Assessing Fixed and Moving Mesh Methods for Hydrodynamic Free Surface Simulation in Induction Melting

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Abstract: This study develops a coupled finite element method (FEM) approach to optimize induction-melting processes by accurately simulating multiphysics phenomena. It integrates a magneto-hydrodynamic model to represent magnetic fields and Lorentz forces, crucial for fluid flow and pressure fields. Comparing fixed and moving mesh techniques, it assesses their effectiveness in capturing free surface deformation. Experimental validation in an aluminum induction-melting furnace confirms the model's accuracy. Insights gained contribute to advancing computational methods in metallurgical process optimization, particularly in understanding magneto-hydrodynamic behavior during induction melting.

Keywords: induction melting; multiphysics modelling

1 Introduction

The optimization of casting processes remains a field of study, where melting processes represent one area where the greatest benefit can be obtained by reducing energy consumption, emissions and process times. Induction melting (IM) is one of the processes with the best expectations [1]. This requires the design of advanced numerical models validated against experimental measurements. The interaction between the magnetic field and the liquid metal leads to recirculation of the melt and surface deformation, with the necessity of accurate modeling for calculating flow recirculation, heat transfer, alloy dissolution, and crucible erosion. Traditional fixed mesh methods like Volume of Fluid (VOF) are commonly used [2]. However, these methods require very fine meshing, high computational resources, and the results are highly dependent on the numerical diffusion of the interface. Thus, this study compares the use of mobile mesh as an alternative, by comparing both methods[3].

2 Experimental procedure

For the IM test, an Inductotherm® furnace with a VIP POWER-TRAK+® power generator was employed. The inductor coil was composed of 10 loops having a rated power of 50 kW at 3 kHz. The melted Al 99% ingots underwent gradual heating up to 750 °C and power was maintained. Once the free surface of the metal reached a stable state, contact probes were introduced into the metal. After allowing the aluminum to wet the probes, the device was removed, leaving a visible mark indicating the melt height and the free surface profile. Also, the electrical variables corresponding to current, voltage, phase, and frequency were measured to feed the posterior simulation. Six trials were done for 5, 7.5, and 10 kg respectively, and two power conditions at 25 kW and 40 kW for the filling case (Figure 1).

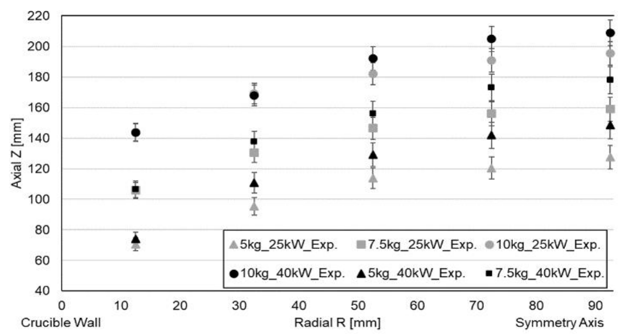

Figure 1 Measured surface profile for IM trials

A meniscus shape surface profile was observed across all the trials. For lower filling levels, the melt's height was higher, leading to more significant surface deformation. This trend was repeated for different power supplies, with the top surface of the melt higher for the 40 kW than the 25 kW case, with the position of the crucible wall probes remaining in a similar place.

3 Numerical Procedure

The numerical model was developed using the finite element tool COMSOL Multiphysics 6.2®. Due to the symmetry of the IM furnace, an axisymmetric 2D model was considered, thus reducing the size of the geometry to be discretized. Based on the dimensions of the IM furnace, the geometry and domains corresponding to the molten aluminum, the crucible of Al_2O_3, the coil of copper and air were defined with their corresponding material properties. To determine the numerical model that rules the coupled magneto-hydrodynamic model, it was first necessary to derive Maxwell's equations in the frequency domain. The resulting equation for the conducting metal is as follows:

$$\mathbf{J_e}=(j\omega_f\sigma)\mathbf{A}+\nabla\times(\mu_r^{-1}\mu_0^{-1}\nabla\times\mathbf{A})+\sigma\mathbf{u}\times(\nabla\times\mathbf{A}) \quad (1)$$

The external current density (J_E) derives from the magnetic field generated by the coil. To model this phenomenon, in the coil solid section the measured power cases have been imposed.

$$P_c=1/2\mathrm{Re}(V_C I_C^{*}\cos(\varphi)) \quad (2)$$

Concerning the fluid dynamics sub-model, the typical Navier-Stokes equations for the conservation of mass and momentum over time have been considered.

$$\nabla\cdot(\rho\mathbf{u})=0 \quad (3)$$

$$\rho(\partial\mathbf{u}/\partial t+(\mathbf{u}\cdot\nabla)\mathbf{u})=\nabla\cdot[-p\mathbf{I}+\mathbf{K}]+\mathbf{F}+\rho\mathbf{g} \quad (4)$$

For the reproduction of turbulence, two additional transport equations are added: the turbulent kinetic energy (k) and dissipation (ε), based on the standard k-ε model and for the model parameters [4].

The necessity for enabling displacement and interaction between phases prompted the adoption of the moving mesh method, utilizing the Arbitrary Lagrangian-Eulerian (ALE) approach. This method tracks the moving boundaries by allowing mesh nodes to follow fluid flow. Free mesh normal direction deformation in the metal domain and slips to the metal-crucible wall boundary for tangential displacement were imposed. To ensure numerical stability during mesh displacement the Winslow smoothening method was employed.

4 Result and discussion

The results of the fixed mesh with the experimental measurements in the case of 25 kW power are represented in Figure 2. The model reproduces the free surface profile in the center of the metal, with an increasing discrepancy towards the walls of the crucible for all three cases of crucible filling. For the 40 kW case, similar trend of the surface profile is achieved, although the discrepancy with the experiment is larger.

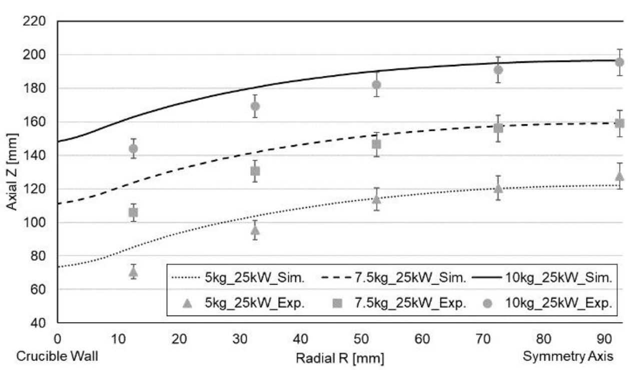

Figure 2 Free surface profile for 25 kW with fixed mesh

In the second case with the moving mesh model, the model also reproduces the free surface profile in a relatively correct way, approaching the experimental measurement, particularly in the region close to the wall (Figure 3). However, in the case of 40 kW and 5 kg, the simulation did not converge, due to the distortion of the grid elements during mesh displacement.

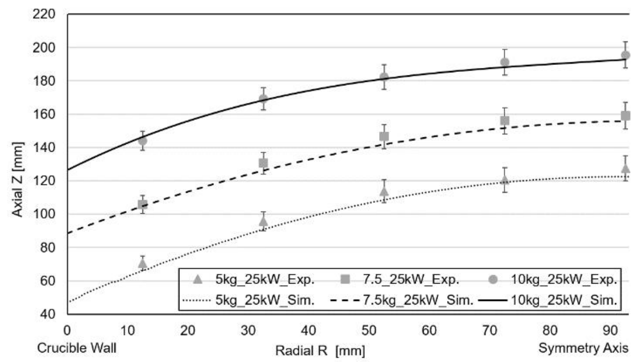

Figure 3 Free surface profile for 25 kW with moving mesh.

5 Conclusion

This analysis has shown the importance of the method employed to define the type of mesh and its impact on the numerical results of magneto-hydrodynamic simulations of the free surface for the IM process. The results obtained indicate that the moving mesh method was more accurate and required less computational time. However, the method lost its validity for large deformations of the free surface, since the stretching and distortion of the mesh elements was excessive leading to computation convergence failures.

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