

Influence of Coil Angle Arrangement on Dynamic Deformation and Stability of Molten Droplet in Electromagnetic Levitation System

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This work presents a transient simulation of electromagnetically levitated deformed droplet based on Arbitrary Lagrangian-Eulerian method. The magnetic, flow, temperature fields as well as free surface deformation of a molten aluminum droplet are coupled to investigate the influence of coil angle arrangement on dynamic deformation and stability of the droplet under terrestrial conditions. Our results confirm that the Arbitrary Lagrangian-Eulerian method can trace the interface of molten droplet more precisely and the calculation of surface effect is more reliable than that of VOF method. Simulation results show that the electromagnetically levitated molten droplet tends to oscillate in vertical direction and the sphere shape deforms largely at the very beginning of simulation. The dynamic deformation of the molten droplet is small during vertical oscillations since the density of aluminum is small. With the increasing of coil angle, the maximum velocity inside droplet decreases gradually and an over 10% difference is observed comparing with 0 and 30 degree coil angles. At the same time, the temperature of droplet declines significantly with the increasing of coil angles, which is of potential interest for temperature control improvement and undercooling processes in electromagnetic device. The deformation of droplet is observed to be most serious with a coil angle of 12 degree, which should be avoided in future coil design for the purpose of stable levitation of massive materials.

KEY WORDS: coil angle; molten droplet; stability; electromagnetic levitation; Arbitrary Lagrangian-Eulerian method.

1. Introduction

The electromagnetic levitation (EML) is one of the most developed techniques and is widely used in material processing. In the EML technique, the alternating current in coils generates an alternating magnetic field and eddy current is induced in conductive materials. The interaction between eddy current and magnetic field enables materials to be levitated and melt. Such a containerless technique enables the melt to achieve deeply undercooled states in solidification.^{1,2)} Besides, thermophysical properties of molten metals, such as surface tension, viscosity, conductivity and heat capacity can be measured using EML technique.^{3–6)} Under terrestrial conditions, coils are divided into two groups. The first group with more turns is used to balance gravity as well as melt materials. The second group is designed with less but opposing turns to yield a minimum energy zone in space. Materials are lifted and limited in the zone between the two groups of coils and levitation is achieved.

In EML technique, experiments showed that both solid

and molten droplets were prone to rotate and oscillate under terrestrial conditions. Intense convections driven by gravity and Lorentz force occur inside molten droplet and the velocity tends to be 10–40 cm/s, which is validated by simulation results.^{7–10)} Obviously, stable levitation state of molten droplet is an important prerequisite for applications of EML technique. As there is no magnetic force along the symmetric axis, surface tension is the only force to balance gravity and hydrostatic pressure in the bottom areas. The molten droplet is stretched vertically and tends to be teardrop-shaped due to gravity. However, intense convections and large deformation will probably lead to ejection and rupture of molten droplet, which is the main reason for unstable levitation of massive materials.

Since the EML technique was proposed by Muck¹¹⁾ in 1923, plenty of works have focused on the study of levitation stability of molten droplet. The stability of levitated small sphere was analyzed by Holmes¹²⁾ and concluded that a constant gradient magnetic field is essential to achieve stable levitation. Clemete and coworkers^{13,14)} proved the existence of the minima absorbed power and suggested that it was possible to reach large undercooling for high melting point metals under terrestrial conditions. The stability analy-

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sis theory for solid sphere levitated in simple circular coils was presented by Priede and Gerbeth^{15–17)} and extended the theory to 3D magnetic fields and found that specific rotation rates can destabilize the flow inside an undeformed sphere. The effect of current ratio of heating and positioning coils on oscillating frequency of molten silicon drop was evaluated by Asakuma and coworkers¹⁸⁾ and found that the oscillating frequency decreases as the current ratio increases.

Obviously, the stability of levitated droplet is closely related to the structural parameters of coils and reasonable arrangement of coils will surely enhance the stability of molten droplet. The stable levitation zone of solid sphere was conducted by Ma and coworkers¹⁹⁾ and concluded that the levitation stability can be improved by optimizing the structural parameters of coils. An electromagnetic-thermal model was developed by Kermanpur *et al.*²⁰⁾ and found that the cylindrical coils provide larger lifting force and higher temperature on solid droplet compared to conical coils. A genetic like algorithm on EML coil design was presented by Royer and coworkers²¹⁾ and the coil geometry was optimized to achieve the lowest sample temperature. However, Due to strong coupling between electromagnetic field, temperature field, flow field and free surface deformation, the droplet was usually assumed to be a solid sphere in previous works and dynamic stability such as deformations and oscillations were neglected.

To couple the free surface deformation and EML process, the two-phase interface capturing method based on Eulerian formulation was usually used such as VOF method^{22,23)} or formulates the equations in Lagrangian formulation.¹⁸⁾ The VOF method in Eulerian formulation is able to deal with large deformed cases, but has problems in accurate calculation of interface location and curvature since the position of interface is interpreted using the discrete VOF values of cells around the interface. Compared to VOF method, the Lagrangian formulation is feasible to trace free surface precisely because the mesh nodes always coincide with the material particles, but it is not appropriate in problem with large deformed shape and the frequent domain remeshing is very time-consuming. The Arbitrary Lagrangian-Eulerian (ALE) method combines the advantages of the Eulerian and the Lagrangian formulations, making it possible to trace the interface accurately and efficiently, and applied successfully in many moving interface problems, such as droplet evaporation and traveling magnetic field simulations.^{24,25)}

In this paper, the ALE method is adopted to simulate the dynamic deformation of molten droplet in EML under terrestrial conditions. Flow field, temperature field and free surface oscillation of molten droplet under a series of levitation coil angles are calculated and analyzed thoroughly to investigate the effect of coil angle arrangement on the stability of molten droplet. To validate our model, we first compared the results of magnetic field, flow field and surface oscillation of droplet with those in literature respectively. Then flow field, temperature field, dynamic deformation and oscillation of molten droplet are calculated based on the ALE method. The stability of molten droplet levitated in various EML devices are analyzed thoroughly to determine the suitable coil arrangement, which is valuable for future coil design under terrestrial conditions.

2. Physical Model

For EML device under terrestrial conditions, more turns are arranged below the sample to balance the gravity and less opposing turns are arranged upper the sample, as seen in Fig. 1. In this way, a quadrupole magnetic field is formed and the sample is limited in space between the lower and upper coils. According to common EML devices, the coil angle θ is set in the range of 0 to 30 degree in this paper. The variations of coil angle may affect the value of coil inductance slightly, but it is ignorable since the changes of coil inductance will not generate notable differences on current frequency and amplitude. In this work, a 4 mm radius aluminum droplet is adopted as an example to investigate the influence of coil angle on its dynamic deformation and stability.

Actually, the Lorentz force generated by alternating currents will not only lift up the sample, but also lead to intense convection inside the molten droplet. The flow regime is believed to be turbulence or transition between laminar flow and turbulent flow. Hence, in some works the known turbulent model such as k - ϵ model was used in predicting the viscosity distribution and flow field. Simulation results showed that the flow regime in the core of molten metal is turbulence, but laminar regime still exists near the surface.⁹⁾ In other works, laminar flow regime was assumed but the effective viscosity was enhanced artificially on the order of 10–40 of molecular viscosity to compensate the differences.^{10,26)} Due to difficulties of strong coupling of turbulence and dynamic deformation, in this paper, the laminar regime is adopted and the artificially enhanced effective viscosity is predicted by k - ϵ model under fixed sphere. Since the temperature distribution over molten droplet is quite uniform, the buoyancy and Marangoni effects are neglected compared with Lorentz force and gravity. Related physical properties of molten aluminum and operating conditions are listed in Table 1.

3. Mathematical Model

The simulation of EML levitated molten droplet contains two parts, the magnetic field calculation and flow field calculation. Previous works indicated the calculation of high-frequency magnetic field in EML can be treated

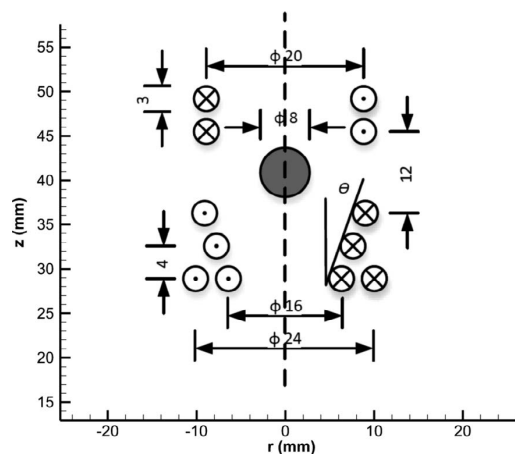


Fig. 1. Structure of coils.

Table 1. Physical properties of molten aluminum and processing conditions.

Physical properties of molten aluminum	
Molecular Viscosity [Pa·s]	0.00238
Effective Viscosity [Pa·s]	0.035
Density [kg/m ³]	2 380
Radius [m]	0.004
Thermal conductivity [W/m·K]	138
Surface tension [N/m]	0.94
Emissivity [–]	0.3
Specific heat [J/kg·K]	854
Electric conductivity [S/m]	3.85×10 ⁶
Melting point [K]	933.5
Operating conditions	
Current in coils [A]	210
Operating frequency [kHz]	200
Ambient temperature [K]	298
Conductivity of coils [S/m]	6.0×10 ⁷

approximately as magnetoquasistatic and the internal fluid flow does not influence the magnetic field calculation. In present work, the magnetic field generated by coils is calculated first, then Lorentz force and absorbed power are submitted into Navier-Stokes and energy equations respectively to calculate flow and thermal fields as well as deformed shape of molten Al droplet. The following assumptions are applied: (1) The model is axially symmetric. (2) There is no net charge in system. (3) Flow inside molten droplet is incompressible and laminar. The time-harmonic Maxwell equations are expressed as:

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (1)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2)$$

$$\mathbf{J} = \sigma \mathbf{E} \quad (3)$$

$$\mathbf{B} = \mu \mathbf{H} \quad (4)$$

Where $\mathbf{H}$ is the magnetic intensity, $\mathbf{J}$ is current density across coils, $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic flux density, σ is electric conductivity, and μ is magnetic permeability. The magnetic field for a given EML model can be obtained through either the mutual inductance or solving differential Maxwell equations. The former way is more efficient while the latter is more accurate.²⁶⁾ Here, to precisely predict the deformed shape of molten droplet, the latter way is adopted. The Lorentz force and absorbed power acted on molten droplet are given by:

$$\mathbf{F} = 0.5\text{Re}(\mathbf{J} \times \mathbf{B}^*) \quad (5)$$

$$\Phi_v = 0.5\text{Re}(\mathbf{J} \cdot \mathbf{J}^* / \sigma) \quad (6)$$

Where Re represents the real part of a complex quantity and the asterisk is the complex conjugate. The skin depth δ is an important quality that measures the distance of magnetic diffusion into molten droplet.

$$\delta = \sqrt{\frac{2}{\mu \sigma \omega}} \quad (7)$$

Where ω is the angular frequency of current in coils. Due to the high-frequency current in coils, the Lorentz force and absorbed power mainly act in a region within the skin depth and achieve the maximum value on the surface. For samples levitated in EML model, the skin depth is on the order of 10% of droplet radius normally. Thus precise prediction of interface is essential to calculate the deformed shape of molten droplet. The continuity equation, Navier-Stokes equations and energy conservation equations in ALE formulations are given:

$$\nabla \cdot \mathbf{u} = 0 \quad (8)$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} - \mathbf{u}_m) \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu_e \nabla^2 \mathbf{u} + \frac{1}{\rho} \mathbf{F} + \mathbf{g} \quad (9)$$

$$\rho c_p \left[\frac{\partial T}{\partial t} + (\mathbf{u} - \mathbf{u}_m) \cdot \nabla T \right] = \lambda \nabla^2 T + \Phi_v \quad (10)$$

Where $\mathbf{u}_m$ is the mesh velocity,²⁴⁾ ρ is the density of molten droplet, ν_e is the effective viscosity, c_p is specific heat and λ is thermal conductivity. The boundary conditions are as follows:

At the center line:

$$\mathbf{u} \cdot \mathbf{n} = \nabla T \cdot \mathbf{n} = 0 \quad (11)$$

At droplet surface, the hydrodynamic stress tensor $\mathbf{\Pi}$ is equal to surface tension in normal component and zero in tangential component:

$$(-p\mathbf{I} + \nu_e \nabla \mathbf{u}) \cdot \mathbf{n} = \mathbf{\Pi}_n = \gamma \mathbf{\Gamma} \cdot \mathbf{n} \quad (12)$$

$$\mathbf{\Pi}_\tau = 0 \quad (13)$$

$$-\lambda \nabla T \cdot \mathbf{n} = \varepsilon \sigma_{sb} (T^4 - T_a^4) \quad (14)$$

Where γ is the surface tension coefficient, $\mathbf{\Gamma}$ is local mean curvature of interface, ε represents the emissivity of molten droplet, σ_{sb} is Stefan-Boltzmann constant and T_a is the ambient temperature. After flow and temperature fields are calculated, the deformed shape of molten droplet is resubmitted into Maxwell equations to calculate the Lorentz force and absorbed power. Thus dynamic oscillations of molten droplet are obtained and the oscillation frequency can be calculated through the Fast Fourier Transform. To reveal the dynamic deformation of molten droplet and avoid convergence problems, a time step size of 1×10^{-4} s is adopted.

4. Model Validation

To validate our calculations, the magnetic field, flow and temperature fields, and free surface oscillation are carried out and compared our results with those in literature respectively. Our results of lifting force and absorbed power of molten droplet and those in Ref. 10) are shown simultaneously in Fig. 2.²⁶⁾ Obviously, both the lifting force and absorbed power show well consistence with those in Ref. 10). The maximum error is 3.75% for lifting force and 2.2% for absorbed power, which proves our calculations of magnetic field are reliable.

Through submitting Lorentz force and absorbed power into Navier-Stokes equations and energy equation respectively, the flow field and temperature field inside a fixed sphere can be obtained.²⁶⁾ **Figure 3** shows such a case and we compared our results with those in Ref. 10). The flow is symmetric and a four loop recirculating pattern is developed due to the Lorentz force induced by a quadrupole magnetic field, which fully consistent with previous works.^{7,10,23)} The maximum velocity is 4.47 cm/s and it is 4.39 cm/s in Ref. 10), with a relative error of less than 2%. Also, the temperature field is symmetric and the highest temperature occurs on the surface where it is closest to coils. The isotherm lines of ours and those in Ref. 10) show great coincidence and the relative error of the maximum temperature is 0.5%.

To validate the calculation of surface tension effects, the free surface oscillation of a 5 mm radius droplet under microgravity is carried out using ALE method. We compared our results with those in Ref. 22) and analytical solutions. The profile of droplet is initialized as the second order Legendre polynomial with an initial deformation of ξ , which is expressed as

$$R = R_0(1 + \xi P_l \cos \theta) \quad (15)$$

The analytical oscillation frequency is given by Rayleigh equation,⁹⁾

$$f = \frac{1}{2\pi} \sqrt{\gamma l(l-1)(l+2)/(\rho R_0^3)} \quad (16)$$

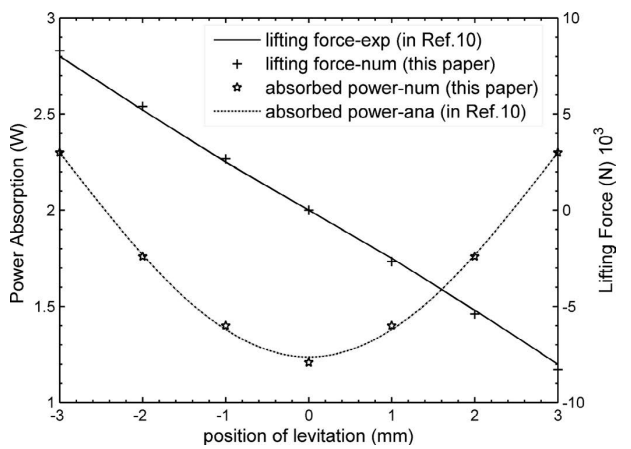
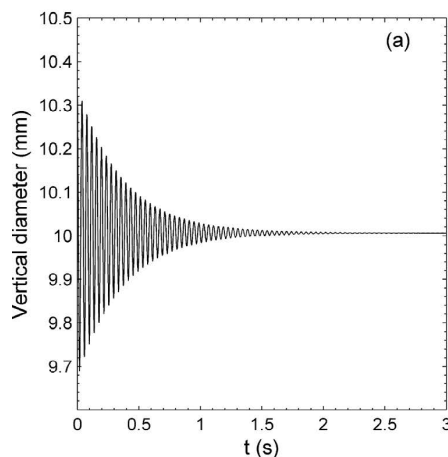


Fig. 2. Calculated lifting force and absorbed power vs. those in Ref. 10).



where γ is the surface tension, ρ is the density, f is the oscillation frequency of droplet. The properties of droplet are the same with those in Ref. 22) and shown as follows: $\gamma=0.94$ N/m, $\rho=2380$ kg/m³, $\xi=3.5\%$, $l=2$. The flow regime is assumed to be laminar with molecular viscosity of $\mu=3.345 \times 10^{-2}$ Pa·s.

Compared with that in Ref. 22) which predicted the oscillation frequency of 22 Hz using VOF method, our results (25.32 Hz, **Fig. 4**) showed better coincidence with analytical value of oscillation frequency (25.30 Hz). It is because that the calculation of surface curvature in ALE is more precise than that in VOF method. This result proves that the ALE method is more suitable to capture the interface of droplet.

5. Results and Discussion

The motion and deformation of the droplet in one oscillating period are obtained under normal gravity condition with a coil angle of 10 degree, as seen in **Fig. 5**. The induced current density and Lorentz force acted on metal droplet are shown simultaneously. Since the current frequency is as high as 200 kHz, the penetration depth in liquid aluminum is very small as seen from Fig. 5. In this case, the induced current and Lorentz force mainly distribute on the areas

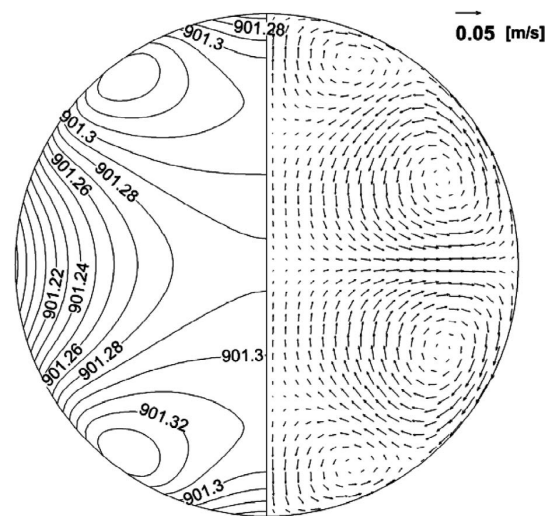


Fig. 3. Flow field and isotherm lines inside an undeformed silver droplet with radius of 5 mm. The temperature is measured in [K].

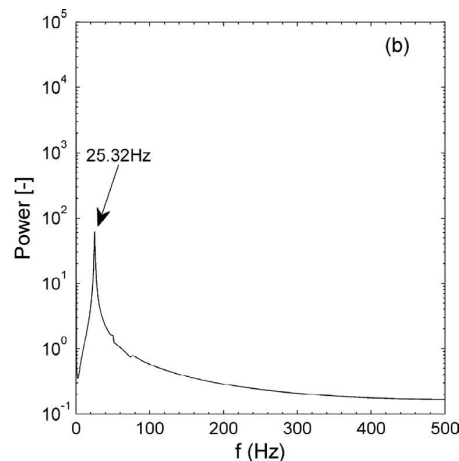


Fig. 4. Computed vertical diameter oscillations of droplet (a) and corresponding frequency using Fourier transform (b).

adjacent to surface. To hold the droplet in space, Lorentz force in these areas is much larger than gravity and the surface tends to be pinched. Since it is initialized as a sphere (Fig. 5(a)), the droplet tends to deform to balance Lorentz force, gravity, surface tension and hydrodynamic pressure at the very beginning of simulation (Fig. 5(b)). In return, the deformed shape enlarges Lorentz force acted on droplet and interprets the balance, thus the droplet rises in vertical direction. And because of stabilizing coils and the decreasing Lorentz force, the droplet declines eventually in specific position (Fig. 5(c)). That is why the molten droplet tends to oscillate in EML devices and the dynamic deformation of droplet is obtained in oscillations. However, as time goes on, the vertical oscillation of droplet damps significantly and the droplet achieves a relatively stable state (Fig. 5(d)).

Figure 6 shows the oscillation and decay of top position on droplet. The oscillation frequencies are obtained through Fast Fourier Transform and three peaks are seen in Fig. 6(b). The dominate frequency is 6.51 Hz, which is the translational motion frequency and represents vertical motion of droplet. The secondary frequency is observed to be 36.18 Hz, corresponding closely to $l=2$ mode Rayleigh

oscillation frequency of 35.36 Hz. Another frequency is seen to be 66.97 Hz and very close to $l=3$ mode theoretical oscillation frequency of 68.48 Hz. Obviously, the intensity of dominate frequency is higher than those of other frequencies, which indicates that the vertical oscillation of aluminum droplet is the main motion in this case. Compared to dominate frequency, the intensities of $l=2$ and $l=3$ mode Rayleigh oscillations are much lower, which implies that the dynamic deformations of liquid aluminum are small during vertical oscillations. We notice that the density of molten aluminum ($\rho=2\,380\text{ kg/m}^3$) is small compared with other metals such as copper ($\rho=8\,000\text{ kg/m}^3$) and silver ($\rho=9\,346\text{ kg/m}^3$), thus the stretches of aluminum in vertical direction are small. A larger deformed shape of molten metal will be observed if the material with higher density is adopted (The detailed result will be shown elsewhere).

During the oscillations, the flow and temperature fields inside the deformed droplet vary rapidly due to the changes of Lorentz force and power absorption. With the decay of oscillation, the flow and temperature achieve a stable state eventually, as seen in **Fig. 7**. There are two vortices in the half of droplet and the highest temperature zone appears

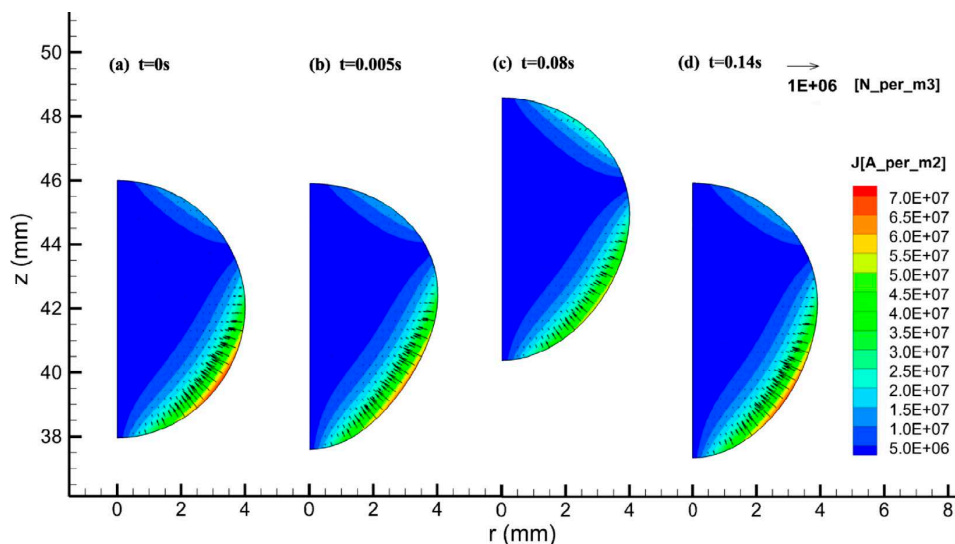


Fig. 5. Oscillation and deformation of liquid aluminum in one oscillating period under 10 degree coil configurations (a) initial shape, (b) deformation after a small time interval, (c) top position in one period, (d) bottom position in one period. The contour in the figures indicates the induced current density and the arrows denote the Lorentz forces. (Online version in color.)

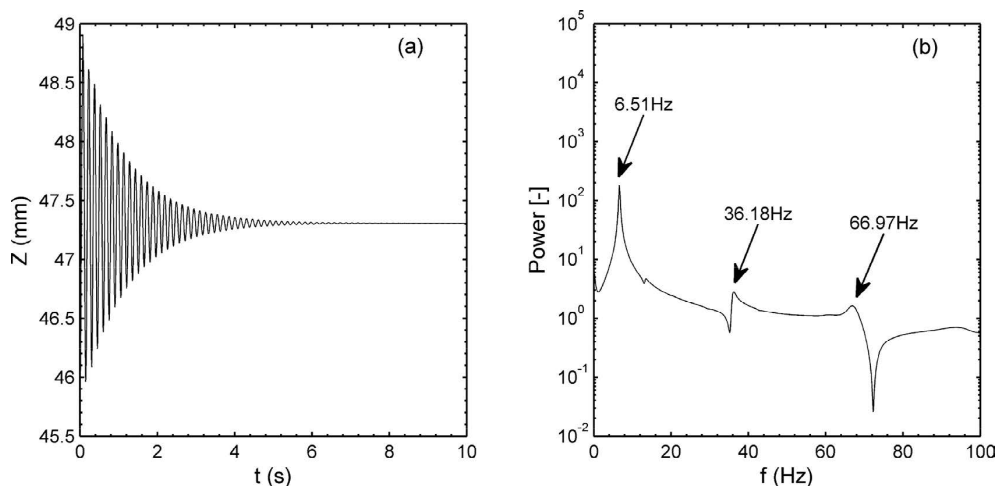
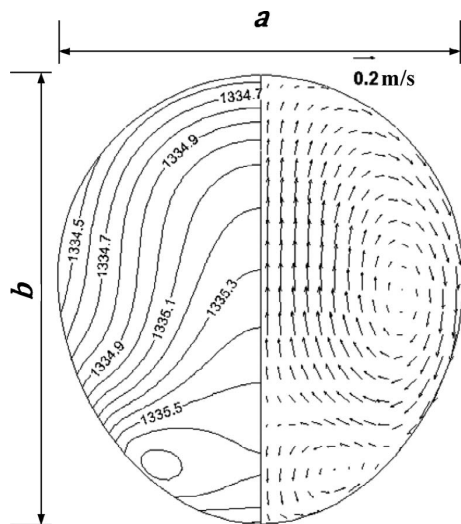


Fig. 6. Oscillation (a) and frequency (b) of top point on droplet under 10 degree coil configuration.

where the surface close to levitating coils, which is observed in many previous works.^{9,10,23)} The maximum velocity and temperature are 26.02 cm/s and 1376 K respectively. Due to the high value of thermal conductivity of aluminum, the temperature difference over the liquid metal is quite small, at the value of 1.3 K in this case. Thus the influence of thermocapillary force on molten droplet is small compared with gravity and Lorentz force and it is reasonable to be ignored. The deformed shape of droplet shows stretches in vertical direction and pinches in horizontal direction due to gravity and Lorentz force in EML system.

In present work, we focus on the influence of levitating coil angle on processing properties such as velocity, temperature and deformation of molten droplet. To achieve good agreements to experimental conditions, the distance between coils is fixed when the coil angle is increased. Thus with the increase of coil angle, coil positions are getting lower in vertical position except for the bottom two coils. The changes of coil positions will surely affect the droplet stable levitation position, as shown in Fig. 8. The droplet is getting lower in position together with the coils and vertical stretch in episphere of droplet is eased whereas it is aggravated for the hyposphere of droplet. That is because the vertical stretch of droplet is proportional approximately to distance



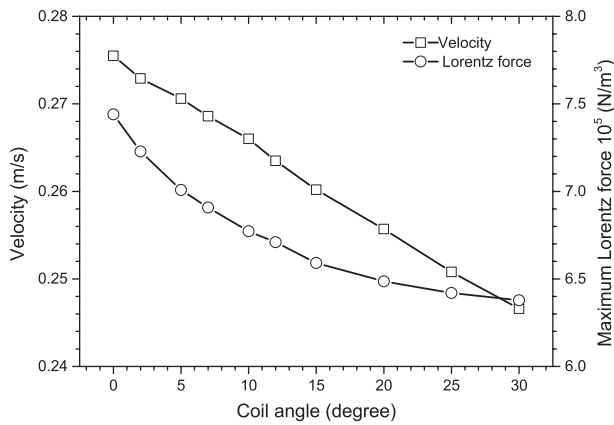


Fig. 11. Velocity and maximum Lorentz force variations with the increase of coil angle configuration.

clear in Fig. 10 that the deformation of droplet increases first at the coil angles of 0–12 degree and declines rapidly after the coil angle exceeds 12 degree, which is quite different from that of horizontal force. We notice that when coil angle is small, the levitating position of droplet is higher than those of large angle coils. The Lorentz force could exert more on areas on the bottom of droplet and the stretch in vertical direction is depressed. With the increase of coil angle, levitating position gets lower and the depression effect on droplet deformation diminishes gradually. Thus the deformation of droplet is observed to be largest at the coil angle of 12 degree, which should be avoided in future coil parameter design. In addition, droplet levitated in cylindrical coils ($\theta=0$) shows better performance in deformation compared to conical coils.

It is talked above that the horizontal component of Lorentz force decreases with the increase of coil angle. Since the vertical component of Lorentz force is equal to gravity and remains unchanged, the total force will decrease too. Thus, the velocity inside molten droplet decreases as the rise of coil angle and due to the reducing of horizontal force on droplet, the gradient of Lorentz force becomes slighter, as seen in Fig. 11. Obviously, the flow inside molten droplet is suppressed to some extent and this helps to enhance the dynamic stability in EML device. Since the physical model we adopted in this work is not allowed to achieve larger coil angles, the most suitable coil arrangements still remains to be studied.

6. Conclusions

In this work, a transient numerical simulation of electromagnetic levitated droplet under terrestrial conditions is performed based on Arbitrary Lagrangian-Eulerian method. The model couples magnetic, flow, temperature fields as well as free surface deformation of droplet simultaneously. Simulation results show that the ALE method can trace the interface of molten droplet precisely, therefore computations of surface tension are more reliable compared with VOF method. The influences of coil angle on dynamic deformation and stability of molten aluminum droplet levitated in EML device are studied thoroughly. The main conclusions

are summarized as follows:

(1) The molten droplet tends to oscillate in vertical direction and deforms largely at the very beginning of simulation. The dynamic deformation of molten droplet is small during vertical oscillations since the density of aluminum is very small. A larger deformed shape of molten metal will be observed if the higher density material is adopted.

(2) With the increase of coil angle, the levitation position of droplet declines gradually and the droplet gets closer to levitating coils and farer to stabilizing coils. As a result, the pinches of episphere are slighter whereas it is aggravated for the hyposphere of droplet. The deformation of droplet reaches a maximum value when the coil angle is 12 degree, implies that the future coil design should avoid such a case to obtain better stable levitation of droplet.

(3) Both the maximum velocity and temperature over molten droplet decrease when the coil angle is large. The intense flow is suppressed and a velocity difference of over 10% is observed compared with 0 and 30 degree coil angles, indicates that the levitation stability of droplet is enhanced significantly. Furthermore, the reducing temperature of droplet will be of potential interest for the temperature control improvement and undercooling processes.

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