Modeling Gravity Wave in 3D with OpenFoam in an Aluminum Reduction Cell with Regular and Irregular Cathode Surfaces

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Michaël Pagé SIMU-K SIMULATION NUMÉRIQUE

Plan of the Presentation

- Introduction
  - Most recent and advanced irregular cathode surface design modeling paper from China (Metallurgical Transaction B 2014)
  - Results of the first MHD-Valdis cell stability study (TMS 2013)
  - Results of the last MHD-Valdis cell stability study (TMS 2015)
- OpenFoam and the free interface wave problem
- 3D OpenFoam VOF gravity wave side slice model
  - Cathode with flat surface base case model
  - Cathode with longitudinal ridges model
- Future work
- Conclusions

Introduction

Examples of irregular cathode surface design in use in China: transversal and longitudinal ridges

Ref: N. Feng and al., "Research and Application of Energy Saving Technology for Aluminum Reduction in China," TMS Light Metals 2012, 563-568.

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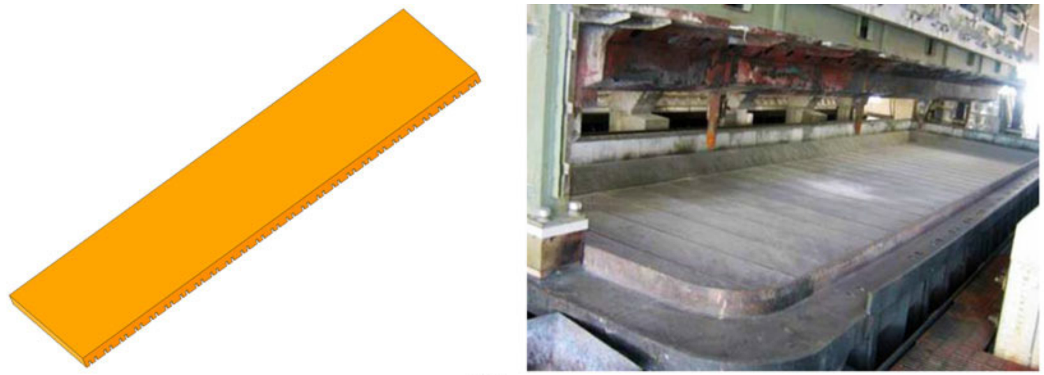
Most recent and advanced irregular cathode surface design modeling paper from China



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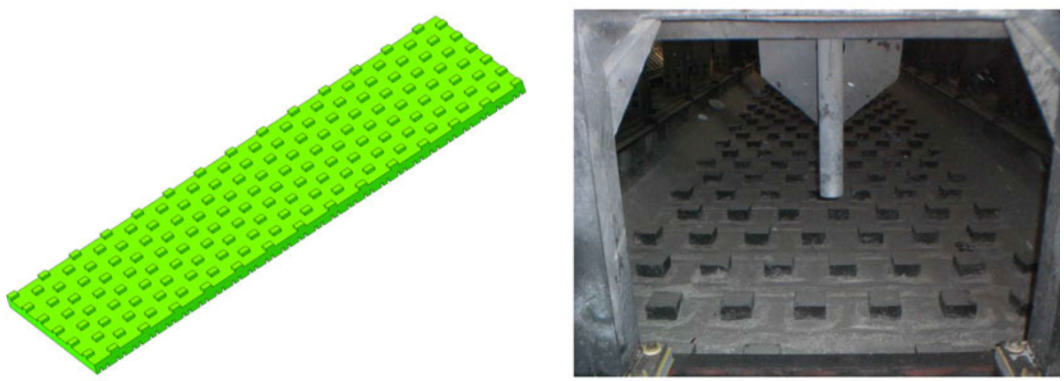

(b)

Ref: Q. Wang and al., "Simulation of Magnetohydrodynamic Multiphase Flow Phenomena and Interface Fluctuation in Aluminum Electrolitic Cell with Innovative Cathode", Metallurgical and Materials Transactions B, Vol 45B 2014, 272-294

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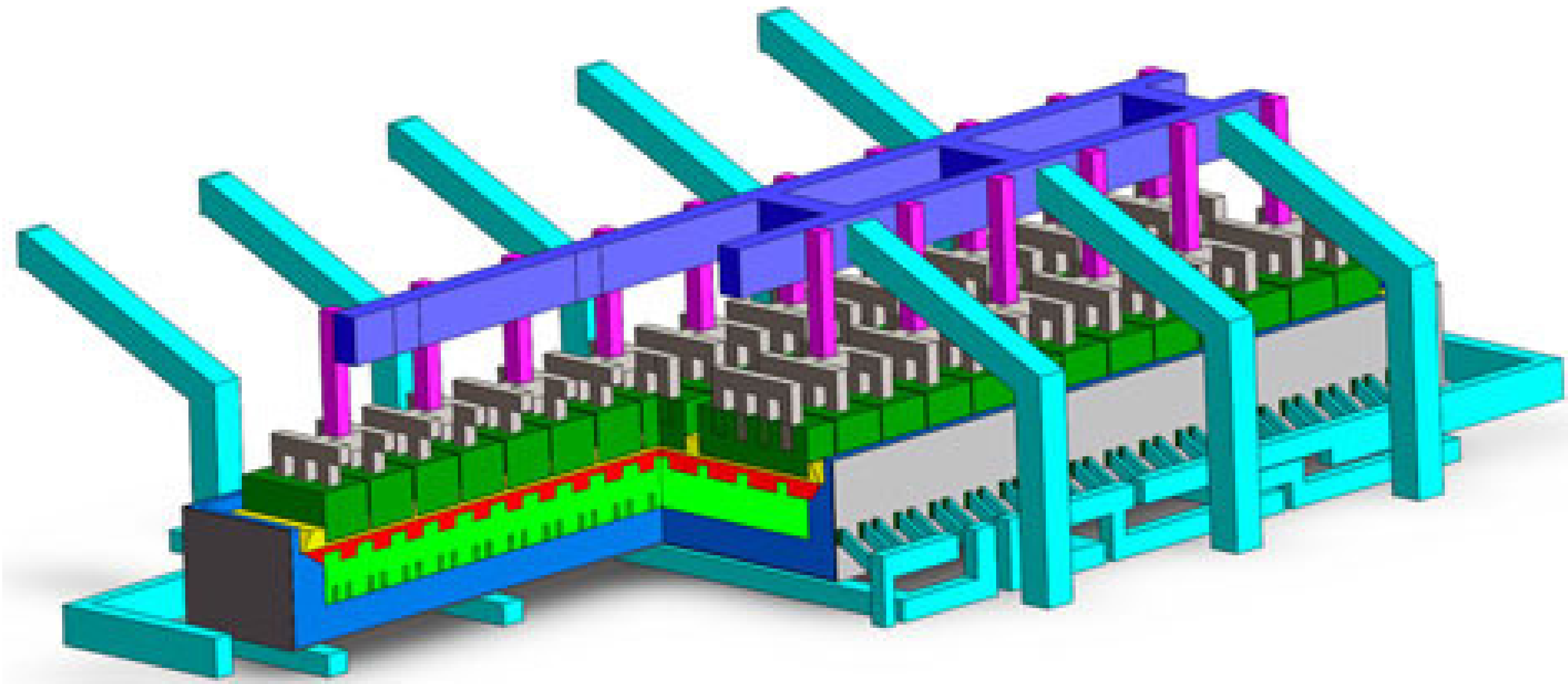

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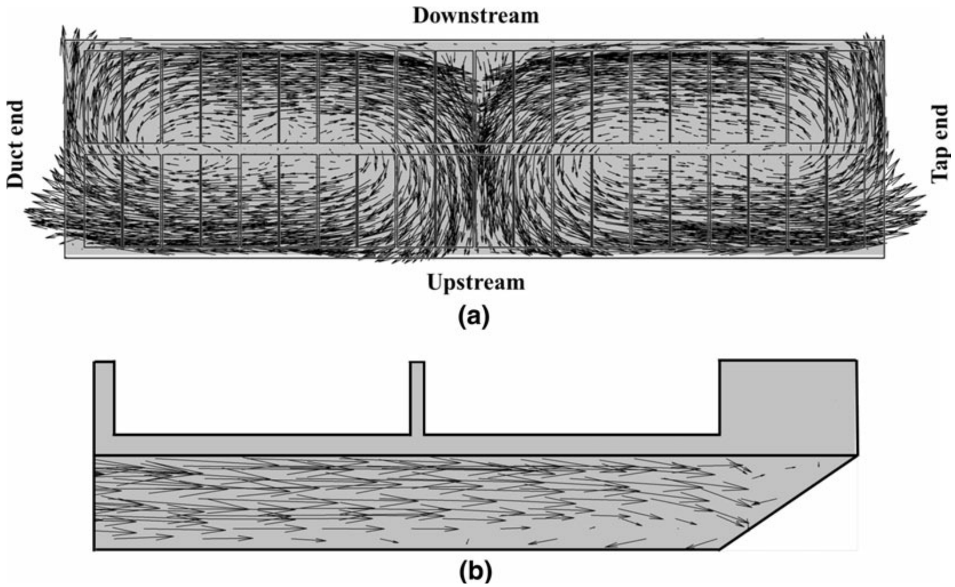
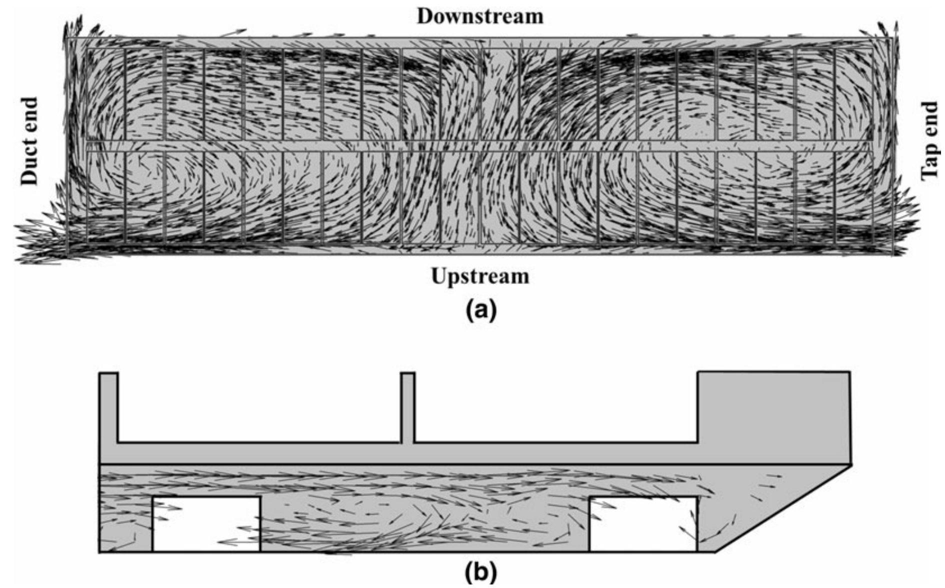
Steady-state 3D MHD VOF model results obtained using ANSYS and CFX





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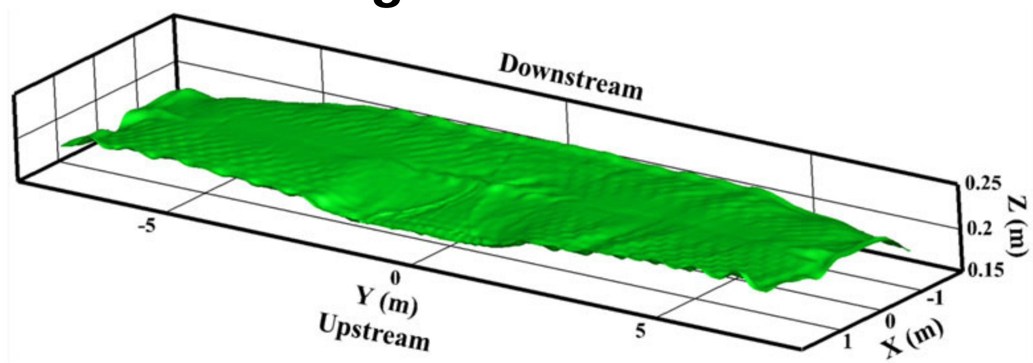

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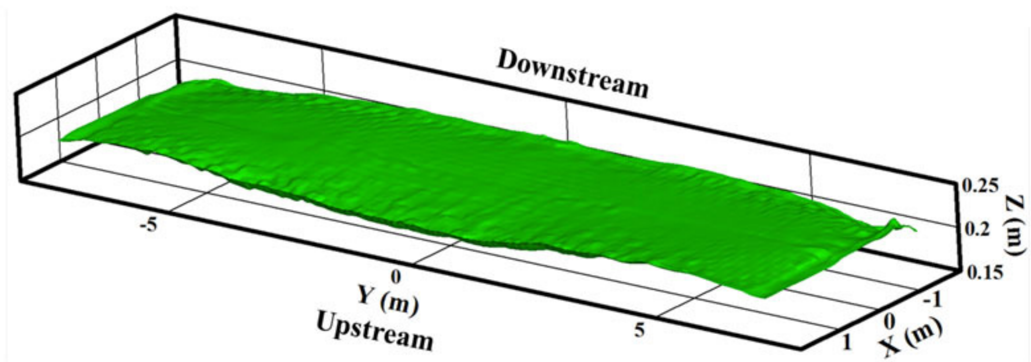

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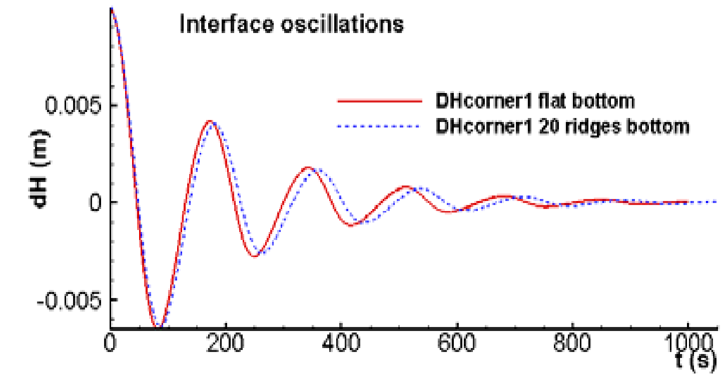
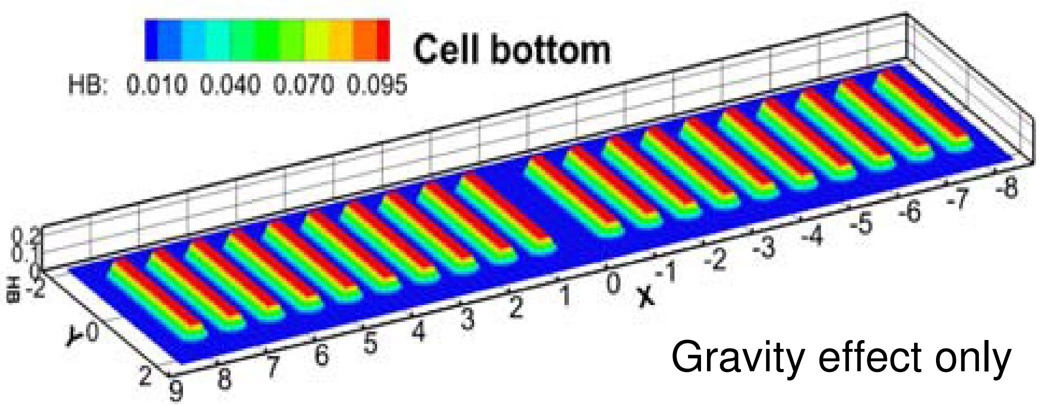
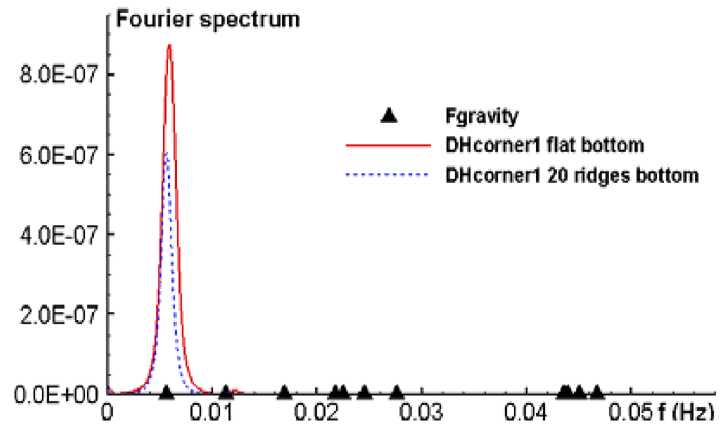
Introduction

Results of the first MHD-Valdis cell stability study

The effect of bottom friction enhancing elements is evaluated using the depth sensitive turbulent velocity model. The sloshing gravity wave without MHD interaction is confirmed to be damped moderately in the presence of the bottom ridge elements.







Gravity effect only

Ref: V. Bojarevics, "MHD of Aluminium Cells with the Effect of Channels and Cathode Perturbation Elements," TMS Light Metals 2013, 609-614.

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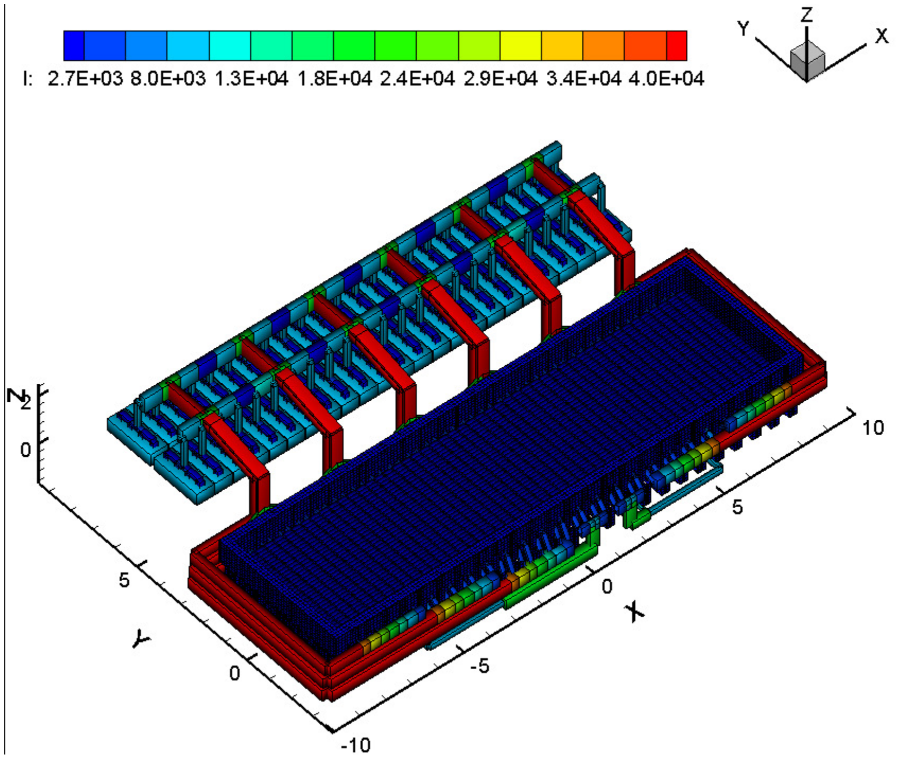
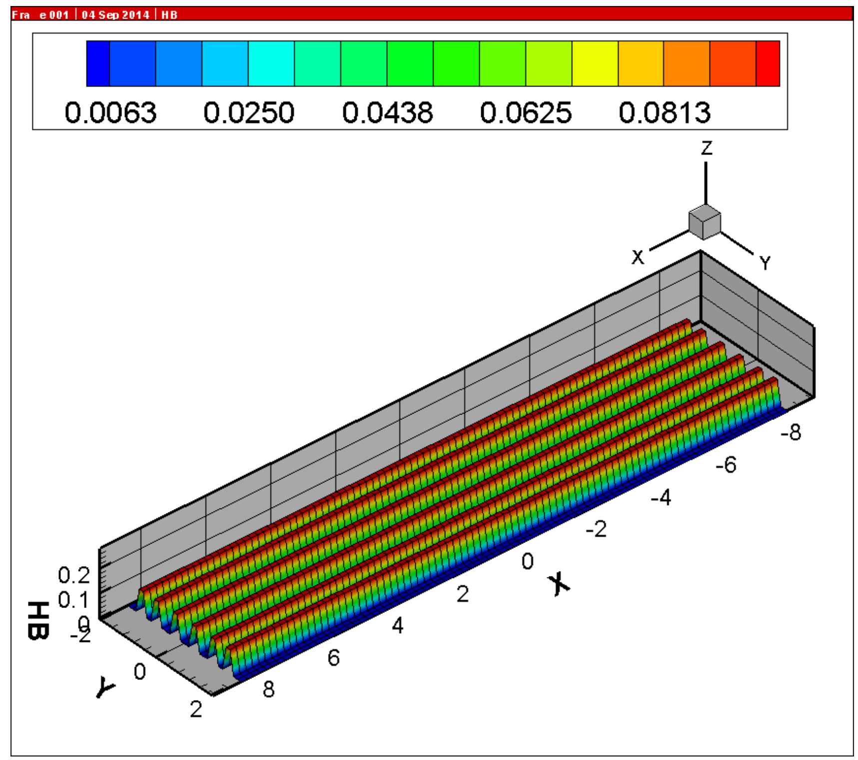
Results of the last MHD-Valdis cell stability study





Ref: M. Dupuis and V. Bojarevics, "Non-linear Stability Analysis of Cells Having Different Types of Cathode Surface Geometry", TMS Light Metals 2015, 821-826.

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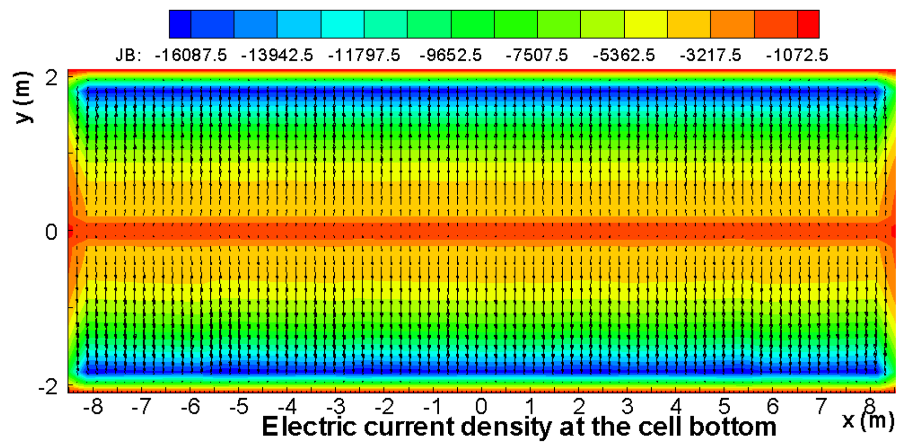

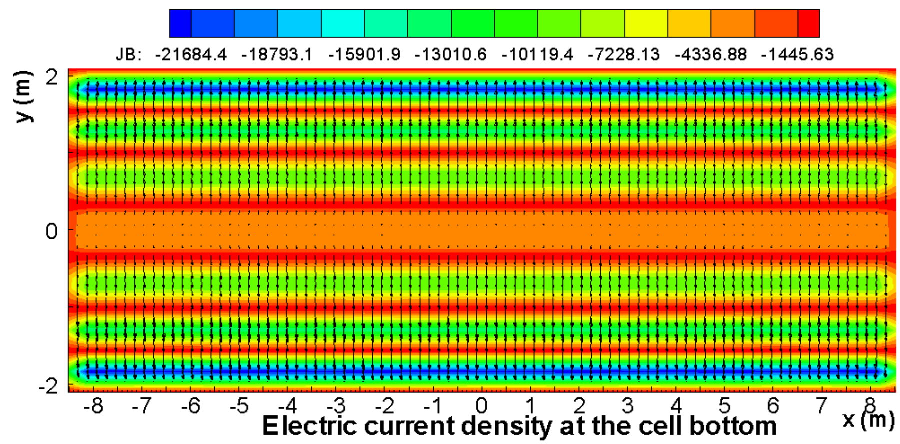

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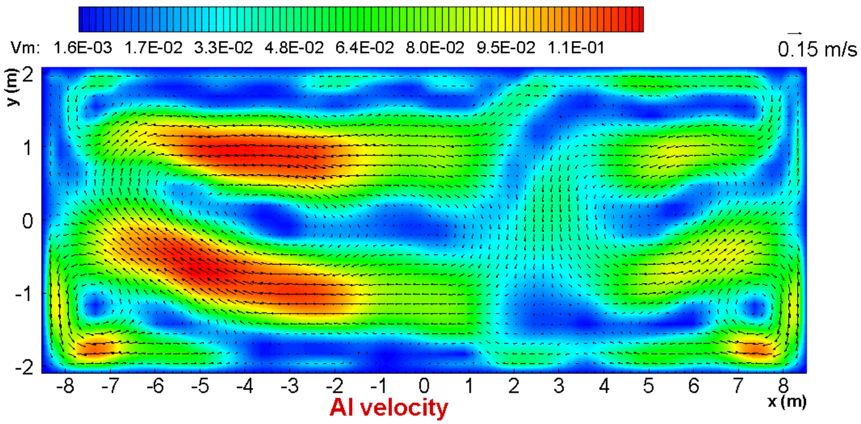

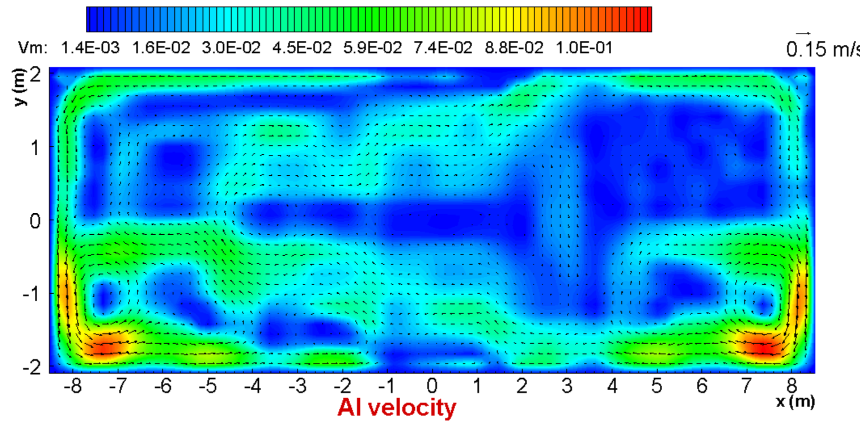

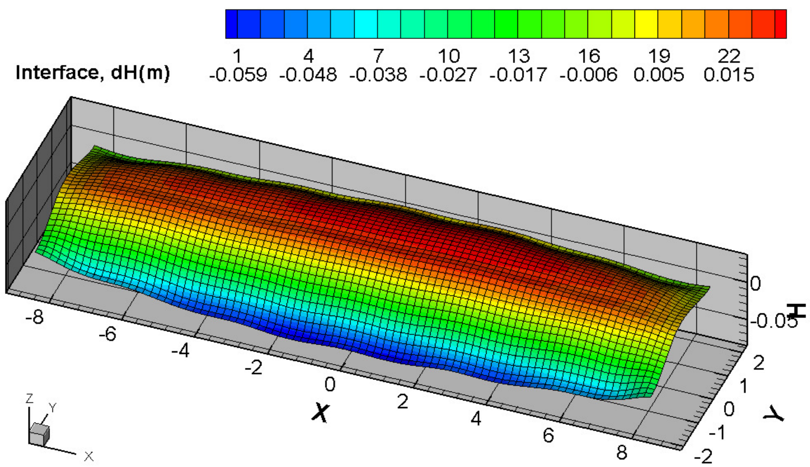

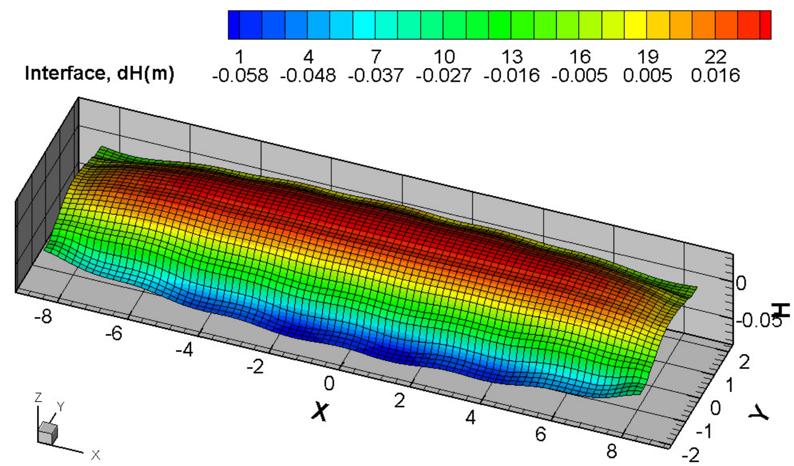

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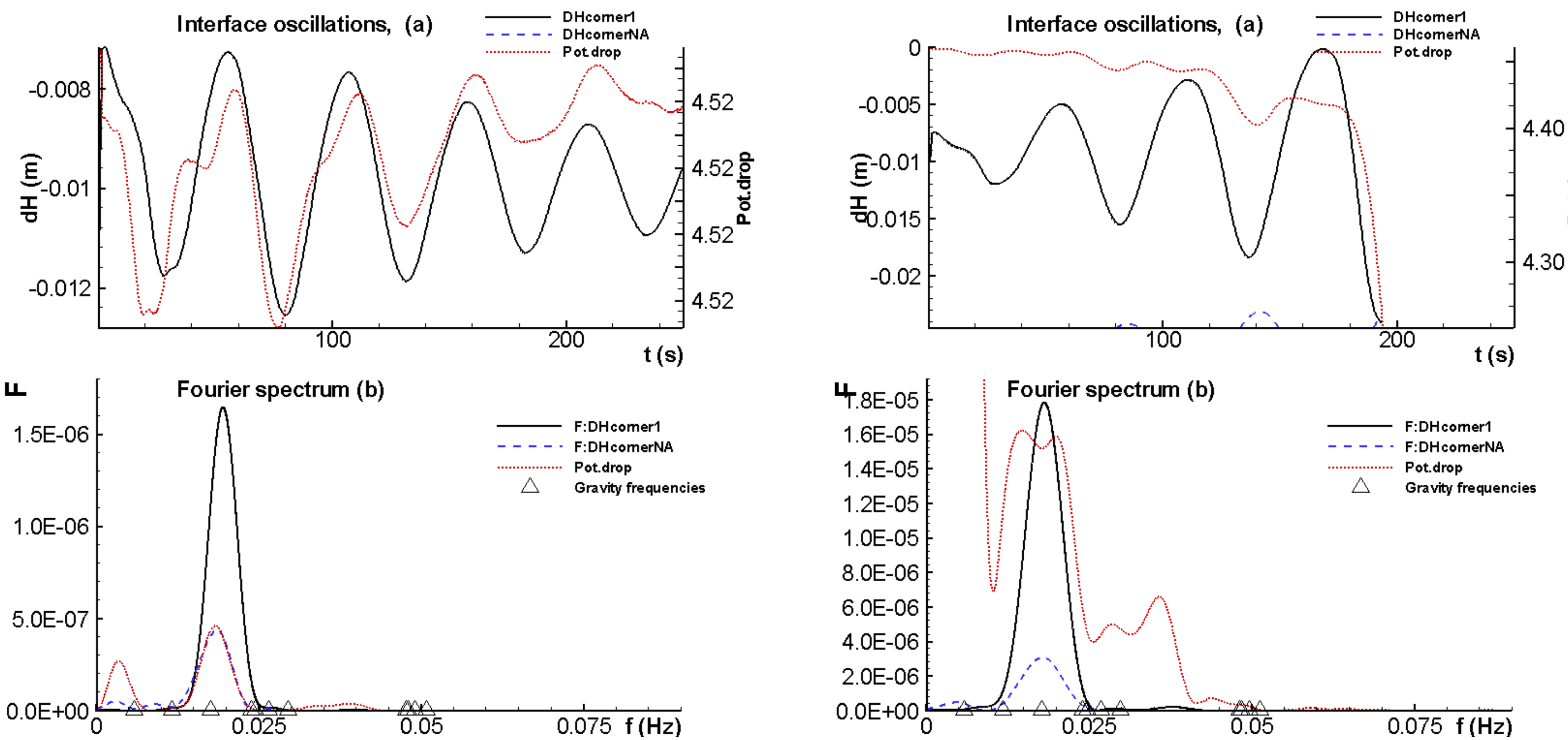

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OpenFOAM: Executive Overview

WIKKI

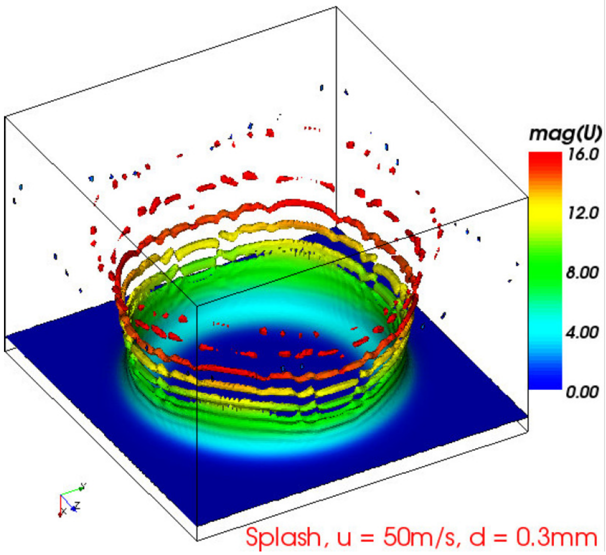
What is OpenFOAM?

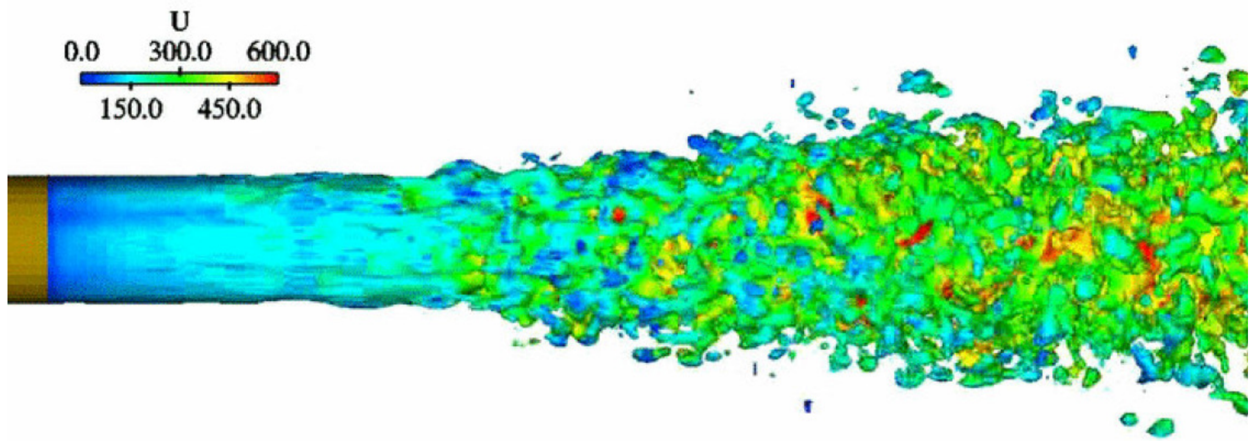
- **OpenFOAM** is a free-to-use Open Source numerical simulation software with extensive CFD and multi-physics capabilities
- Free-to-use means using the software without paying for license and support, including **massively parallel computers**: free 1000-CPU CFD license!
- Software under active development, capabilites mirror those of commercial CFD
- Substantial installed user base in industry, academia and research labs
- Possibility of extension to non-traditional, complex or coupled physics: Fluid-Structure Interaction, complex heat/mass transfer, internal combustion engines, nuclear

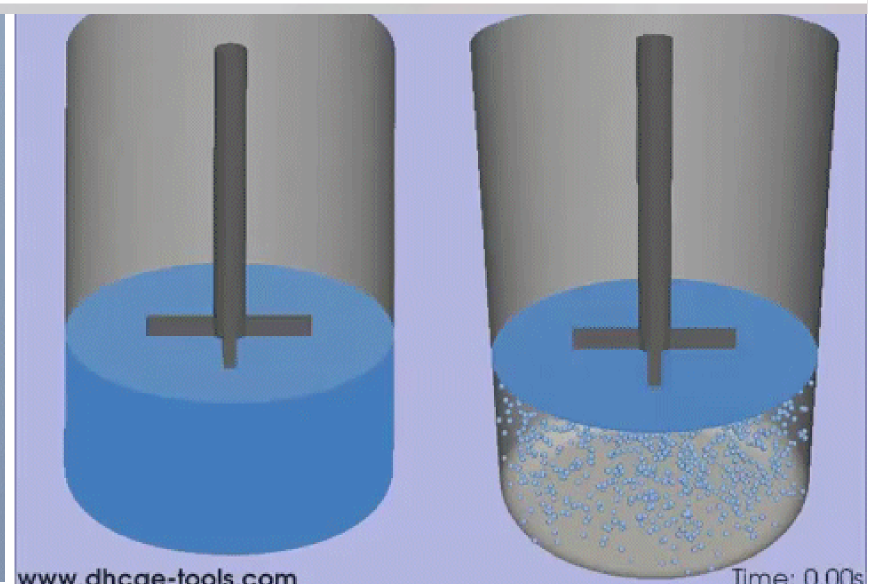
Main Components

- Discretisation: Polyhedral Finite Volume Method, second order in space and time
- Lagrangian particle tracking, Finite Area Method (2-D FVM on curved surface)
- Massive parallelism in domain decomposition mode
- Automatic mesh motion (FEM), support for topological changes
- All components implemented in library form for easy re-use
- Physics model implementation through **equation mimicking**

Some OpenFoam VOF Applications







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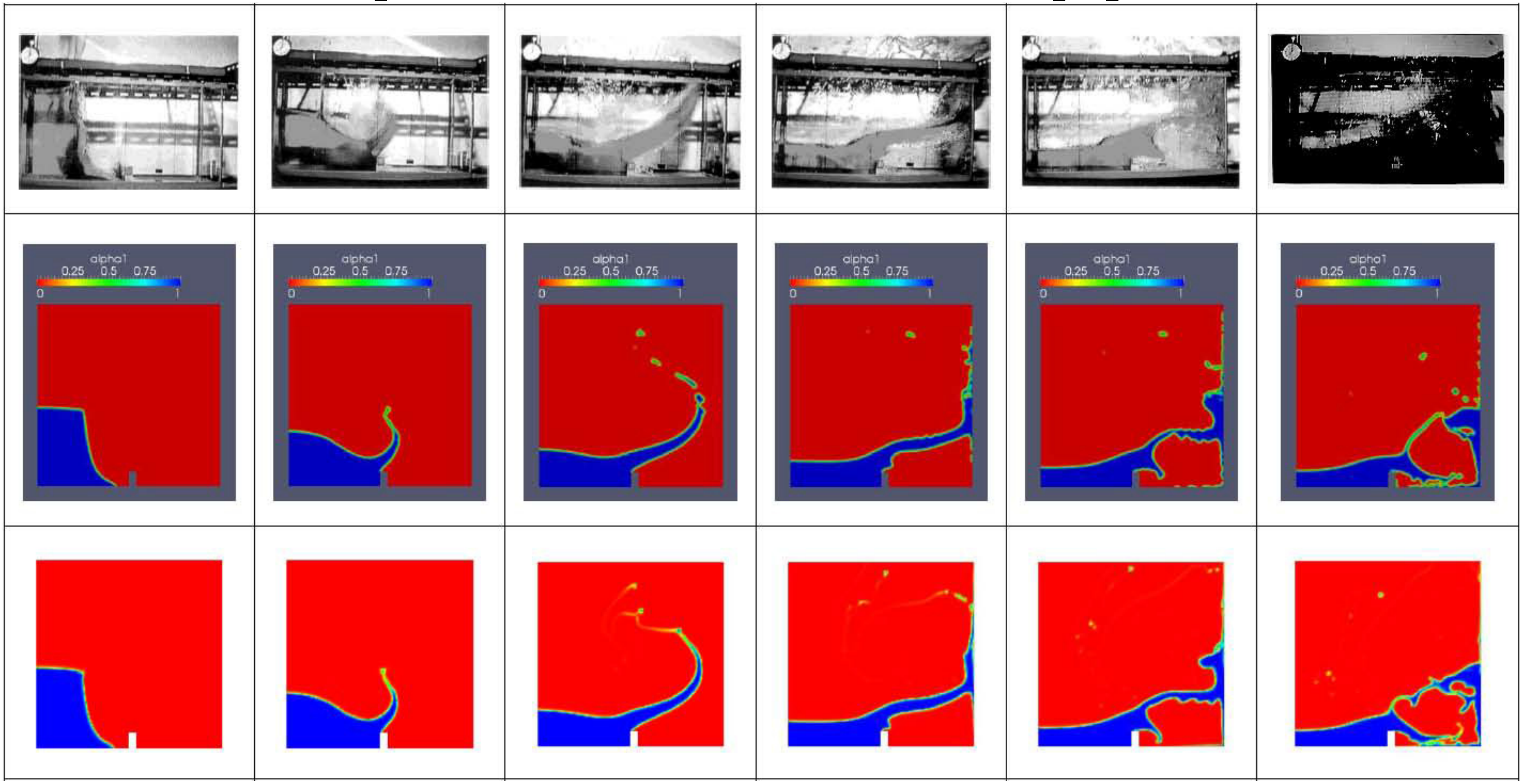
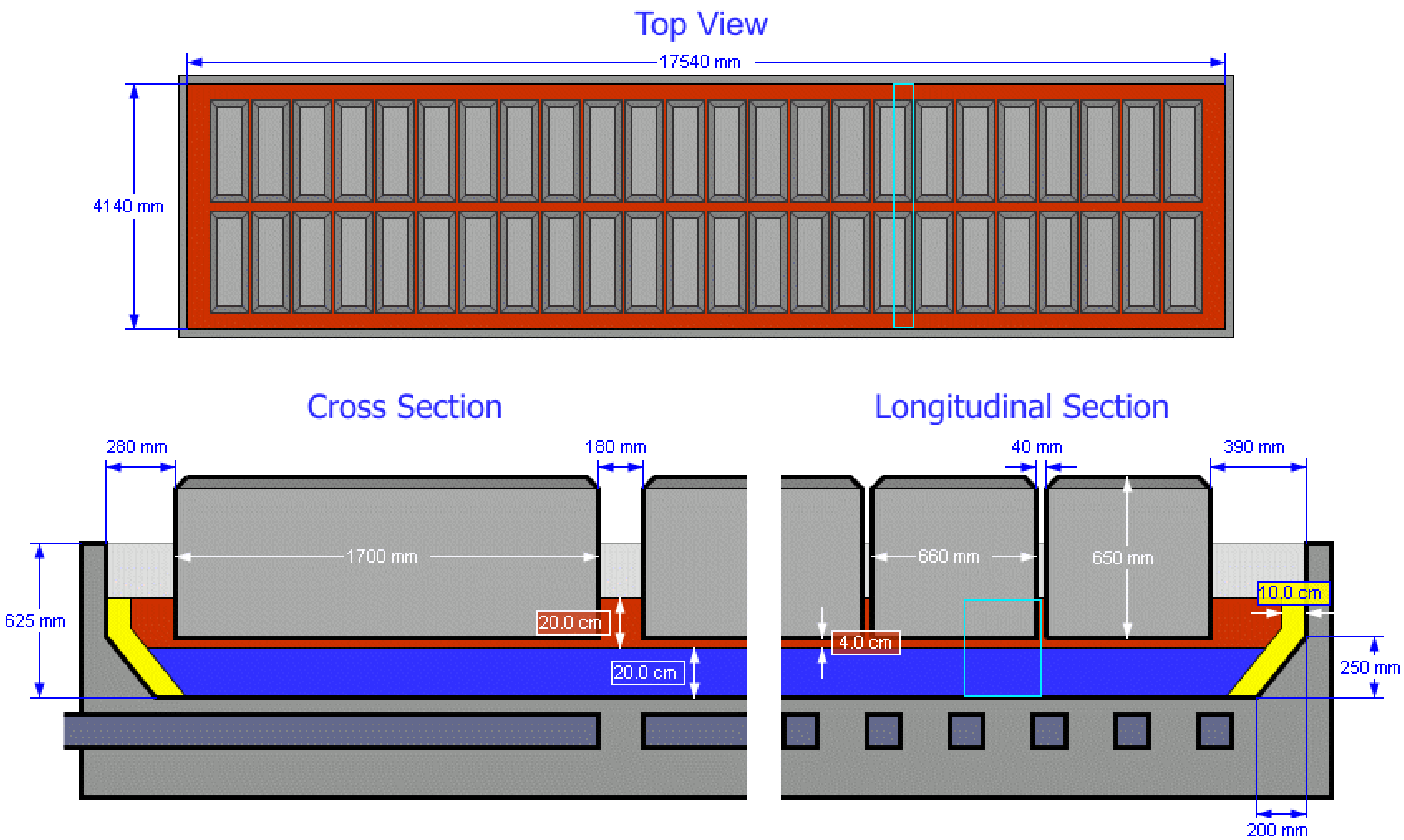


Top experimental, middle OpenFOAM 2.1.1, bottom CFX 14.0

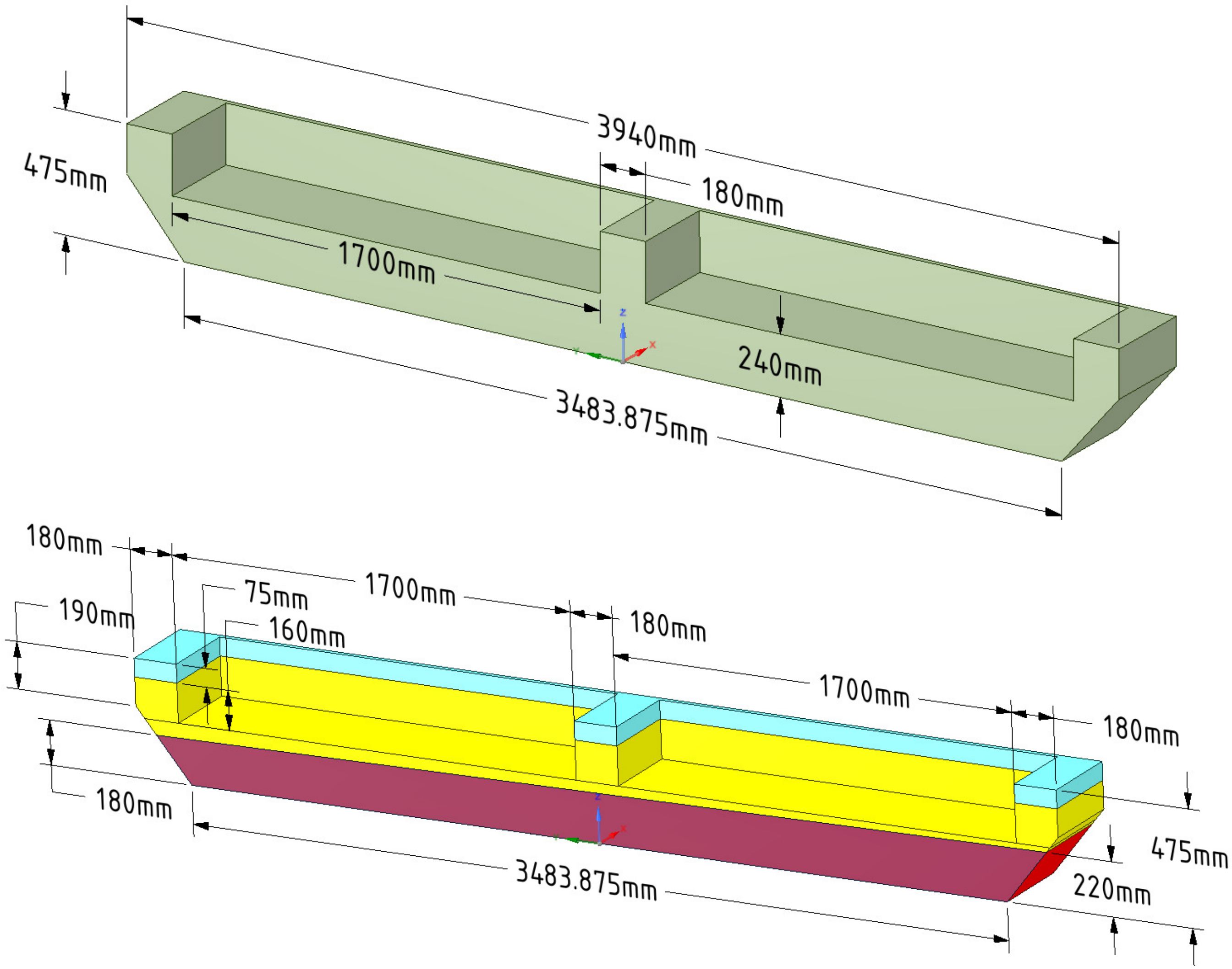
Ref: S. Hansch, D. Lucas, T. Hohne, E. Krepper and G. Montoya, "Comparative Simulations of Free Surface Flows Using VOF-Methods and a New Approach for Multi-Scale Interfacial Structures", Proceedings of the ASME 2013 Fluids Engineering Division Summer Meeting.

3D OpenFoam VOF Gravity Wave Model



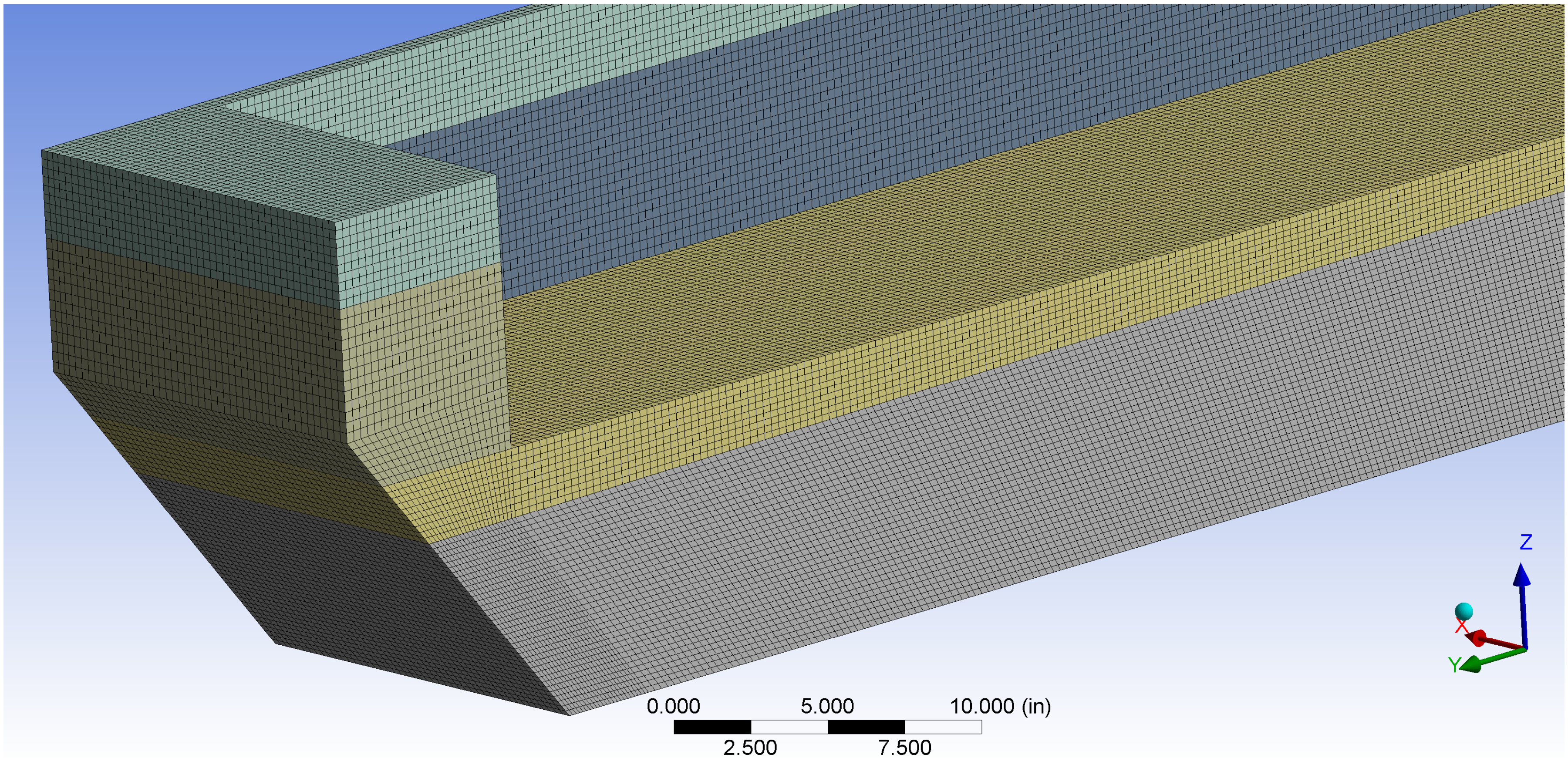
Sketch of the GY420 cell design that inspired the cell side slice model geometry

3D OpenFoam VOF Gravity Wave Model



Geometry of the cell side slice model

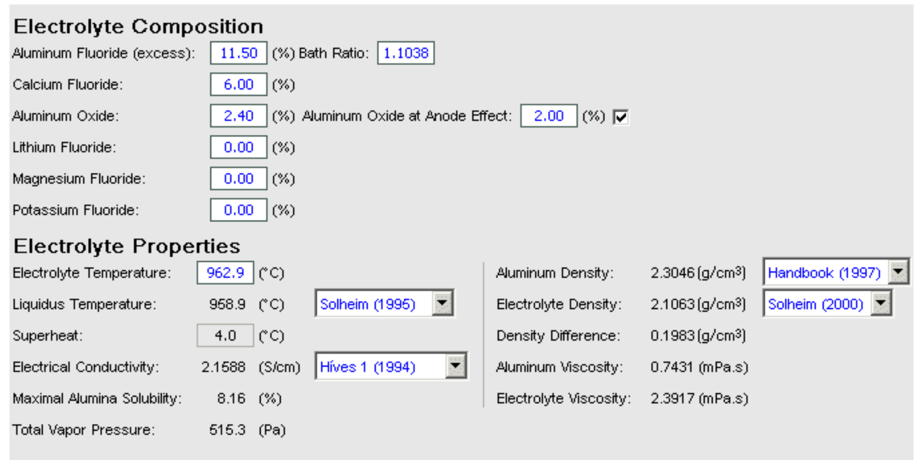
3D OpenFoam VOF Gravity Wave Model



Mesh of the cell side slice model

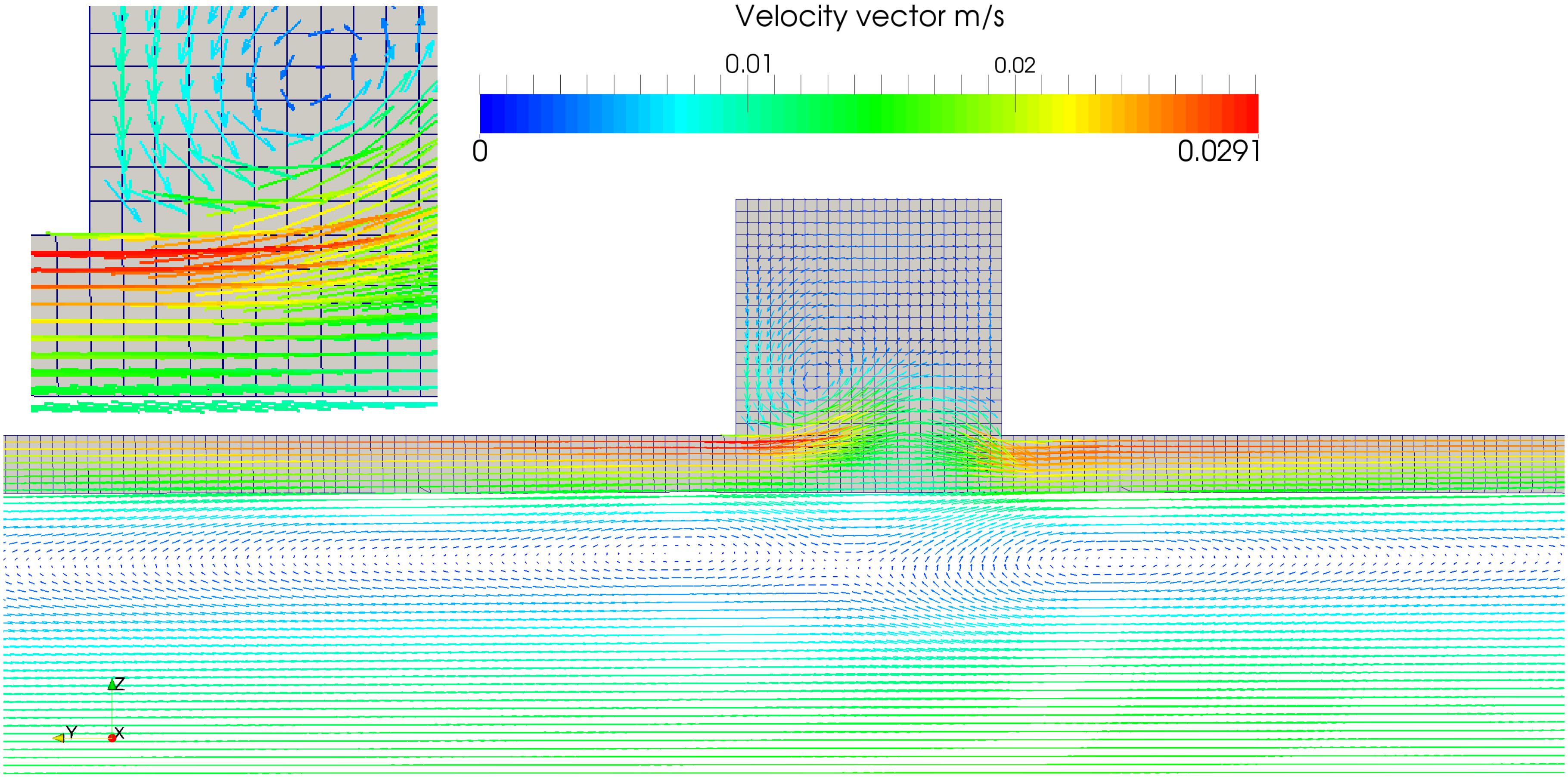
3D OpenFoam VOF Gravity Wave Model

- The model contains 1,180,980 hex finite volumes with an orthogonal quality of 0.77
- The model is using k-ω SST (shear stress transport) turbulence model
- The bath and metal properties used where obtained using Perter Entner's AlWeb application


Electrolyte Composition
Aluminum Fluoride (excess): 11.50 (%) Bath Ratio: 1.1038
Calcium Fluoride: 6.00 (%)
Aluminum Oxide: 2.40 (%) Aluminum Oxide at Anode Effect: 2.00 (%)
Lithium Fluoride: 0.00 (%)
Magnesium Fluoride: 0.00 (%)
Potassium Fluoride: 0.00 (%)
Electrolyte Properties
Electrolyte Temperature: 962.9 (°C)
Liquidus Temperature: 958.9 (°C) Solheim (1995)
Superheat: 4.0 (°C)
Electrical Conductivity: 2.1588 (S/cm) Hives 1 (1994)
Maximal Alumina Solubility: 8.16 (%)
Total Vapor Pressure: 515.3 (Pa)
Aluminum Density: 2.3046 (g/cm³) Handbook (1997)
Electrolyte Density: 2.1063 (g/cm³) Solheim (2000)
Density Difference: 0.1983 (g/cm³)
Aluminum Viscosity: 0.7431 (mPa.s)
Electrolyte Viscosity: 2.3917 (mPa.s)

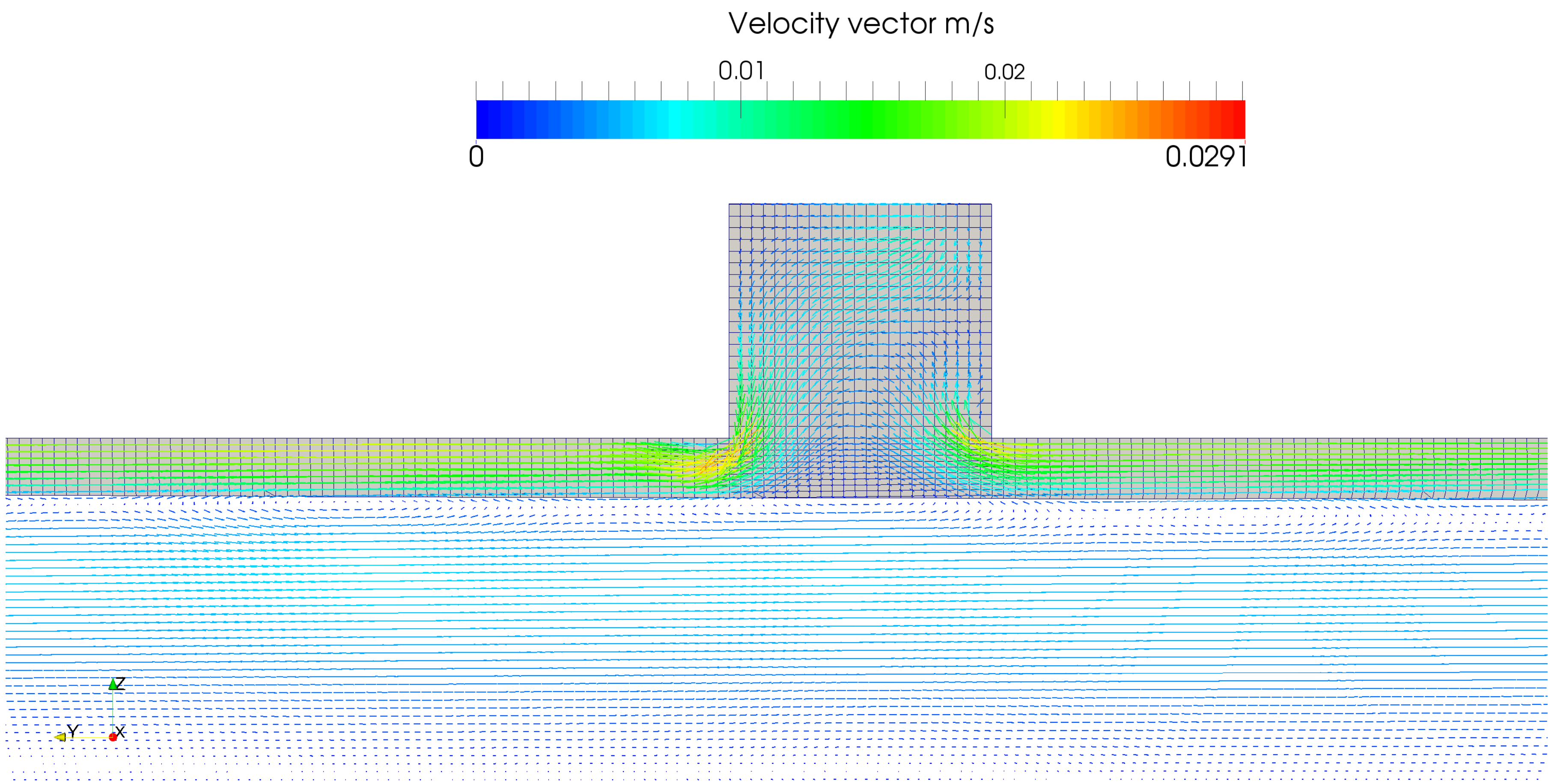
- The transient evolution of the system was calculated for a total of 60 seconds, using the multiphase Euler solver available in OpenFoam 2.3.0
- The transient evolution of the system was calculates using a maximum courant number of 0.05 and a maximum time step of 0.002 seconds
- The calculations were performed using a Dell 28 cores Xeon ES-2697 V3 computer having 128 GB of RAM at its disposal
- That computer took about 30 CPU hours to solve that problem using all 28 cores

3D OpenFoam VOF Gravity Wave Model



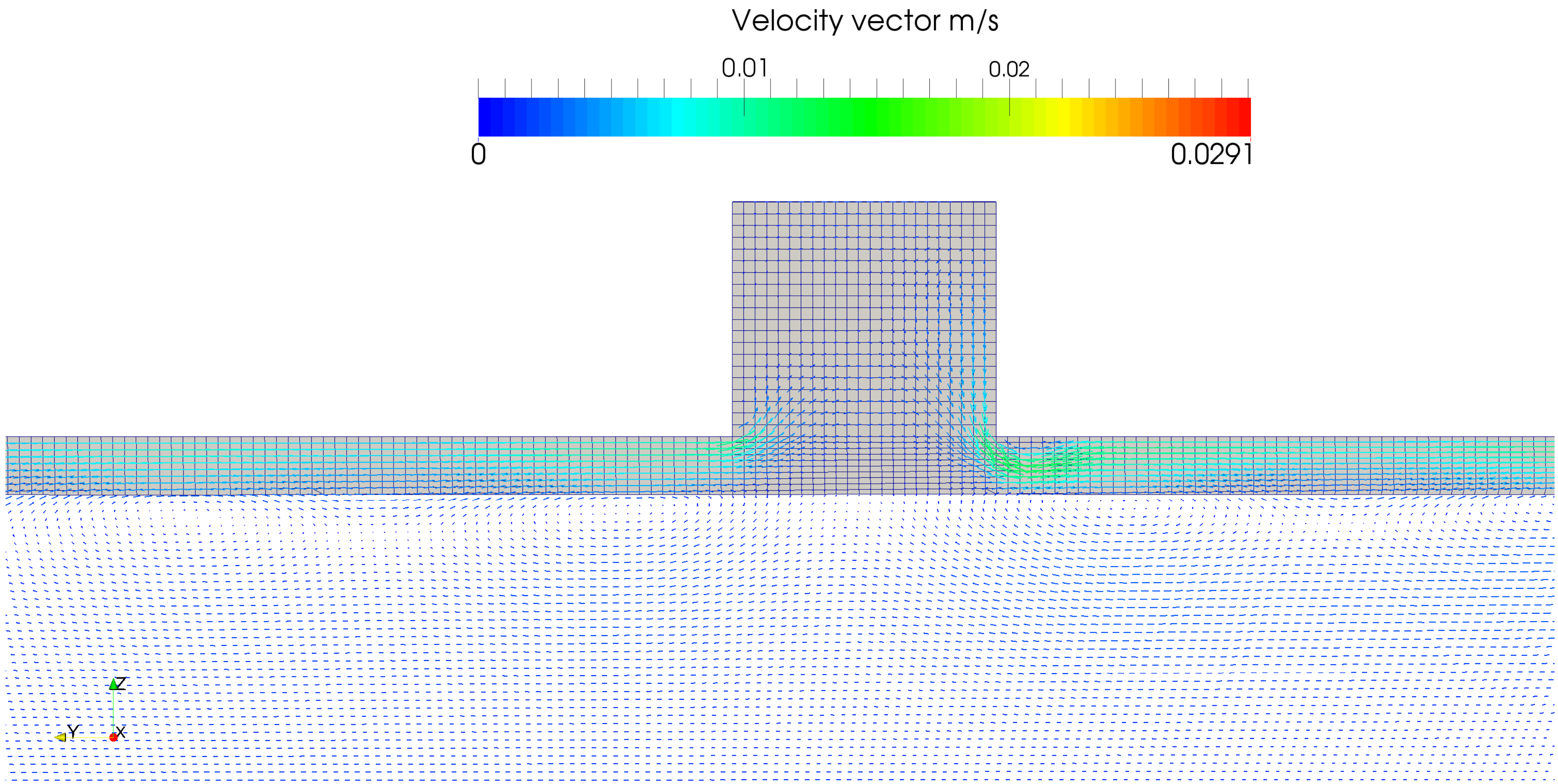
Velocity field after 15 seconds, bath region is in gray

3D OpenFoam VOF Gravity Wave Model



Velocity field after 30 seconds, bath region is in gray

3D OpenFoam VOF Gravity Wave Model



Velocity field after 60 seconds, bath region is in gray

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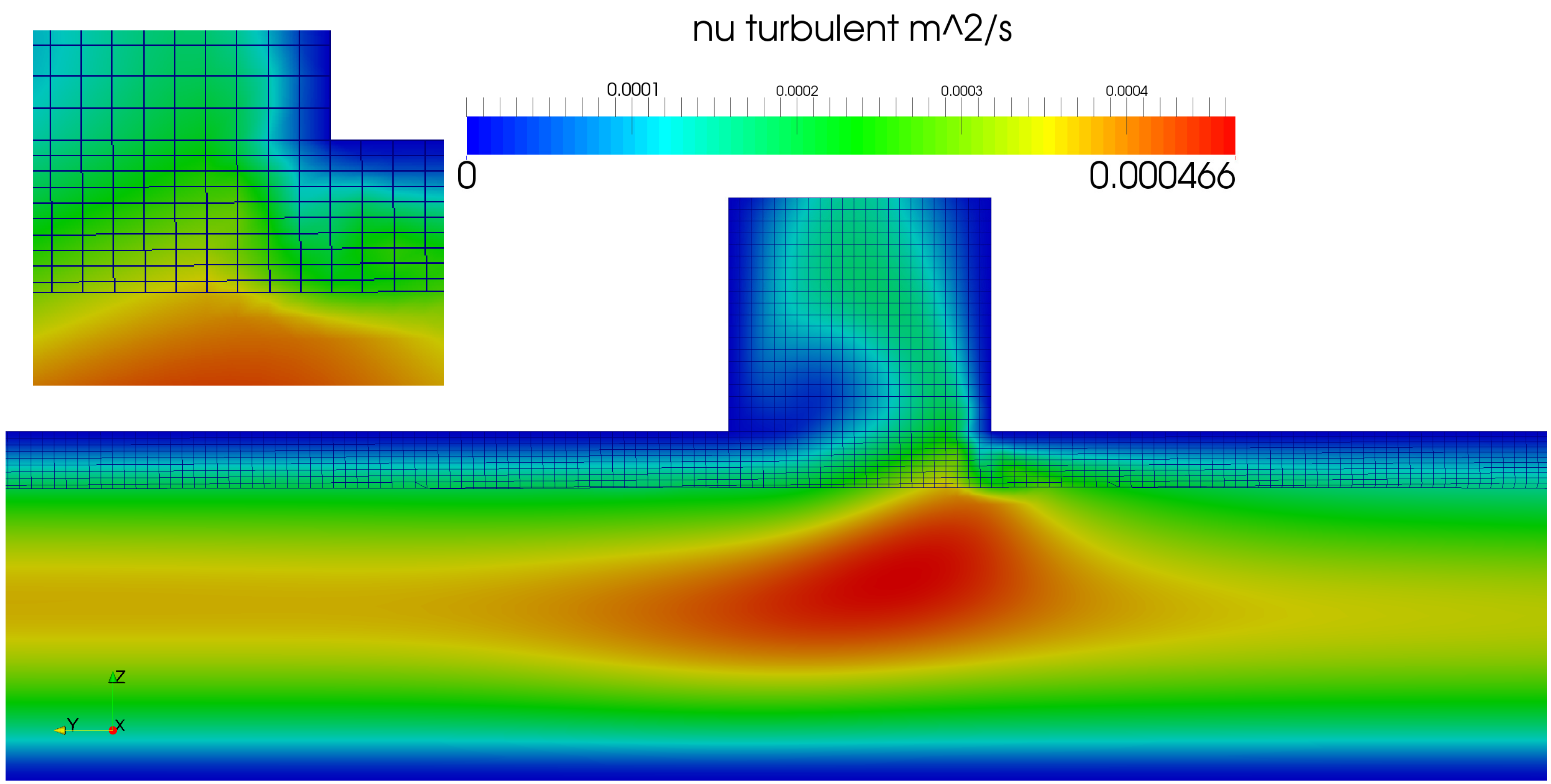
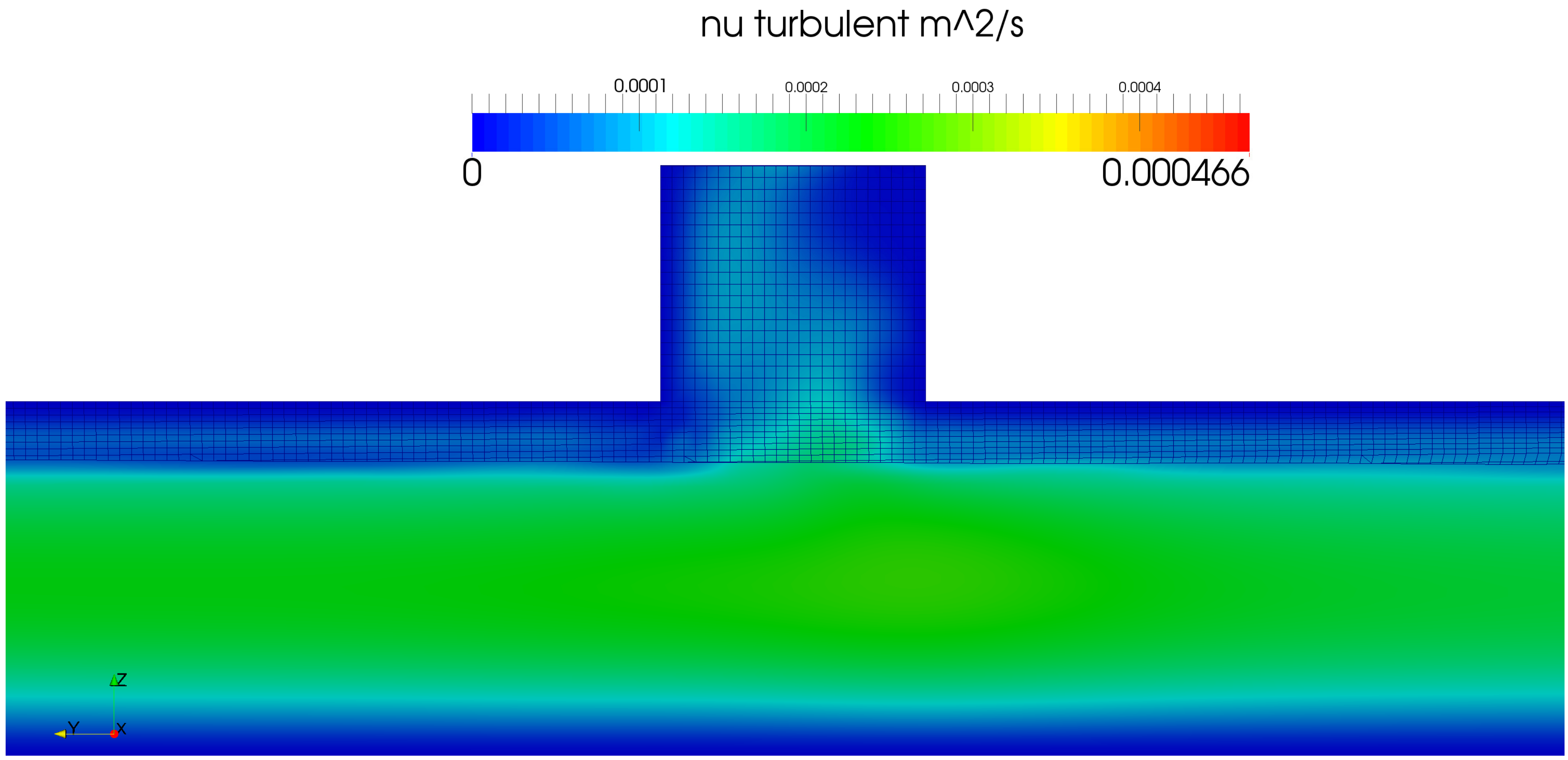


Metal laminar viscosity: 3.224e-7 m^2/s

Turbulent viscosity after 15 seconds, bath volumes are visible

3D OpenFoam VOF Gravity Wave Model



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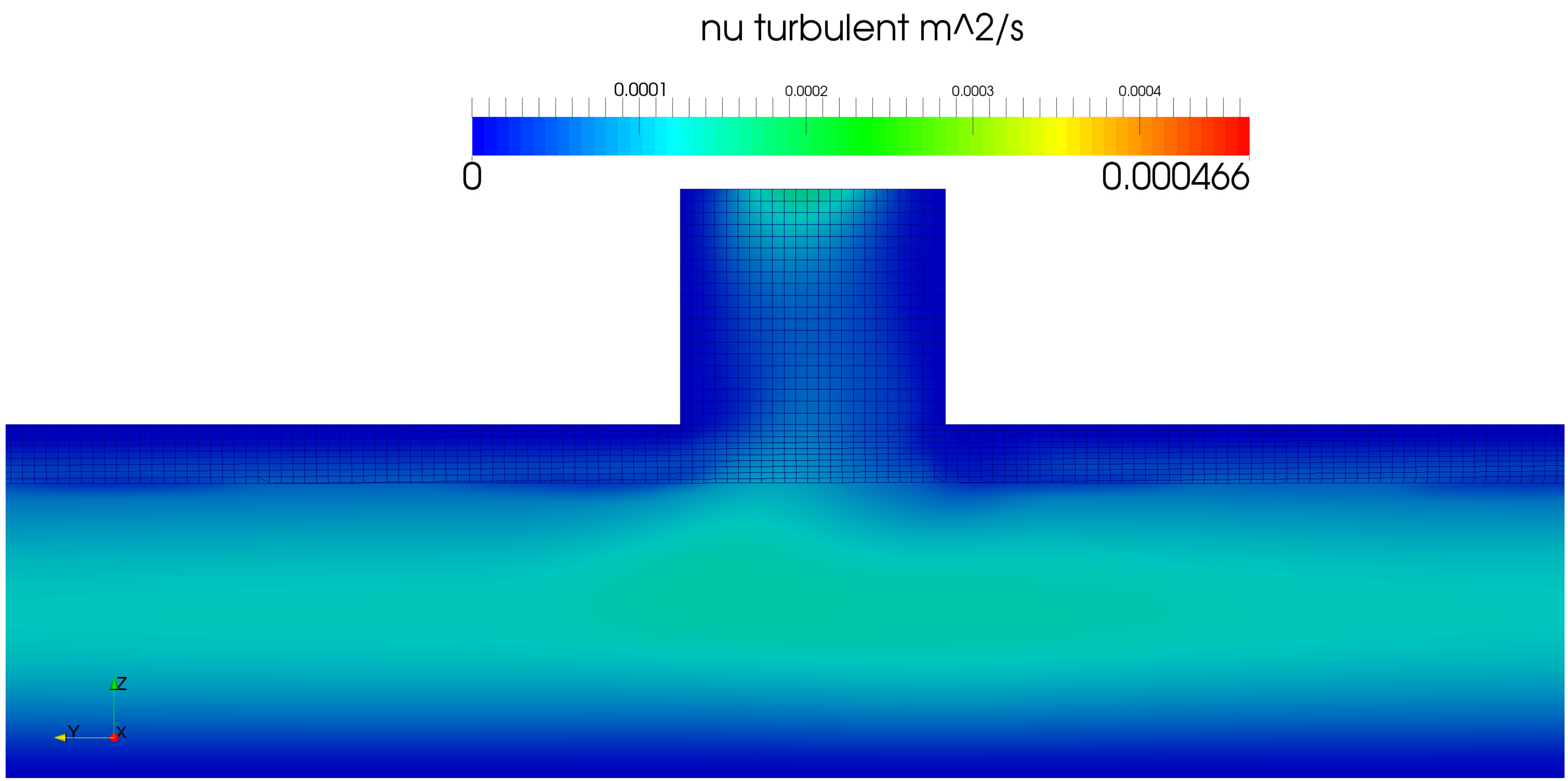

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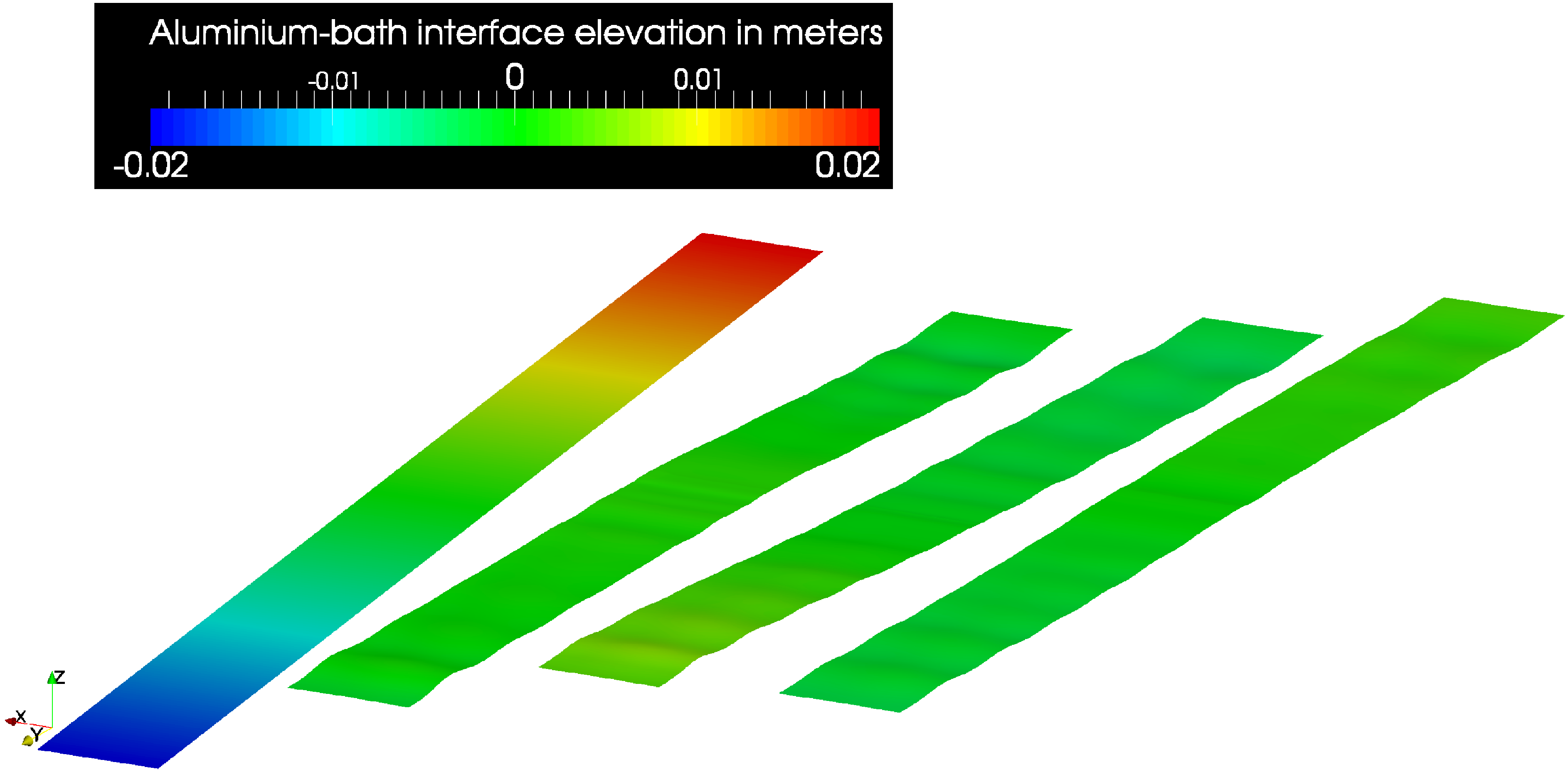
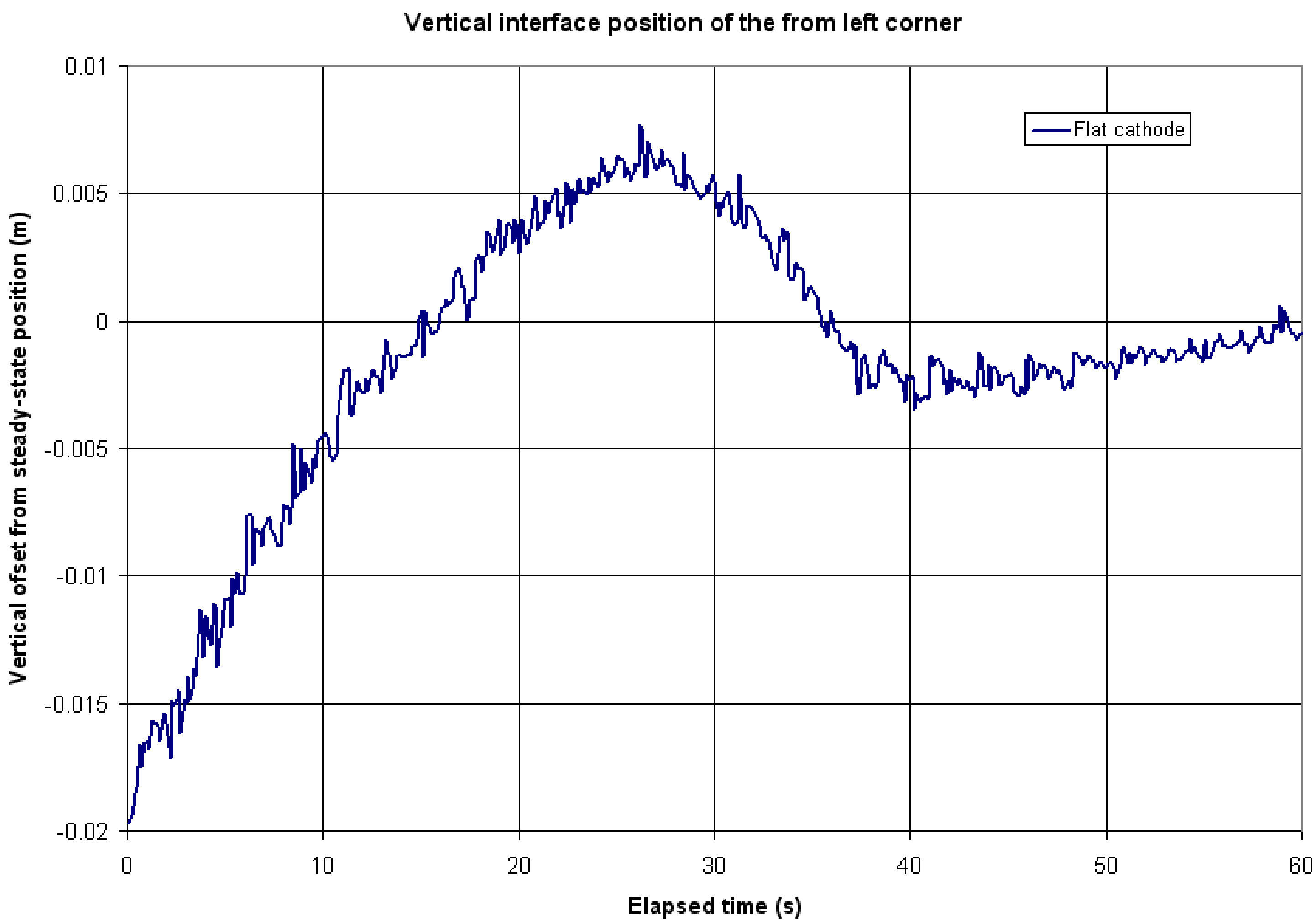


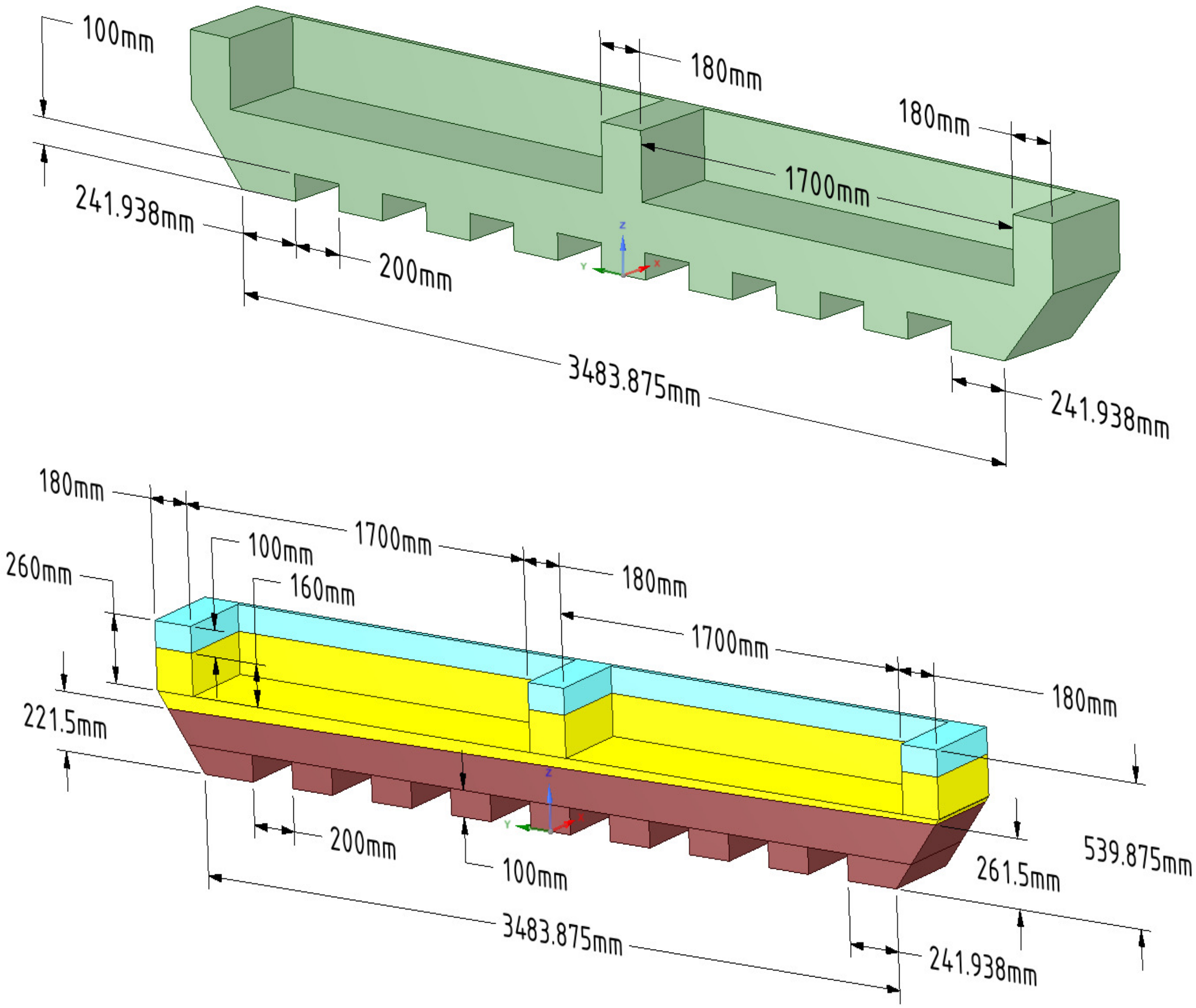
Position of the bath-metal interface every 15 seconds from 0 to 45 seconds

3D OpenFoam VOF Gravity Wave Model



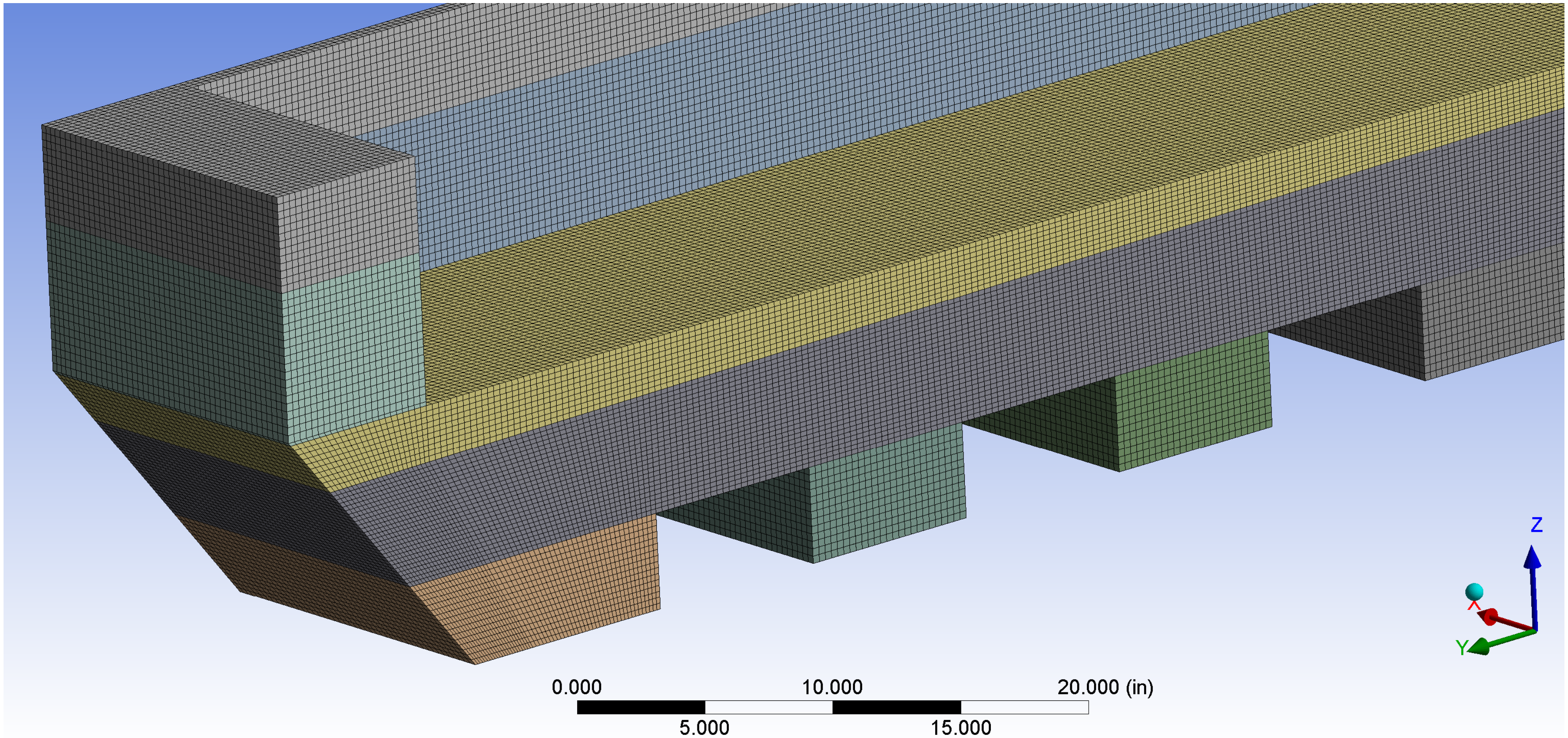
Evolution of the interface front left corner

3D OpenFoam VOF Gravity Wave Model



Geometry of the irregular cathode cell side slice model

3D OpenFoam VOF Gravity Wave Model



Mesh of the irregular cathode cell side slice model

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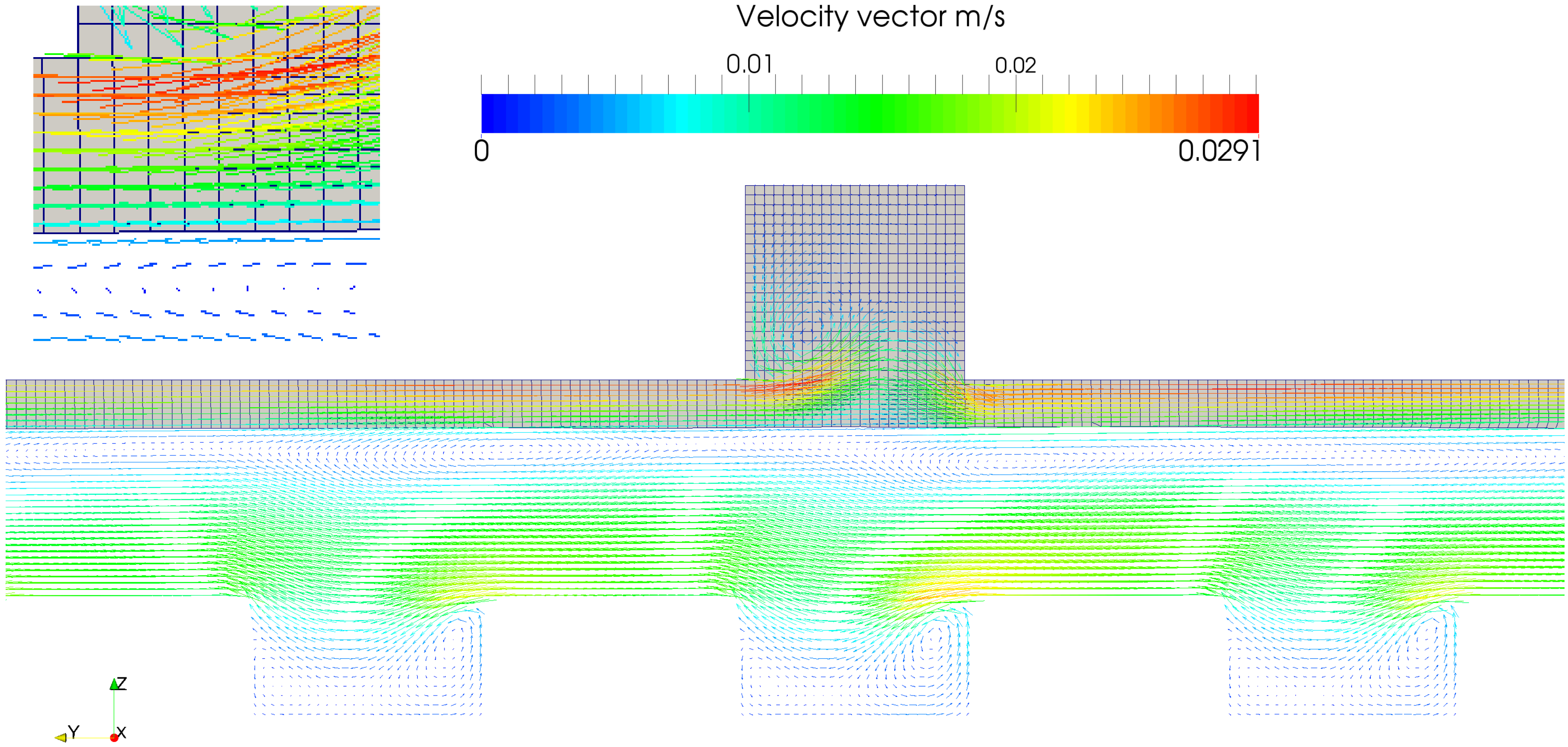

Velocity field after 15 seconds, bath region is in gray

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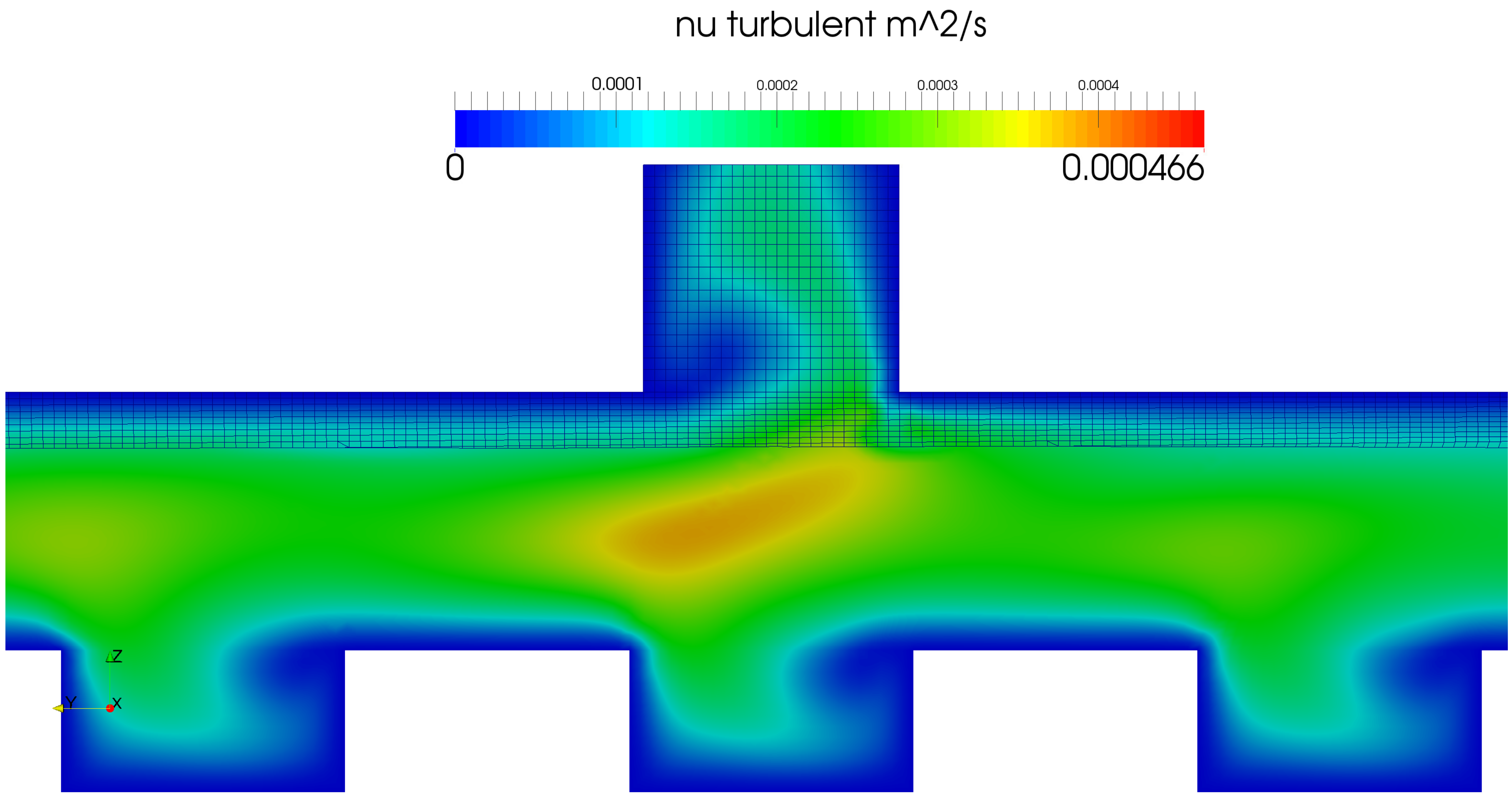

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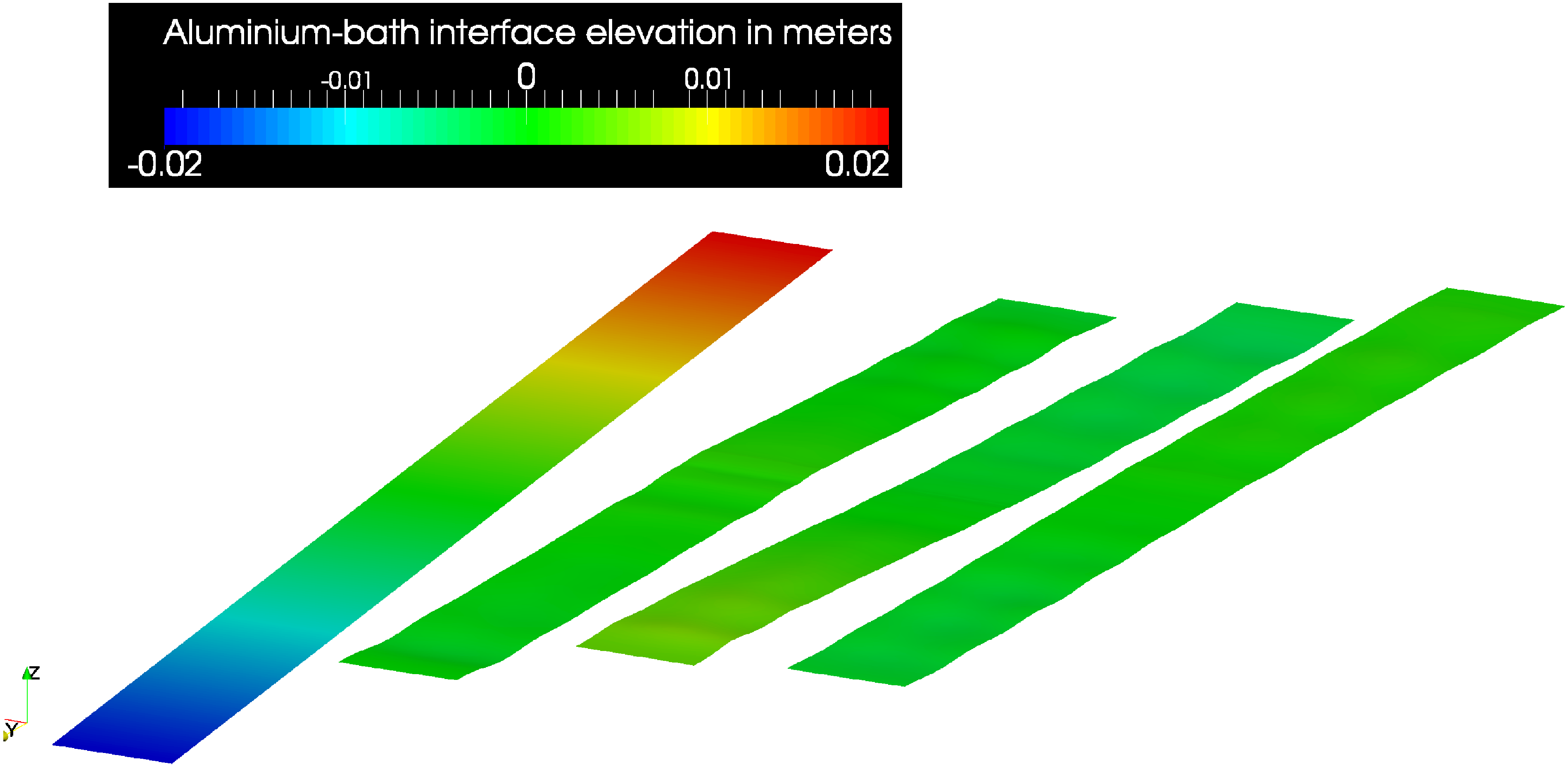

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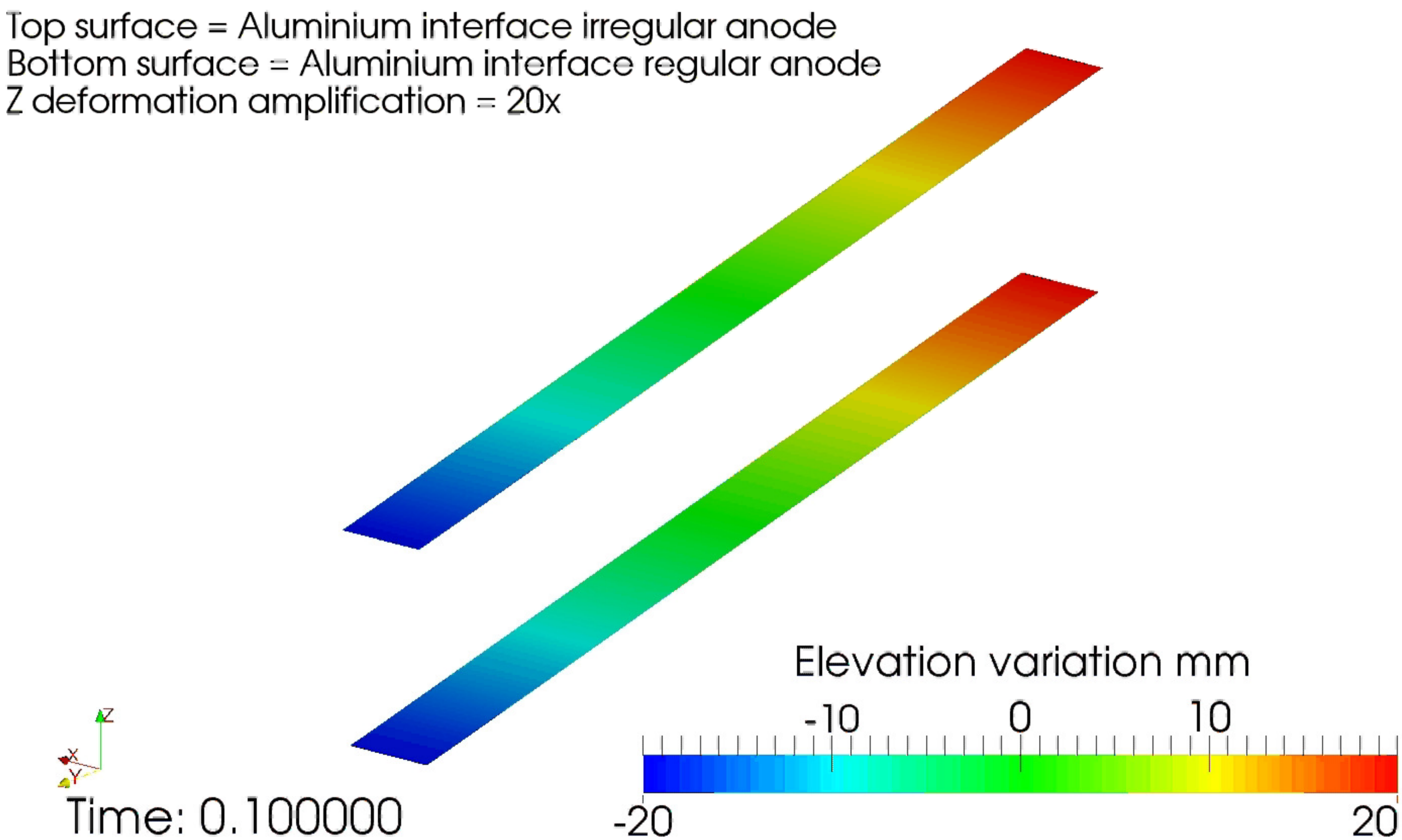
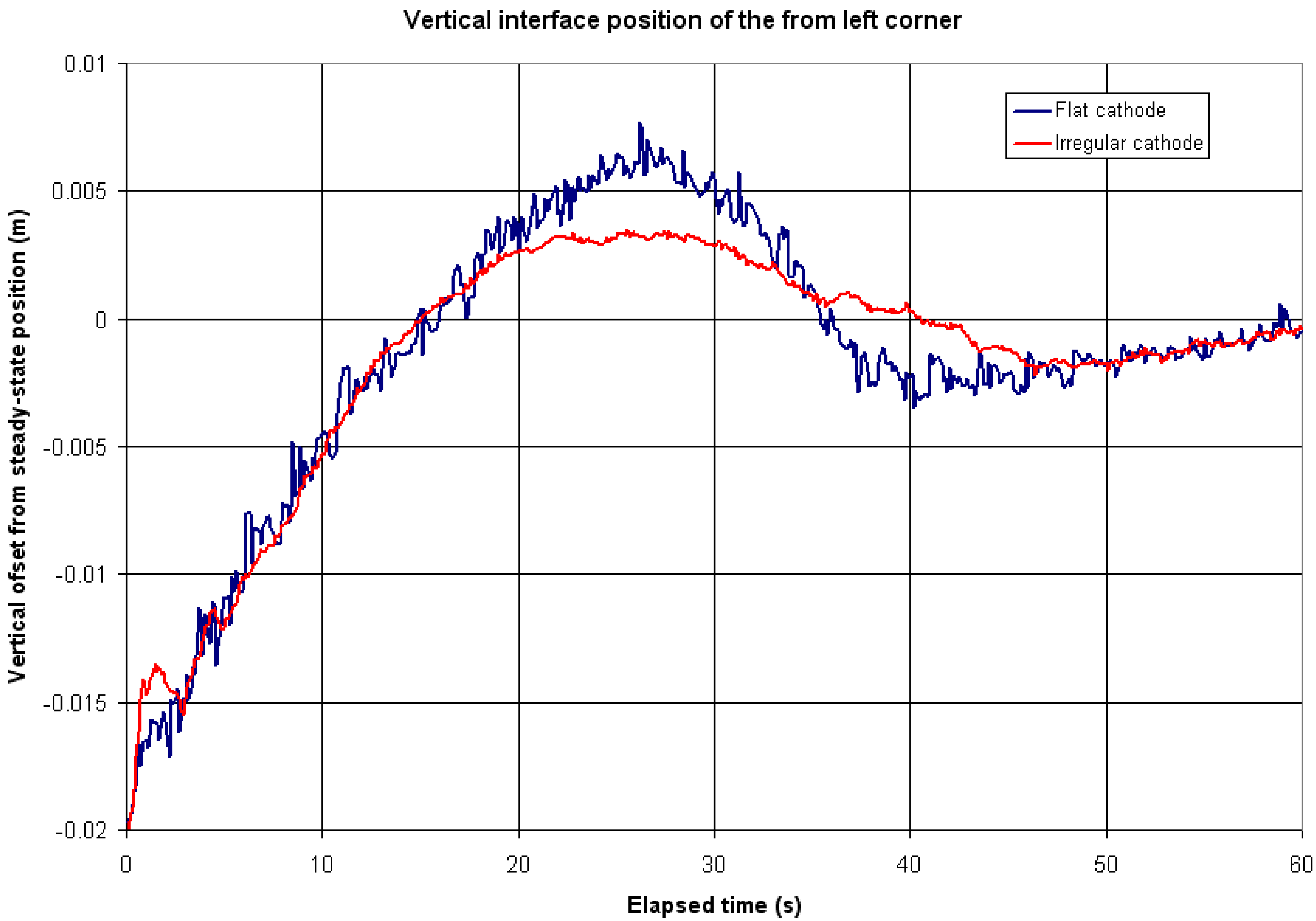


Comparative animation of the bath-metal interface

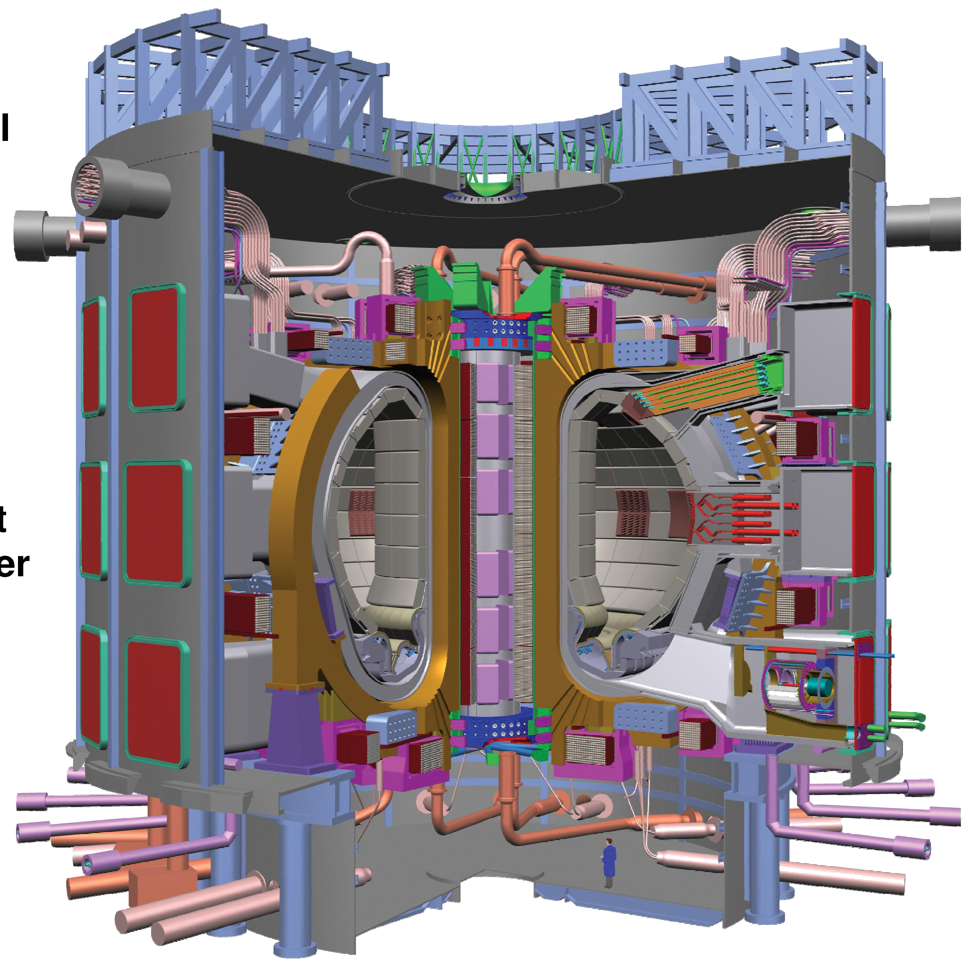
3D OpenFoam VOF Gravity Wave Model



Evolution of the interface front left corner

Future Work

- For a cell design having 48 anodes, modeling a longitudinal gravitational wave in a half cell model using the same mesh refinement used in that study would require a model more than 24 times bigger.
- Even with a linear increased of the required CPU time, solving such a half cell slice model would require about 750 CPU hours which is about 1 month of CPU time on the computer used in this study.
- Adding the MHD physic to an even bigger 3D full cell OpenFoam model is also quite possible to do. OpenFoam has already been successfully used to solve MHD flows.



Conclusions

- A lateral gravity wave have been successfully simulated in a 3D cell side slice model using the VOF formulation in OpenFoam.
- Solving for just 60 seconds of transient evolution using a Dell 28 cores Xeon ES-2697 V3 computer took about 30 CPU hours.
- Comparing regular flat cathode case model results with the irregular cathode surface case model results revealed that there is definitively less overshoot in the case of the irregular cathode so clearly there is somewhat more damping in that second case.
- Yet this observation is not in contradiction with what was previously published using MHD-Valdis 2D shallow layer model as this new study confirms that the extra damping effect of the irregular cathode surface technology is not that significant.
- A bigger computer than the Dell 28 cores Xeon ES-2697 V3 computer used in the present study would be required in order to obtained a practical turn around time to solve a transient 3D full cell VOF model.
- Adding the MHD physic to such a 3D full cell OpenFoam model is also quite possible to do. OpenFoam has already been successfully used to solve MHD flows.