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Convection and instability of thermocapillary flow in a liquid bridge subject to a non-uniform rotating magnetic field

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ABSTRACT

A three-dimensional liquid bridge is considered in this study to numerically investigate the effects of an external non-uniform rotating magnetic field (RMF) on the thermocapillary flow in semiconductor melt under microgravity. Simulations are carried out to examine the convection and instability features of the thermocapillary flow over a range of Marangoni numbers (Ma = 15–50) under a non-uniform RMF. The present results show that applying an external non-uniform RMF enhances the maximum tangential velocity and depresses the maximum axial velocity. As a consequence, an approximately axisymmetric flow is maintained in the melt under the effect of the non-uniform RMF, which is beneficial for growing high quality crystal. Further investigation of the thermocapillary flow subject to different non-uniform RMFs (corresponding to Taylor numbers $Ta = 3.8 \times 10^2$–1.86×10^4 and Rotating Reynolds number $Re_\omega = 2.2 \times 10^4$) reveals that the thermocapillary convection may undergo a transition from the approximately axisymmetric steady flow to a periodically oscillatory flow for Ma above a critical value. The critical Ma generally increases with the intensity of the non-uniform RMF.

1. Introduction

Bulk single crystal of semiconductors, which is used to manufacture integrated circuits and optical devices, is an extremely important material for many industrial applications. Among the various methods for growing single crystal, the floating-zone technique, which is a unique contactless method avoiding contamination by crucible, is a very promising method for growing high quality crystal. Under microgravity, the effect of hydrostatic pressure is greatly reduced, and thus it is possible to grow large size crystal. Since the buoyancy effect is also minimized under microgravity, the adverse effect of buoyancy driven flow on crystal quality may also be minimized. In this case, the thermocapillary flow driven by unbalanced surface tension on the free surface, which is characterized by the Marangoni number (Ma), becomes the dominant mechanism of convection in the floating zone [1–6]. Further, instability of the thermocapillary flow may result in macro- and micro-segregation in the crystal and in turn the deterioration of crystal quality. Therefore, controlling the thermocapillary flow is very important for growing high quality crystal.

Due to the excellent electrical conductivity of semiconductor melt, it is possible to apply an external magnetic field to control the thermocapillary convection and ultimately to improve the quality of the grown crystal. Applying a static magnetic field (SMF) is a common strategy which has been used to depress undesirable convection in semiconductor melt [7,8]. Compared to the convection control using a SMF, applying a rotating magnetic field (RMF) can create an electromagnetic body force to stir the melt. This provides a strategy to control the mass transport within the melt and may eliminate any asymmetry of heat distribution in the melt, which enables the crystal to solidify with much better properties [9–12]. In addition, a RMF consumes much less power than a SMF. Therefore, the RMF has become increasingly popular for convection control in crystal growth [13–19].

A RMF is a periodic transverse magnetic field which rotates in the azimuthal direction about the center axis of the melt. It can be generated by a number of magnetic poles placed at equally spaced azimuthal positions around the crystal growth furnace and connected to successive phases of a multiphase AC power source. Currents induced by the alternating magnetic field in the semiconductor melt will interact with the magnetic field, resulting in electromagnetic force that determines the convection characteristics in the melt. The electromagnetic force is dependent on several factors. Among them, the magnetic-field pattern determined by the number of pole pairs of the RMF is an important one

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[16]. According to the number of pole pairs, RMF can be classified as uniform RMF with only one pair of south and north poles and non-uniform RMF with two or more pole pairs.

Existing research on convection control using RMF in the floating zone technique has mostly focused on uniform RMF. Dold *et al.* [20] experimentally investigated the effects of a uniform RMF on the thermocapillary flow in Si melt. Their results demonstrate that the non-uniformity of the dopant is effectively reduced by the uniform RMF comparing to that without magnetic field. Further, their numerical results also show that the three-dimensional unsteady convection present in the melt without magnetic field is well controlled, and an approximately axisymmetric flow is formed in the melt under a uniform RMF. Witkowski and Walker [21] studied the interaction between the thermocapillary flow and the convection driven by Lorentz force associated with a uniform RMF. Based on a linear stability analysis, Walker *et al.* [22] reported that, when the Ma is beyond a critical value, the flow structure in the melt changes from an axisymmetric steady flow to a three-dimensional oscillatory flow under a uniform RMF. Yao *et al.* [23] numerically investigated the influence of a uniform RMF on the thermocapillary flow in a liquid bridge under microgravity. It was observed that the thermocapillary flow without influence of magnetic field undergoes two-stage transitions as the Ma increases, firstly from an initially axisymmetric steady flow to a three-dimensional steady flow, and then to an oscillatory flow. The above transitions of the thermocapillary flow to a three-dimensional steady flow and an oscillatory flow may be effectively controlled by applying a uniform RMF, and an axisymmetric steady flow may be maintained in the melt [23]. Yao *et al.* [24] also reported that there exists a critical Ma, beyond which the thermocapillary flow will lose stability and become oscillatory under the uniform RMF.

Reports on convection control using a non-uniform RMF are rare. Vizman *et al.* [25] numerically studied the influence of a non-uniform RMF with two pole pairs on the buoyant convection in classical cylindrical Rayleigh-Bénard configurations. They concluded that a relatively weak non-uniform RMF can effectively damp the disturbing temperature fluctuations and stabilize the heat and mass transfer process. Further, Wang *et al.* [18] investigated the impact of the number of pole pairs of the RMF on the dopant distributions in vertical Bridgman crystal growth.

The above literature survey shows that few studies have considered the control of the thermocapillary convection in the floating zone configuration using a non-uniform RMF. Further, most of the existing research on convection control using RMF has assumed an axisymmetric flow to simplify the three-dimensional thermocapillary convection, which is very limiting. Accordingly, a full three-dimensional liquid bridge model is adopted in the present study. The purpose here is to numerically investigate the influence of an imposed external non-uniform RMF (with two pole pairs) on the thermocapillary flow under microgravity. The characteristics of the convection and instability of the thermocapillary flow over a range of Ma (15–50) subject to a non-uniform RMF (corresponding to $\text{Ta} = 3.8 \times 10^2$–$1.86 \times 10^4$ and $\text{Re}_\omega = 2.2 \times 10^4$) will be described based on the numerical data.

2. Problem description and numerical formulation

2.1. Problem description

A liquid bridge, a simplified model of the floating-zone crystal growth process, is widely used to investigate the convection characteristics of the thermocapillary flow in the floating zone [1–3,26–29]. It is also adopted in the present study. Under microgravity, the liquid bridge is idealized as a cylindrical melt suspended between two discs, which are maintained at different temperatures T_{top} and T_{bottom}, respectively, with $\Delta T = T_{bottom} - T_{top} > 0$. The geometry of the numerical model is shown in Fig. 1(a). The height and radius of the liquid bridge are H and R, respectively, and the aspect ratio is fixed at $\text{As} = \text{H}/R = 1$ in this study. The free surface of the liquid bridge (i.e. the vertical cylindrical surface) is assumed to be non-deformable since dynamic deformation of the surface is negligibly small, and the surface is assumed adiabatic from the ambient gas. The surface tension on the free surface is considered to be a linearly decreasing function of the temperature, i.e. $\sigma = \sigma_0 - \sigma_k T$, where, σ_0 is the surface tension at the reference temperature, and σ_k is the coefficient of surface tension, and T is the surface temperature [1]. A Cartesian coordinate system with its origin placed at the centre of the lower disc of the liquid bridge is adopted.

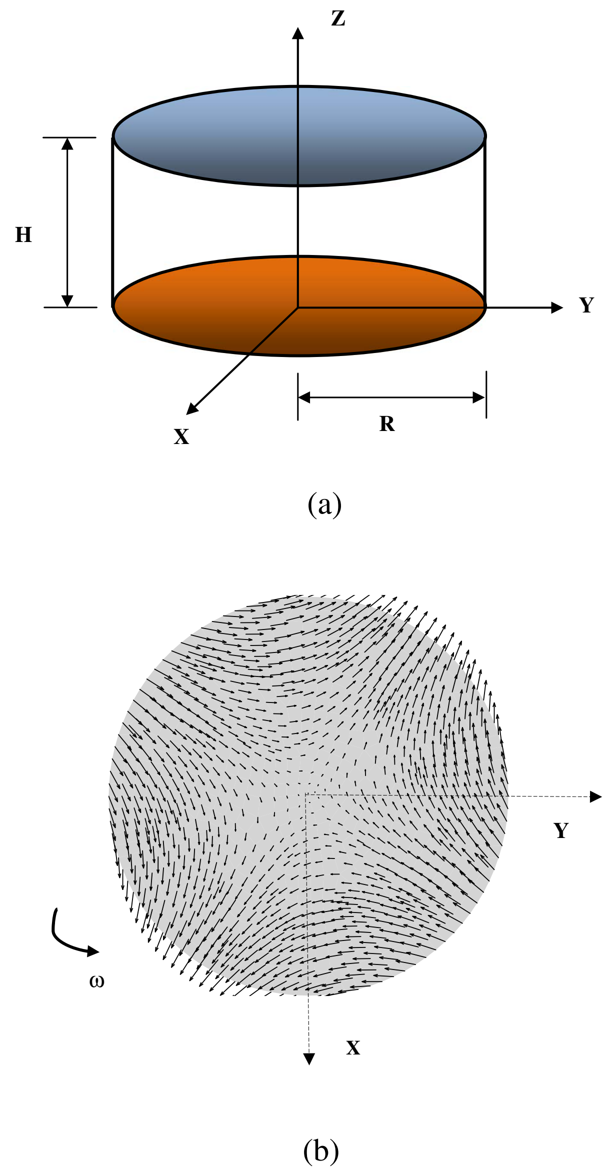

Fig. 1. (a) The liquid bridge model, and (b) the distribution of the non-uniform RMF on the X-Y plane.

The non-uniform RMF applied to the liquid bridge is described as follows:

$$\vec{B}_{rot}(x, y, t) = \frac{\text{B}_0}{\text{R}}[-\vec{e}_x(x\cdot\sin(\omega t) - y\cdot\cos(\omega t)) + \vec{e}_y(x\cdot\cos(\omega t) + y\cdot\sin(\omega t))]. \quad (1)$$

Here, B_0 is the amplitude of the magnetic field, and $\frac{\omega}{2}$ is the angular frequency of an AC electric power source for the non-uniform RMF (the rotation frequency of the magnetic field pattern is $\frac{1}{2}\frac{\omega}{4\pi}$). $\vec{e}_x$, $\vec{e}_y$ represent the unit vectors in the X and Y directions, respectively. The distribution of the non-uniform RMF (plotted in Fig. 1b on an X-Y