NUMERICAL MODELLING OF FREE SURFACE DYNAMICS OF MELT IN INDUCTION CRUCIBLE FURNACE

SPITANS[1] Sergejs, JAKOVICS[1] Andris, BAAKE[2] Ekbert, NACKE[2] Bernard.
[1]Laboratory for Mathematical Modelling of Environmental and Technological Processes, University of Latvia, Zellu Str. 8, LV-1002, Riga, Latvia.
[2]Institute of Electrotechnology, Leibniz University of Hannover, Wilhelm-Busch-Str. 4, D-30167 Hannover, Germany.
e-mail address of corresponding author: sergejs.spitans@lu.lv

Abstract: In this work recirculated flow of Wood's metal alloy and its free surface dynamics in external electromagnetic feld of axially symmetric induction crucible furnace is studied. Applying ANSYS modeling features the externally coupled 2D electromagnetic and 2D hydrodynamic calculation of free surface dynamics is developed. The model verifcation is performed by free surface steady state result comparison to other models and appropriate experimental data, as well as, free surface oscillation period comparison to analytical estimation. By implementation of self-written filtering procedures 2D model is generalized on 3D and on the basis of developed approach 3D free surface dynamics is discussed.

1. Introduction

One of the overriding issues of metallurgical industry is to provide metallic materials with enhanced quality and refined engineering specifications. Resulting material properties are usually varied with an appropriate additive amounts and in this respect it becomes essential to be able to insulate alloy from oxidation and undesirable admixtures found in crucible, as well as, to ensure sufficient particle homogenization in a certain time.

Behaviour of meniscus shape in induction furnaces might be slightly unsteady due to furnace parameter changes and turbulent HD oscillations. Free surface instabilities might lead to slag displacement and undesirable contact between melt and active atmosphere accompanied with chemical reactions and thermal losses. Moreover, severe switches may even cause alloy to splash.

Besides, efficiency of light particle homogenization appears to be dependent on meniscus shape, because greater free surface deformations near crucible walls intensify light particle injection from the surface.

Eventually, free surface consideration proves to be essential in terms of processing safety, efficiency and precision and determines the necessity of numerical tools that are capable of modelling the free surface dynamics.

In this work previously developed 2D model for free surface dynamics calculation in axially symmetric consideration is extended on 3D and the first results are discussed.

2. Two-dimensional model

By means of ANSYS implemented Volume of Fluid (VOF) technique, numerical approach for externally coupled 2D hydrodynamic (HD) and 2D electromagnetic (EM) calculation of free surface dynamics of conductive melt in axially symmetric induction crucible furnace (ICF) was formulated previously [1].

Geometry of axially symmetric single-phase induction crucible furnace with Wood's metal conductive alloy was adopted from [2] and used for 2D model formulation (Figure 1).

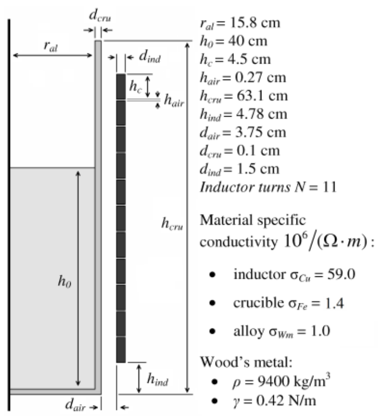


Figure 1. Geometry and material properties for ICF model.

The 2D HD model results for quasi steady state meniscus were compared to calculation results of other models: self-developed 2D hydrostatic [1], M. Kirpo model [2] and O. Pesteanu model [3], as well as, appropriate experimental measurements [2] (Figure 2).

The height of meniscus measured in experiment was 18 mm and 2D HD model predicted 20 mm that made approximately the difference only of 10%. However, for applied furnace parameters (I_{ef} = 2 kA and f = 386 Hz) the height of meniscus was very small in comparison to crucible radius and alloy initial height (Figure 3). For profound model verification experimental data for quasi steady state meniscus shapes of greater deformations is required.

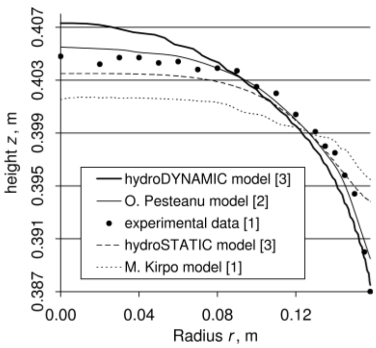


Figure 2. Comparison of 2D HD model results for quasi steady state meniscus shape to experimental data and other models.

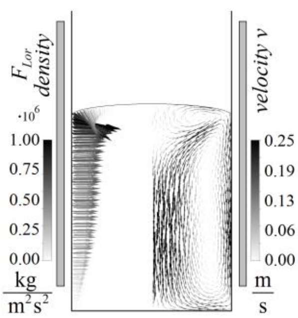


Figure 3. F_{Lor} density, steady state flow pattern and meniscus shape obtained with 2D HD model.

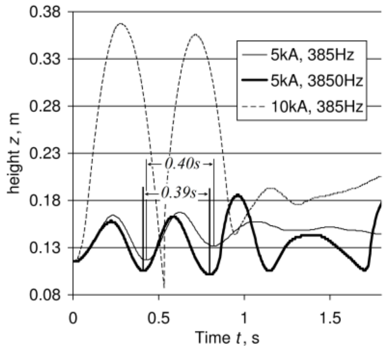


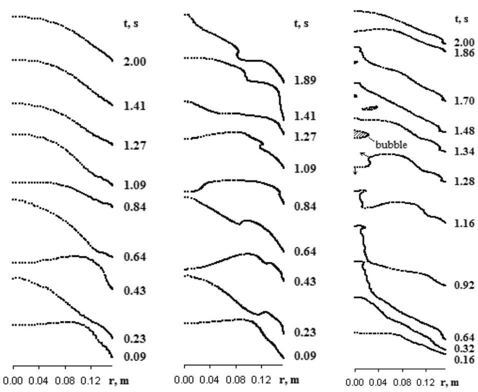
Figure 4. Free surface point oscillations on symmetry axis calculated with different current and frequency values.

The verification of surface oscillation period T in case of small amplitude oscillations according to analytical formula (1) adopted from [4] approved model accuracy (Figure 4).

$$T_{theor} = 2\pi \sqrt{\frac{r_{al}}{\lambda_1 \cdot g}} \cdot tgh\left(\frac{\lambda_1 \cdot h_0}{r_{al}}\right) = 0.41\text{s}, \quad (1)$$

where r_{al} is radius of alloy, h_0 – alloy filling, g – acceleration of gravity and λ_1 = 3.83 – Bessel function J_1 solution.

On the basis of developed approach the current and frequency effect on dynamics was discussed [1]. It was shown that greater inductor currents and frequencies signify non-linear effects of free surface dynamics (Figure 5) that make sense of numerical models capable of providing precise solutions in wider energy scales.



(a) (b) (c)

Figure 5. Amplitude normalised free surface dynamics calculated with:

(a) I = 5 kA, f = 385 Hz;
(b) I = 5 kA, f =3850 Hz;
(c) I = 10 kA, f = 385 Hz.

3. Three-dimensional model

Experimental monitoring of the HD alloy movement indicated on significant azimuthal mass transfer and the lack of axial symmetry in physical process and initiated further model expansion on 3D.

The same as in 2D axially symmetric consideration, numerical calculation is arranged by means of ANSYS Classic for 3D EM calculation, ANSYS/CFX for 3D HD VOF calculation and their external coupler (V. Geza, UL) (Table 1).

Table 1. Schematic representation of 3D calculation arrangement.

	ANSYS Classic					*ANSYS/CFX*
5	Export of Lorentz force density distribution $f_i(x_i,y_i,z_i)$	→	***External coupler***	→	***6***	f_i interpolation on Euler CFX mesh and multiplication with *VF*
	↑					↓
4	EM calculation. Derivation of Lorentz force distribution in alloy $F_{Lor}(x_i,y_i,z_i)$				***7***	HD calculation for sufficiently small time (VOF + k-ω SST)
	↑					↓
3	Mesh generation upon free surface shape				***8***	Retrieval of free surface as isosurface of $VF = 0.5$
	↑					↓
2	Read of free surface data and performance of filtering procedures	←		←	***9***	Export of free surface: • Free surface KP • KP connectivities
	↑					
1	Initial free surface shape					

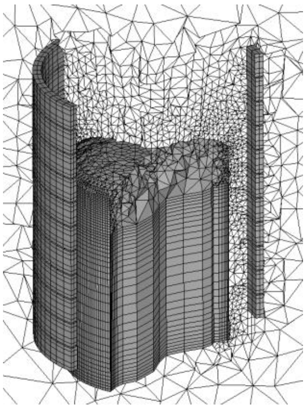


Figure 6. Free surface shape dependent 3D mesh for EM calculation.

Initial free surface shape as well as every transient state of meniscus shape obtained with VOF calculation is retrieved as isosurface of volume fraction at 0.5 and defined by keypoints (KP) and KP connectivities. KP connectivities are named sequences of KP numbers that indicate the order of KP line connection for definition of elementary polygons.

Transferring free surface elementary polygons from CFX to ANSYS Classic a self-written filtering procedures were introduced in order to avoid generation of degenerate surface elements that cause errors in ANSYS Classic volume mesher. Filtering procedures were aimed mainly on close KP merging, polygon reconstruction and further decomposition to maximally equilateral triangles.

Finally, free surface consisting of elementary triangular non-degenerate areas was obtained and mesh for EM calculation was generated (Figure 6).

Inductor (Figure 7) was considered as 11 separate ring-shaped turns with small gaps at $\varphi = 90^\circ$ for application of EM boundary conditions (I_{ef} = 3kA, f = 385 Hz). The length of the gap was 1.8˚ or 6 mm. It must be pointed out that such gap initially introduced the axial asymmetry of F_{Lor} distribution in 3D consideration. For initial (flat) free surface the gap caused the difference of 9% in maximal force density values obtained near crucible walls at $\varphi = 90^\circ$ and at $\varphi = 270^\circ$.

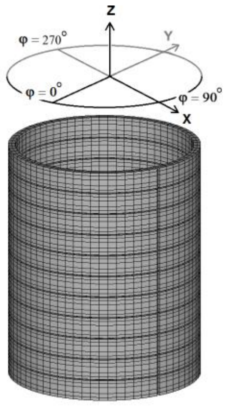


Figure 7. Separate inductor turns with gap for application of EM loads.

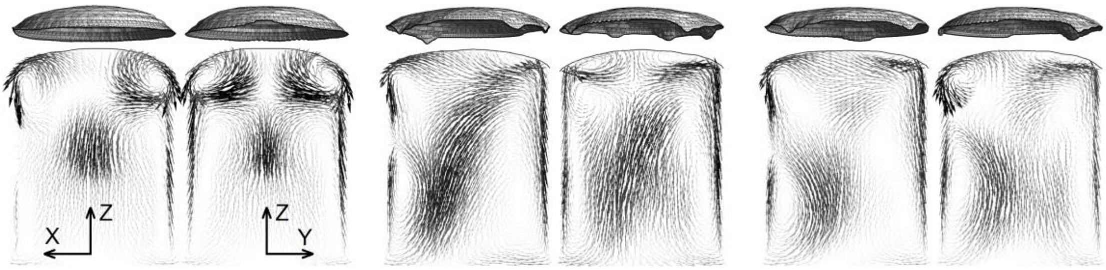
Eventually, EM calculation is performed and obtained F_{Lor} density is interpolated on the Euler mesh for HD calculation.

Lorentz force recalculation rate independent free surface dynamics calculation is bounded on assumption that during sufficiently small time interval of HD calculation the change of free surface shape is so small that Lorentz force distribution can be considered constant. For particular 3D calculation, the first second of flow was calculated refreshing Lorentz force distribution after each 10ms and for the further flow calculation, Lorentz force refresh period was increased to 50ms.

After another transient HD calculation for sufficiently small flow time succeeded and new free surface shape is obtained the calculation loop is repeated.

The coupled 3D HD and 3D EM calculation of 7 s of flow was performed on 4 kernels (~2 GHz) and took 8 days of clear computation time.

The results of 3D model transient calculation: vector plots flow velocity on XZ and YZ planes, as well as, free surface shapes, are presented in Figure 8.



t = 1.32 s t = 4.29 s t = 6.34 s

Figure 8. Flow pattern (0–0.4m/s) and free surface shapes at different time moments.

At t = 0 s the initial free surface is flat and all free surface perimeter keypoints are on the maximum height of z = 0.115 m (Figure 9). It is clearly noteable, that small prominence, caused by less EM pressure, appears shortly at $\varphi = 90^\circ$, next to the inductor gap. For all the further calculation steps it remains at the same φ value.

After 2 s the HD flow is sufficiently developed and despite 2D model predictions the flow velocity azimuthal component is strongly perceived. HD assymetry leads to upward flow along crucible walls and introduces other prominences at different φ values (Figure 10).

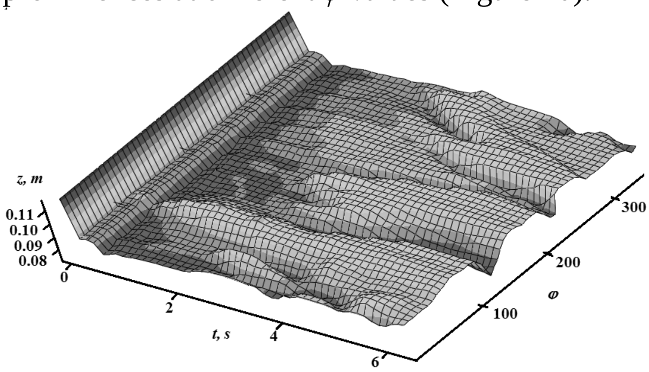


Figure 9. Surface plot representing the heights of meniscus perimeter points z as a function of time t and azimuthal angle φ.

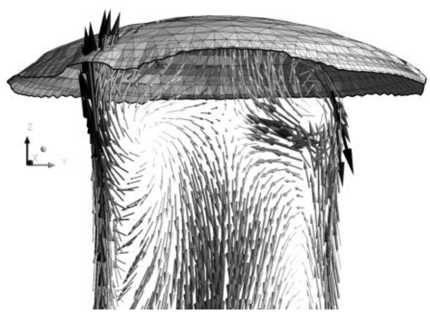


Figure 10. HD asymmetry (t = 2.5 s) leads to upward flow along the walls and causes free surface perturbations.

During further calculations these perturbations appear and vanish ($\varphi = 50^\circ$; 2 s < t < 4 s), as well as, travel along the free surface perimeter ($250^\circ < \varphi < 360^\circ$; 3 s < t < 6 s), merge and separate.

For small amplitude surface oscillations in crucible of particular geometry and filling the oscillation period was estimated as T_{theor} = 0.41 s. In 2D model calculation with inductor current I_{ef} = 5 kA the obtained period was T_{5kA}^{2D} = 0.40 s (Figure 11).

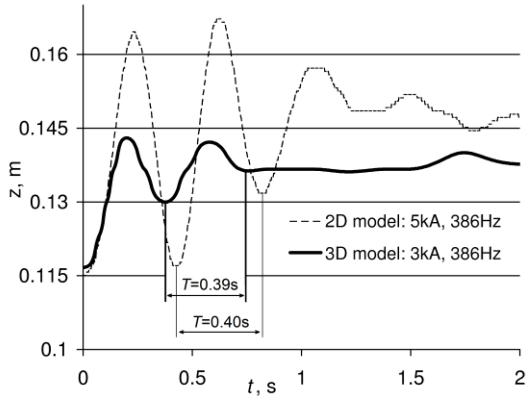


Figure 11. Comparison of free surface point oscillations on symmetry axis for 2D and 3D models.

In 3D model calculation with I_{ef} = 3 kA the obtained period is T_{3kA}^{3D} = 0.39 s.

In general, the aim of this calculation was to inspect the stability and continuity of computation process of externally coupled 3D EM and 3D HD problems. Consciously, in order to accelerate the calculation, rough space and time discretization was applied.

Presumably, this might be the reason for differencies in oscillation dynamics obtained with 2D and 3D models.

However, 3D calculation with finer space and time discretization, as well as, finer Lorentz force recalculation period, is in progress.

4. Conclusions

The approach of coupled 3D EM and 3D HD continuous calculation of metal melt surface dynamics in ICF is developed. Further model verification and parameter studies applying finer space and time discretization, as well as, calculation of free surface dynamics with LES turbulence model, form further plans of research.

5. Acknowledgements

Current research was performed with the financial support of the ESF project of the University of Latvia, contract No. 2009/0223/1DP/1.1.1.2.0/09/APIA/VIAA/008.

I would like to acknowledge Prof. O. Pesteanu for his help in geometry and material property precision that led to better correlation between 2D model results and experimental measurements for steady state meniscus.

6. References

[1] Spitans, S.; Jakovics, A.; Baake, E.; Nacke, B.: Numerical Modelling of Free Surface Dynamics of Conductive Melt in the ICF. Magnetohydrodynamics. 46 (2010) 425-436.

[2] Kirpo, M.: Modelling of Turbulence Properties and Particle Transport in Recirculated Flows. PhD Thesis (2008), University of Latvia.

[3] Pesteanu, O.; Baake, E.: Contribution to the Simulation of Free Surface Flows in Electromagnetic Field. In proceedings of the 54_{th} International Scientific Colloquium on Information Technology and Electrical Engineering. Ilmenau, Germany, 2009. 361-362.

[4] Hegewaldt, F.; Buligins, L.; Jakowitsch, A.: Transient Bath Surface Bulging at Energization of an Induction-type Crucible Furnace. Elektrowarme International, 51 (1993) 28-42.