Oscillations of the Electromagnetically Levitated Liquid Droplet

Hailin Li[1], Dongsheng Yuan[1], Youpeng Huangfu[1], Hanke Feng[1], Shuhong Wang[1], *senior member of IEEE*, and Jianguo Zhu[2]

[1]State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering, Xi'an Jiaotong University, 28 West Xianning Rd, Xi'an 710049, China, shwang@mail.xjtu.edu.cn
[2]University of Technology, Sydney, PO BOX 123 Broadway NSW 2007, Australia, Jianguo.Zhu@uts.edu.au

Numerical simulation of the electromagnetic levitation method is conducted by employing the finite element method. The electromagnetic levitation method could be used for the thermal physical properties measurement of reactive liquid metals. This process involves Multiphysics coupled problem, which coupled the electromagnetic, thermal, and fluid flow fields. The oscillations of the suspended liquid metal droplet is computed. The moving and deformation of the liquid droplet under the influence of electromagnetic force are tracked by adopting arbitrary Lagrangian-Eulerian (ALE) formulation. The dynamic model put forward in this paper could be used for the thermal physical properties measurements of reactive metal in uncontaminated conditions.

***Index Terms*—arbitrary Lagrangian-Eulerian (ALE) formulation, electromagnetic levitation, liquid droplet, oscillations.**

I. Introduction

Electromagnetic levitation (EML) method becomes increasing significant for thermalphysical properties measurement of reactive molten metals for its accuracy and reliability. EML provides a good way for non-contact measurement. And it also has the following advantages [1]: undercooled state could be maintained for a certain time; high temperature could be achieved. Some researchers have conducted studies of the EML. Jonghyun observed performances by adopting the magneto hydrodynamic theory to research the convection inside the levitated Co-Cu droplets [2]. Bojarevics analyzed oscillations of the levitated liquid droplet in AC and DC magnetic fields by using the pseudo-spectral technique and Lagrangian method to solve the turbulent fluid flow field and track its free surface [3].He also studied the levitation melting process of metals under the frequency AC and DC magnetic field [4]. Sergejs studied the free surface dynamics of melt of the EML by using conbinition of the commercial software ANSYS and FLUENT [5-7]. However, only the electromagnetic, fluid flow field were coupled.

By adopting the Lagrangian method when it comes to large deformations, the mesh would be distorted, even inverted. The arbitrary Lagrangian-Eulerian (ALE) formulation combines merits of Eulerian and Lagrangian formulations and overcomes their shortcomings at the same time. The ALE formulation has been successfully used to track the shape of fluid flow in many numerical simulations [8], [9].

In this paper, the oscillations of the suspended liquid metal droplet is computed. And the moving and deformation of the liquid droplet under the influence of electromagnetic force are tracked by adopting arbitrary ALE formulation while the two-way interactions of electromagnetic, thermal, and fluid flow fields are also performed.

II. Mathematical Model

A. Principle of EML

The schematic diagram of the EML is shown in Figure 1 (a). A sample placed at the vacuum ambient would be exposed to high frequency harmonic magnetic field, and the eddy current generated is concentrate on the surface of the sample because of skin effect. Usually, the coils consist of two parts: the levitation part which generates electromagnetic force to suspend the sample, and the stabilization part which prevents the sample from oscillating. The calculation model is given in Figure 1(b).

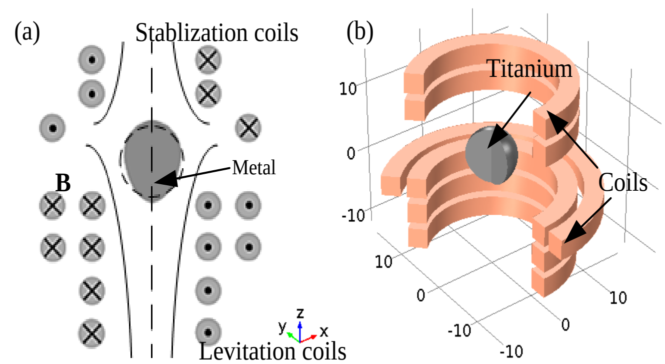

Fig.1. (a) Schematic diagram of EML and (b) its calculation model

B. Governing equations

Since the thermal time constant is typically 104 times larger than the electrical time constant, it would be difficult to solve such fully-coupled system. We model electromagnetic problem as a time-harmonic system weakly coupled to a time-transient non-linear thermal and fluid flow system. The time step is 0.01 s for both thermal, fluid flow fields.

1）Magnetic field governing equations

A harmonic magnetic field is generated due to AC current exerted on the excitation coils.

For eddy current simulation of axisymmetric model in the eddy current region, $\dot{A}_\theta = A_\theta \mathbf{e}_\theta$, A_r=A_z=0. Hence, the final governing equations for eddy current region are:

$$\frac{1}{\mu_0 \mu_{em}}\left[\frac{\partial}{\partial z}\left(\frac{1}{r}\frac{\partial(r\dot{A}_\theta)}{\partial z}\right)+\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(r\dot{A}_\theta)}{\partial r}\right)\right]=j\omega\sigma\dot{A}_\theta$$

$$\dot{J}_\theta = -j\sigma\omega\dot{A}_\theta$$

where μ_{em} is the relative permeability, μ_{em}=1, and μ_0 is the vacuum permeability, σ is the electrical conductivity which is dependent on temperature, ω is angular frequency. $\dot{\boldsymbol{J}}_\theta$ is the eddy current density. $\dot{\boldsymbol{J}} = \dot{J}_\theta \mathbf{e}_\theta$, $\boldsymbol{J}_r$=$\boldsymbol{J}_z$=**0.**

2）Thermal and fluid flow field governing equations

The governing equations of thermal field and fluid flow field (incompressible and Newtonian fluid flow) of transient analysis can be described as follows:

$$\rho\nabla\cdot\boldsymbol{u}=0$$

$$\rho\,\partial\boldsymbol{u}/\partial t+\rho\boldsymbol{u}\cdot(\nabla\boldsymbol{u})=\nabla\cdot\left\{-p\mathbf{I}+\mu\left[\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^{\mathrm{T}}\right]\right\}+\boldsymbol{f}$$

$$\rho C_{\mathrm{p}}\left[\partial T/\partial t+(\boldsymbol{u}\cdot\nabla)T\right]=\nabla\cdot(k\nabla T)+q$$

where ρ is current density of the metal, μ is the viscosity, k is the thermal conductivity, $\boldsymbol{u}$ is velocity vector, $\mathbf{I}$ is unit diagonal matrix, $\boldsymbol{f}$ is volume force, T is temperature, p is the pressure, C_{p} is the modified specific heat which accounts for latent heat, q is the heat source term.

III. Results and Discussion

A. Oscillations of the liquid metal droplet

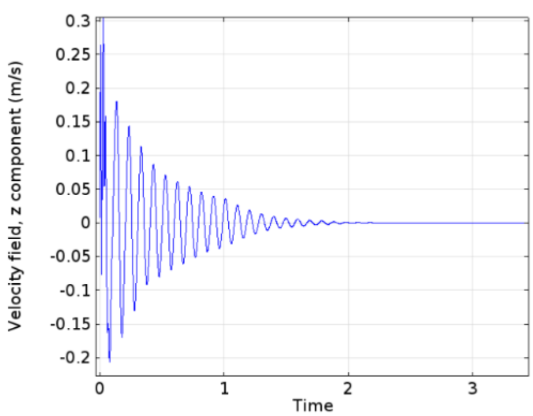

Fig.2. The velocity at the top position of the liquid droplet.

This part presents the simulation results of the liquid metal droplet, which include the oscillations of the top position of liquid metal droplet and the shape deformation of its surface.

The oscillations of top position is given in Figure 2 which presents the velocity at different time. And the shape deformation during the oscillation process are also shown in Figure 3.

IV. Conclusions

The mathematical model presented in this paper could be used as a numerical tool to study the thermal properties of the liquid metal with the container eliminated. However, the measurement could be interfered by the oscillations caused by the gravity and electromagnetic force. And this is the situations should be avoided. The mathematical model could be used study the matters that could affect the measurement and try to minimize their effects.

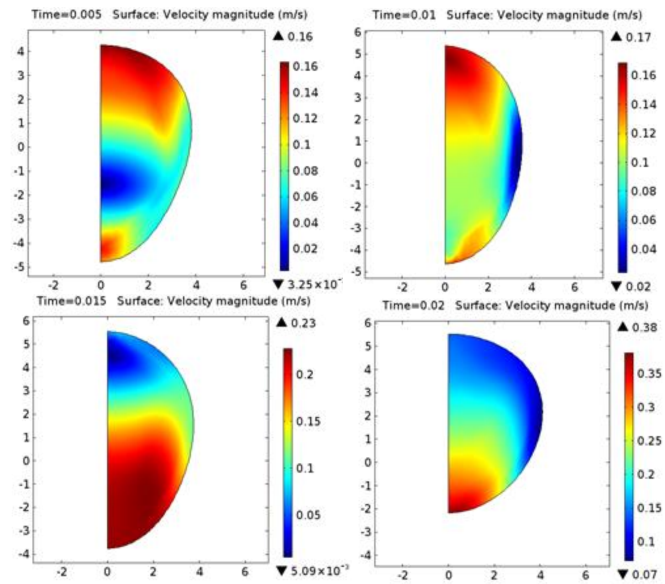

Fig.3. The deformation of liquid droplet under the exertion of electromagnetic force at different time

References

[1] Bakhtiyarov, Sayavur I., and D. A. Siginer, “Electromagnetic Levitation, Part II: Thermophysical Property Measurements in Terrestrial Conditions,” *Fluid Dynamics & Materials Processing*. Vol.4, no.3, 2008, pp.163-184.

[2] Jonghyun Lee, *et al*, “Magnetohydrodynamic Modeling and Experimental Validation of Convection Inside electromagnetically Levitated Co-Cu Droplets,” *Metallurgical and Materials Transactions B*, 45b, 2014, pp.1018-1023.

[3] Bojarevics, Valdis, and K. Pericleous, “Modelling electromagnetically levitated liquid droplet oscillations,” *Isij International* vol.43, no.6, 2003, pp.890-898.

[4] Bojarevics, Valdis, and K. A. Pericleous, “Dual frequency AC and DC magnetic field levitation melting of metals,” *International Journal of Applied Electromagnetics & Mechanics* vol.44, no.2, 2014, pp.147-153.

[5] Spitans, Sergejs, *et al*, “Numerical Modeling of Free Surface Dynamics of Melt in an Alternate Electromagnetic Field: Part I. Implementation and Verification of Model,” *Metallurgical & Materials Transactions B* vol.44, no.3, 2013, pp.593-605.

[6] Spitans, S., *et al*, “Numerical Simulation of Electromagnetic Levitation in a Cold Crucible Furnace,” *Magnetohydrodynamics* vol51, no.3, 2015, pp.567-578.

[7] Spitans, Sergejs, *et al*, “Numerical Modeling of Free Surface Dynamics of Melt in an Alternate Electromagnetic Field. Part II: Conventional Electromagnetic Levitation,” *Journal of Iron & Steel Research* vol.47, S1, 2012, pp.593-605.

[8] Braess, H. and P. Wriggers, “Arbitrary Lagrangian Eulerian finite element analysis of free surface flow,” *Computer Methods in Applied Mechanics and Engineering*, vol.190, pp. 95-109. 2000.

[9] Kai, Y., H. Fangjun, and C. Ping, “A fully coupled numerical simulation of sessile droplet evaporation using Arbitrary Lagrangian-Eulerian formulation,” *International Journal of Heat and Mass Transfer*, vol. 70, pp. 409-420. 2014.