International Scientific Colloquium
Modelling for Material Processing
Riga, September 16-17, 2010

Magnetic Levitation of Large Liquid Volume

V. Bojarevics, A. Roy, K. A. Pericleous

Abstract

Magnetic levitation confinement mechanism for volumes of fluid larger than 10-1000 ml is investigated. Levitation of a large volume of liquid is achievable when, in addition to the surface tension effects, the imposed external body force generates a strong tangential upward flow along the curved bottom surface of the liquid. The dynamic interaction of the flow along the moving interface, confined by the magnetic force, is analysed using the spectral numerical model SPHINX. Additionally, 3D solution using the finite element package COMSOL shows that the electromagnetic field in the levitated liquid metal is approximately axisymmetric, and is largely unaffected by the presence of the copper crucible segmented structure. The presence of the segments significantly reduces the overall energy efficiency of the full crucible. Possible applications to processing of reactive metals are discussed.

Introduction

There is a growing number of applications where an electrically conducting fluid volume is confined or even levitated using a high frequency AC magnetic field. A well known example is the non-contact measurement of material properties, particularly of liquid metals or silicon which can be deduced from experimental observation of the thermal and surface oscillations in a levitated liquid sample (typically 1-10 mm in diameter) [1]. On a larger scale, there is a demand for melting reactive materials without contamination, for example titanium alloys, for high quality castings. However, it is often difficult to achieve the required superheat in the melt with traditional 'cold' crucible-type furnaces due to a partial contact with the water cooled copper walls [2]. If the contact was avoided, thermal losses would be limited only by radiation and possible evaporation. This would produce a higher superheat and permit investigation of materials at extreme temperatures, allow large volumes of metal to be evaporated for coating purposes [3], or to supply superheated melt without contamination for metal powder production.

Existing experimental evidence suggests that it is possible to melt and levitate several kilograms of liquid metal [4], but the underlying mechanisms are not understood completely. A very challenging example of 'semi-levitating' up to 500 kg of molten titanium is presented in a recent publication [5]. In the present work, we show by numerical simulation that it is possible, with optimised geometry, to levitate 2 kg of liquid metal without allowing contact to occur with the cold crucible walls. Two independent numerical models: the commercial package COMSOL and the spectral-collocation based free surface code SPHINX [6] are used for this task. SPHINX solves the transient electromagnetics, fluid flow and thermodynamic equations, which describe the dynamic behaviour of the levitated droplet. COMSOL is used to investigate 3-dimensional features of the electromagnetic field associated with the finger segments, and to confirm the validity of an assumption used in the

SPHINX analysis - namely that the field seen by the levitated charge is approximately axisymmetric.

1. Numerical Model SPHINX

The SPHINX model is based on the numerical solution of the turbulent momentum and heat transfer equations for an incompressible fluid with variable effective viscosity ν_e, which is computed from the time dependent 2-equation k-ω model [2,6]. The boundary conditions at the external free surface are stated for the hydrodynamic stress tensor Π component projections on the surface. In addition to the dynamic boundary conditions, the calculated material fluid velocity $\mathbf{v}(t)$ moves continuously the interface position $\mathbf{R}(t)$, giving the instantaneous liquid shape. The thermal boundary conditions are the radiation loss on the free surface of the levitated fluid. SPHINX uses the k-ω turbulence model which allows for the effect of magnetic field on turbulence. The coupled set of equations are solved numerically using continuous transformation functions to account for shape change in the physical space, and the spectral-collocation method based on Chebyshev-Legendre transformations [6].

The electromagnetic force is computed using the integral equation representation for the axisymmetric shape of the metal, coil and the effective representation of the cold crucible wall. The electric current distribution is given by the magnetic vector potential $\mathbf{A}$, the electric potential φ and the motion induced part $\mathbf{v}\times\mathbf{B}$. On the other hand, the electric current distribution is related to the magnetic field $\mathbf{B}=\nabla\times\mathbf{A}$ and the vector potential $\mathbf{A}$ by the Biot-Savart law to the electric current distribution, which permits to solve the electrodynamic equations efficiently in the axisymmetric case of harmonic fields. The motion induced contribution $\mathbf{v}\times\mathbf{B}$ gives the time average (over the AC period) contribution to the electromagnetic force.

2. COMSOL Model and Comparison to SPHINX

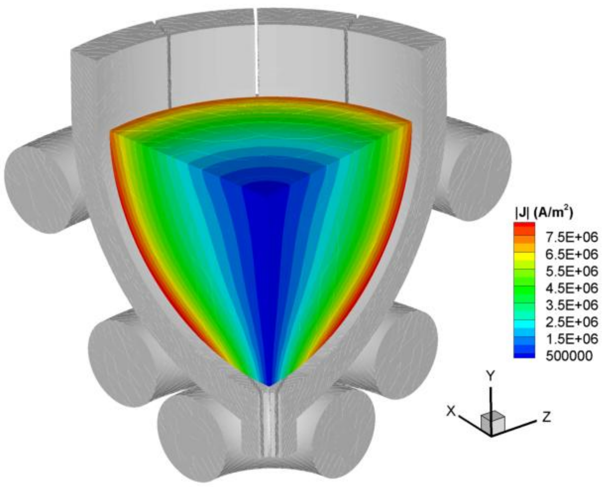

Fig. 1. One quarter of the crucible showing |**J**| in the titanium computed with COMSOL; coil current I_{eff}=5 kA, f=2 kHz

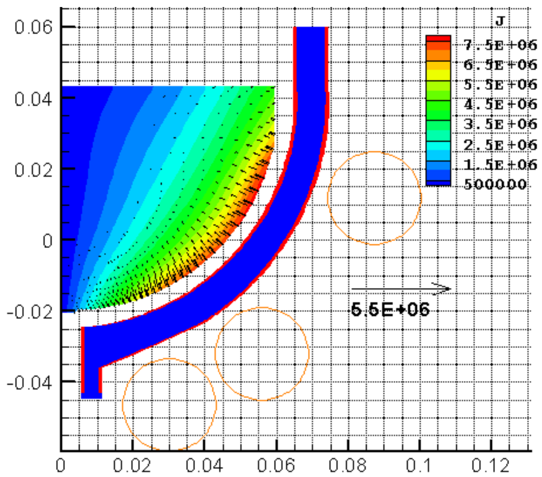

Fig. 2. Axisymmetric solution showing |***J***| and the force distribution in the titanium computed by the SPHINX model; coil current I_{eff}=5 kA, f=2 kHz

COMSOL was used to predict the 3D electromagnetic field in a crucible consisting of the three turn coil, sixteen copper segments (fingers) and a hemi-spherical titanium charge of fixed geometry. The induced electric current concentrates on the inner surfaces of the coil and is confined to a thin skin as indicated in Fig. 3. Current **J** penetrates to a greater depth in the titanium due to the lower electrical conductivity. Allowing for some minor discrepancies, the 3D distribution of |**J**| in the charge produced with COMSOL (Fig. 1) was in good agreement with corresponding 2D results by SPHINX using the integral equation (Fig. 2). Hence it can be concluded that, the averaged axisymmetric approach implemented in SPHINX is sufficiently accurate to represent the effect of the full 3D electromagnetic field in the titanium, which is the main region of interest for this modelling.

To model the crucible, we exploit periodicity of the field and consider an appropriate 3D wedge of the geometry consisting of half a segment and half a gap. Fig. 3 shows 3D streamlines of magnetic flux passing through the air gap between two adjacent copper wall segments. Some flux penetrates the segments but it is confined to a thin skin-layer. In the titanium charge the lines are distributed more uniformly along the azimuthal direction. The relatively low frequency (2 kHz) used in this example permits visualisation of the field within the copper segments. The magnitude of |**J**| is indicated by the colour flooding. Plots of J_z component (not shown) suggested that very little current flows axially in the segments, but this is thought to depend on the particular arrangement of the geometry. The magnitude of induced current density is rather non-uniform over the external surfaces of the copper fingers. This reflects the position of the coils turns.

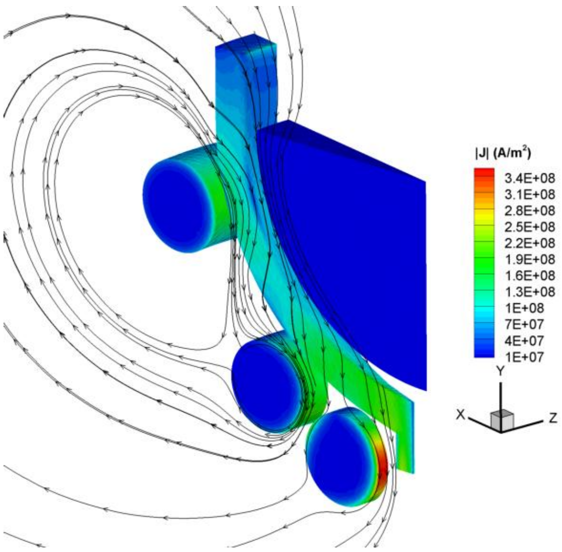

Fig. 3. Model showing (i) 3D streamlines of magnetic flux squeezing through the space between the fingers and (ii) scalar plot of |**J**| with Ieff=5kA and f=2kA (due to symmetry only half a finger/air gap is considered)

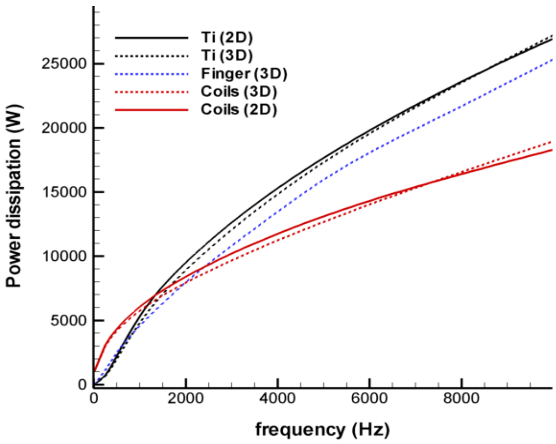

Fig. 4. Power dissipation in conducting regions as a function of frequency when Ieff=5 kA

Further insight to the quantitative behaviour of the electromagnetic integral characteristics is obtained by inspecting the total Joule heating in different conducting regions of the model. Fig. 4 shows how power dissipation depends on frequency and compares the 3D model (which includes the finger) with the 2D model (no fingers). The results indicate that Joule heating within the liquid titanium and the copper coil over the range of frequencies considered is largely unaffected by the presence of the finger segments. A very similar conclusion is apparent from the total force in the vertical direction (not shown) acting on the titanium load. As the frequency increases the force will asymptotically approach a constant value. The 3D effect of the fingers is very important when considering the total power requirements of the electromagnetic system. The internally circulating induced electric currents in the fingers account for a significant part of the total electrical energy consumption, as demonstrated in Fig. 4. The efficiency of the cold crucible for both the 2D and 3D cases reaches a saturation level at higher frequencies.

3. SPHINX Results for the Melt Dynamics

The axis-symmetric approximation is a reasonable choice for the liquid metal region, as we have seen from the results of the previous section. The integral equation formulation used in the SPHINX code avoids the need to mesh the surrounding air volume; instead the mesh used for the fluid dynamics can be directly used for the electromagnetic field calculations in the fluid. The additional current carrying regions (coil and the cold crucible wall) can be approximated as axisymmetric using the effective azimuthal current representation as described in previous publications [2,6]. The validity of this approach is supported by the COMSOL 3D simulations. The SPHINX model follows the dynamic development of the liquid surface supported by the magnetic force and the associated velocity field. The final position of the liquid metal surface is determined by the complex interaction of the induced electromagnetic fields in various regions and the turbulent fluid dynamic effects.

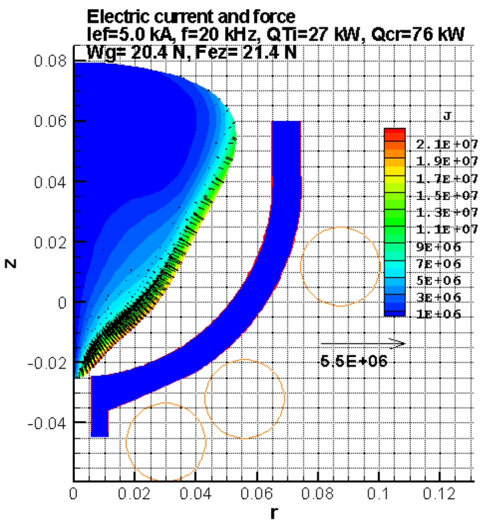

Fig. 5. Axisymmetric solution showing |**J**| and the force distribution in the hemi-spherical titanium at initial time moment; coil current I_{eff}= 5kA, f=20 kHz

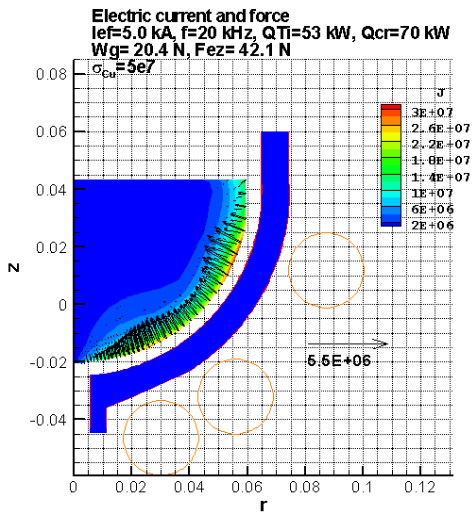

Fig. 6. Axisymmetric solution showing |**J**| and the force distribution in the magnetically levitated liquid titanium after several seconds of the flow and shape adjustment to a quasi-stationary shape computed by the SPHINX model; coil current I_{eff}= 5 kA, f=20 kHz

There is a pronounced dependence of the flow intensity on the applied AC field frequency because of the change in the electromagnetic field penetration depth. The cases considered in the previous section are limited to 2-10 kHz by the ability of the 3D finite element meshing to accurately resolve the skin effect in the conducting domains. A higher frequency AC field is preferable because of the lower penetration to the liquid domain, concentrating the magnetic confinement force near the surface and stabilising it. Therefore levitation of a large fluid mass needs a high frequency solution. The following solutions for stably levitated liquid metal were run using a higher AC frequency of 20 kHz. Fig. 5 demonstrates the electromagnetic solution at initial time for the hemispherically-shaped liquid metal zone. The electromagnetic force is concentrated in a thin skin-layer, and is variable along the boundary. The computed estimates give 70 kW of the power dissipated in the cold crucible walls (copper segments) and 53 kW of Joule heating for the liquid titanium. The computed total electromagnetic force in the vertical direction on the whole volume of the liquid metal is about 42.1 N, which well exceeds the total weight 20.4 N of the metal load.

However, the force distribution is such that the curl of the local electromagnetic force $(curl\ \mathbf{f}_{\mathbf{e}})$ drives intense fluid flow, the liquid interface moves and the electromagnetic force distribution changes in time. After several seconds of intense flow development, computed numerically in adjusting 2^{nd} order accurate implicit time stepping $(\Delta t \le 0.0005s)$ [6], the interface moves to the relatively stable position shown in Fig. 6 and 7 which show the electromagnetic and velocity field representations respectively. The total Joule heating decreases significantly compared to what was achieved with the initial hemispherical profile due to the surface being pushed away from the container walls. The total electromagnetic force acting on the fluid volume drops significantly, approaching in an oscillating way the value of the total weight of the liquid metal. During the surface and flow adjustment process the liquid surface performs several oscillations. The bottom initially flows down to reach the contact to the solid wall, but then is pushed up, detaches and, after several oscillations, assumes the quasi-steady levitated position. The zoom-in view for the bottom velocity field at a particular time is shown in the Fig. 8. The bottom shape is slightly oscillating which constantly readjusts the electromagnetic, velocity and temperature field. But on a larger scale the liquid appears to be levitated completely, being supported by the magnetic forces only.

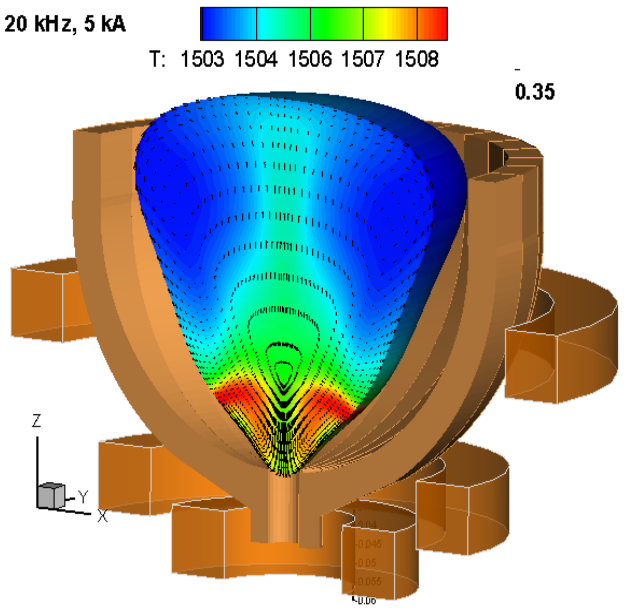

Fig. 7. The velocity field and temperature distribution in the magnetically levitated liquid titanium after several seconds of the flow and shape adjustment to a quasi-stationary shape computed by the SPHINX model

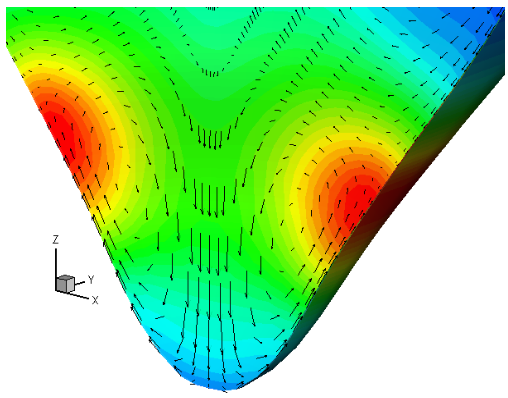

Fig. 8. The zoom-in to the velocity field at the bottom part of the magnetically levitated liquid titanium in a quasi-stationary shape

The mechanism of the levitation and particularly the magnetic support at the bottom appears to be dynamic in nature. The electromagnetic force is zero at the bottom tip position (see Fig. 6) and the surface tension effect is clearly not sufficient to support the 2 kg of liquid titanium in this rather rounded shape of relatively large curvature radius. The explanation for the fact that the liquid at the bottom is prevented from leaking and flowing down, is related to the particular velocity field in this region. The bottom vortex in Fig. 8 is maintained by the rotational nature of the electromagnetic force $(curl\ \mathbf{f_e} \neq 0)$, which drives the fluid tangentially upwards at the side surface of the liquid, away from the bottom stagnation point. Due to the continuity $(div\ \mathbf{v} = 0)$ of the velocity field the outflow at the bottom is redirected to the intense flow upwards along the side surface. The final appearance is rather smooth, but during the detachment process there are quite abrupt changes in the velocity field topology, requiring dynamic time step adjustment to account for the curvature change and the surface tension. To achieve the full levitation of the large fluid mass rather elaborate optimization of the bottom flow field is required. This involves multiple numerical test runs and adjustment of the coil position until the desired force field is created to ensure the dynamic balance at the bottom.

Conclusions

Two independent numerical codes are used to model the AC magnetic levitation of a large mass of liquid. The full 3D simulation using COMSOL shows that the field seen by the liquid metal is approximately axisymmetric and is largely unaffected by the presence of the finger segments. The integral equation approach in the SPHINX code permits high frequency solutions at dynamically adjusted surface positions. Full levitation of the liquid metal is achievable but requires careful optimisation of the electromagnetic force for generating tangential flow along the surface away from the bottom stagnation point. The bottom confinement is dynamic in nature.

References

[1] Egry, I., Diefenbach, A., Dreier, W., Piller, J.: *Containerless processing in space – thermophysical property measurements using electromagnetic levitation.* Int. J. Thermophys., Vol. 22, 2001, pp. 569-578.

[2] Bojarevics, V., Harding, R.A., Pericleous, K., Wickins, M.: *The Development and Validation of a Numerical Model of an Induction Skull Melting Furnace*. Metallurgical and Materials Transactions B, Vol. 35B, 2004, pp.785-803.

[3] Baptiste, L., van Landschoot, N., Gleijm, G., Priede, J., Schade van Westrum, J., Velthuis, H., Kim, T.-Y.: *Electromagnetic levitation: A new technology for high rate physical vapour deposition of coatings onto metallic strip.* Surface & Coatings Technology, Vol. 202, 2007, pp. 1189–1193.

[4] Tadano, H., Fujita, M., Take, T., Nagamatsu, K., Fukuzawa, A.: *Levitational Melting of Several Kilograms of Metal with a Cold Crucible*. IEEE Trans. Magn., Vol. 30(6), 1994, pp. 4740-4742.

[5] Okumura, T., Yamamoto, K., Shibata, M.: *Large Scale Cold Crucible Levitation Melting Furnace with Bottom Tapping Nozzle*. Proc. 6th Internat. Conf. Electromagnetic Processing Materials, Dresden, Germany, 2009, pp. 521-524.

[6] Bojarevics, V., Pericleous, K.: *Modelling Electromagnetically Levitated Liquid Droplet Oscillations*. ISIJ International, Vol. 43(6), 2003, pp. 890-898.

Authors

Dr. Bojarevics, Valdis
Dr. Roy, Alan
Prof. Pericleous, Koulis
School of Computing and
Mathematical Sciences
University of Greenwich
London SE10 9LS, UK
E-mail:v.bojarevics@gre.ac.uk
E-mail: A.A.Roy@gre.ac.uk
E-mail:
K.Pericleous@gre.ac.uk