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Investigation of The Thermocapillary Flow in A Liquid Bridge subject to A Non-uniform Rotating Magnetic Field

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Abstract

The effect of an external non-uniform rotating magnetic field (RMF) on the thermocapillary flow in a liquid bridge under microgravity is studied numerically. The thermocapillary flow subject to a non-uniform RMF (7mT, 25Hz) is investigated over a range of Marangoni numbers (15-40). The results indicate that, in comparison with the thermocapillary flow without the magnetic field, the maximum tangential velocity is greatly enhanced and the maximum axial velocity is reduced significantly due to the effect of the non-uniform RMF. As a consequence, the thermocapillary flow remains steady and approximately axisymmetric under the effect of the non-uniform RMF. These results demonstrate that a non-uniform RMF can be used as an effective method to control the thermocapillary flow.

Introduction

The float-zone technique, a unique contactless method for growing high quality semiconductor crystals, is effective in avoiding contamination from crucible. Under microgravity condition, the thermocapillary flow driven by unbalanced surface tension, which is characterized by the Marangoni number (Ma), becomes the dominant mechanism of convection. As the Ma increases, the thermocapillary flow may become oscillatory, which may result in macro- and micro-segregations in crystals and in turn deteriorate the crystal quality [2,5-7,12]. Therefore, the control of the thermocapillary flow is a key issue for growing high quality crystals.

Due to the excellent electrical conductivity of semiconductor melt, an external magnetic field can be used to control the thermocapillary flow [1,3,8-11,13,16-17]. Among the various configurations of magnetic fields such as transversal, axial and rotating magnetic fields, a rotating magnetic field (RMF) consumes much less power and can eliminate asymmetry of heat distribution and reduce radial segregation in the melt. Therefore, the RMF has become increasingly popular for convection control in crystal growth. Based on the number of magnetic pole pairs, RMFs are classified as uniform RMF with only one pair of south and north poles, and non-uniform RMF with two or more sets of pole pairs. Applying a uniform RMF, Dold et.al. [4] investigated the effects of the RMF on the thermocapillary flow in Si melt. They reported that the extent of the dopant non-uniformity was effectively reduced and the three-dimensional unsteady convection was well controlled. An approximately two-dimensional axisymmetric flow was observed under the effect of the uniform RMF. The interaction between the thermocapillary flow and the convection driven by the Lorentz force subject to a uniform RMF was studied by Witkowski and Walker [14]. By using a linear stability analysis, Walker [15] reported that there existed a critical Reynolds number for the thermocapillary convection, beyond which the melt changed from a steady axisymmetric flow to a periodic non-axisymmetric flow under a uniform RMF. Yao et.al. [18] investigated the influence of a uniform RMF on the thermocapillary flow in a liquid bridge and reported that the double instabilities, which occur with increasing Ma without RMF, were controlled effectively under the external uniform RMF, and the flow became steady and approximately axisymmetric. To date few studies have considered convection control by a non-uniform RMF in a float-zone configuration. To further explore the effectiveness of RMF for convection control, the effect of a non-uniform RMF with two pole pairs on the thermocapillary flow is investigated in this study.

Physical and Mathematic Model

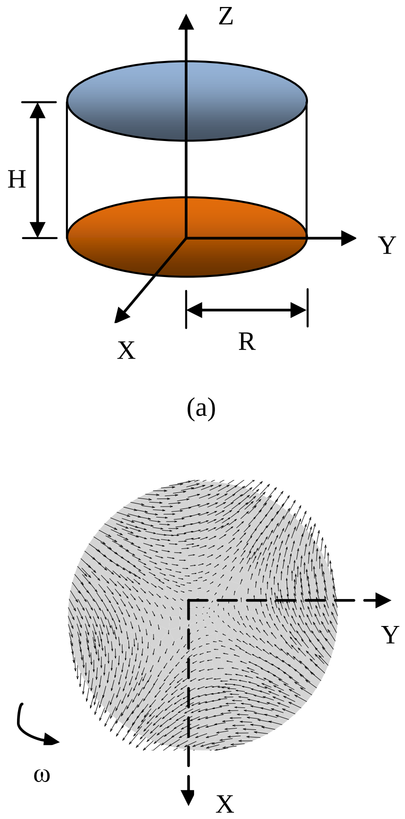
Under microgravity, a liquid bridge model may be idealized as a cylindrical melt as shown in Figure 1(a), which is suspended between two discs with different temperatures fixed at T_{top} and T_{bottom}, respectively. The height and the radius of the liquid bridge are H and R, respectively. The free surface of the liquid bridge is assumed to be non-deformable and adiabatic. The surface tension on the free surface is considered to be a linearly decreasing function of the temperature given by $\sigma = \sigma_0 - \sigma_k T$, where, σ_0 is the surface tension at the reference temperature, and σ_k is the coefficient of surface tension.

Non-uniform RMF

The external non-uniform RMF with two pole pairs can be described as:

$$\vec{B}_{rot}(x,y,t) = \frac{B_0}{R}[-\bar{e}_x(x\cdot\sin(\omega t) - y\cdot\cos(\omega t)) + \bar{e}_y(x\cdot\cos(\omega t) + y\cdot\sin(\omega t))] \quad (1)$$

Here, B_0 is the magnetic field amplitude at the radius R and $\frac{\omega}{2}$ is the circular frequency of the AC electric power source for the RMF with two pole pairs (the rotation frequency of the magnetic field pattern is $\frac{1}{2}\frac{\omega}{4\pi}$). The distribution of the magnetic lines of the non-uniform RMF, which is plotted on the X-Y plane in Figure 1(b), is assumed to be the same along the Z-axial direction. The rotating frequency of the magnetic field pattern adopted in this study is 25Hz, which makes the skin depth $\alpha = \sqrt{1/\sigma_e \mu_0 \omega} \gg$ R, where σ_e is the electrical conductivity of the melt and μ_0 is the permeability of vacuum. Therefore, the magnetic lines of the RMF are assumed to permeate the whole melt zone, and the skin effect is negligible [11,13,16,18].



(b)

Figure 1. (a) The liquid bridge model; (b) the distribution of the magnetic lines of the non-uniform RMF on the X-Y plane.

Dimensionless Governing Equations

The semiconductor melt in the liquid bridge may be considered as an incompressible Newtonian fluid. The surface tension and Lorentz force are added into the momentum equations as source terms. Choosing H, k/H (where k is the thermal diffusivity), H^2/k, $k\mu/H^2$ (μ is the dynamic viscosity) and B_0k as the characteristic scales for the length, velocity, time, pressure and electric potential, the non-dimensionalised governing equations are written as:

$$\nabla\cdot\vec{U}^*=0$$

$$\frac{1}{\Pr}\left(\frac{\partial\vec{U}^*}{\partial t^*}+(\vec{U}^*\cdot\nabla)\vec{U}^*\right)=-\nabla P^*+\Delta\vec{U}^*+2\mathrm{Ta}\Pr\vec{F}^*_{rot}-\vec{F}^*_s\delta(r^*-R^*(z^*)),\qquad(2)$$

$$\frac{\partial T^*}{\partial t^*}+(\vec{U}^*\cdot\nabla)T^*-\nabla^2T^*=0$$

Here, the dimensionless temperature is given by $T^*=\frac{T-T_{top}}{\Delta T}$. $\vec{F}^*_{rot}$ represents the Lorentz force term, which is produced by the interaction of the external RMF and the induced currents in the semiconductor melt. $\vec{F}^*_S\delta(r^*-R^*(z^*))$ indicates that the surface tension only acts on the free surface, where $r^*=\sqrt{x^{*2}+y^{*2}}$, and R^* is the dimensionless radius of the liquid bridge. The dimensionless surface tension $\vec{F}^*_S$ is expressed as: $\vec{F}^*_s=\mathrm{Ma}\left[\frac{\partial T^*}{\partial x^*}\vec{e}_x+\frac{\partial T^*}{\partial y^*}\vec{e}_y+\frac{\partial T^*}{\partial z^*}\vec{e}_z\right]$ .The Prandtl, Rotating Reynolds, Marangoni and Taylor numbers are defined as:

$$\Pr=\frac{\nu}{k},\ \mathrm{Re}_\omega=\frac{\omega H^2}{\nu},\ \mathrm{Ma}=\frac{\sigma_k\Delta TH}{\rho\nu k},\ \mathrm{Ta}=\frac{\sigma_e B_0^2\omega H^4}{2\nu\mu}.$$

where, ν is the kinematic viscosity. For brevity, the superscript "*" is dropped in the following equations. The dimensionless Lorentz force components in the X, Y and Z directions under the non-uniform RMF are given by (the subscript 2 represents the Lorentz force generated by the RMF with two pole pairs):

$$f_{2x}=\frac{1}{2}\left[\frac{1}{\mathrm{Re}_\omega\cdot\Pr}\left[\left(\frac{\partial\phi_{21}}{\partial z}y+\frac{\partial\phi_{22}}{\partial z}x\right)-(x^2+y^2)u_x\right]-\frac{(yx^2+y^3)}{2}\right],$$

$$f_{2y}=\frac{1}{2}\left[\frac{1}{\mathrm{Re}_\omega\cdot\Pr}\left[\left(\frac{\partial\phi_{21}}{\partial z}x-\frac{\partial\phi_{22}}{\partial z}y\right)-(x^2+y^2)u_y\right]+\frac{(xy^2+x^3)}{2}\right],\qquad(3)$$

$$f_{2z}=\frac{1}{2}\frac{1}{\mathrm{Re}_\omega\cdot\Pr}\left[\left(-\frac{\partial\phi_{21}}{\partial x}y-\frac{\partial\phi_{21}}{\partial y}x-\frac{\partial\phi_{22}}{\partial x}x+\frac{\partial\phi_{22}}{\partial y}y\right)-2u_z(x^2+y^2)\right].$$

where u_x, u_y and u_z are the components of the dimensionless velocity in the X, Y and Z directions, respectively. The dimensionless electric potential equations are written as:

$$\nabla^2\phi_{21}=\frac{\partial u_x}{\partial z}y+\frac{\partial u_y}{\partial z}x-\left(\frac{\partial u_z}{\partial x}y+\frac{\partial u_z}{\partial y}x\right),$$

$$\nabla^2\phi_{22}=\frac{\partial u_x}{\partial z}x-\frac{\partial u_y}{\partial z}y-\left(\frac{\partial u_z}{\partial x}x-\frac{\partial u_z}{\partial y}y\right).\qquad(4)$$

Boundary Conditions

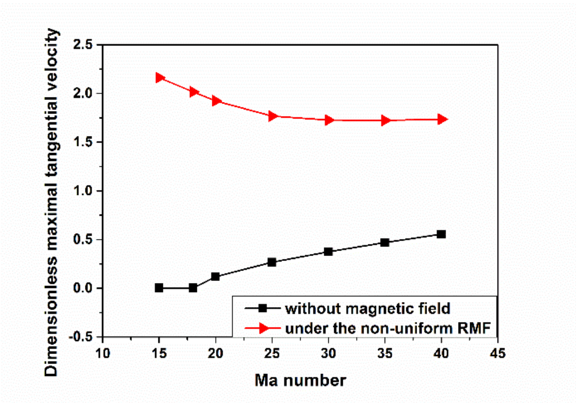
The velocity on the top and bottom discs are $\vec{U}=0$; the temperature is T=0 on the top disc and T=1 on the bottom disc. The free surface is impervious to flows of mass, momentum and energy. The boundary condition of the electric potential is determined by $\vec{j}\cdot\vec{n}=0$.

Numerical Results and Discussion

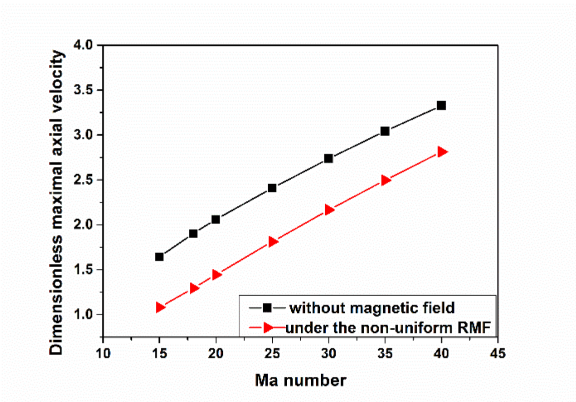
Numerical Method

In order to investigate the characteristics of the thermocapillary convection in the liquid bridge under the non-uniform RMF, numerical simulations are conducted based on the above-described three-dimensional liquid bridge model. A non-uniform grid system is adopted in this study, which are refined near all the boundaries. After checking the grid independence, a non-uniform grid of (R×Θ×Z=60×68×60) is adopted. The basic governing equations and the boundary conditions are discretized by a finite volume method. The central difference approximation is applied to the diffusion terms; the second-order upwind scheme is applied to the convection terms; and the whole flow field is solved using the SIMPLE scheme for pressure-velocity coupling.

The intensity of the applied non-uniform RMF at the radius R is fixed at 7mT, and the rotation frequency of the magnetic field is set to 25Hz. Other dimensionless parameters are specified as H/R=1, Pr=0.01, $\mathrm{Re}_\omega=2.2\times10^4$, and $\mathrm{Ta}=1.86\times10^4$. The value of the Ma, which is determined by the temperature difference between the top and the bottom discs, is varied over the range from 15 to 40.



(a)



(b)

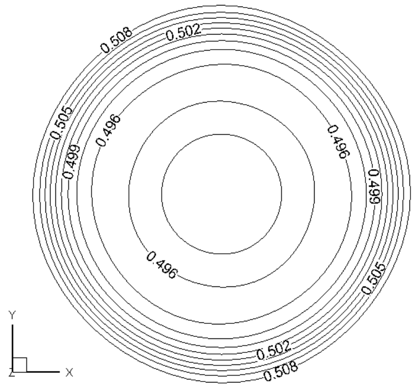
Figure 2. (a) Dimensionless maximal tangential velocity; and (b) Dimensionless maximal axial velocity for Ma=15-40 under the non-uniform RMF (7mT, 25Hz) and without RMF.

Thermocapillary Flow with Different Ma under the Non-uniform RMF

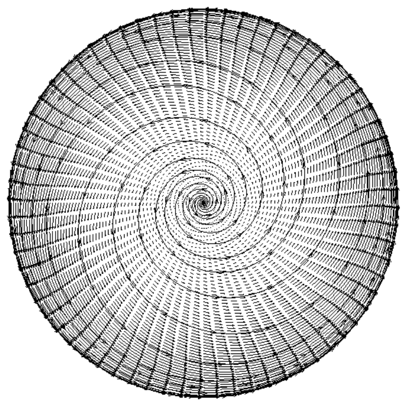
The characteristics of the thermocapillary convection in the liquid bridge with different Ma (ranging from 15 to 40) are investigated without magnetic field and with the non-uniform RMF (7mT, 25Hz) respectively. The numerical results in terms of the dimensionless maximal tangential and axial velocities are presented in Figure 2.

As shown in Figure 2, because of the stirring effect of the external non-uniform RMF, the maximal tangential velocities in the non-uniform RMF are significantly larger than that without the magnetic field (refer to Figure 2a), and the dimensionless maximal axial velocity in the non-uniform RMF is obviously lower than that without the magnetic field (refer to Figure 2b). In particular, it is seen in Figure 2(a) that the dimensionless maximal tangential velocity for Ma=15 increases from a very low value close to zero when without the magnetic field to a very high value over 2 under the non-uniform RMF. The increment of the dimensionless maximal tangential velocity is slightly smaller at higher Ma numbers. Accompanying the electromagnetic stirring action of the non-uniform RMF in the tangential direction, the dimensionless maximal axial velocities are greatly reduced. Figure 2(b) shows that the dimensionless maximal axial velocity in the non-uniform RMF is approximately 34% smaller than that without the magnetic field for Ma=15, about 25% smaller for Ma=25, and about 18% smaller for Ma=35.

The features of the thermocapillary convection for Ma=25 under the non-uniform RMF (7mT, 25Hz) are shown in Figure 3. Figure 3(a) exhibits the melt temperature contours at the Z=0.5 plane under the non-uniform RMF, which comprise a series of concentric circles around the central axis of the liquid bridge. Figure 3(b) shows that the melt velocity at Z=0.5 plane flows out from the center axis of the melt to the free surface in a spiral fashion. Clearly, there exists a strong circumferential flow. The results indicate that the thermocapillary flow for Ma=25 is approximately axisymmetric under the effect of the applied non-uniform RMF.



(a)



(b)

Figure 3. (a) Temperature contours (from 0.496 to 0.509 with an interval of 0.0015; and (b) velocity vectors and Streamlines on the Z=0.5 plane for Ma=25 under a non-uniform RMF (7mt, 25Hz).

The above numerical results have demonstrated that applying a non-uniform RMF can effectively control the thermocapillary convection to maintain an approximately axisymmetric flow in the liquid bridge.

Conclusions

The characteristics of the three-dimensional thermocapillary convection in a liquid bridge under microgravity and subject to a non-uniform rotating magnetic field (7mT, 25Hz) are investigated numerically. The results indicate that, due to the stirring action of the external non-uniform RMF, the maximum tangential velocity is greatly enhanced, and the axial convection is effectively depressed over the range of the Ma from 15 to 40. The thermocapillary flow remains approximately axisymmetric and steady under the effect of the non-uniform RMF. It is demonstrated that the non-uniform RMF with two pole pairs can be used as an effective method to grow high quality crystal.

Acknowledgments

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