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Numerical Modelling of Free Surface Dynamics of Melt in Induction Crucible Furnace (ICF)

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Abstract

In this work the flow of Wood's metal alloy and its free surface dynamics in external electromagnetic field of axially symmetric ICF is analyzed. Applying ANSYS modeling features the 2D model for phase surface dynamics caused by inductor switch on is developed and current and frequency affect on dynamics discussed. The model verification is performed by free surface steady state result comparison to other models and appropriate experimental data. On the basis of obtained results the analysis of steady state free surface dependence on inductor current and frequency is performed.

Introduction

One of the overriding issues of metallurgical industry is to provide metallic materials with enhanced quality and refined engineering specifications (resistance to corrosion, mechanical, electrical characteristics etc.), simultaneously reducing energy demands and expenses, increasing productivity and ecological compatibility. In this context induction crucible furnaces (ICF) that ensure contact less control of hydrodynamic (HD) alloy stirring, temperature and free surface shape are widely applied.

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 undesirable admixtures found in atmosphere and crucible. For instance, in great industrial furnaces free surface of melt is usually covered with dross layer that appears to be both thermal and chemical insulator. Significant change in furnace operational current or frequency values may lead to free surface perturbation and undesirable contact between melt and active atmosphere accompanied with chemical reactions and thermal losses. Moreover, severe switches may even cause alloy to splash. In some cases, it is essential to reach overheating temperatures, consequently, thermal energy losses upon thermal conduction through crucible and melt contact regions should be reduced by increasing of free surface area. For especially pure alloys unique furnace design leads to melt levitation and in this case the contact between crucible walls and alloy is obviously forbidden (Fig. 1).

Fig. 1. Typical surface deformation in IF with cold crucible [3] (left) and melt levitation (right)

All the mentioned above clarifies that in such type of furnaces behaviour of meniscus shape might be slightly unsteady due to furnace parameter changes and turbulent HD oscillations that proves the necessity for precise prediction and manipulation ability of free surface. In this work the model for phase surface dynamics calculation in 2D axially symmetric consideration is developed and its verification performed by validation of oscillation frequency and comparison of steady state meniscus to other models and appropriate experimental data.

1. Former Research

Lorentz force density that arises as the result of interaction of external alternate electromagnetic (EM) field and induced currents can be split into two parts

$$\vec{f} = \frac{1}{\mu_0}\left(\nabla \times \vec{B}\right) \times \vec{B} = \frac{1}{\mu_0}\left(\vec{B} \cdot \nabla\right) \cdot \vec{B} - \nabla\left(\frac{\vec{B}^2}{2\mu_0}\right), \quad (1.1)$$

where $\vec{f}_{WH} = \frac{1}{\mu_0}\left(\vec{B} \cdot \nabla\right) \cdot \vec{B}$ is a whirling part of force and corresponds for HD stirring and $\vec{f}_{POT} = -\nabla\left(\frac{\vec{B}^2}{2\mu_0}\right)$ is potential part that gives the expression for EM pressure:

$$p_{EM} = \frac{\vec{B}^2}{2\mu_0} = \frac{\vec{B}_0^2}{4\mu_0}. \quad (1.2)$$

Varieties of articles are devoted to steady state meniscus shape calculations for ICF [1]-[2] in hydrostatic consideration taking into account only potential part of Lorentz force and neglecting the whirling part that corresponds for recirculative alloy movement. The hydrostatic steady state free surface in first approximation calculated as constant pressure surface considering hydrostatic, surface tension and electromagnetic pressure contribution where the last is derived from the potential part of Lorentz force (1.2).

More precise steady state free surface shape models are developed using the full Lorentz force for calculations and considering HD alloy movement. The first model [3] proposes that low magnetic Reynolds number allows splitting the problem in EM and HD parts and solving them consequently. At first the initial free surface is defined and using ANSYS Classic EM part is solved and Lorentz force distribution is found. Then HD part is solved with ANSYS/CFX using Volume of Fluid (VOF) features with RANS k-ε turbulence treatment and electromagnetic force found previously as mechanical momentum source. External solver component coupling ensures iterative approach for steady state free surface determination.

The second model [4] was developed in FORTRAN with advanced VOF algorithm and implementation of Local Height Function (LHF) that ensures better uncompressible fluid volume conservation and prevents from "numerical creation of unphysical holes".

Both models are verified with appropriate experiment [3] and typical results are shown in Fig. 5.

The calculation of free surface dynamics is based on assumption that for sufficiently small time interval the change in shape is so insignificant that during one time step Lorentz force distribution can be considered stationary. It is clear that appropriate time step should be several orders lower than transition process typical time scale *τ*. In case of surface oscillations, oscillation period *T* can be found analytically [5] treating Lorentz force as constant and radial that approximately is satisfied in consideration of small amplitude oscillations. In this simplified case the typical oscillation period *T* is fully dependent on crucible geometry (1.3)

$$T = 2\pi\sqrt{r_0 / \lambda_1 \cdot g \cdot tgh\left(\lambda_1 \cdot h_0 / r_0\right)}, \quad (1.3)$$

where r_0 is crucible inner radius, h_0 is initial melt filling and $\lambda_1 = 3.83$ - Bessel function J_1 solution. Approved correlation with experimental data obtained for formula (1.3).

2. Models

2.1. Hydrostatic Steady State Free Surface Model

The steady-state meniscus shape in ICF is formed by the external alternate magnetic field and it is clear that the shape of conductive alloy affects the field distribution too. Such reciprocal interaction determines the necessity of iterative method for free surface calculation.

Assuming that the free surface has a constant pressure, the meniscus shape in one iteration can be obtained from hydrostatic, electromagnetic and surface tension pressure equilibrium:

$$\rho g h = \gamma \left(\frac{1}{r_1} + \frac{1}{r_2} \right) + p_{EM} \, . \tag{1.4}$$

Axially symmetric single-phase induction crucible furnace with Wood's metal conductive alloy is considered (Fig. 2). 2D axially symmetric EM field distribution for constant meniscus shape is calculated using ANSYS. Then electromagnetic pressure (1.2) obtained is used for free surface equation (1.4) solution. In the end of iterative process the hydrostatic steady-state meniscus shape is obtained (Fig. 3).

EM calculations are performed on fixed structured mesh with refinement near free surface and wall regions. It is ensured that at least 5 mesh elements resolve EM field penetration depth δ

$$\delta = \sqrt{2\rho_{Wm} / \omega\mu_0} \, , \tag{1.5}$$

where ω is inductor current angular frequency and μ_0 – magnetic constant.

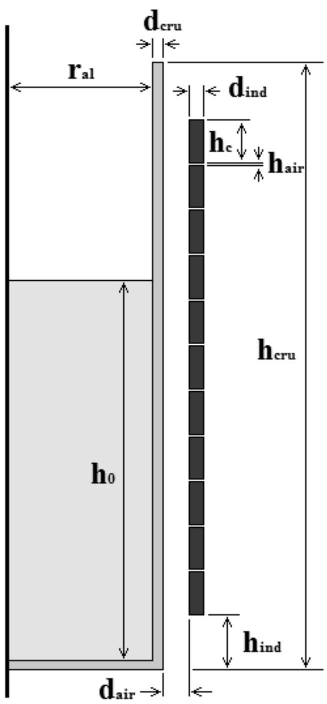
r_{al} = 15.8 cm
h_0 = 40 cm
h_c = 4.5 cm
h_{air} = 0.27 cm
h_{cru} = 63.1 cm
h_{ind} = 4.78 cm
d_{air} = 3.75 cm
d_{cru} = 0.1 cm
d_{ind} = 1.5 cm
N = 11

Non magnetic material specific resistivity $\Omega \cdot m$:

- inductor ρ_{Cu} = 0.16949e-7
- crucible ρ_{Fe} = 0.15e-6
- alloy ρ_{Wm} = 1e-6

Wood's metal:

- ρ = 9400 kg/m^3
- γ = 0.42 N/m



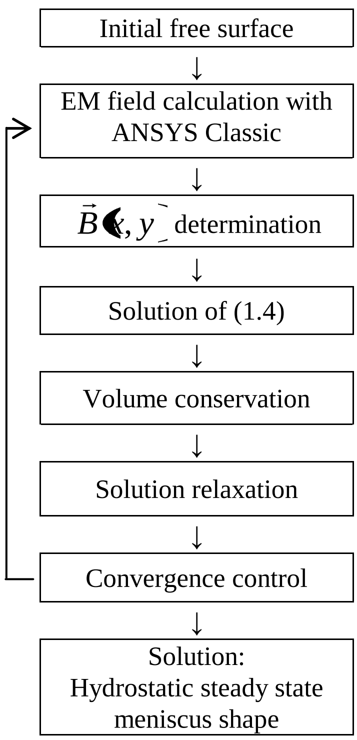


Fig. 2. 2D axially symmetric ICF model   Fig. 3. Calculation algorithm

2.2. Hydrodynamic Model for Free Surface Dynamics Calculation

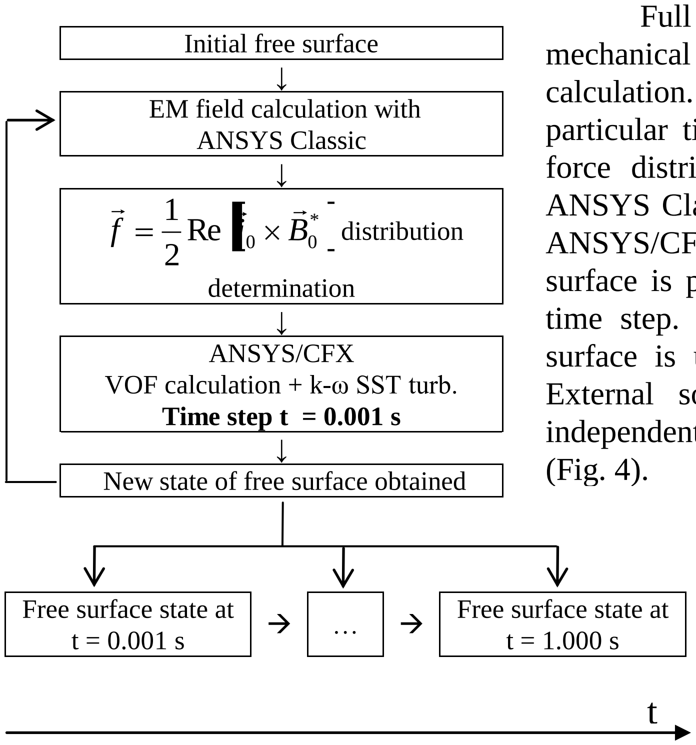


Fig. 4. Algorithm for dynamics calculation

Full Lorentz force (1.1) is used as mechanical momentum source for dynamics calculation. For fixed free surface shape at particular time moment EM field and Lorentz force distribution is calculated by means of ANSYS Classic. Then EM forces are loaded in ANSYS/CFX and VOF calculation of free surface is performed for one sufficiently small time step. Afterwards the new shape of free surface is used for recurrent EM calculation. External solver coupling ensures time step independent free surface dynamics computation (Fig. 4).

Self developed script in ANSYS Classic allows to perform 2D dynamics calculations with ambiguous transitional free surface states, for instance, several droplets of alloy levitate in atmosphere and, on contrary, air bubbles confined in alloy (see results).

3. Result Validation for Steady State Meniscus Shape

Hydrostatic and hydrodynamic model results for steady state meniscus shape are compared to other models [3]-[4] and experimental data [3] with Fig. 3 corresponding geometry. Effective inductor current I = 2 kA, alternate current frequency f = 385 Hz and initial crucible filling h_0 = 400 mm are used as input parameters.

None of models precisely describe experimentally measured meniscus shape near the crucible wall (r = 0.158 m). This might be concerned with oxides on the surface of melt that concentrate mainly in lowest regions of free surface and cause shape deformation in experiment.

Hydrodynamic model (solid line) shows a shade better agreement with experiment (points) rather than hydrostatic model (dashed line); however, alloy HD movement has a small effect on meniscus shape (Fig. 5).

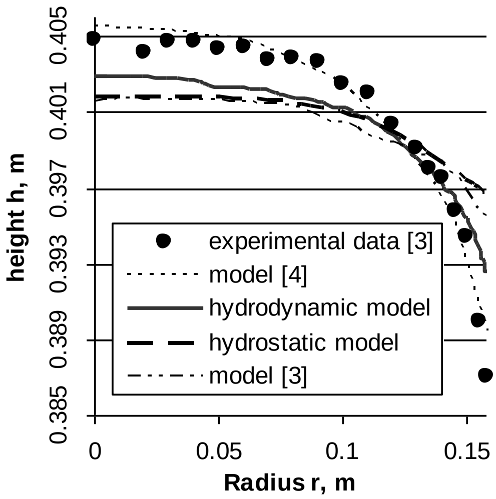


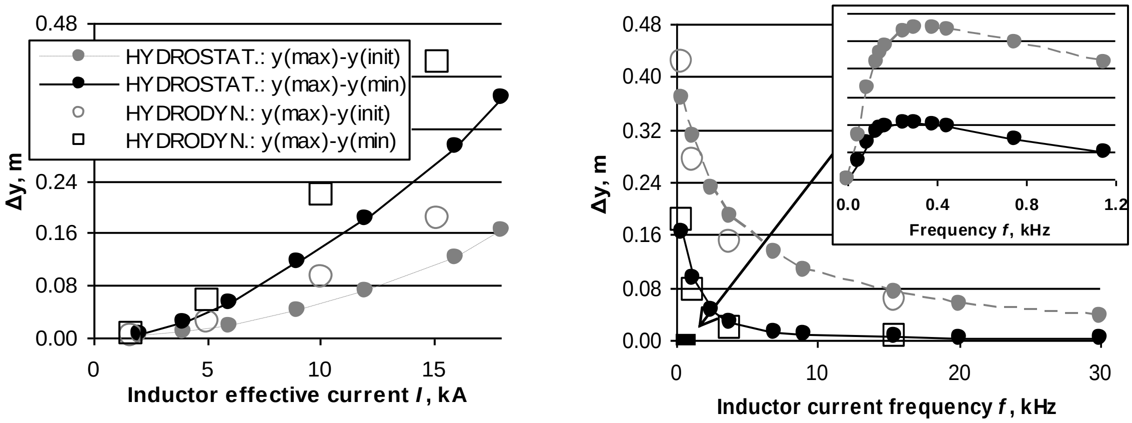
Fig. 5. Steady state meniscus shape. Models and experiment comparison

It was taken into consideration that ANSYS Classic works with amplitude input values for inductor current and calculates the distribution of Lorentz force, whereas ANSYS/CFX requests Lorentz force density distribution as input values for VOF calculation. Despite that model [4] has better agreement with experiment. Presumably, inaccuracy might be reduced using adaptive mesh rather than fixed for VOF calculations. This hypothesis proof forms part of further plans for research. However, model [4] and experiment parameter match should be verified.

4. Results

4.1. Steady State Meniscus Shape Dependence on Furnace Parameters

Steady state meniscus shapes were calculated with hydrostatic and hydrodynamic models varying inductor *I* with *f* held constant (Fig. 6, a) and conversely (Fig. 6, b). Enhancing current magnifies EM force that squeezes alloy radially and causes greater surface deformations and free surface area growth. For hydrodynamic model in first approximation maximal velocities are directly proportional to *I*. Greater flow intensities enlarge contribution of whirling part of EM force and cause growing differences between models results (Fig. 6, a).



a) *f* = 385 Hz b) *I* = 9 kA

Fig. 6. Hydrostatic and hydrodynamic models results for steady state meniscus height or y(max)-y(min) and height above initial level y(max)-y(init) dependence of a). *I* and b). *f*

Observing meniscus deformation dependence on frequency a good agreement between models obtained. Models also predict existence of particular frequency for which meniscus deformation is the greatest (Fig. 6, b). As well as there should be frequency for which flow intensity is the greatest. Increasing frequency forces out field and sharp surface deformation is obtained only very close to crucible. On symmetry axis surface is flat. Decreasing frequency leads to situation when alloy can be considered as absolutely transparent for magnetic field and on surface do not appear B_0^2 gradients that cause surface deformations.

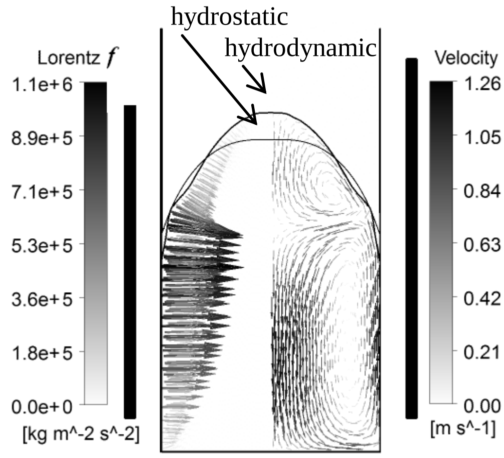


Fig. 7. Steady state flow pattern for *I* = 10 kA and *f* = 385 Hz

Typical results for quasi steady state flow pattern shown in Fig. 7.

4.2. Free Surface Dynamics Results

A time interval after inductor switch on is considered and it is assumed that before initial time moment crucible already contains liquid alloy and there is no current in inductor. For $t \geq 0$ s current momentary reaches the value of 5 or 10 kA. Three configurations are considered, basic case with *I* = 5 kA and *f* = 385 Hz, a case with enhanced current - *I* = 10 kA and *f* = 385 Hz and enhanced frequency - *I* = 5 kA and *f* = 3850 Hz. Free surface states for base configuration at different time moments are shown in Fig. 8.

Analytical estimation of characteristic oscillation period according to formula (1.3) gives the value of T_{teor} = 0.41 s that is in good agreement with calculated period T_{calc} = 0.39 s

(Fig. 9). Obviously, for small amplitude oscillations T is mainly defined by geometry and filling. Possible reasons for period discrepancies can be explained by Lorentz force dependence on meniscus shape that in analytical estimation [5] is neglected.

Smaller surface oscillation period correspond to greater current frequency values (Fig. 9). Greater frequencies lead to less field penetration and slighter alloy volumes with accordingly less time of inertia being set in motion.

Example of ambiguous surface state is shown at a particular time moment (Fig. 10).

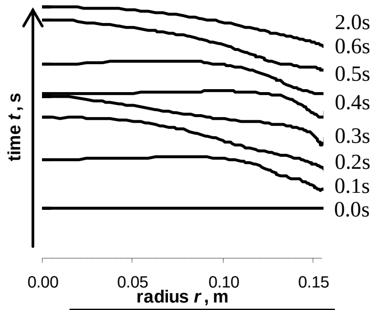


Fig. 8. Free surface dynamics. I = 5 kA and f = 385 Hz

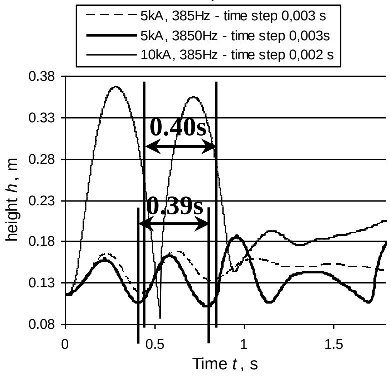


Fig. 9. Free surface point oscillations on symmetry axis. Typical oscillation period

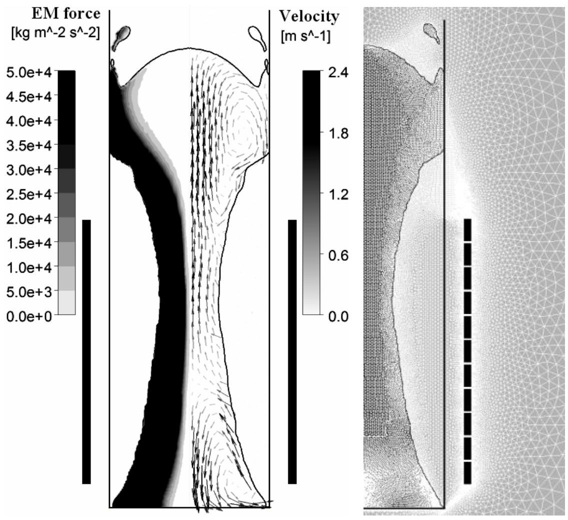


Fig. 10. Ambiguous free surface transient state. I = 32 kA and f = 385 Hz. Flow pattern and mesh

Conclusions

The model for ICF alloy free surface dynamics in 2D axially symmetric consideration is proposed. The verification of results for dynamics and steady state approves model accuracy. Model generalization for 3D and adaptation for LES turbulence treatment forms the further plans of research.

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