NUMERICAL SIMULATION OF ELECTROMAGNETIC LEVITATION IN A COLD CRUCIBLE FURNACE

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Abstract: Design considerations of a cold crucible (CC) levitation melting furnace have been examined in the course of the literature studies. Meanwhile, 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 has been developed and verified. The 3D model with a Large Eddy Simulation (LES) turbulence description is applied for the case of 1 kg of liquid titanium levitation in a CC furnace. Calculation results are compared to a simplified model of the furnace section.

1. Introduction

The conventional induction furnace with CC is a very useful technology for EM processing of a high purity materials. The application areas range from manufacturing of titanium parts for aerospace, automotive or medical industry, photovoltaic silicon purification and crystallization, up to the treating of nuclear fusion products [1].

Due to the air gaps the sectioned metallic crucible is partially transparent for EM field and acts as a secondary inductor. In this case EM pressure prominently squeezes the melt and semi-levitation is achieved. The crucible is cooled by the water and the melt is mainly abutted upon the skull - in such way interaction between the melt and crucible material is reduced. However, thermal losses through the water-cooled crucible and melt contact regions appear to be a limiting factor for reaching a higher level of overheating and efficiency.

From this point of view, a CC for complete EM levitation melting is an attractive option. In this case there is no contact between the melt and crucible and heat losses are limited only to radiation and evaporation. This ensures a higher level of superheat, permits investigation of materials at extreme temperatures and metal evaporation for coating purposes [2].

In the same time, industrial requirements must be satisfied for the scale-up potential of the CC levitation melting processes and for this purpose numerical simulation is an advantageous tool. 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. Detailed verification of the model has approved accuracy of our calculation approach [3]-[4].

In this work a review of recent developments and design considerations in the field of CC construction is presented. Generalized CC design is used for simulation of EM levitation of 1 kg of liquid titanium by means of full 3D model with LES turbulence description. Calculation results are compared to the simplified k-ω SST model of a single CC section.

2. Literature studies and a cold crucible furnace design considerations

In the following articles [5, 6] it is shown that levitation in CC with a small number of segments can lead to a flower like charge shape and a contact between the molten metal and the centre of a palisade. Furthermore, a cone-shaped crucible is considered to be the best for a stable CC levitation melting [5 - 7]. Application of different AC frequencies for lower and upper inductors can be tailored specially to separate control of levitation (with several kHz) and heating (with several tens of kHz) [5], [7]. Taking into account these considerations, authors were able to levitate and melt 2.3 kg of titanium in two to three minutes [5].

In article [2] it is stressed that on a larger scale the mechanism of levitation confinement is considerably different from a small droplet case, where surface tension plays the key role. A numerical investigation led to a conclusion that the levitation of a large fluid mass requires a high AC frequency, because lower penetration depth concentrates the EM force near free surface and stabilizes it. On top of that higher intensity of a turbulent flow that perturbs free surface corresponds to a lower AC frequency and greater penetration depth. Full levitation of 2 kg of titanium melt has been achieved in a 2D k-ω numerical simulation using EM field frequency of 20 kHz. Despite the singularity of EM forces and the lack of surface tension to ensure confinement on the axis the leakage of the melt was not observed because of tangential flow along the surface away from the bottom stagnation point.

The work [6] describes the design, optimization and experimental realization of a CC levitation melting system for light alloys. By appropriate shape of a lower part of CC it was possible to compress magnetic field lines through the nozzle at the bottom of crucible and to increase the field gradient around critical null point. Moreover, stability of the levitated melt was enhanced by the null-field region introduced by a number of reverse turns. In result, few hundred grams of light metal alloy were successfully melted and solidified in levitation conditions using 10 kHz frequency [6].

Taking into account some of these considerations, authors were able to melt 0.85 kg of titanium and 0.15 kg of tantalum in levitation conditions and to produce 1 kg of uniform composite using 3 kHz and 50 kHz for levitation and heating coils accordingly [7].

Promising study [1] is devoted to a prominent enhancement of cold crucible efficiency by decreasing vertical adjacent surfaces of gaps and increasing the distance between them.

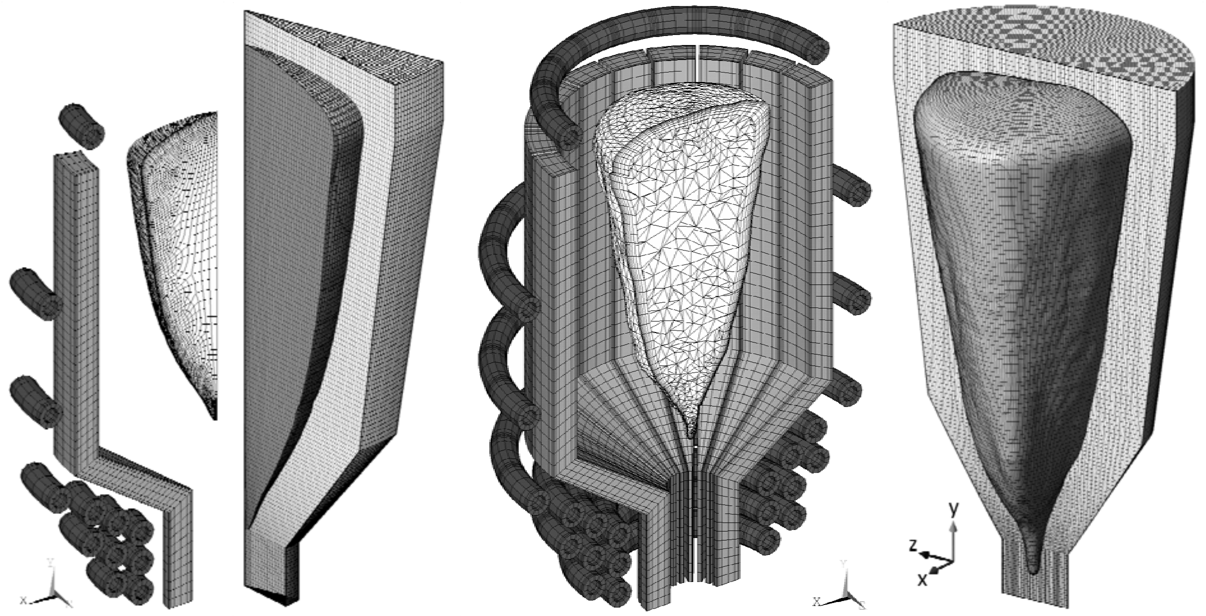
3. Numerical simulation

Two numerical models have been used for simulation of 1 kg of liquid titanium levitation: a simplified model considering a single CC section (fig. 1, a) and a full 3D model of CC furnace and titanium charge (fig. 1, b). Example of numerical mesh applied for a simplified (10^5 elem.) and full ($5 \cdot 10^5$ elem.) harmonic EM problem with fine resolution of magnetic field penetration depth δ_{em} = 2.1 mm is shown next to numerical mesh for the simplified ($0.8 \cdot 10^5$ elem.) and full ($13 \cdot 10^5$ elem.) transient HD calculation of two-phase turbulent flow. In the HD part of the problem k-ω SST and precise LES turbulence descriptions have been used for simulation of a single section and a full CC furnace accordingly. Lorentz force recalculation upon the new free surface shape was performed every 6 ms of the flow time. The full 3D LES simulation of 2 s of flow takes 1 month of computation time on a cluster with 14 nodes (3 GHz each).

The following temperature independent material properties of liquid titanium were used: density ρ_{Ti} = 4110 kg/m^3, surface tension γ_{Ti} = 1.557 N/m, electrical conductivity σ_{Ti} = 0.56 MS/m and dynamic viscosity η_{Ti} = 4.42 mPa·s.

The modification of a cold crucible melting apparatus described in [7] is used for numerical simulation of liquid titanium EM levitation. Our CC is composed of 20 palisades separated by the gaps of 1.5 mm. In principle, gap size can be increased, because no contact is expected between the CC and levitated melt.

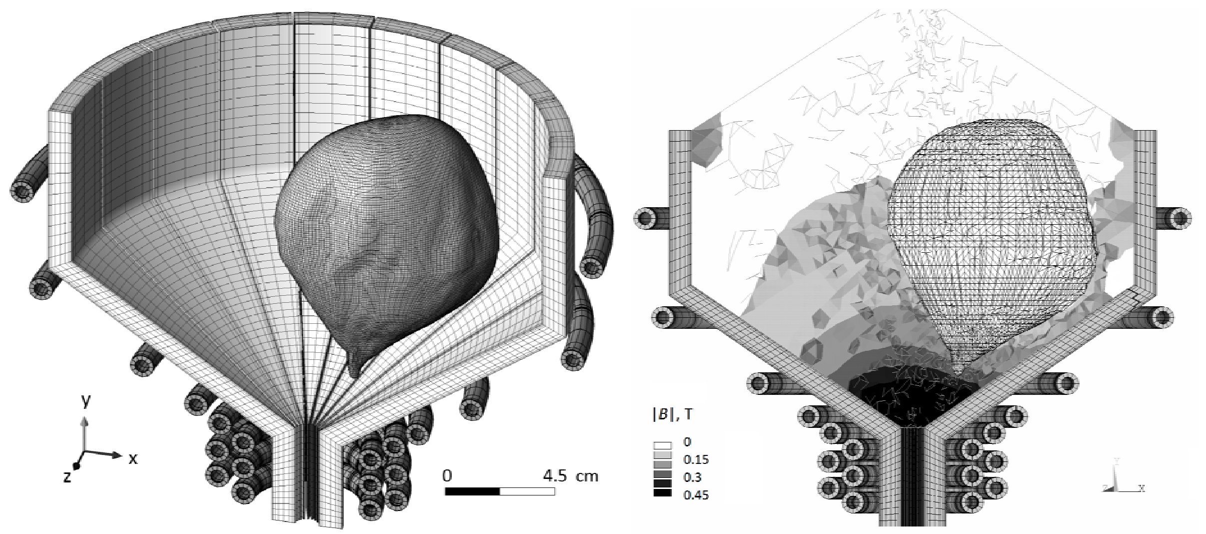
The bottom tapping nozzle has inner diameter d_{noz} of 2 cm. This part of CC is responsible for squeezing EM field lines and increasing the field gradient in the critical null point region on the symmetry axis. Greater inner diameter d_{noz} will lead to a greater curvature radius of the melt at the bottom point and may cause a leakage; however, making d_{noz} too small makes it hard to install the cooling system in the palisade, as well as to drain the melt with no contact to CC. The angle α between the cone-shaped wall of palisade and a horizontal plane is 35º.



(a) (b)

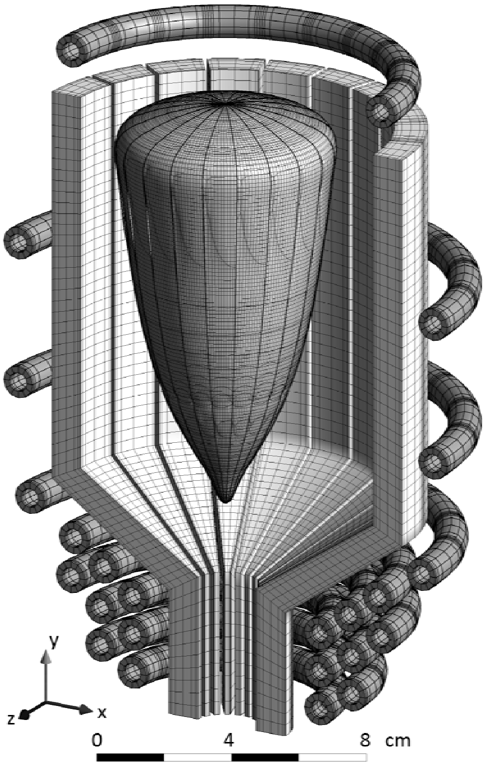
Figure 1: numerical mesh for EM and two-phase HD calculation of a molten titanium levitation. Simplified model considering a single CC section (a) and complete 3D model of CC furnace and titanium charge (b).

Inner diameter of CC walls d_{wall} is 10 cm. Initially d_{wall} was chosen to be 20 cm (fig. 2, a) in order to reduce the contribution of EM forces that squeeze the melt in radial direction and results in greater height of the melt and hydrostatic pressure at the critical bottom point. However, in this case isosurface of magnetic field inside the CC have a pronounced local maximum right above the nozzle. Magnetic field distribution in the air inside the CC is shown below (fig. 2, b). Because of that position and shape of liquid metal is asymmetric, moreover, it might "jump" along this local ring-shaped EM field minimum from one palisade centre to another.



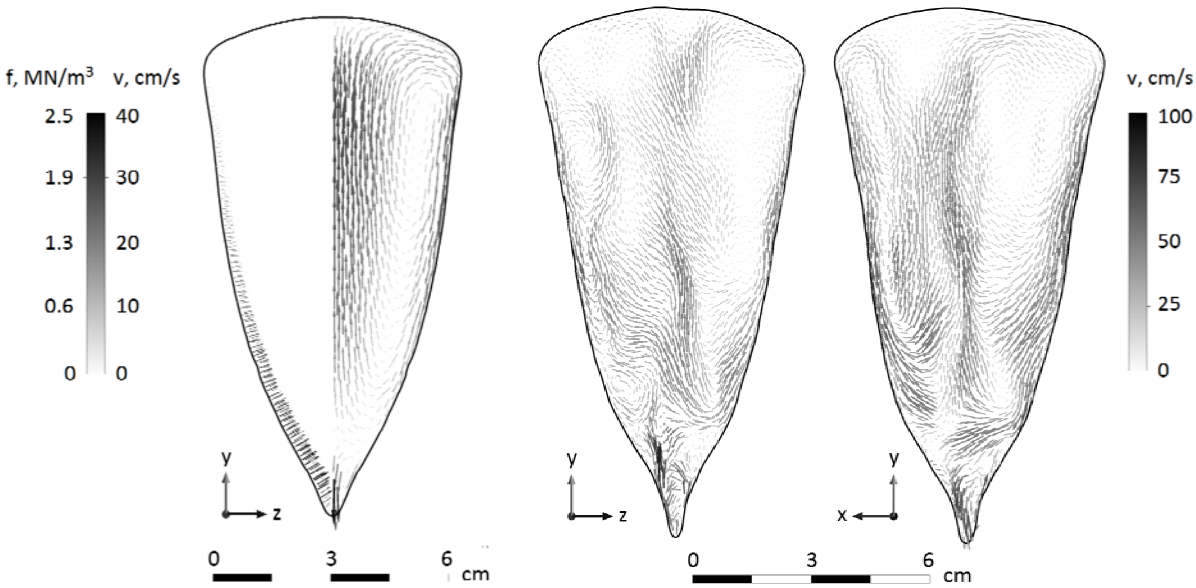
(a) (b)

Figure 2: asymmetric position of levitated titanium (1 kg) in CC furnace with d_{wall} = 20 cm obtained by 3D LES simulation (a) due to the magnetic field maximum above the nozzle (b).



(a) (b)

Figure 3: free surface shape of liquid titanium (1 kg) obtained by simplified k-ω SST calculation of a single section (a) and full 3D LES simulation of CC levitation furnace (b).



(a) (b)

Figure 4: EM force (on the left) and flow pattern (on the right) obtained by k-ω SST calculation of a single section (a) and instant velocity pattern calculated with full 3D LES model of CC levitation furnace (b).

11 turns of inductor mainly concentrated in the nozzle region and additional reverse turn above the crucible are fed with effective current I_{ef} of 3.44 kA at a frequency f of 100 kHz. Applying lower frequency causes higher flow intensity and instability of free surface, moreover, lower frequency leads to a greater δ_{em} for which the lower part of the melt with

small curvature radius of approx. 1 mm becomes transparent and results in a melt leakage predicted by our 3D LES calculation. It must be mentioned, that k-ω SST calculation of a single CC section predicts high turbulent viscosity of 1.5 Pa·s in the lower vortex region. Because of that levitation is retained even at lower EM field frequencies by k-ω SST model.

Free surface shape of liquid titanium at a quasi steady state regime obtained by simplified k-ω SST calculation of a single section and revolved for better visualization (fig. 3, a), as well as full 3D LES simulation of CC levitation furnace (fig. 3, b) is shown. According to k-ω SST Reynolds-averaged calculation the EM force, free surface shape and the flow with maximal velocity of 40 cm/s adjust themselves to a completely steady state regime with characteristic two torroidal vortex structure (fig. 4, a). Meanwhile, the finer flow structures resolved with LES reach up to 100 cm/s (fig. 4, b) and contribute to continuous free surface fluctuations, especially notable in the lower vortex region.

4. Conclusions

Important design considerations of the CC levitation furnace have been obtained in the course of literature studies. Following this experience a pilot design of CC has been proposed.

By means of recently developed and verified 3D LES numerical approach for calculation of liquid metal flow with free surface dynamics in EM field the pilot design of CC furnace has been optimized in order to meet conditions for stable levitation of 1 kg of liquid titanium.

In comparison to a simplified calculation of a single CC section the 3D model is able to predict asymmetric allocation of charge due to the specific EM field distribution. In comparison to k-ω SST calculation, 3D LES model predicts fluctuating behavior of velocity and free surface shape, much greater instant flow intensity, as well as metal leakage in case of lower EM field frequencies. Calculation of 3D EM levitation with free surface dynamics and LES turbulence model is in principle a new approach that permits more precise and detailed investigation of free surface instabilities in levitation furnaces of different kinds.

The developed 3D numerical approach with précised LES turbulence description can be used for further optimization of EM levitation melting installations.

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