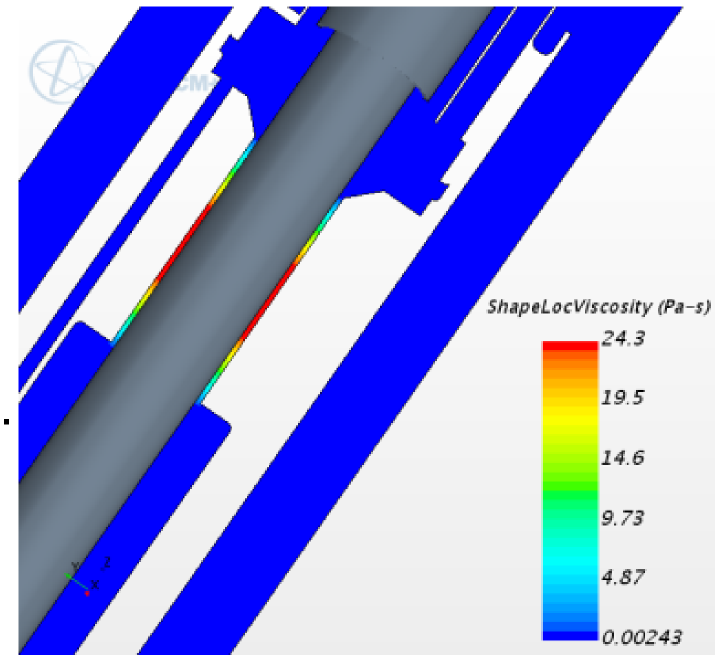
- Increased LBE dynamic viscosity by N orders of magnitude around the seal, χ: for $Z_0 \leq Z \leq Z_0 + h$, $R_{seal} \leq X \leq R_{damper}$,

$$\boldsymbol{\mu_1 = \mu_0 + \mu_0 10^N \chi}, \ N = 3, 4$$





- Increased viscosity above the damper; a graphite ring is foreseen to keep the CR assembly stable.



Divergence of the turbulence variables at damper entrance. Unrealistic high velocities in the above damper gap.

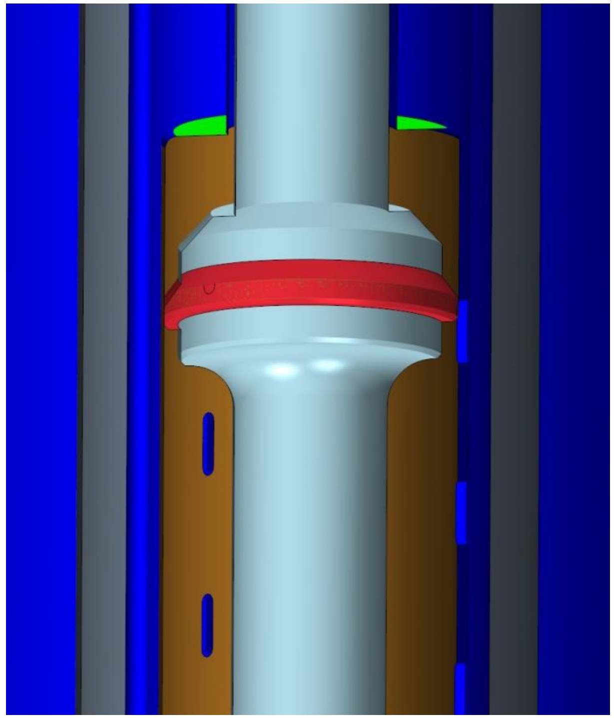
LBE dynamic viscosity increased by means of a **shape function**; reduced viscosity high gradients.

A long and windy road….

Focus on the damper treatment, without bundle

- Two types of difficulties have been faced, mesh-related and physics-related:
  - Mass loss
  - Pressure oscillations
  - Numerical oscillations
  - Divergence
  - Floating point exception

- Suitable mesh size in the overlapping zones
  - Difficult handling of the geometry differences
- Volumetric controls: circular bands
  - Versatile tool for customization of the overset mesh

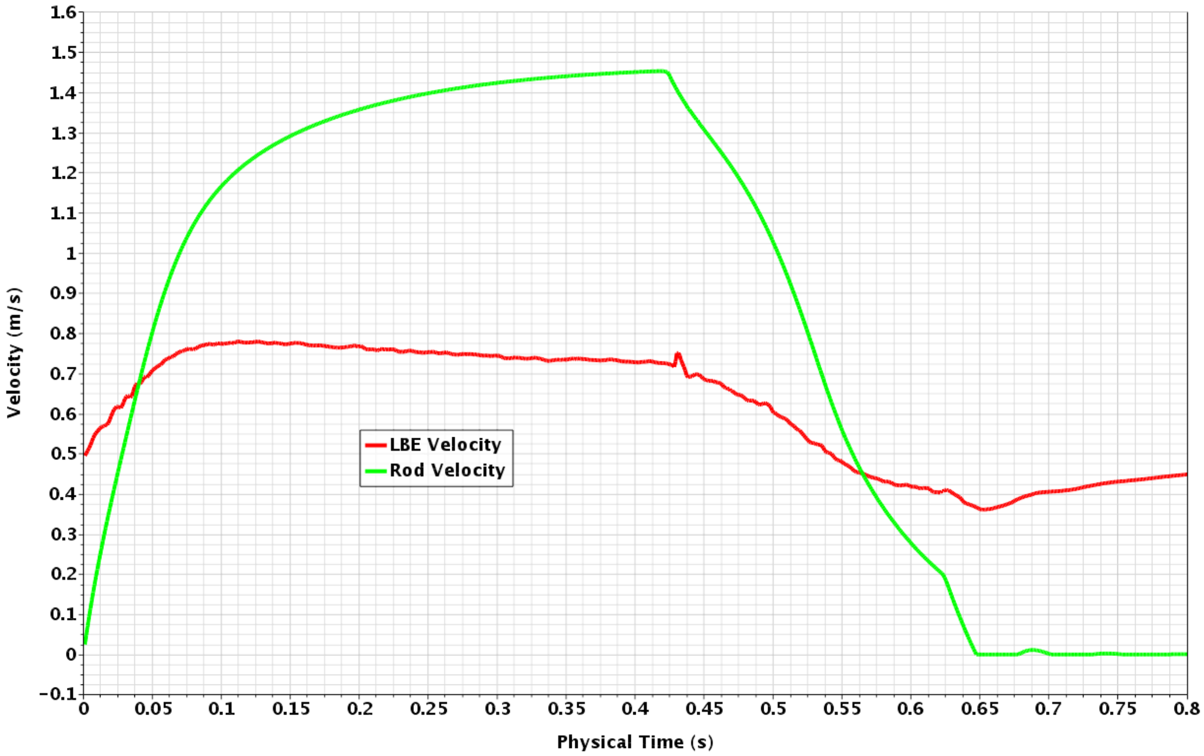


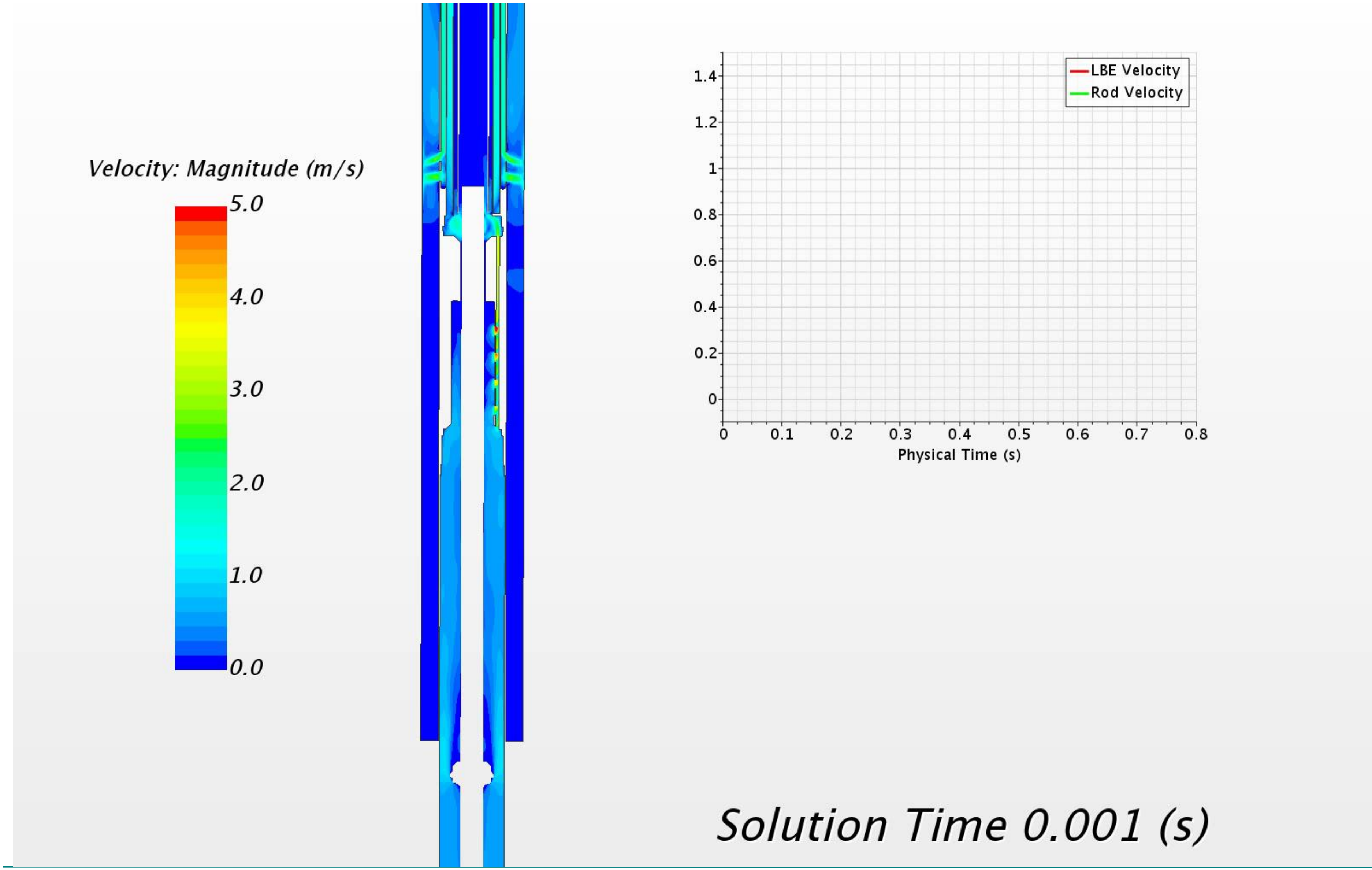
Light came with ZeroGap Interface

Imposed Motion Derived from 1D Theoretical Model

Overset Mesh ZeroGap Interface

- Just after the release, the rod is accelerated by buoyancy.
- Then the acceleration is damped by the fluid resistance.
- When the seal enters the damper the rod is decelerated.



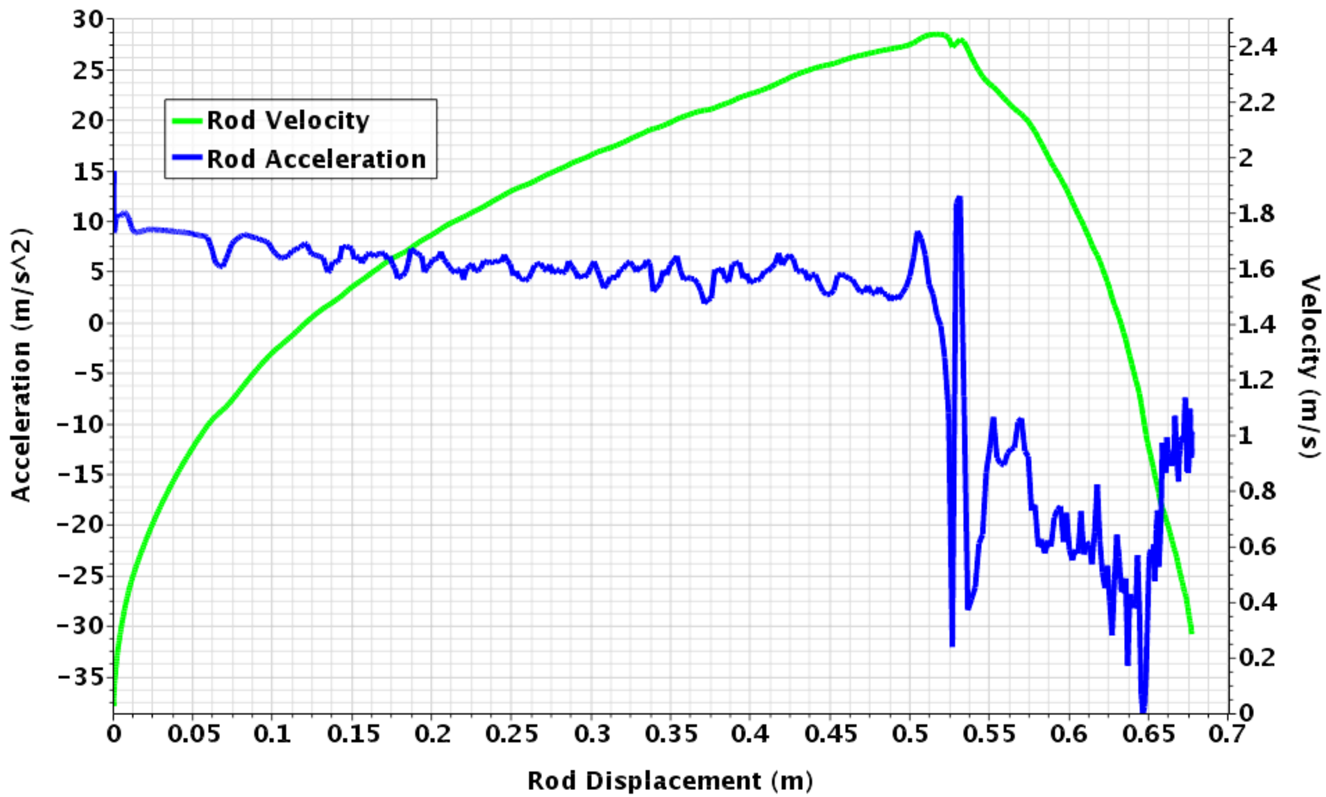

Velocity: Magnitude (m/s)
5.0
4.0
3.0
2.0
1.0
0.0
LBE Velocity
Rod Velocity
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Physical Time (s)
Solution Time 0.001 (s)

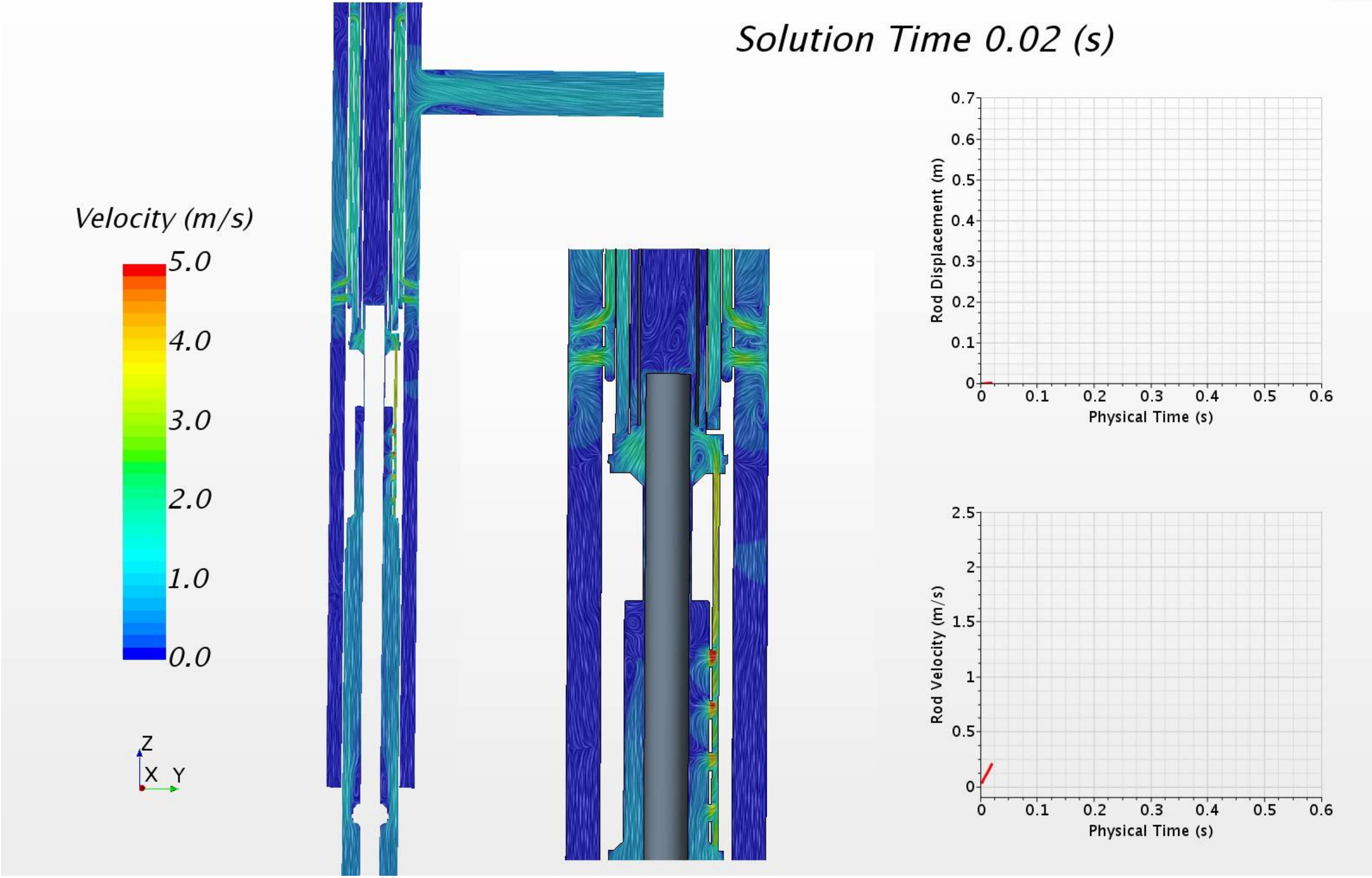
Two-way Coupling Motion from Force Balance

Fully explicit coupling

Acceleration = Force/mass

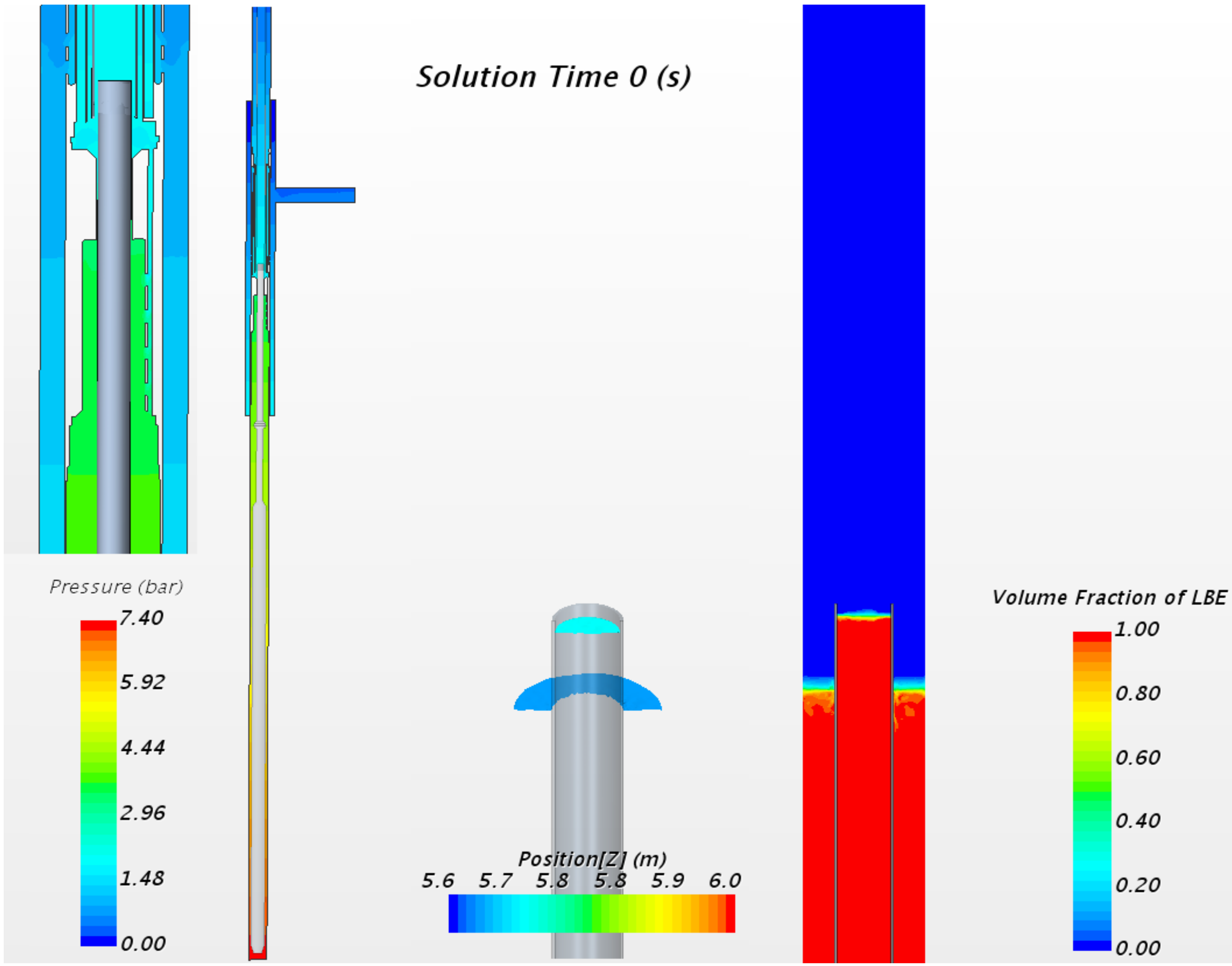
The rod velocity is calculated by time integration of acceleration and is assigned to the CR in a translation motion.




Solution Time 0.02 (s)
Velocity (m/s)
5.0
4.0
3.0
2.0
1.0
0.0
Z
X
Y
Rod Displacement (m)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
Physical Time (s)
Rod Velocity (m/s)
2.5
2
1.5
1
0.5
0
Physical Time (s)

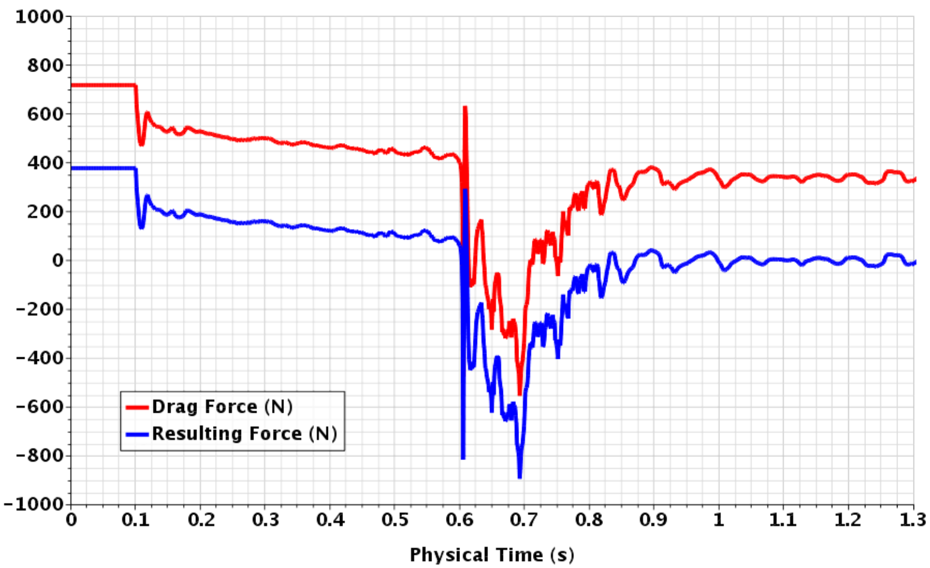
Eulerian Two-phase Flow with LBE and Argon

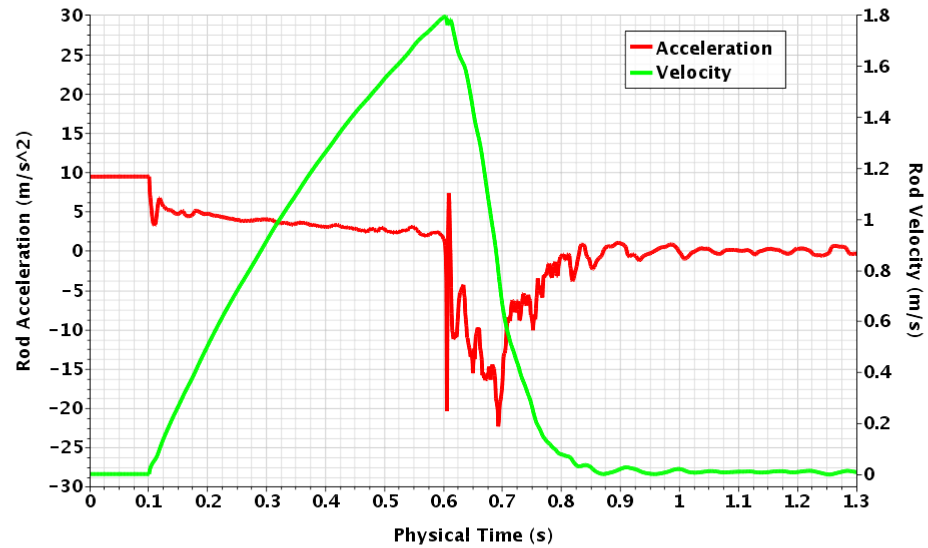
Volume of Fluid

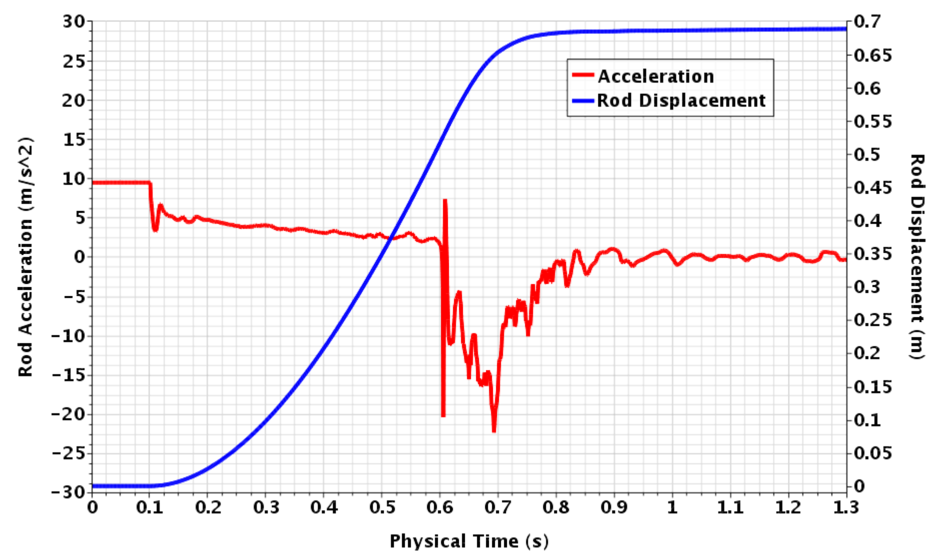


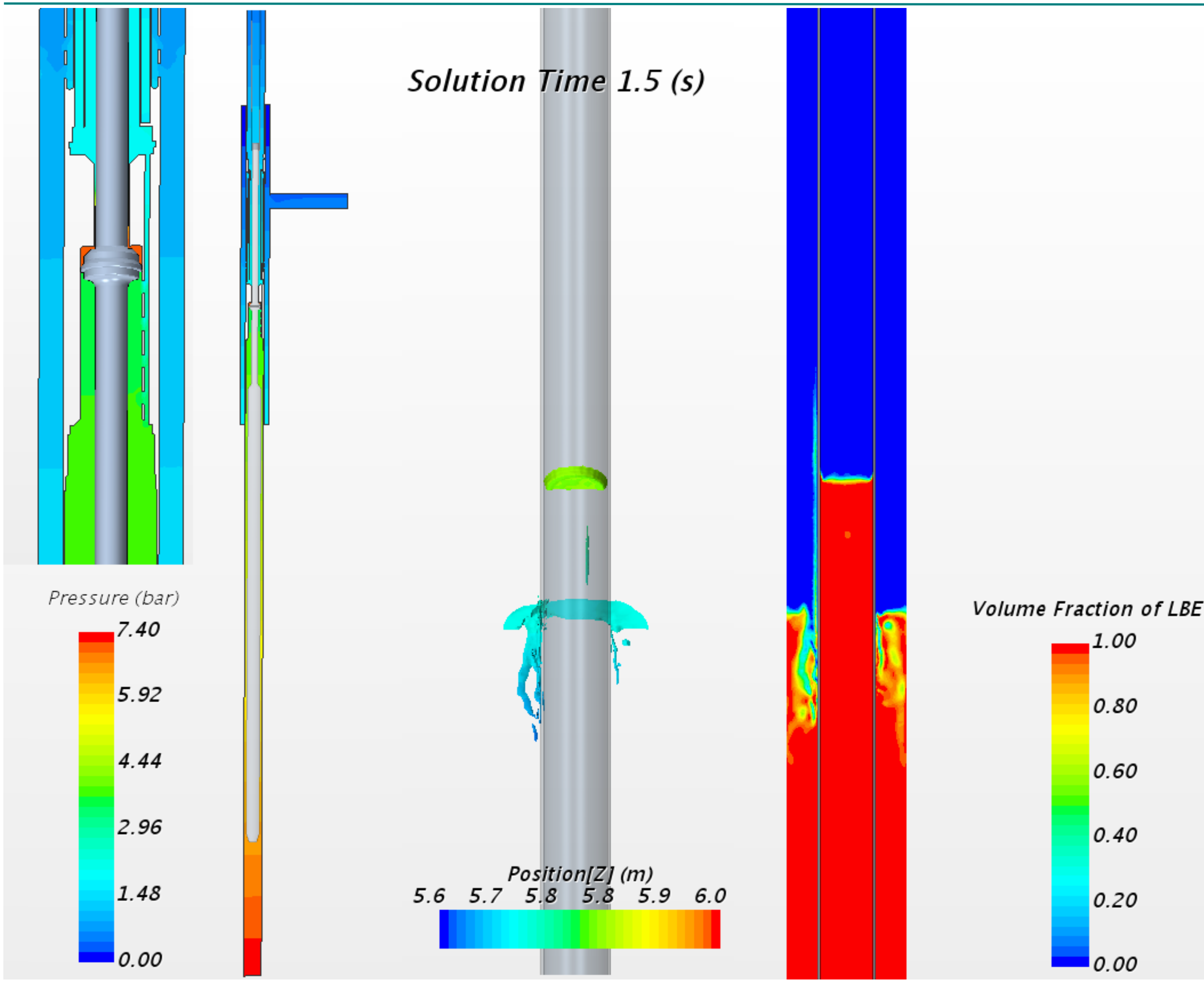
Two-way Coupling Motion in Two-phase Flow

$$F_R = \text{Drag} + \text{Buoyancy} - mg$$

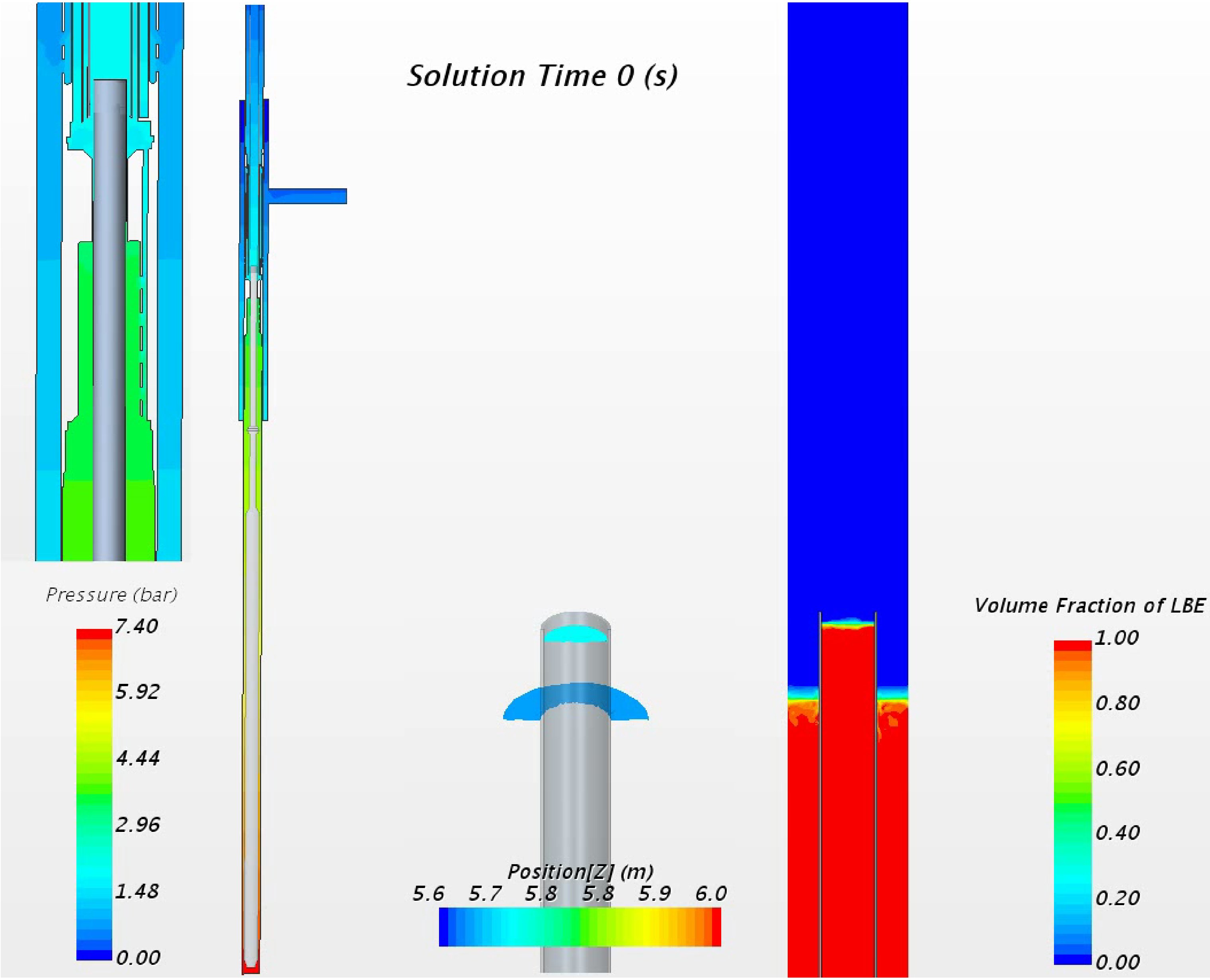


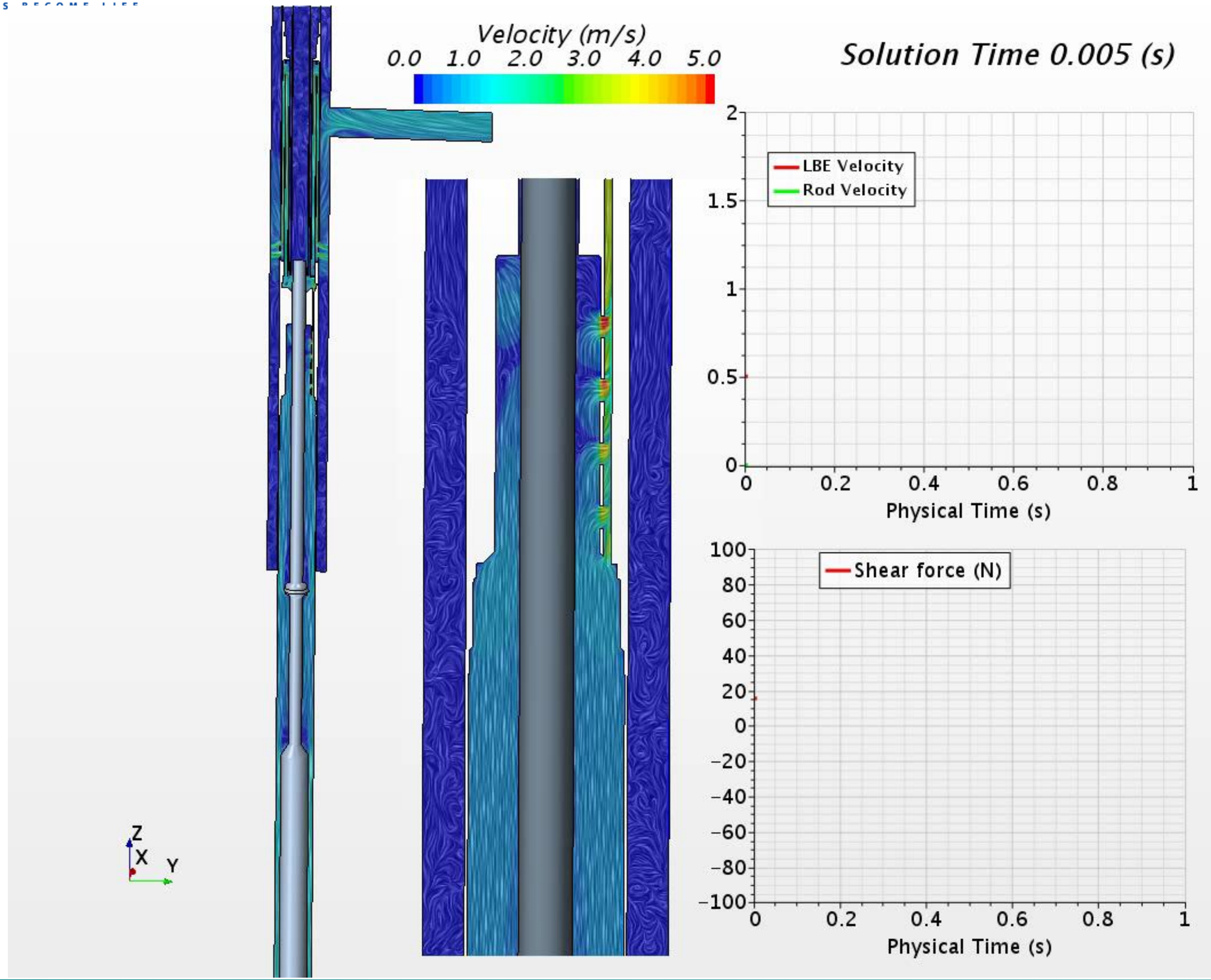


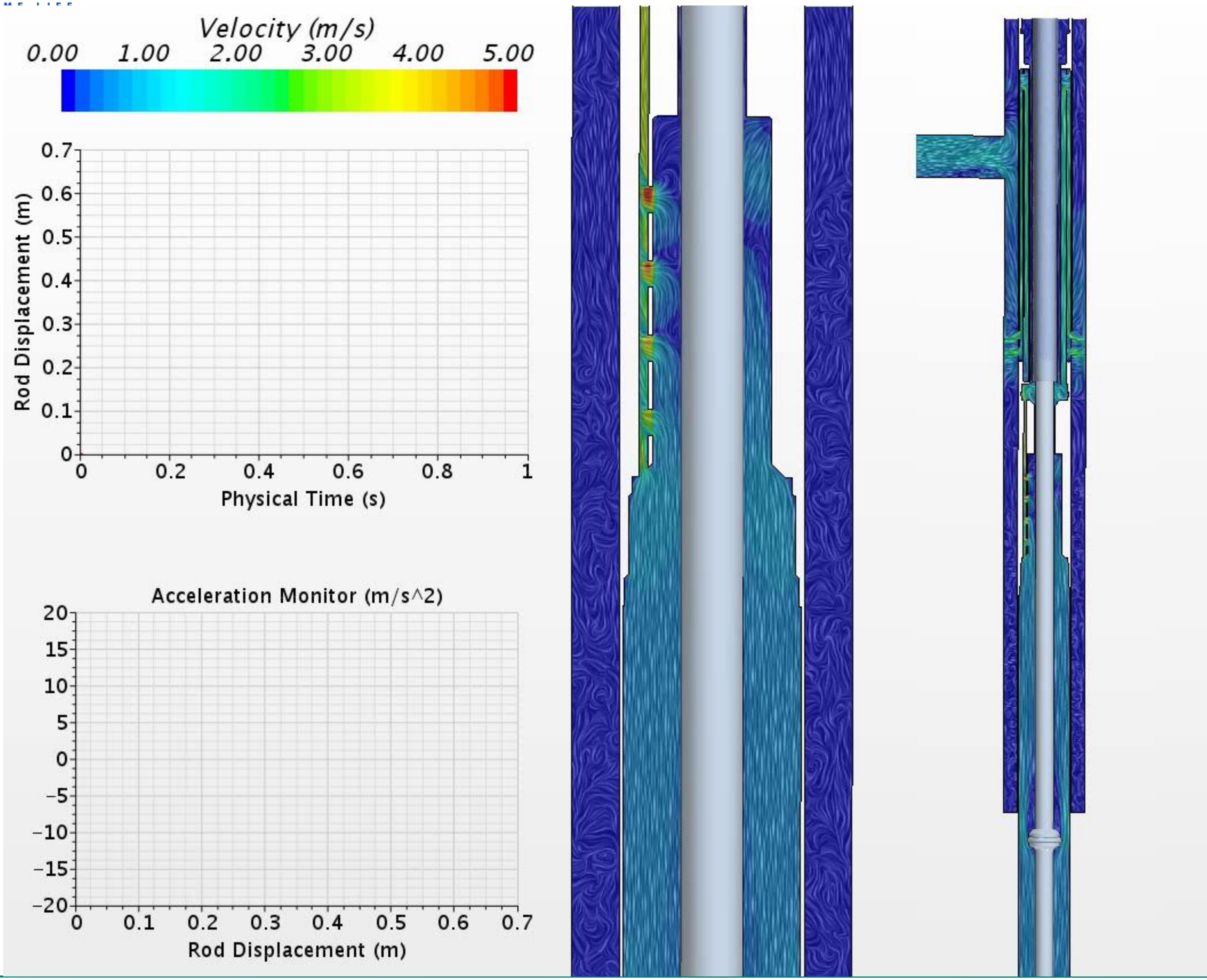


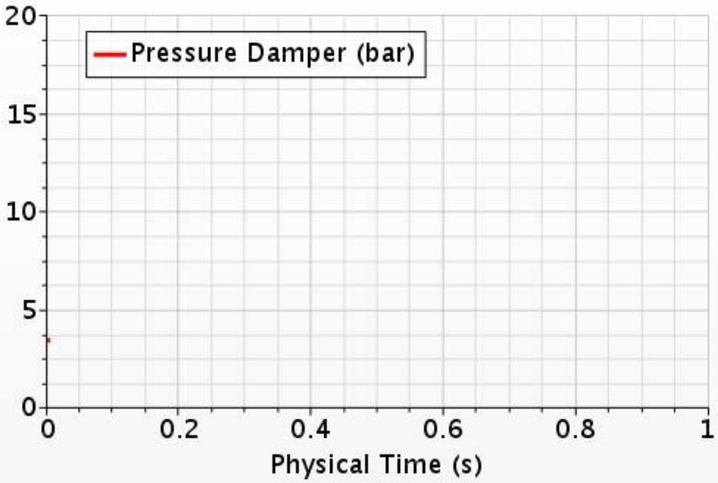


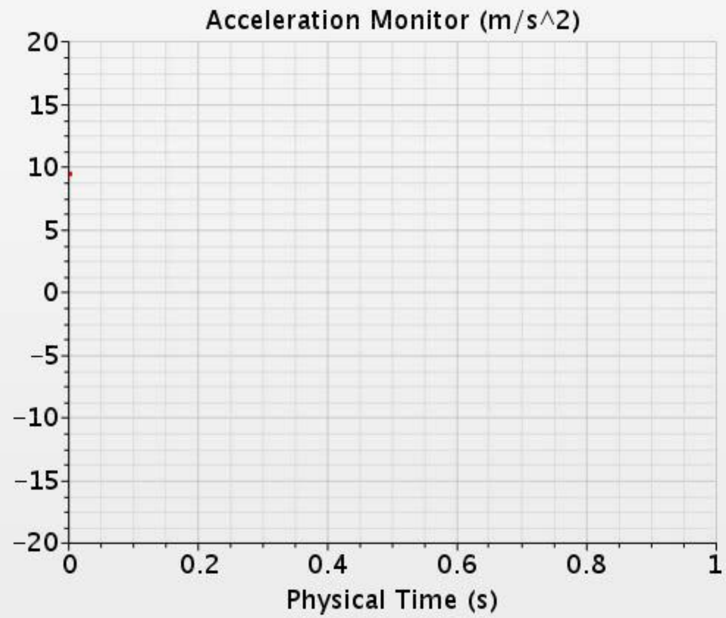
Overset mesh motion perfectly compatible with multiphase set-up!

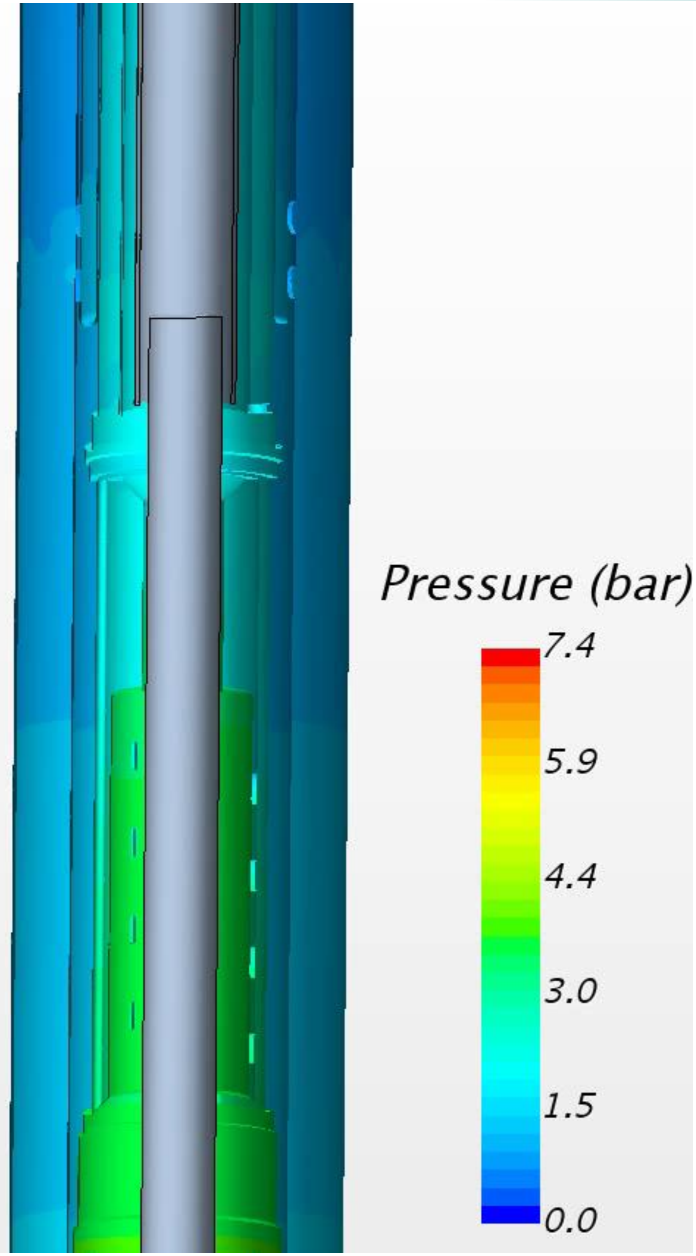

Solution Time 0 (s)
Pressure (bar)
7.40
5.92
4.44
2.96
1.48
0.00
Position[Z] (m)
5.6 5.7 5.8 5.8 5.9 6.0
Volume Fraction of LBE
1.00
0.80
0.60
0.40
0.20
0.00


Velocity (m/s)
0.0 1.0 2.0 3.0 4.0 5.0
Solution Time 0.005 (s)
LBE Velocity
Rod Velocity
Physical Time (s)
Shear force (N)
Physical Time (s)
Z
X
Y


Velocity (m/s)
0.00 1.00 2.00 3.00 4.00 5.00
Rod Displacement (m)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
Physical Time (s)
0 0.2 0.4 0.6 0.8 1
Acceleration Monitor (m/s^2)
20 15 10 5 0 −5 −10 −15 −20
Rod Displacement (m)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7

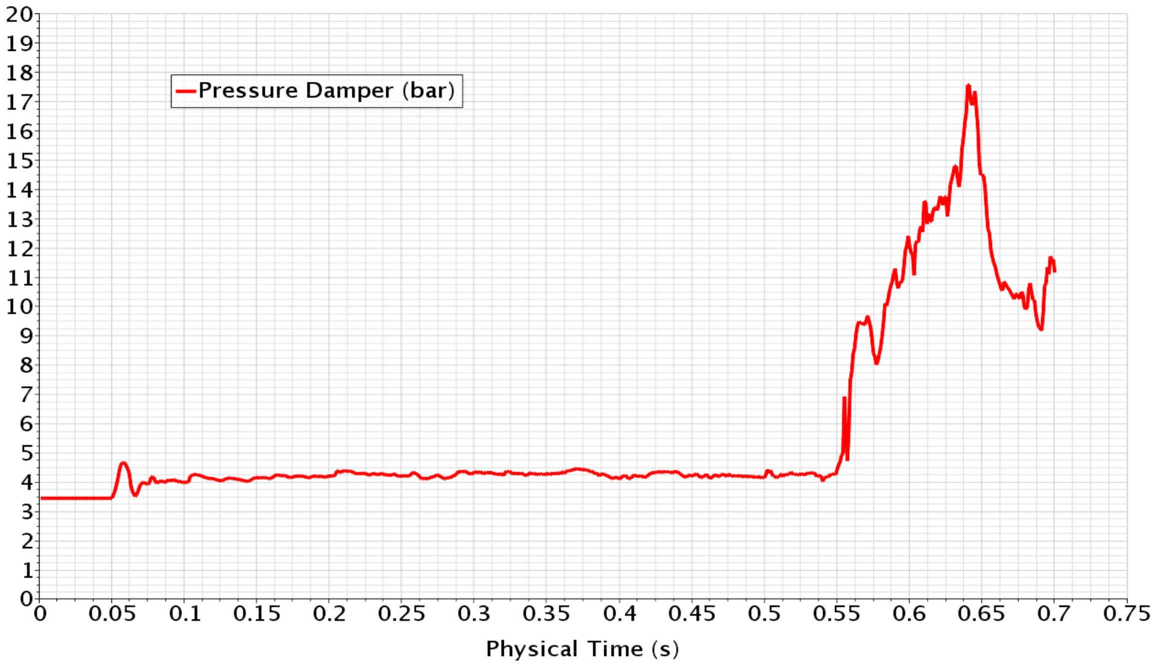

Pressure Damper (bar)
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
Physical Time (s)

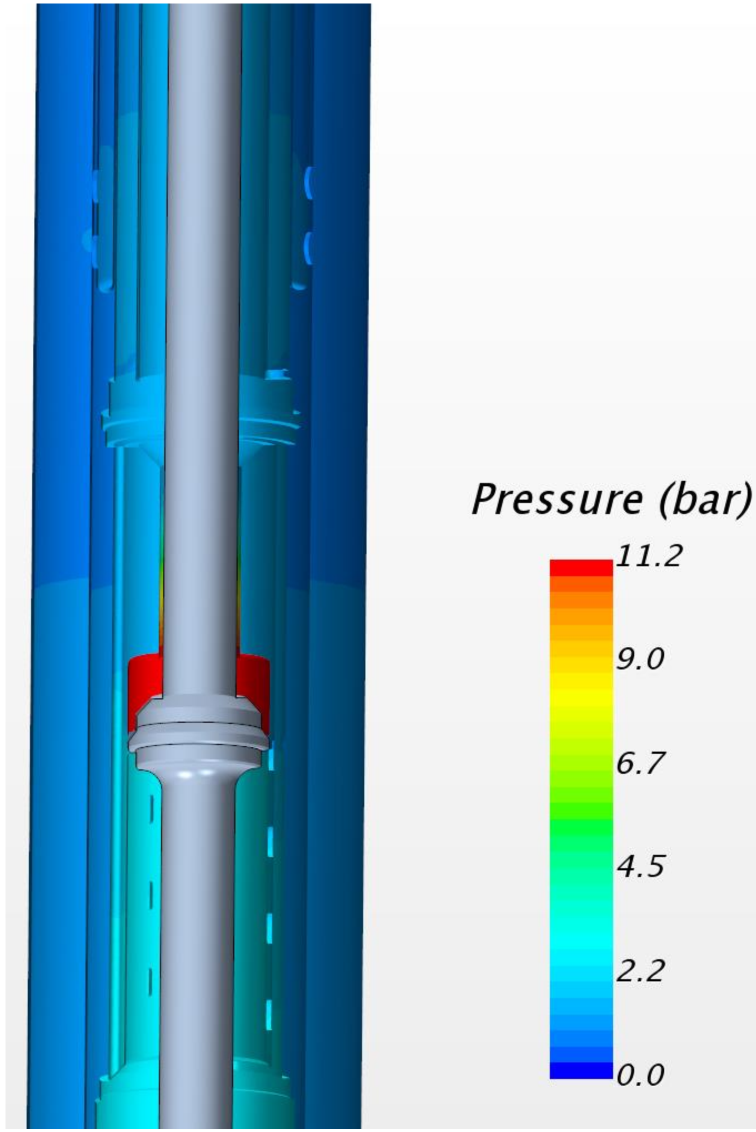

Acceleration Monitor (m/s^2)
20
15
10
5
0
−5
−10
−15
−20
0
0.2
0.4
0.6
0.8
1
Physical Time (s)


Pressure (bar)
7.4
5.9
4.4
3.0
1.5
0.0

Hydraulic Damper Effect

- Well captured by the CFD simulation
- Consistent overpressure in the damper
- Oscillations, likely numerical, present when the seal covers the slots at the passage in the damper





Concluding Words

- Sustained approach to the Overset Mesh method in stiff flow path configuration
  - A good control has been acquired.
- Remarkable upgrade of the author in tandem with STAR-CCM+'s
  - Highlight on Overset Mesh ZeroGap interface
- Quite easy transition of the two-way coupling overset mesh motion to a two-phase flow set-up:
  - Free surface behaves well with the moving component passing through
- Our challenge was to use the innovative CD-adapco technology, which was foreseen to reach sufficient maturity, in the present nuclear framework stiff context.
  - We feel confident in opening new fields of CFD applications.

Next: Perform a meaningful confront with the experimental set-up

- What remains to do?
- Establish suitable boundary conditions for the experimental set-up.
- How?
    - Complete the CFD model of the COMPLOT test section at the bottom by adding a buffer tank with an LBE inlet free surface.

Thank you for your attention!