Numerical Modelling of Free Surface Dynamics of Melt in an Alternate Electromagnetic Field

SPITANS Sergejs[1], JAKOVICS Andris[1], BAAKE Egbert[2], NACKE Bernard[2]

(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 Hanover, Wilhelm-Busch Str. 4, D-30167, Hanover, Germany)

Abstract: On account of ANSYS Classic and ANSYS/CFX external coupling a numerical model for free surface dynamics of conductive fluid in an alternate EM field is developed. The model is adjusted for the case of EM levitation and extended on 3D with LES turbulence description. Results for the steady state free surface calculations are compared to other models and experimental measurements in induction furnaces and EM levitation melting device. Calculation results of free surface dynamics are compared to analytical estimation of small amplitude free surface oscillation periods. 3D k-ω SST free surface dynamics calculation in ICF indicates on regular low-frequency instability of flow and meniscus, meanwhile, 3D LES calculation is initiated and influence of turbulence model on meniscus is discussed.

Key words: ANSYS, EM induction, MHD, free surface, VOF

1 Introduction

Induction furnaces that ensure contact less control of EM stirring, melt temperature and free surface shape are widely applied in metallurgical industry. Requirements for the free surface shape and behavior are dedicated by the different tasks of particular technological process. In the meantime, free surface control is complicated by the reciprocal interaction between EM field and free surface shape, mean flow instability and turbulence.

Heat and mass transfer processes in induction furnaces with fixed hydrostatic meniscus, as well as considering free surface dynamics in 2D, are actively studied numerically. Latest developments in this field revealed interesting results of 3D numerical modelling of liquid droplet dynamics in a high DC magnetic field with simplified two-equation turbulence description [1]. Meanwhile, there is no 3D model for numerical calculation of free surface dynamics of melt in alternate EM field with application of précised LES approach.

2 Model implementation

In our recent work the model for free surface dynamics calculation in simplified 2D axisymmetric consideration was developed. Later on account of self written free surface filtering procedures 2D model was extended on 3D consideration and by means of light fraction velocity manipulation adjusted for the case of EM levitation [2]. The calculation was arranged by means of ANSYS Classic for EM problem, ANSYS/CFX for hydrodynamic (HD) problem and their external coupler written by our laboratory colleague (V. Geza, UL). Volume of Fluid (VOF) numerical technique and k-ω SST turbulence model were applied for high Reynolds number two phase flow calculations. Due to the low magnetic Reynolds number in comparison to non-dimensional frequency the EM and HD parts of the complicated magnetohydrodynamic (MHD) problem were solved separately, considering only the free surface shape reciprocal interaction with EM field distribution. Moreover, because of much greater inertia times of melt in comparison to the alternate EM field timescale, only the averaged part of the oscillating Lorentz force was taken into account.

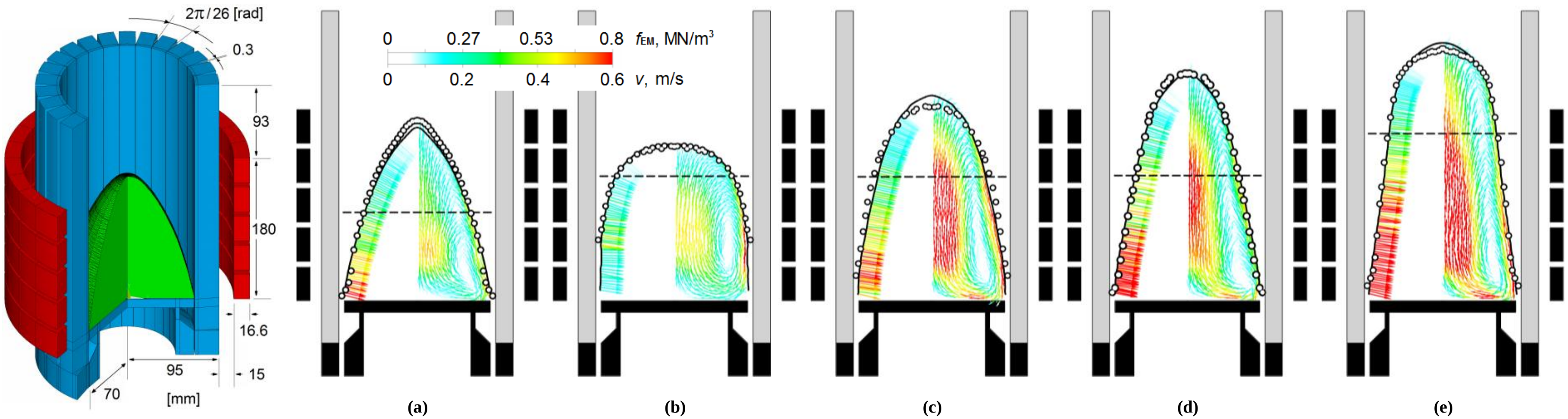


Fig. 1 Geometry of IFCC model, calculated Lorentz force density f_{EM} (left) and flow pattern (right), and comparison between experimentally measured (points) [3] and calculated (solid line) steady state free surface shapes for different initial fillings *IF* (dashed line) in respect to inductor height and effective inductor currents I_{ef}:
(a) *IF* = 46%, I_{ef} = 3154 A; (b) *IF* = 65%, I_{ef} = 1929 A; (c) *IF* = 65%, I_{ef} = 2956 A; (d) *IF* = 65%, I_{ef} = 3566 A; (e) *IF* = 87%, I_{ef} = 3789 A;

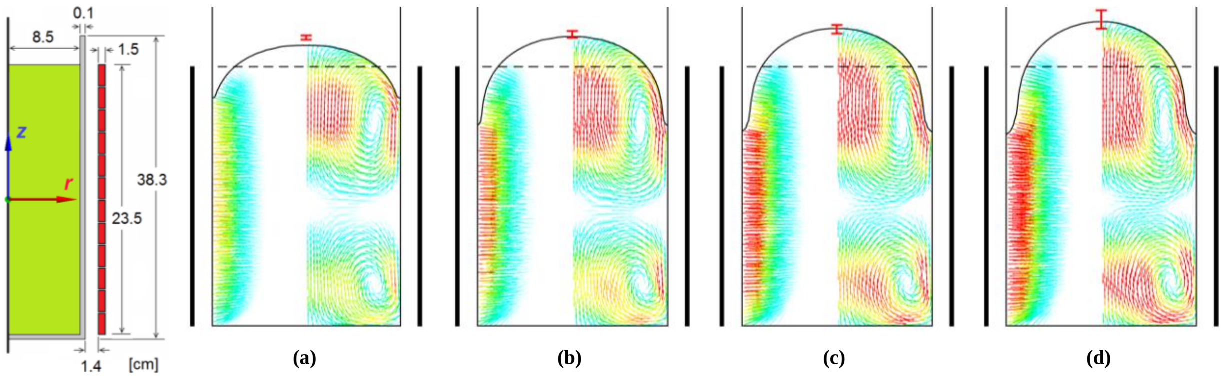


Fig. 2 Geometry of small ICF, calculated f_{EM} (left) and flow pattern (right) and comparison between experimentally measured meniscus heights (ticks) and calculated (solid line) steady state free surface shapes for *IF* = 100% and different I_{ef}:
(a) I_{ef} = 1753 A; (b) I_{ef} = 2020 A; (c) I_{ef} = 2262 A; (d) I_{ef} = 2464 A;

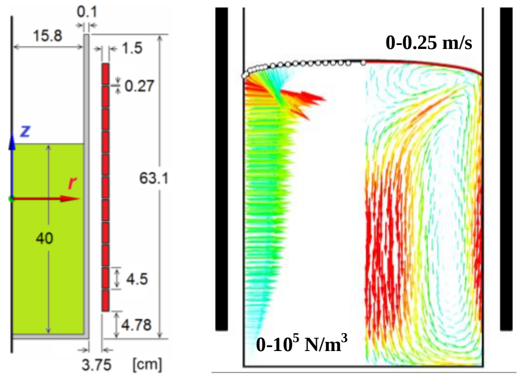


Fig. 3 Big ICF, calculated f_{EM} (left) and velocity (right). Meniscus measurements (points) [4], our model (black line) and O. Pesteanu calculation (red line) [5].

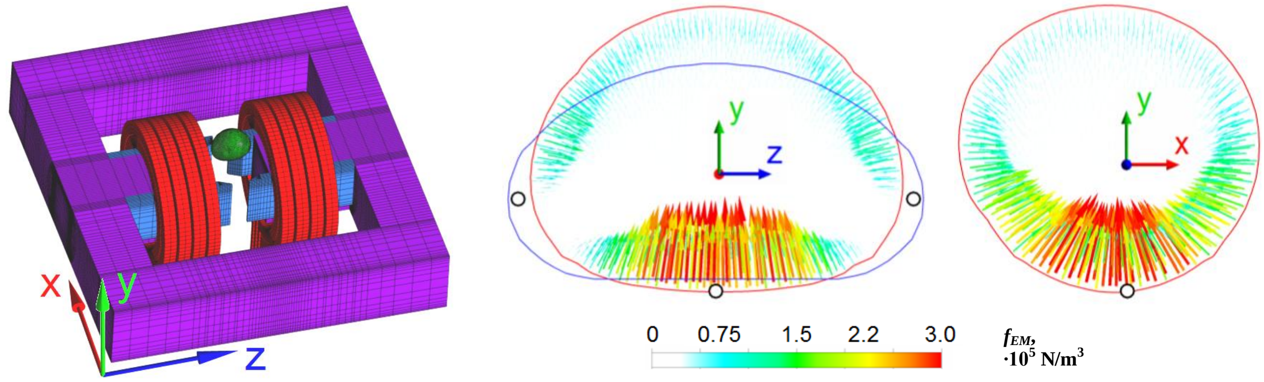
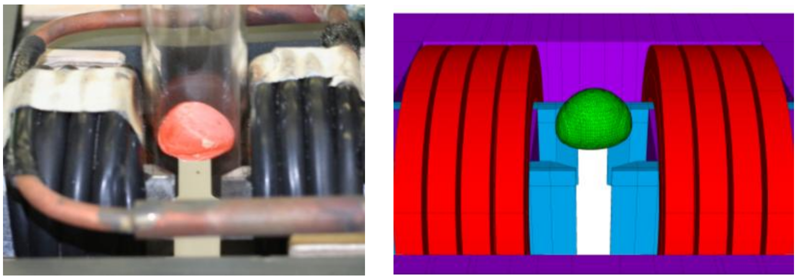


Fig. 4 Geometry of single frequency EM levitation melting device [5] and comparison between experimental measurements for EM levitating drop bottom and greater radius (points), O. Pesteanu 2D model (blue line) and our 3D model (red line), as well as f_{EM} distribution obtained in our calculation.



(a) (b)

Fig. 5 Qualitative comparison between experimentally observed [5] (a) and numerically predicted (b) free surface shape of EM levitating drop.

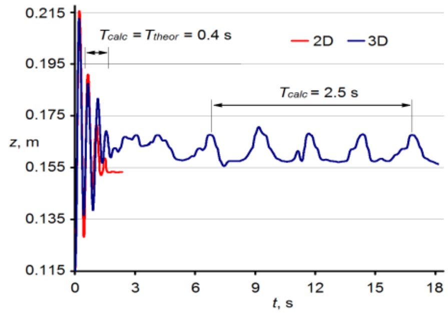


Fig. 6 Free surface point oscillations on Z axis in big ICF operating at $I_{ef} = 5$ kA.

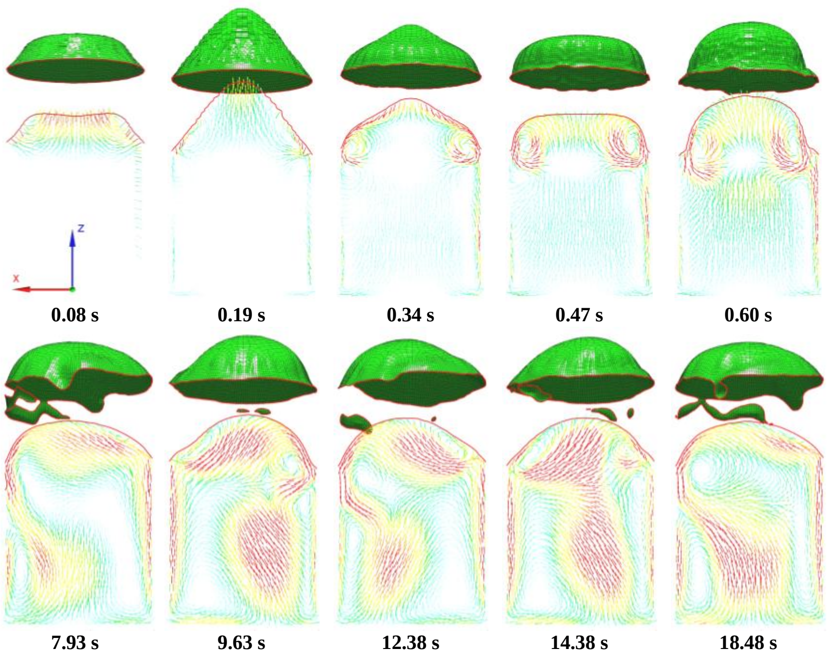


Fig. 7 Instantaneous flow pattern (0-0.6 m/s) and free surface shape of melt in big ICF operating at $I_{ef} = 5$ kA obtained with 3D k-ω SST model that illustrates initial high frequency damping oscillations and further low frequency instability.

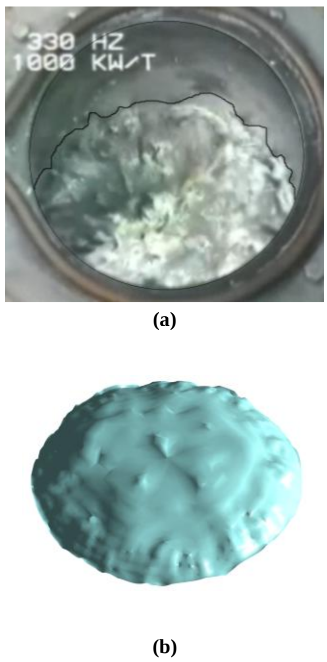


Fig. 8 Qualitative comparison of experimentally observed (a) and LES calculated (b) meniscus structure

The verification of free surface oscillation period T in case of small amplitude deviation according to analytical formula approved 2D and 3D model accuracy [2].

In this paper the further model verification and calculation results are discussed.

3 Results

3.1 Model verification

The comparison between the measured and calculated free surface shapes of aluminum melt in IFCC for different initial fillings and inductor effective currents revealed good correlation between the model prediction and experiment (Fig. 1). To put in remembrance, the previous comparison between experimental measurements for Wood's metal meniscus heights above initial filling (E. Baake) in small ICF (Fig. 2), as well as meniscus profile in big ICF (Fig. 3), also approved model accuracy.

Furthermore, good agreement was obtained between experimental measurements, O. Pesteanu 2D calculation and our 3D calculation results for the steady state free surface shape of EM levitating aluminum drop in single frequency EM levitation melting device (Fig. 4). Qualitative comparison of drop shape in experiment and 3D simulation signify on characteristic drop stretching along magnetic flux lines (Fig. 5).

3.2 3D free surface calculation

3D k-ω SST calculations of Wood's metal free surface dynamics in big ICF (I_{ef} = 5 kA, f = 385 Hz) were performed for the first 18 s considering flat free surface and zero velocity at t = 0 s. Coupled EM and HD computation lasted 6 months on *Intel i7* machine (8·3.4 GHz, 8 Gb RAM). Free surface oscillations on Z axis illustrate initial damping oscillations that are in good agreement with 2D calculation and analytical estimation of free surface oscillation period (Fig. 6). After the first 6 s the mean flow appears to be highly unstable and fluctuating. Upper and lower torroidal vortexes periodically reallocate, meanwhile, complicated reciprocal interaction between EM field and free surface shape contribute to meniscus low frequency staggering with typical period of 2.5 s. Instantaneous velocity patterns on the XZ cross-section, as well as free surface shapes illustrate the dynamics of the process (Fig. 7).

Smaller flow structures resolved with LES on account of dynamic pressure contribute to meniscus perturbation on a smaller scale and in comparison to the mean flow and smooth meniscus obtained with 3D k-ω SST calculation are in better qualitative agreement with experimentally observed meniscus (Fig. 8).

4 Conclusions

(1) Recently developed 2D model for calculation of free surface dynamics of melt in an alternate EM field is adjusted for the case of EM levitation and extended on 3D with application of LES turbulence description.

(2) Comparison of k-ω SST calculation results and experimental measurements for steady state free surface in the wide range of EM induction furnaces, as well as comparison of free surface small amplitude oscillation period to analytical estimation, approved accuracy of developed model.

(3) 3D k-ω SST calculation results of free surface dynamics in ICF sketch an interesting phenomenon of low frequency regular meniscus staggering on account of free surface shape, EM field and intensive mean flow complicated reciprocal interaction.

(4) 3D LES calculations predict free surface perturbations on a smaller scale that is in better agreement with experimental observations in comparison to 3D k-ω SST calculation results.

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Biography: Sergejs Spitans (21.09.1988), male, University of Latvia, MSc in Physics; **E-mail:** sergejs.spitans@lu.lv