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Effect of Marangoni number on thermocapillary convection in a liquid bridge under microgravity

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Three dimensional numerical simulations are carried out to investigate the effect of Marangoni number (*Ma*) on the thermo-solutal capillary convection in a liquid bridge under microgravity. Upper and lower disks of the liquid bridge maintain a constant temperature and solute concentration. The computational results show that two rows of interlaced vertical waves form at the center of the $r = 0.5$ cm ring surface. The number of the interlaced vertical bar waves increases from 10 to 12 with *Ma* increase from 3.58×10^3 to 5.37×10^3, which inferred the enhancement in strength and instability of thermocapillary convection with *Ma*. On the $\theta = 0^\circ$ plane of the liquid bridge, the low concentration of oxygen displays a 'dumbbell shape' at the center. On the $z/L = 0.5$ plane of the liquid bridge, the oxygen concentration appears an inhomogeneous 'star shape' distribution. Moreover, the concentration and radial segregation effect of oxygen increase with the increment of *Ma* in floating zone.

1. Introduction

Under a microgravity condition, the thermocapillary convection driven by surface tension variation at a free-surface with unbalanced thermal gradients and the solutocapillary convection driven by concentration gradients are fundamental model problems for several material processing technologies. It is well known that the instability of thermocapillary and solutocapillary convections is the major cause of inhomogeneity of impurity concentration during floating zone crystal growth process [1]. In order to produce homogeneous bulk silicon crystals under microgravity, the oscillatory thermocapillary and solutocapillary convection must be theoretically analyzed in liquid bridges. Numerous theoretical [2], numerical [3] and experimental [4] efforts were devoted to understand the instability of thermocapillary flow in liquid bridges. Yano et al. [5] investigated the instability and associated roll structures of Marangoni convection in liquid bridges on the International Space Station. The roll structures travelled along the same direction as the surface flow (co-flow direction) for $1.00 \leq Ar \leq 1.25$, while they travelled in the opposite direction (counter-flow direction) for $Ar \geq 1.50$ (where Ar = height/diameter). Analysis was also performed on the solutocapillary convection. Zhou and Huai [6,7] investigated the thermo-solutocapillary convection in an axisymmetric liquid bridge with a dynamic free-surface. When thermocapillary intensity overwhelmed that of solutocapillary, the flow field was filled by one anticlockwise rotating convective cell. When thermocapillary intensity was equivalent to that of solutocapillary, the flow field consisted of one clockwise and one anticlockwise rotating convective cell. Minakuchi et al. [8] investigated the relative contributions of thermo-solutal Marangoni convections on flow patterns in a liquid bridge. His results revealed that the flow field became three-dimensional and time dependent when the solutal Marangoni number exceeded a critical value. The flow patterns and the azimuthal wave number varied due to the competing contributions of the thermocapillary and solutocapillary convective flows. Moreover, the critical thermal Marangoni number for thermo-solutal Marangoni convection was larger than that of pure thermal Marangoni convection. Witkowski and Walker [9] numerically simulated the instability of solutocapillary convection in liquid bridges and discovered the base flow strongly affected by growth velocity. For large growth velocity, the base flow was only driven by a thin solutal layer close to the crystal-melt interface. Under a cusp-shaped magnetic field, Won, Kakimoto and Ozoe [10]

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Nomenclature

Ar	aspect ratio, $\mathrm{Ar} = L/r_1$
C	oxygen concentration
D	oxygen diffusion coefficient ($\mathrm{m^2 \cdot s^{-1}}$)
L	length of the liquid bridge (cm)
Ma	Marangoni number, $Ma = \Delta TL\lvert\sigma_T\rvert/\mu\alpha$
P	pressure (Pa)
Pr	Prandtl number, $Pr = \mu C_p/\lambda$
Q	convergence criteria
r	radius of the liquid bridge (cm)
Re	Reynolds number, $Re = \rho VL/\mu$
t	time (s)
T	temperature (K)
ΔT	temperature difference, $\Delta T = T_2 - T_1$ (K)

Greek symbols

μ	dynamic viscosity ($\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$)
υ	kinematic viscosity ($\mathrm{m^2 \cdot s^{-1}}$)
α	thermal diffusivity ($\mathrm{K^{-1}}$)
ρ	density ($\mathrm{kg \cdot m^{-3}}$)
C_p	specific heat ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$)
λ	thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$)
σ	surface tension ($\mathrm{N \cdot m^{-1}}$)
σ_T	temperature coefficient of surface tension ($\mathrm{N \cdot m^{-1} \cdot K^{-1}}$)
u, v, w	the velocity components in the r, z and θ directions ($\mathrm{cm \cdot s^{-1}}$)
r, θ, z	radial, azimuthal and axial coordinates

Subscripts

av	average
1	cold wall
2	hot wall

carried out numerical investigation on the transient oxygen concentration in a silicon melt. The simulation results indicated that the oxygen concentration at a fixed point oscillated periodically as a function of time. The local and average oxygen concentrations in the silicon melt were less than the values without a magnetic field. Under a rotating magnetic field, numerical simulations were carried out to analyze the effect of crystal and crucible rotating directions on heat and oxygen transport in Czochralski crystal growth system [11]. The computational results showed that the effect of crystal rotation were stronger than that of crucible rotation on the melt turbulent flow and oxygen transport. The solutocapillary convection and mass transport were also investigated by Walker et al. [12] in a cylindrical liquid bridge under a strong magnetic field. They found that the strong magnetic field could improve the impurity distribution in floating zone crystal growth. As is well known, many experimental and numerical evidences indicate that unsteady 3D heat flows prevail in the molten zone accompanied with the dopant distribution and instability. Nevertheless, the effect of unsteady strength of 3D heat flows still remains untouched with the various flow pattern and spatio-temporal developments not adequately investigated.

In this work, we aim to understand the behavior of the thermocapillary convection and oxygen concentration in floating zone crystal growth. We focus on investigating the effect of Marangoni number on thermocapillary convections behaviors and oxygen concentration in a liquid bridge under microgravity.

2. Physical and mathematical models

The physical configuration of the present study is shown in Fig. 1. The liquid bridge with a non-deformable cylindrical free surface of radius r_1 ($r_1 = 1$ cm) is suspended between two co-axial disks with distance L ($L = 1$ cm). The aspect ratio of the liquid bridge is $\mathrm{Ar} = L/r_1 = 1$. The liquid bridge is filled with silicon melt and its detailed properties are shown in Table 1 [13]. Different temperatures and concentrations are applied at the upper disk (T_1, C_1) and lower disk (T_2, C_2) with $T_1 < T_2$ and $C_1 < C_2$. A cylindrical coordinate system (r, θ, z) is adopted with z-axis corresponding to the centerline of the liquid bridge originating from the center of the lower disk.

The following assumptions are introduced in our models: (1) the fluid is incompressible Newtonian fluid; (2) the flow is laminar; (3) the system is under microgravity condition; (4) the free surface is taken to be non-deformable and adiabatic from the environmental gas and (5) the surface tension at the interface is assumed to be a linear function of temperature,

$$\sigma = \sigma_0 - \sigma_T(T - T_0) \tag{1}$$

where σ_0 is the surface tension at $T = T_0$. T_0 denotes the reference temperature of the initial surface tension, which is equal to the melting point temperature [14]. $\sigma_T = -(\partial\sigma/\partial T) > 0$ is the negative surface tension change rate with temperature.

2.1. Governing equations

With the above assumptions, the following governing equations of the liquid phase are obtained respectively from the overall mass conservation, the balance of momentum, the balance of energy and the conservation of mass of species.

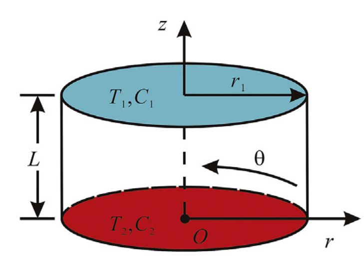

Fig. 1. Physics model and coordinate system.

Table 1
Thermophysical properties of silicon-melt.

Property	Symbol	Value
Density ($\mathrm{kg \cdot m^{-3}}$)	ρ	2.53×10^3
Dynamic viscosity ($\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$)	μ	8.89×10^{-4}
Thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$)	λ	67
Specific heat ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$)	C_p	1×10^3
Thermal diffusion coefficient ($\mathrm{m^2 \cdot s^{-1}}$)	α	2.65×10^{-5}
Diffusion coefficient ($\mathrm{m^2 \cdot s^{-1}}$)	D	5×10^{-8}
Surface tension gradient ($\mathrm{N \cdot m^{-1} \cdot K^{-1}}$)	σ_T	-2.8×10^{-4}