MODELING GRAVITY WAVE IN 3D WITH OPENFOAM IN AN ALUMINUM REDUCTION CELL WITH REGULAR AND IRREGULAR CATHODE SURFACES

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Abstract

In recent years extensive modeling work has been done to assess if the usage of an irregular cathode surface does or does not increases the MHD cell stability.

So far, 2 types of studies have been carried out: full 3D steady-state analysis and 2D shallow layer dynamic analysis. Cell stability being a transient phenomenon, steady-state results are not providing any direct answer to the question.

2D shallow layer dynamic analysis can directly answer the question, but unfortunately, irregular cathode surface introduces a third dimension to the flow, so this type of 2D analysis is not the best suited to analyze this type of 3D flow problem.

The current work presents a new way to analyze the problem and answer the question. Lateral gravity waves have been simulated in a 3D cell slice model using VOF formulation in OpenFoam. Results obtained for cells using regular and irregular cathode surfaces are compared.

Introduction

Irregular cathode surface technology is still the subject of research in China where it is still quite popular. The most recent Chinese paper known to the authors on the subject was published in Metallurgical and Materials Transaction B in 2014 [1].

That paper presents a very detailed 3D model based on ANSYS and CFX solvers. Four steady-state solutions are presented with and without irregular cathode and with and without considering the effect of the gas release under the anodes.

In addition to these four 3D steady-state solutions, two 2D transient solutions were presented with and without irregular cathode that model only the gas release.

When comparing the two 2D transient solutions, no major difference in the global deformation or evolution of the bath/metal interface can be identified (see Figure 16 of [1]).

When comparing the two 3D solution of the conventional cathode with and without the effect of the gas release, a major difference in the local deformation of the bath/metal interface in the small channel between anodes can be identified (comparing Figure 14 a) with Figure 28 a) of [1]).

This local effect is far less intense in Figure 28 b) when compared with Figure 28 a) for the irregular cathode which seems to contradict what is observed in Figure 16.

In any cases, as presented in last year review [2], it is the opinion of the authors that a transient cell stability analysis is required to make any prediction of the impact of irregular cathode surface technology on the cell stability as bath/metal interface wave dynamic is a time dependant phenomenon.

As demonstrated in [2], MHD-Valdis is the perfect tool to model and hence study MHD driven cell stability in the case of regular flat cathode surface as the model only represents and solves the key physics required, nothing more, which make MHD-Valdis an extremely efficient model.

One of the key simplification in MHD-Valdis solver is the use of the 2D shallow layer CFD model to solve the bath and metal flow. Yet, as Figure 12 b) of [1] clearly demonstrates, for cells using irregular cathode technology, this simplification is no longer valid as the flow is now fully 3D in nature.

MHD-Valdis also does not consider the impact of gas bubble release on the bath flow. This was demonstrated to be quite a valid simplification as it is clear that the dynamic of the gas bubble release under the anodes, which strongly affects the global bath resistance, is decoupled from the cell stability problem. Otherwise no cell stability model developed up to now would be valid.

In [2] and in previous studies presented before that [3,4,5], MHD-Valdis could not clearly show the impact of irregular cathode technology on cell stability, maybe because of the 2D flow structure simplification.

Yet it is not by mistake that results of a full 3D transient MHD driven cell stability analysis was not presented in [1]. Even nowadays, CPU resources are still too sparse and too expensive for such an analysis to be carried out without a huge R&D budget.

The need for a third modeling approach

If reducing the metal flow to a shallow layer representation is not a justified simplification in the case of irregular cathode surface and if solving a full 3D transient cell stability problem is still not practical, clearly there is a need to find a new modeling approach.

There are two parts to the MHD driven cell stability issue: the energy source part coming from the presence of the variable Lorentz force in the metal pad as explained by Urata and Davidson among others [6,7] and the energy dissipation part coming from viscous damping.

Clearly the aim of irregular cathode surface technology is to affect this second energy dissipation part by increasing the viscous damping in the metal pad.

Yet for a bath/metal interface wave to move around, not only the metal must be displaced but also the bath. Furthermore, since the ACD layer thickness is much less than the metal pad thickness, the required bath flow velocity needs to be much greater than the required metal flow velocity.

So clearly, the viscous damping in the bath is very important and must be considered in the analysis which will be the case in a 3D analysis of the damping rate of a gravity bath/metal interface wave in an aluminium reduction cell.

This approach reduces the difficulty of a study of the viscous damping effect of irregular cathode surface which is perfectly valid as this is the key effect that needs to be investigated.

Furthermore, if we choose to study a lateral gravitational wave, the geometry of the problem can be reduced to a cell side slice as presented in Figure 1.

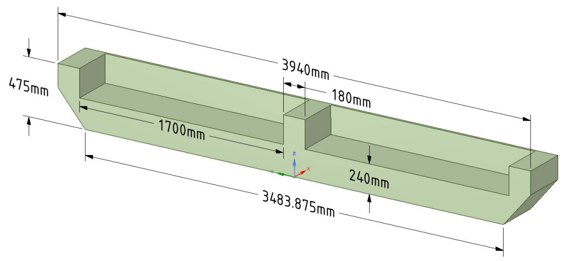

Figure 1: Geometry of the cell side slice model

OpenFoam and the free interface wave

Even reduced both in terms of physic and geometry, we are still left with a quite difficult question to solve namely a transient 3D multiphases (three in this case: metal, bath and air) flow. Very few codes are able to cope with this problem, the open source code OpenFoam being one of them.

OpenFoam has quickly become a very popular code in many fields such as marine applications due to its free surface modeling capabilities [8]. Its free surface capabilities are comparable to other VOF solvers like CFX. A direct comparison between experimental, OpenFoam and CFX results for a free surface study are presented in [9].

The free interface wave between a gas and a liquid or between two non-miscible liquids in a closed rectangular container has been extensively studied experimentally, as can be seen per example in Figure 2, a reproduction of Figure 16 in [10]. As explained in [11], it is very difficult to measure experimentally in a reproducible manner the damping rate of such a gravity driven, viscous damping wave problem.

Recently, OpenFoam has been quite successfully used to model this type of free surface wave topic, per example [12] is a Ph.D. thesis on the subject.

The problem of modeling the damping of a gravity bath-metal interface wave in an aluminium reduction cell is a very similar question with the extra difficulty that there are immersed anodes in the top liquids and that it will be very difficult to get physical measurements for model validation.

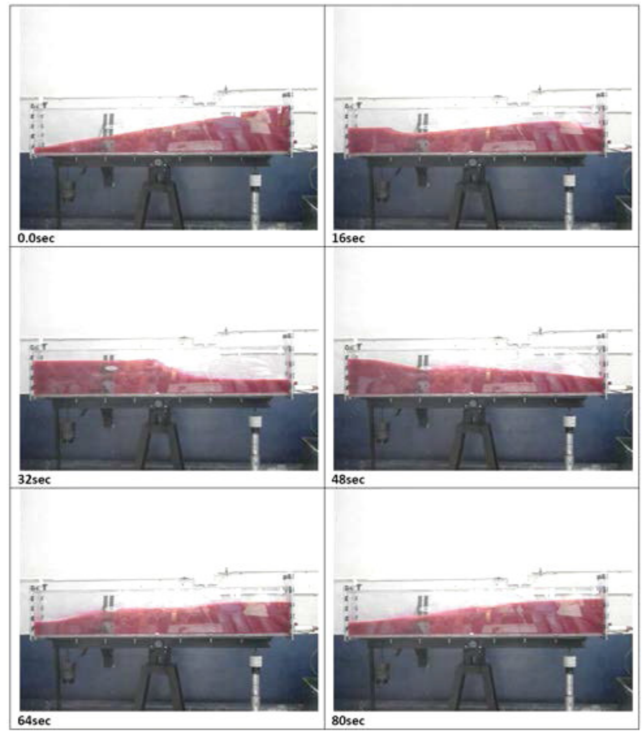

Figure 2: Experimental results for a free interface wave motion between two liquids in a closed container (Figure 16 in [10])

Base case model setup

The geometry of the base case model, with regular flat cathode surface was already presented in Figure 1. The model depth extends from a front frictionless symmetry plane located at half the anode width to the back frictionless symmetry plane located at half width of the small channel between two anodes. The length of the model is typical of a cell cavity width minus a 10 cm uniform ledge thickness in both ends: 3.94 m. The height of the model is enough cavity depth to leave room for 20 cm of metal pad thickness, 20 cm of bath thickness and 7.5 cm of air on top.

The model mesh is presented in Figure 3. The mesh is fine enough to resolve fairly well the boundary layer problem close to the solid surfaces (cathode, ledge and anodes). It is constituted of hexagonal finite volumes of approximately uniform size. The mesh also perfectly aligned with the initial bath-metal position in order to have a perfectly smooth initial position of that bath-metal interface.

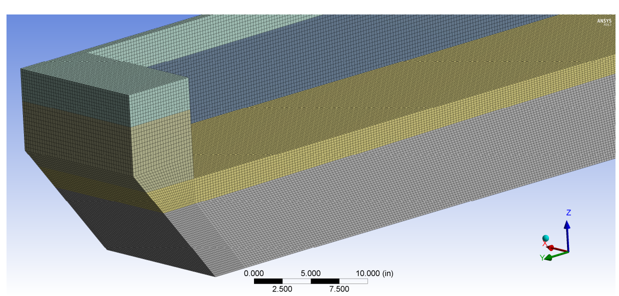

Figure 3: Mesh of the cell side slice model

The model contains 1,180,980 hex finite volumes with an orthogonal quality of 0.77. It uses a k-ω SST (shear stress transport) turbulence model because of its demonstrated capability to well predict drag [13].

The bath and metal properties utilized where obtained using Peter Entner's AlWeb application [14]. A quite standard bath composition has been selected, see Figure 4.

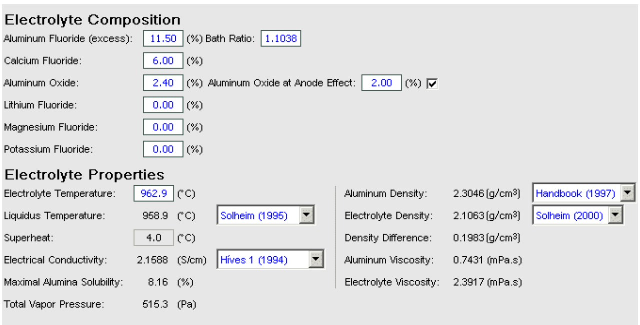

Figure 4: Bath and metal properties from AlWeb

The transient evolution is starting from a resting position having a sloped bath metal interface of -2 cm on the left side to +2 cm on the right side as shown in Figure 5.

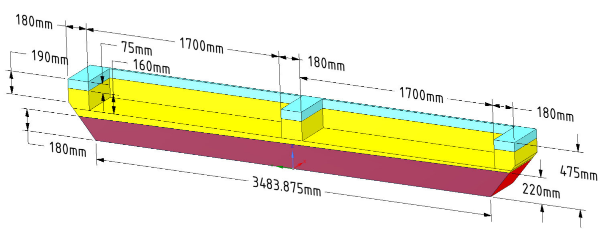

Figure 5: Initial bath-metal interface position

The transient evolution of the system from that starting point is calculated using an explicit solver available in OpenFoam 2.3.0 [15], the multiphase Euler solver using a maximum courant number of 0.05 and a maximum time step of 0.002 seconds.

The transient evolution of the system was calculated for a total of 60 seconds which is more than 1 total period of the lateral wave oscillation. 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.

Base case model solution

Figure 6 is showing the position of the bath-metal interface position every 15 seconds. That gravity lateral wave happens to die almost completely in a single period.

The maximum velocity is reached a little before the 15 sec. mark. Figure 7 is showing the velocity field of the front plane. The solver assumed continuity of the velocities at the interfaces so the solution shows that the bath flow drags the top layer of the metal so the flow reversal is occurring in the metal pad and not at the bath-metal interface. The maximum bath velocity is about 3 cm/s.

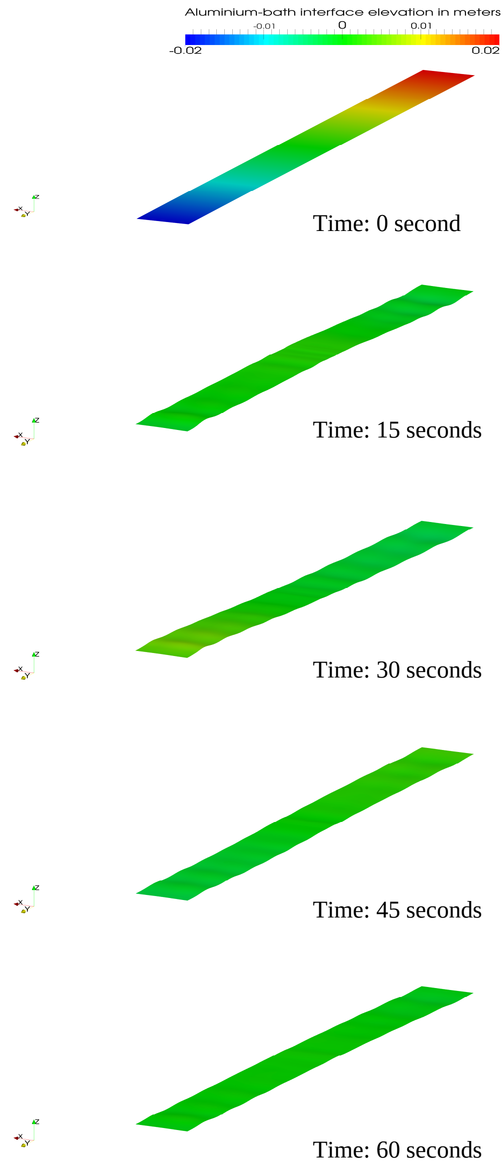

Figure 6: Position of the bath-metal interface every 15 seconds from 0 to 60 seconds

Figure 8 is showing the velocity field after 60 seconds, indicating that the wave has been already almost completely damped down. Figure 9 illustrates the turbulent viscosity after 15 seconds. Since the laminar viscosity of the metal is 3.224e-7 m^2/s and the maximum turbulent viscosity 4.66e-4 m^2/s, the maximum turbulent viscosity is 1447 time the laminar viscosity.

Irregular cathode surface case model setup

The geometry of the irregular cathode surface case model is presented in Figure 10. The geometry of the cathode surface has been changed when compared to the base case model. But the mass of metal, the mass of bath and the 4 cm ACD have remained the same.

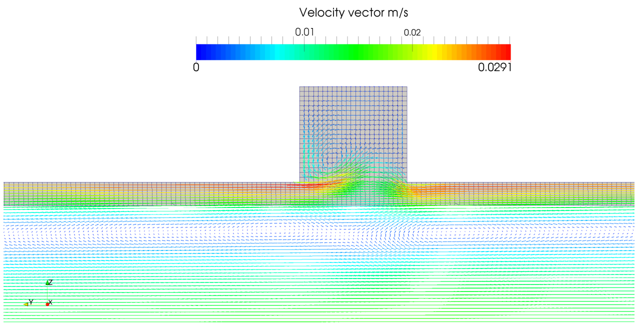

Figure 7: Velocity field after 15 seconds (bath region has gray background)

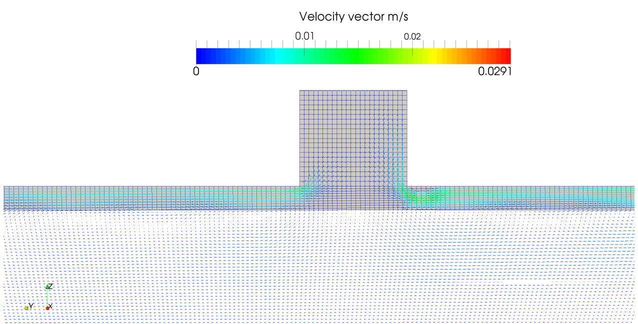

Figure 8: Velocity field after 60 seconds (bath region has a gray background)

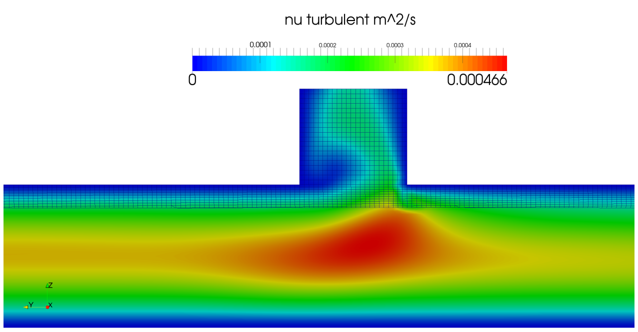

Figure 9: Turbulent viscosity after 15 seconds (bath mesh is visible)

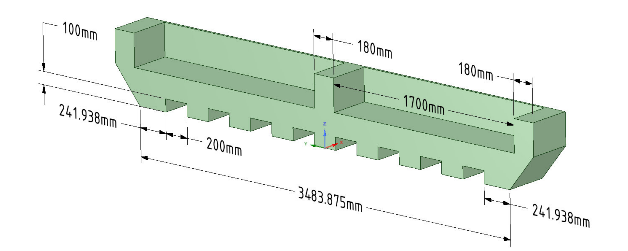

Figure 10: Geometry of the cell side slice model with irregular cathode surface

The model mesh presented in Figure 11 contains 1,152,016 hex finite volumes. Figure 12 is showing the initial bath-metal interface position. Figures 13 and 14 illustrate the velocity and the turbulent viscosity after 15 seconds. Figure 15 is showing the position of the bath-metal interface position every 15 seconds.

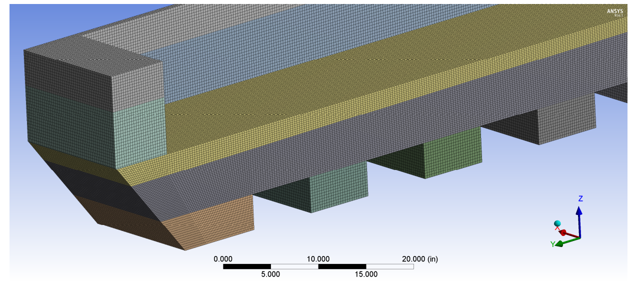

Figure 11: Mesh of the cell side slice model with irregular cathode surface

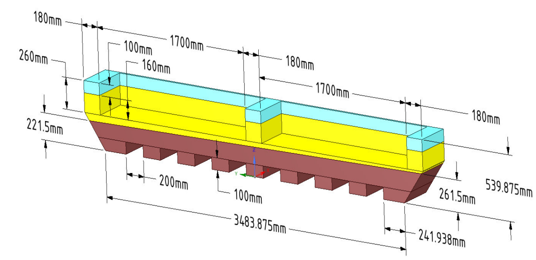

Figure 12: Initial bath-metal interface position

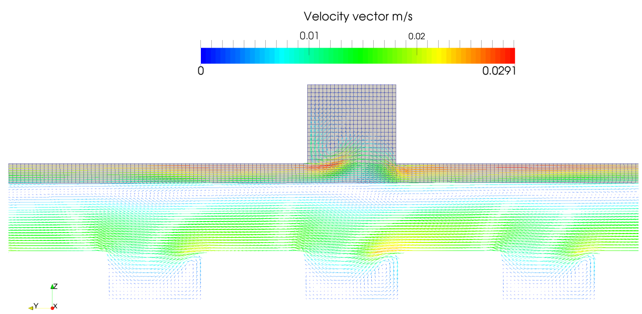

Figure 13: Velocity field after 15 seconds (bath region has a gray background)

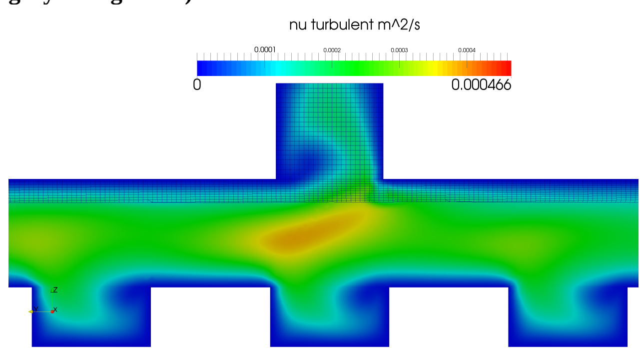

Figure 14: Turbulent viscosity after 15 seconds (bath mesh is visible)

Due to the presence of the flow obstacles, the flow in the metal pad is now quite different. Notice that flow around obstacles has been extensively studied and successfully modeled using OpenFoam [16]. Notice also that the mesh density used in [16] makes the one used in this study looking somewhat coarse!

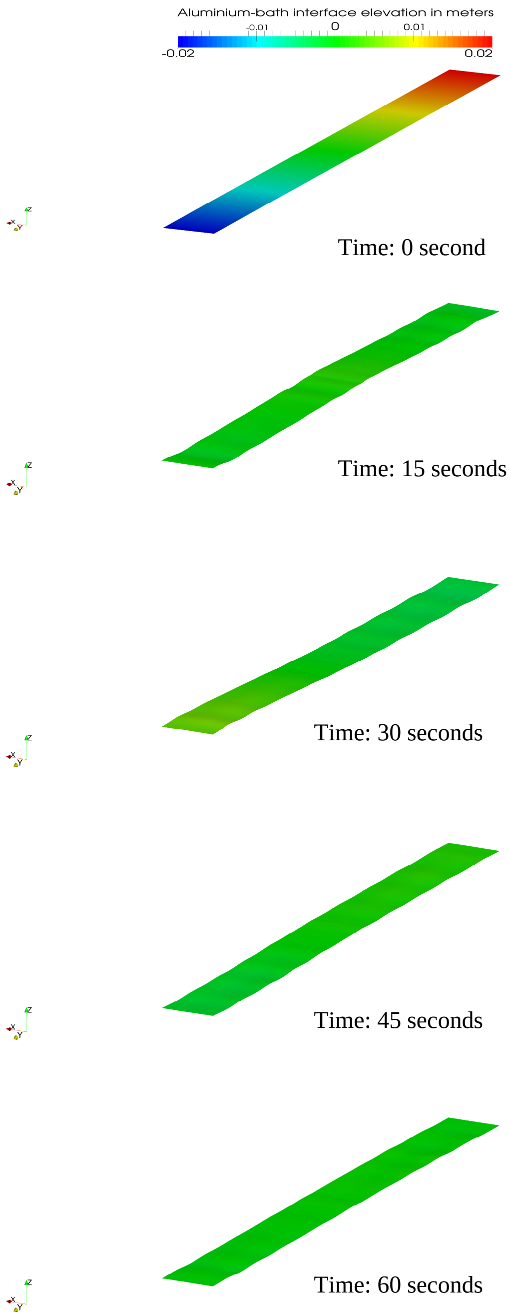

Figure 15: Position of the bath-metal interface every 15 seconds from 0 to 60 seconds

Comparison of the damping rate

The comparison between Figure 6 and Figure 15 interface positions reveals very little difference. Figure 16 is more useful for that, for it shows the transient evolution of the vertical position of the front left corner of the interface for the two cases.

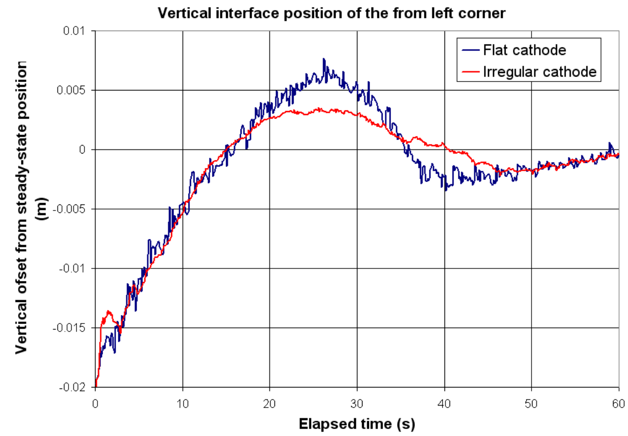

Figure 16: Evolution of the interface front left corner

There is definitively less overshoot in the case of the irregular cathode and also less secondary ripples on the interface so clearly the obstacles are somewhat performing as intended [17].

Yet this observation is not in contradiction with what was previously published in [2,3,4,5] in general and in Figure 7 of [5] in particular. The damping effect of the irregular cathode surface technology is not very important so many other changes to the cell design can have more impact on the cell stability.

Future work

The geometry of the cell side slice model is coming from the cell design presented in Figure 17 produced using Peter Entner CellVolt application [18]. That cell geometry was inspired from the GY420 420 kA cell design presented in [19]. Since that cell design has 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.

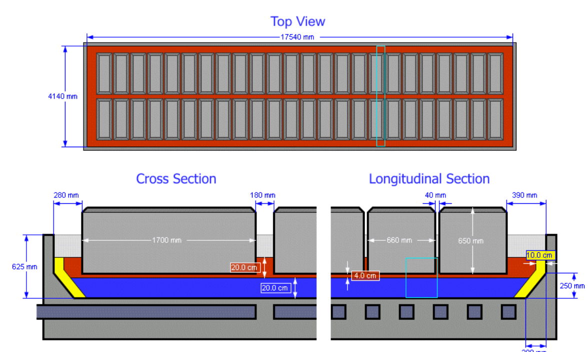

Figure 17: Sketch of the GY420 cell design that inspired the cell side slice model geometry

A model optimization study might reveal that a coarser mesh and a bigger time step could be used without losing much accuracy, so performing such a model optimization would be important. Yet, it is probable that a bigger computer than the Dell 28 cores Xeon ES-2697 V3 computer used in this study would be required in order to obtained a practical turn around time to solve a transient 3D full cell gravitational wave VOF OpenFoam model.

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 [20,21].

Conclusions

Lateral gravity wave can be successfully simulated in a 3D cell side slice model using 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. Many other changes to the cell design can have more impact on the cell stability.

A bigger computer than the Dell 28 cores Xeon ES-2697 V3 computer used in the present study would be required in order to obtain a practical turn around time to solve a transient 3D half cell VOF model to study a longitudinal gravitational wave.

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.

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