3D LES TWO-PHASE FLOW SIMULATION OF CONVENTIONAL ELECTRO-MAGNETIC LEVITATION MELTING EXPERIMENT

SPITANS[1,2] S., BAAKE[1] E., NACKE[1] B., JAKOVICS[2] A.
[1]Institute of Electrotechnology, Leibniz University of Hannover,
Wilhelm-Busch Straße 4, 30167 Hannover, Germany
[2] Laboratory for Mathematical Modelling of Environmental and Technological Processes,
University of Latvia, Zellu Street 8, LV-1013 Riga, Latvia
E-mail address of the corresponding author: spitans@etp.uni-hannover.de

Abstract: By means of external coupling between electromagnetic (EM) and hydrodynamic (HD) problems a numerical model for the liquid metal flow with free surface dynamics in an alternate EM field is developed. The 3D model with precise Large Eddy Simulation (LES) turbulence description is applied for the case of conventional EM levitation. Simulation results are compared to experimental measurements of the levitated molten metal free surface shape, as well as calculation results obtained with other models.

1. Introduction

Numerical simulation in the field of magnetohydrodynamics (MHD) at the present moment is the main widely available tool for investigation of EM induced flow. Advanced multiphysical processes like energy and mass transfer, crystallization and homogenization of alloying particles in induction furnaces are calculated nowadays in 3D with fixed hydrostatic steady free surface shape and précised LES turbulence description [1].

Free surface dynamics of EM levitated melt, flow and energy transfer in 2D axisymmetric consideration, as well as crystallization processes with free surface behavior in EM induction furnaces were successfully simulated using simplified two-parameter turbulence models [2]. The results of 3D numerical calculation of a liquid droplet dynamics in a high DC magnetic field were published recently [3].

However, at the present moment there is no approach developed for 3D calculation of multiphysical processes in EM induction equipment with consideration of free surface dynamics and application of LES description for turbulent flow. The previous investigations revealed that in case of Induction Crucible Furnace (ICF) with two characteristic mean flow vortexes only the LES model gives comparable results to experimental measurements [1].

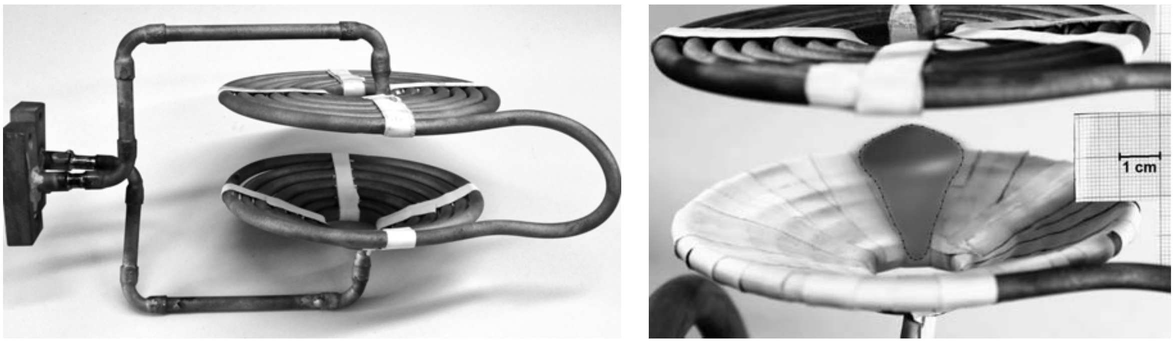
Meanwhile, by means of external coupling between *ANSYS Classic*, *FLUENT*, *CFX-Post* and a self-written surface filtering procedure a numerical model for the liquid metal flow with free surface dynamics in an alternate EM field has been developed. The comparison of our k-ω SST calculation results to experimental measurements and results of other models for the molten metal free surface shape in ICF, induction furnace with cold crucible and EM levitation setup, as well as comparison of free surface small amplitude oscillation period to analytical estimation, revealed a good correlation and approved accuracy of our approach [4].

In this article the further validation of our numerical model is presented. Our two-phase flow 2D k-ω SST, 3D k-ω SST and 3D LES calculations of EM levitated molten aluminum are compared to experimentally observed free surface shape and simulation results of V. Bojarevics *et. al.* [5].

2. Conventional EM levitation melting experiment

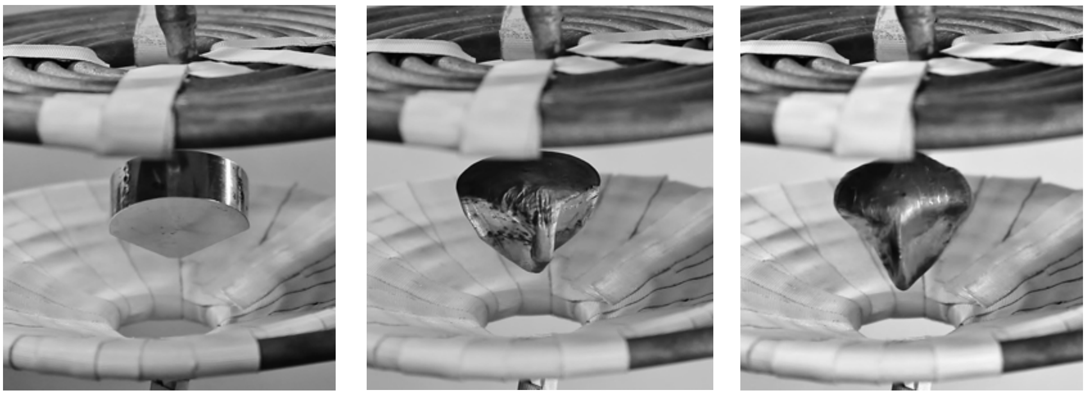
For EM processing of metallic materials at great temperatures and high purity a contactless method of EM levitation melting is known to be appropriate since older times. In particular, melting and EM levitation of liquid aluminum sample (m = 21.5 g) in a laboratory-scale levitation furnace was investigated experimentally in the early fifties [6]. The experimental setup consisted of two coaxial inductors - upper pancake coil and a lower cone-shaped coil - that were fed with counter oriented alternate currents of I_{ef} = 600 A at a frequency of f = 9.6 kHz. The sketch of the setup with dimensions can be found in [6].

However, the article [6] did not provide any quantitative information about the dynamics and average shape of the levitated melt so it was decided to repeat the experiment ourselves. The copper water-cooled inductor we have manufactured and used in experiment is shown in fig. 1, a. Levitation melting of aluminum sample (m = 19.6 g) was successfully performed at I_{ef} = 650 A and f = 9.65 kHz. As the sample was molten completely the series of experiment photos were post-processed and a time-averaged free surface shape of the liquid aluminum charge was obtained (fig. 1, b).



(a) (b)

Figure 1: Our experimental setup for repeating of Okress *et. al.* levitation melting experiment (a) and a post-processed time-averaged shape of the molten aluminum sample (b).



(a) (b) (c)

Figure 2: Solid (a), partially molten (b) and completely liquid (c) aluminium sample covered with oxide layer in our levitation melting experiment.

To reduce the instability of a solid sample at the beginning of experiment the specimen initial cylindrical shape was modified as shown on fig. 2, a. During the experiment not yet molten part of the sample remained above the liquid part because of a higher solid electrical conductivity, meanwhile edged shape of the solid aluminum introduced wrinkles on the free surface of the melt (fig. 2, b). The experiment was performed in an open air conditions so the surface of the sample was covered with an oxide layer. Because of oxide shell these wrinkles partially remained even after the sample was completely molten (fig. 2, c).

However, first experiments failed because of the leakage of the semi-molten sample. It could be noticed that right before the leakage the unmolten aluminum had detached from top and accelerated by the flow drag started to circulate with the flow introducing additional free surface instability that caused draining.

Nevertheless, completely molten aluminum sample was successfully levitated for 3 minutes, after that inductor current was slowly decreased down to I_{ef} = 600 A and the sample was drained into a container with sand avoiding the contact to inductor.

3. Numerical simulation and validation

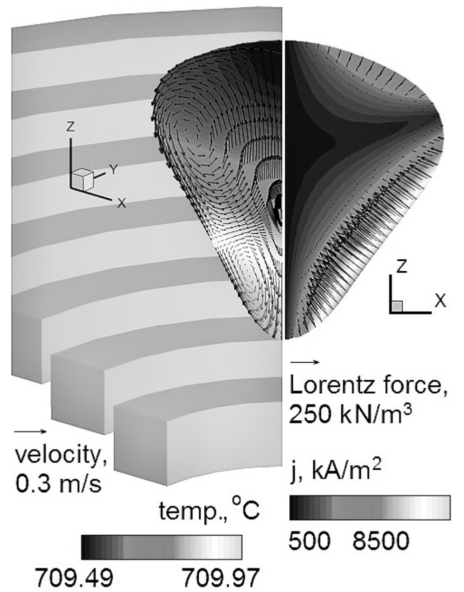


Figure 3: Velocity (on the left), EM force (on the right) and a shape of molten aluminium by V. Bojarevics *et. al.* transient 2D calculation [5].

A transient numerical simulation of the heat transfer, levitated molten metal flow and free surface shape in this original experiment [6] has already been performed by V. Bojarevics *et. al.* in 2D axisymmetric consideration using a modification of k-ω turbulence model and a self written software [2]. The results appeared to be in a good agreement with experimentally observed "spinning top" shape and indicated on a fully turbulent two torroidal vortex flow structure and nearly homogeneous temperature distribution (fig. 3).

In order to supplement the previous verification of our model [4] the particular levitation experiment was numerically calculated in 2D axisymmetric and full 3D consideration using k-ω SST and LES turbulence models. The following temperature independent material properties of liquid aluminum were used in our and V. Bojarevics *et. al.* numerical simulations: density ρ_{Al} = 2380 kg/m^3, surface tension γ_{Al} = 0.94 N/m, electrical conductivity σ_{Al} = 3.85 MS/m and dynamic viscosity η_{Al} = 2.38 mPa·s.

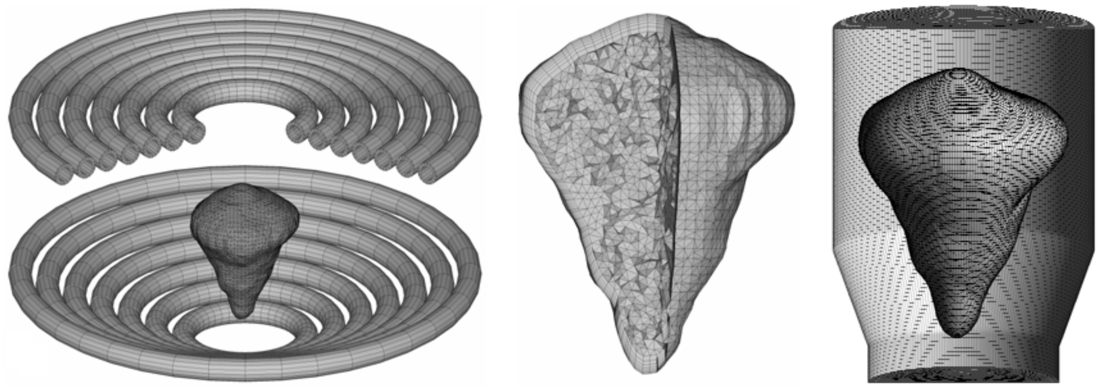
Example of our 3D model mesh at particular instant free surface shape for EM problem ($4\cdot10^5$ elements) with precise resolution of EM skin-depth δ_{em} = 2.6 mm (fig. 4, a and b) and a fine HD mesh ($7\cdot10^5$ elements) for LES two-phase flow calculation (fig. 4, c) is shown. Lorentz force recalculation upon the new free surface shape was performed every 5 ms of the flow time. The simulation of 3 s of flow took 1 month of computation time on a cluster with 10 nodes (3 GHz each).

According to our transient 2D (fig. 5, a) and 3D (fig. 5, b) k-ω SST calculations (black lines), as well as transient 2D k-ω calculation of V. Bojarevics (grey line), the EM field, free surface shape and the flow adjust themselves to a completely steady state regime with characteristic two torroidal vortex structure. Velocity patterns predicted by 2D and 3D k-ω SST models, as well as confining EM forces for the 2D k-ω SST case are shown below (fig. 5, a and b). The calculation of the free surface shape and position of the mass centrum by these models are nearly the same, however, our 2D and 3D k-ω SST models predict 15 % and 50 % less maximal velocity in comparison to 2D k-ω model of V. Bojarevics.

Meanwhile, these URANS models still differ from our measurements of the time-averaged droplet shape, as well as do not predict the fluctuating behavior of velocity and free surface in a quasi steady state regime observed in experiment.

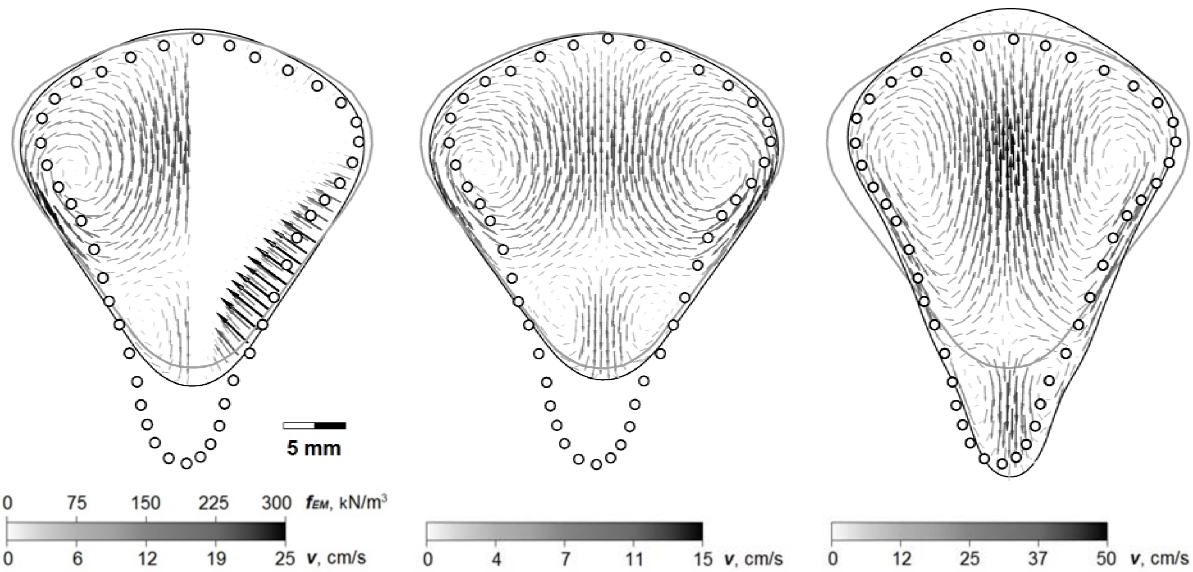
Time-averaged free surface shape obtained with our 3D LES calculation (fig. 5, c) appears to be in a better agreement with time-averaged experimental measurements (fig. 1, b) and maximal velocity of the time-averaged flow pattern proves to be 67 % greater than in calculation of V. Bojarevics.

In comparison to the Reynolds-averaged flow and a smooth free surface shape obtained with transient 2D and 3D k-ω SST calculations (fig. 5, a and b) the finer flow structures resolved with LES reach up to 1 m/s in velocity maximum value (fig. 6, c) and on account of dynamic pressure contribute to free surface fluctuations. Instability of molten aluminum free surface shape at a quasi steady state regime observed in experiment (fig. 6, a) is in a good qualitative agreement with the transient 3D LES results (fig. 6, b).



(a) (b) (c)

Figure 4: numerical mesh for 3D EM calculation (a) with a fine resolution of the molten metal skin-depth (b) and numerical mesh for 3D LES two-phase flow calculation (c).



(a) (b) (c)

Figure 5: comparison of experimentally measured time-averaged free surface shape (O) and 2D k-ω calculation results of V. Bojarevics (—) to our 2D k-ω SST (a), 3D k-ω SST (b) and 3D LES (b) time-averaged solution.

5. Conclusions

3D numerical model for coupled free surface and liquid metal flow calculation in EM field is developed. The model is adjusted for the case of EM levitation and can be used with précised LES turbulence description.

In comparison to k-ω Reynolds-averaged calculation the 3D LES model is able to predict the fluctuating behavior of velocity and free surface shape at a quasi steady state regime, much greater instant flow velocity values and better agreement with time-averaged and instant free surface shapes obtained in experiment.

Using the developed model it is planned to tailor the design of the novel levitation melting setup [7] and configuration of EM field in order to meet the conditions for stable EM levitation of industrial-scale molten metal charge and reproduce it in the laboratory experiment.

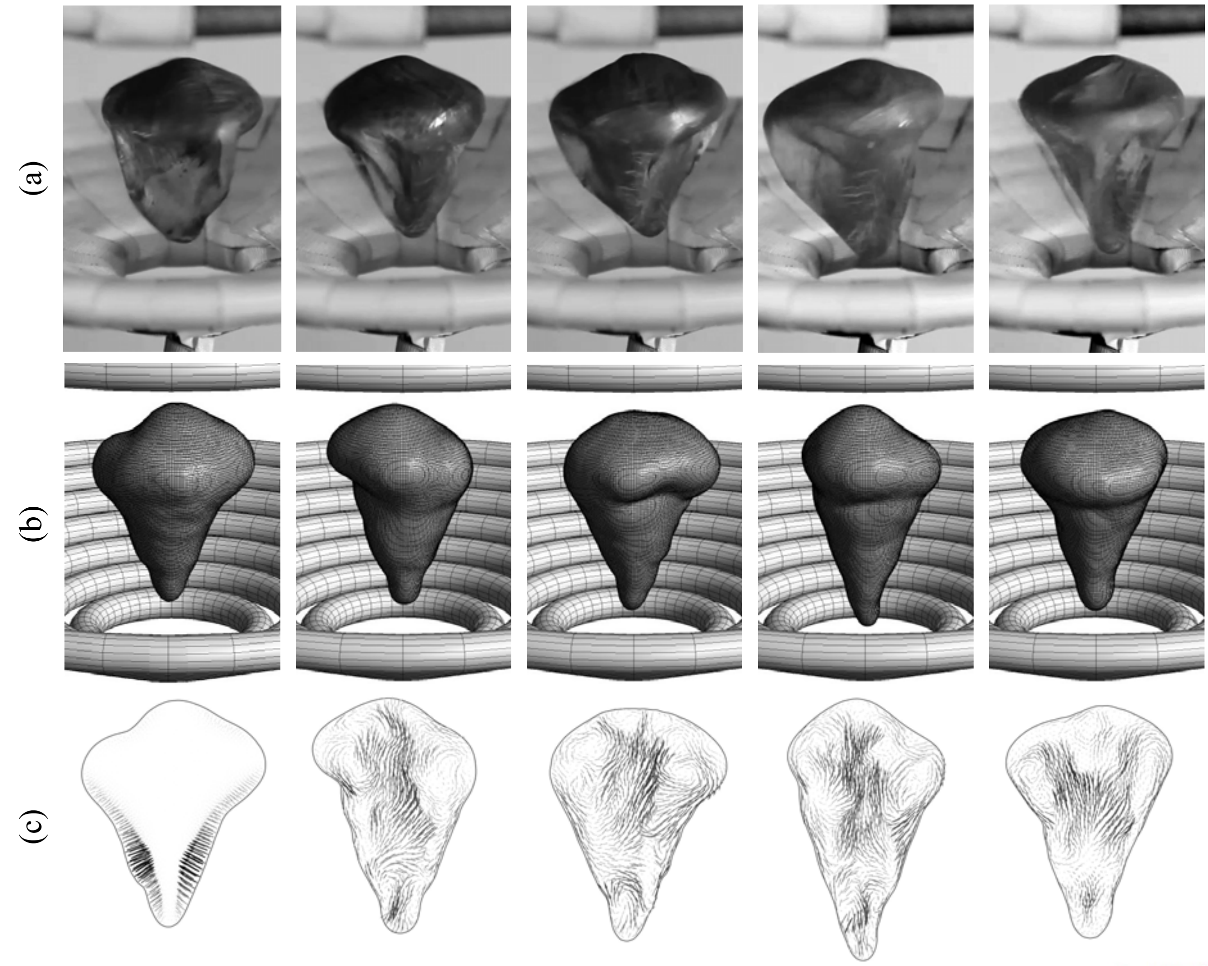
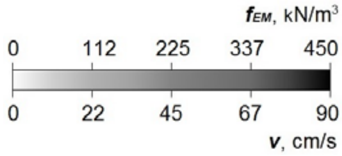


Figure 6: comparison of experimentally observed (a) and numerically simulated (b) free surface shape diversity, as well as instant EM force distribution at particular free surface shape and instant velocity patterns obtained by 3D LES simulation (c).



5. Acknowledgements.

Current research was performed with financial support of the ESF project of the University of Latvia, contract No. 2009/0138/1DP/1.1.2.1.2/09/IPIA/VIAA/004. The authors wish to thank the German Research Association (DFG) for supporting this study under the Grant No. BA 3565/3-1. The authors would like to acknowledge Dr. Valdis Bojarevics for kindly sharing his simulation data of E. C. Okress *et. al.* experiment.

6. References

[1] Kirpo, M.: Modelling of turbulence properties and particle transport in recirculated flows. Ph. D. Thesis, University of Latvia, Riga (2008).

[2] Bojarevics, V.; Harding, R.; Pericleous, K., Wickins, M.: The development and experimental validation of a numerical model of an induction skull melting furnace. *Met. Mat. Trans. B*, 35 (2004) 785-803.

[3] Easter, S., Bojarevics, V., Pericleous, K.: Numerical modelling of liquid droplet dynamics in microgravity. *J. Phys. Conf. Ser.*, (2011) 327 012027.

[4] Spitans, S.; Jakovics, A.; Baake, E., Nacke, B.: Numerical modelling of free surface dynamics of melt in an alternate EM field. Part I: implementation and verification of model. *Met. Mat. Trans. B*, 44/3 (2013) 593-605.

[5] Simulation data obtained through a personal communication with Dr. Valdis Bojarevics.

[6] Okress, E.; Wroughton, D.; Comenetz, G.; Brace, P. and Kelly, J.: Electromagnetic Levitation of Solid and Molten Metals. *J. Appl. Phys.*, 23 (1952) 545-552.

[7] Baake, E., Spitans, S., Jakovičs A.: New technology for EM levitation melting of metals. In the Proc. of Int. Conf. on Heating by Electromag. Sources HES-13, Padua, Italy, 21-24 May, 2013, pp. 1-8 (addendum).