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► **To cite this version:**

S Spitans, E Baake, A Jakovics. Electromagnetic levitation melting of metals on a large scale: simulation and experiments. 8th International Conference on Electromagnetic Processing of Materials, Oct 2015, Cannes, France. hal-01336015

HAL Id: hal-01336015

<https://hal.archives-ouvertes.fr/hal-01336015>

Submitted on 22 Jun 2016

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Electromagnetic levitation melting of metals on a large scale: simulation and experiments

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Abstract

In this paper, a drip- and leakage-free approach for electromagnetic (EM) levitation melting of metallic samples in horizontal and orthogonal two-frequency fields is studied further. The developed numerical model is used to investigate instabilities of liquid metal shape excited by the interaction of two-frequency EM fields and to design a scaled-up experimental setup for a stable levitation melting of 500 g of aluminum for further validation of the method.

Key words: levitation melting, scale-up, free surface flow, two-frequency field, numerical simulation, LES

Introduction

Induction melting of metals under complete levitation conditions has two main advantages over conventional ceramic crucible or cold crucible induction furnaces. EM levitation in a non-reactive atmosphere prevents contamination of the melt with the crucible material and results in a significantly enhanced purity of alloy. Moreover, heat losses from the liquid metal are limited only to radiation and evaporation that permits EM processing at extremely high temperatures.

The levitation melting was invented in the 1920's [1], whereas the application started only thirty years later [2] as the first high-frequency generators became available. The method is well known for measurements of thermophysical properties, such as viscosity, surface tension and heat conductivity of molten metals in experiments with small levitated droplets of 1-10 mm in diameter [3]. However, levitation melting obviously meets requirements for a growing number of large-scale industrial applications [4].

In axisymmetric EM levitation melting furnaces, the Lorentz force vanishes at the symmetry axis [5]. The melt outflow and leakage can be hindered at this lowest point on the axis of a levitated sample mainly by melt surface tension. Therefore, the charge weight is limited to 50-100 g [6], and industrial needs for the scale-up remain unsatisfied.

The new method applies two EM fields of different AC frequencies, whose field lines in the absence of a charge are horizontal and orthogonal in order to exert EM lift forces also at the axis of the levitated sample [7], [8]. Therefore, the charge weight can be increased and the charge can be drip- and leakage-free melted.

A numerical model for simulation and optimization of a particular EM levitation melting technology has been developed and verified previously [9]. Computation of EM induced flow and free surface dynamics is ensured by means of external coupling between EM force recalculation in ANSYS, Volume of Fluid (VOF) simulation of a two-phase turbulent flow in FLUENT, free surface shape reconstruction in CFD-Post and a self-written surface filtering procedure.

The method for EM levitation melting in horizontal fields has been successfully validated by a series of experiments and 3D calculations in a novel two-frequency EM levitation melting setup [10]. In this work the developed numerical model is used to investigate stability of contactless EM confinement in two-frequency horizontal and orthogonal fields and to design an experimental setup for a stable levitation melting of 500 g of aluminum.

Stability of a liquid metal column in a two-frequency EM field

In a simplified XY-planar consideration, the instant Lorentz force density component f_{em}^x in two-frequency (ω_1 and ω_2) EM fields can be written as follows:

$$\begin{aligned} -f_{em}^x = & \frac{1}{2} \left\{ B_{y1}^{Re} \cdot J_{z1}^{Re} + B_{y1}^{Im} \cdot J_{z1}^{Im} + B_{y2}^{Re} \cdot J_{z2}^{Re} + B_{y2}^{Im} \cdot J_{z2}^{Im} \right\}^* \\ & + \frac{1}{2} \left\{ \left[B_{y1}^{Re} \cdot J_{z1}^{Re} - B_{y1}^{Im} \cdot J_{z1}^{Im} \right] \cdot \cos(2\omega_1 t) + \left[B_{y2}^{Re} \cdot J_{z2}^{Re} - B_{y2}^{Im} \cdot J_{z2}^{Im} \right] \cdot \cos(2\omega_2 t) \right\}^{**} \\ & + \frac{1}{2} \left\{ \left[B_{y1}^{Re} \cdot J_{z2}^{Re} + B_{y2}^{Re} \cdot J_{z1}^{Re} - B_{y1}^{Im} \cdot J_{z2}^{Im} - B_{y2}^{Im} \cdot J_{z1}^{Im} \right] \cdot \cos((\omega_1 + \omega_2)t) \right. \\ & \left. + \left[B_{y1}^{Re} \cdot J_{z2}^{Re} + B_{y2}^{Re} \cdot J_{z1}^{Re} + B_{y1}^{Im} \cdot J_{z2}^{Im} + B_{y2}^{Im} \cdot J_{z1}^{Im} \right] \cdot \cos((\omega_1 - \omega_2)t) \right\}^{***}, \end{aligned}$$

where B^{Re} , B^{Im} , J^{Re} and J^{Im} are, respectively, the real and imaginary parts of the magnetic induction and current density complex amplitudes, the lower indices denote the spatial component and the EM field frequency. Inverting the x and y indices and neglecting the ‘-’ sign in front of the force component will yield an expression for f_{em}^y .

The terms in the first parentheses $\{J\}^*$ are time-independent and correspond to the steady part of the Lorentz force. Note that eddy currents interact only with magnetic fields of the same frequency. That is why it is possible to apply the superposition principle to the Lorentz forces itself. In other words, the total steady Lorentz force induced by EM fields of two frequencies is the sum of the steady parts obtained separately in the first and in the second EM field.

The terms in the second parentheses $\{J\}^{**}$ stand for the oscillatory part of the Lorentz forces. It is a common practice to neglect them as they oscillate with a double EM field frequency. If the frequency is high enough, the melt is not able to react against the rapidly oscillating force due to inertia.

The terms in the third parentheses $\{J\}^{***}$ stand for the cross-interaction between eddy currents and magnetic fields of different frequencies. Terms, which oscillate with a frequency of $\omega_1 + \omega_2$ can be also neglected if the frequency is high, however, terms, which oscillate with a frequency of $\omega_1 - \omega_2$ can be neglected only if the difference of two frequencies is also high enough.

An appropriate choice of two different frequencies makes it possible to consider only the steady part of the Lorentz force and reduce computational efforts significantly. In order to prove that, we have developed a conceptual 2D-planar model of the two-frequency levitation melting setup from [10] (Fig. 1a) and considered oscillations of a liquid column in a two-frequency EM field.

At the initial time moment $t = 0$ s, the column has the initial radius $r = 15$ mm and zero velocity. The frequency f_1 is varied from 25000.25 Hz to 25020.00 Hz and the second frequency $f_2 = 25000$ Hz is fixed. Because f_1 and f_2 are in the range of several kHz, we neglect the Lorentz force terms with $\cos(2\omega_1 t)$, $\cos(2\omega_2 t)$ and $\cos((\omega_1 + \omega_2)t)$. Only the steady part and the $\cos((\omega_1 - \omega_2)t)$ term are considered. We ensure Lorentz force recalculation due to the changes of the shape, time evolution and track oscillations of the column radius r in the direction of the largest deformation (Fig. 1b).

In case of two different frequencies $f_1 > f_2$, a typical period $T = 1/(f_1 - f_2)$ can be calculated. At a time moment $t = n \cdot T$ ($n = 0, 1, 2, \dots$), the melt is squeezed by the Lorentz forces in one direction and at $t = n \cdot T + T/2$ in the orthogonal direction. At $t = n \cdot T + T/4$ and $t = n \cdot T + 3T/4$, the EM field, respectively, rotates clockwise and counter-clockwise and the melt is confined in both orthogonal directions. Because of only four poles, the azimuthal Lorentz force component is too small.

If the frequency difference is large enough, e.g., $f_1 - f_2 = 20$ Hz, the change of the Lorentz force is so fast that the melt is not able to respond. This results in negligible oscillations of a radius r and a steady flow pattern generated by the steady part of the Lorentz force (Fig. 1b).

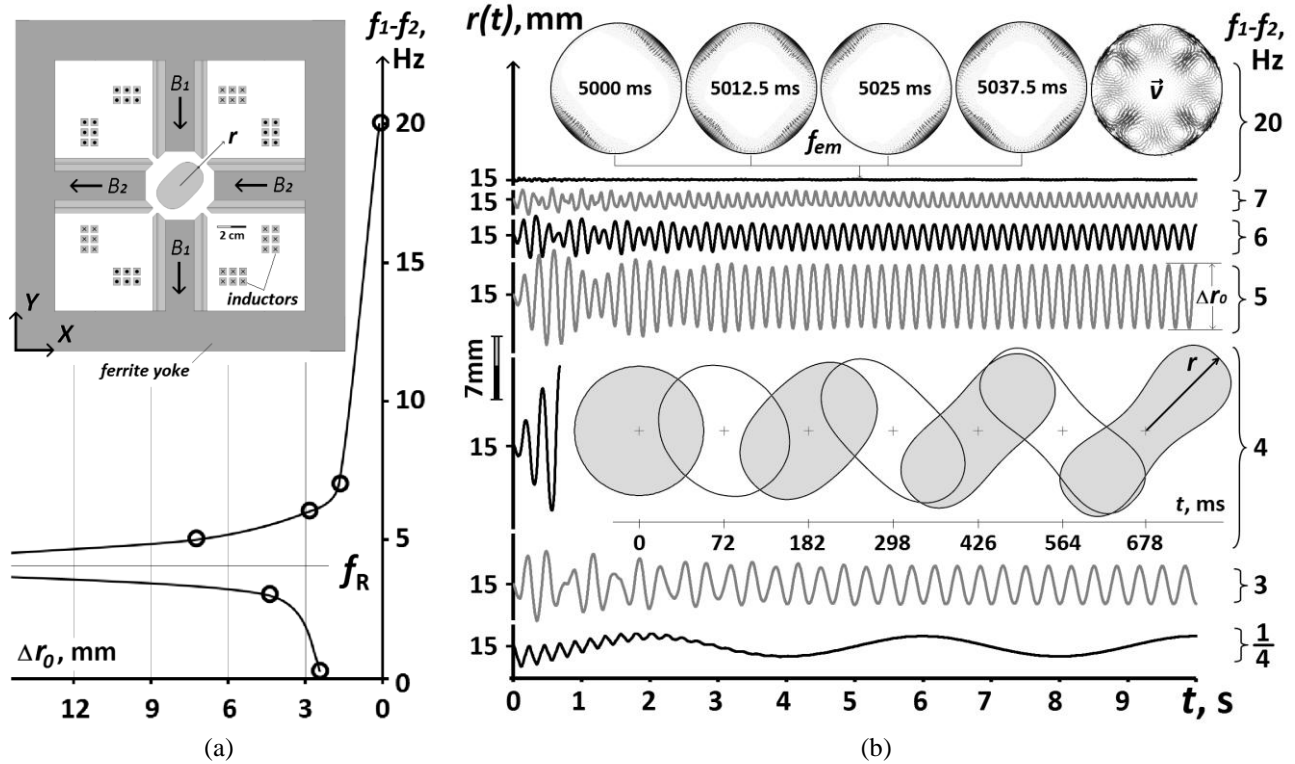


Fig. 1: 2D-planar model of the two-frequency levitation melting setup and simulation dynamics for the liquid column oscillation amplitude Δr_0 dependence on $f_1 - f_2$ (a), as well as oscillation dynamics $r(t)$ (b).

As the frequency difference f_1-f_2 decreases, the amplitude $r_{max}-r_{min}=\Delta r_0$ of the fully developed oscillations increases (Fig. 1a). At $f_1-f_2 = 4$ Hz, the oscillations of the liquid column evolve so fast that in less than 1 s the metal touches the ferrite pole, and it is not possible to detect Δr_0 (Fig. 1b). The resonance frequency appears to be the Rayleigh frequency f_R for the fundamental oscillation mode [11]. In case of our 2D-planar column, it can be calculated as

$$f_R = \frac{1}{2\pi} \sqrt{\frac{6\gamma}{R^3\rho}} = \frac{1}{2\pi} \sqrt{\frac{6 \cdot 0.9}{0.015^3 \cdot 2300}} = 4.2 \text{ Hz.}$$

As we continue to decrease f_1-f_2 , in the considered case of small inductor current, the oscillation amplitude Δr_0 goes down to a minimum (Fig. 1a). However, this part of the graph is dependent on the ratio between the electromagnetic and the surface tension forces and might have another maximum near $f_1=f_2$.

Eventually, in order to suppress the natural free surface oscillations and consider only the steady part of the Lorentz force, the frequency difference f_1-f_2 must be much greater than the Rayleigh frequency f_R . The requirement is easy to fulfill in practice, because the typical AC frequency range for the levitation melting is 1-100 kHz, whereas the fundamental mode is within several Hz.

Numerical simulation of EM levitation melting scale-up

Using the developed and verified numerical model, the two-frequency EM levitation melting furnace has been optimized to meet conditions for a stable levitation melting of 500 g of aluminum.

The final scale-up configuration has a ferrite yoke and two pairs of inductors arranged on the orthogonal lines (Fig. 2b). Each pair of the coils is fed by an effective current of $I_{ef} = 1.1$ kA at frequencies $f_1 = 30$ kHz and $f_2 = 40$ kHz, accordingly. Both EM frequencies and their difference are high enough to consider only the steady part of the Lorentz force in our numerical simulation.

The specific shape of the yoke enhances the concentration of the magnetic field in the gap region. Alignment of the inner inductor turn at the inner edge of the ferrite poles reduces the parasitic magnetic field looping through the neighboring poles. The outer ferrite ring separates the closing magnetic flux that might decrease the magnetic field in the gap region.

A transient 3D simulation was performed, using a spherical free surface shape with a diameter of 7.5 cm and zero velocity at $t = 0$ s. As the flow became fully developed, the time averaging for the next 5 seconds was performed.

The close-up of the time averaged molten aluminum shape, the levitation melting furnace, as well as the symmetry planes of the inductor coils used for representation of the Lorentz force and melt velocity are shown in Fig. 2a. The lower part of the melt appears to be stable, as it is tightly confined by the high frequency EM field, whereas the upper part above the inductors is fluctuating due to the turbulent and unsteady flow. The Lorentz force minimum at the magnetic field separation points creates four bulges of the free surface next to the ferrite poles.

Experimental setup has been manufactured for validation of the simulated scaled-up configuration (Fig. 2c).

Time-averaged results for the free surface shape, Lorentz force (Fig. 3a) and the flow (Fig. 3b), as well as the instant free surface shape and velocity (Fig. 3c), are shown on the orthogonal cross-sections. The Lorentz force domination at the bottom of the melt contributes to a formation of one toroidal vortex with a maximum velocity of 0.4 m/s.

The 3D transient calculation with a precise LES turbulence model shows that the levitation of 500 g of molten aluminum is possible in a horizontal two-frequency EM field configuration. Experimental validation of numerical results determines the future research.

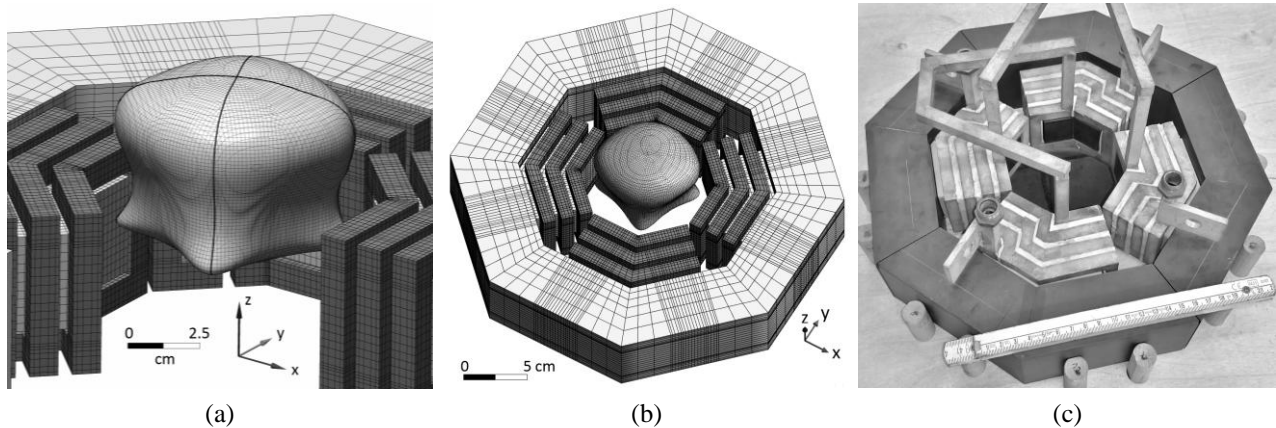


Fig. 2: A 3D model of a scaled-up and optimized two-frequency EM levitation melting setup (b), a close-up of the time averaged shape of molten aluminum ($m = 500$ g) with two orthogonal planes for representation of results (b) and manufactured experimental setup for further validation of numerical model (c).

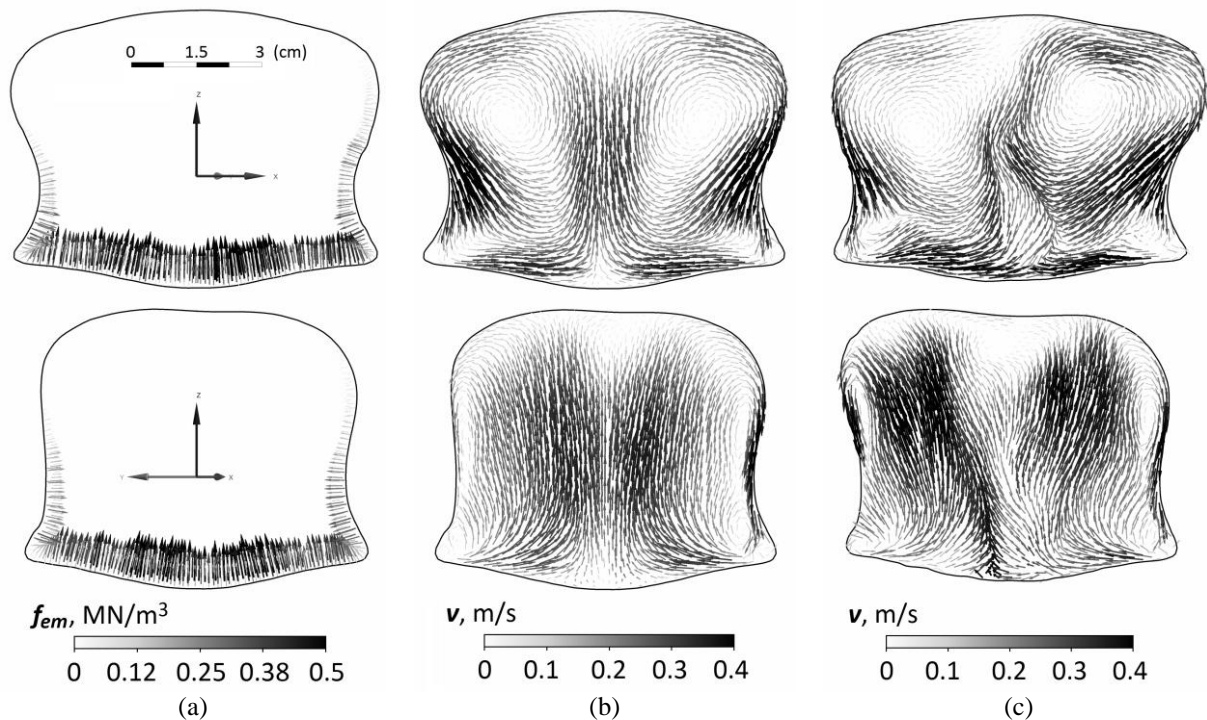


Fig. 3: 3D LES numerical results for the time-averaged free surface shape, Lorentz force (a) and velocity pattern (b), as well as instant flow (c) over the orthogonal cross-sections.

Conclusions

- The appropriate choice of two different AC frequencies for levitation melting in horizontal fields makes it possible to account only for the steady part of the Lorentz force, therefore to avoid resonance with Rayleigh frequencies and to reduce computational efforts significantly.
- Using the developed and verified numerical approach, the design of the furnace has been tailored to meet the conditions of stable EM levitation of 500 g of molten aluminum.
- Experimental validation of numerical results for the scale-up configuration is on top of the day.

Acknowledgment

The current research was performed with the 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 are grateful to the German Research Association for supporting this study under grant No. BA 3565/3-2. The authors would like to thank Prof. Dr.-Ing. O. Pesteanu (*1945-†2012) for the development of a particular technology and acknowledge his contribution and support in this research.

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