International Journal of Heat and Mass Transfer 54 (2011) 1698–1705

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Effect of interfacial heat exchange on thermocapillary flow in a cylindrical liquid bridge in microgravity

Bo Xun [a], Kai Li [a,*], Wen-Rui Hu [a], Nobuyuki Imaishi [b]

[a] Key Laboratory of Microgravity (National Microgravity Laboratory), Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China
[b] Institute for Materials Chemistry and Engineering, Kyushu University, Kasuga 816-8580, Japan

ARTICLE INFO

Article history:
Received 9 October 2009
Received in revised form 19 January 2011
Accepted 24 January 2011

Keywords:
Liquid bridge
Interfacial heat exchange
Thermocapillary flow
Critical Marangoni number

ABSTRACT

The effect of interfacial heat exchange on thermocapillary flow in a cylindrical liquid bridge of 1 cst silicone oil (with Prandtl number 16.0) with aspect ratio 1.8 in microgravity, was investigated in an extended range of Biot number. With both constant and linearly distributed ambient temperature, the computed results predict that the marginal stability curve for the thermocapillary flow exhibits a roughly convex trend. In the range of small Biot number, however, a sharp local maximum exists with a special oscillation mode of azimuthal wave number $m = 0$, in contrast to the other cases with $m = 1$. In addition, the normalized "thermal" energy balance between the basic state and the critical perturbation of the thermocapillary flow was investigated. Finally, the effect of the interfacial heat exchange on the thermocapillary flow in a liquid bridge of low Prandtl number fluid in microgravity was investigated as a comparison.

1. Introduction

A liquid bridge model consists of a liquid column floating between two differently heated solid rods (see Fig. 1). It was initially introduced to mimic half of the floating zone technique for space materials science [1], and has now become one of the typical models for the investigation, both experimentally and theoretically, of the principles of thermocapillary flow. Motivated by the experimental work of Chun and Wuest [2,3] and Schwabe et al. [4,5], extensive theoretical studies (e.g. linear instability analyses [6–9], energy stability analyses [10,11] and direct numerical simulations [12–14]) have established that an axisymmetric (2D) stationary thermocapillary flow first loses its stability to an asymmetric (3D) stationary flow, then to an oscillatory flow in liquid bridges of low Prandtl number fluids ($Pr \leqslant 0.06$), while it transits to oscillatory flow directly in liquid bridges of higher Prandtl number fluids. However, the corresponding critical conditions determined through the theoretical studies do not give quantitative agreement with the experimental results, especially for high Prandtl number fluids. It should be noted that most of the theoretical studies were carried out with an adiabatic free-surface assumption, in other words there is no interfacial heat exchange on the free surface. In practice interfacial heat exchange in the experiments, especially under high temperature conditions, may play an important role in the fluid dynamics [15–20]. Kamotani et al. [15,19] investigated experimentally the effect of interfacial heat exchange in liquid bridges of high Prandtl number fluids, taking into account the ambient air flow. They calculated the average interfacial heat transfer rate with respect to the dimensionless average Biot number (Bi), and found that the critical Marangoni number decreased with increasing heat-loss to the environment in the range of average Bi less than 1.5, while the critical Marangoni number was only slightly affected by increasing heat-gain from the environment. Melnikov and Shevtsova [17] investigated numerically the effect of interfacial heat exchange on coupled thermocapillary flow and buoyancy flow in a cylindrical liquid bridge ($Pr = 14$ and $\Gamma = 1.8$) with a constant ambient temperature (the effect of free-surface deformation was ignored) [20]. They found that the heat-loss serves as a stabilizing effect on the flow at large Bi ($Bi \geqslant 5$) contrary to the destabilizing effect at small Bi ($Bi \leqslant 2$). Kousaka and Kawamura [18] studied numerically thermocapillary flow in a liquid bridge ($Pr = 28.1$ and $\Gamma = 1.0$) in microgravity with a linearly distributed ambient temperature. The destabilization of thermocapillary flow by interfacial heat-loss in the range of small Bi ($Bi < 1$) was also found. However, due to the computational task of 3D direct numerical simulations, the results available in Ref. [18] are still fragmentary (there are only two data points in the range $0 < Bi < 1$ where steep variation of the marginal curve occurs, according to the present study). However, with the aim of manipulation of oscillatory thermocapillary flow in a liquid bridge through external application of forced gas flow, which closely relates to the effect of interfacial heat exchange, a space experiment co-operated by ESA and JAXA researchers is scheduled in ISS in the

* Corresponding author. Tel.: +86 10 82544098; fax: +86 10 82544096.
E-mail address: likai@imech.ac.cn (K. Li).

0017-9310/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2011.01.026

Nomenclature

A	matrix in eigenvalue problem
B	matrix in eigenvalue problem
$Bi = \frac{hR}{k}$	Biot number
D_{th}	thermal dissipation
E_{th}	"thermal" energy of disturbances
h	heat transfer coefficient on free surface
$h(z)$	free surface local radius
i	$\sqrt{-1}$
J_i	interactive term in "thermal" energy equation decomposed in cylindrical coordinates
k	thermal conductivity coefficient
L	height of the liquid bridge
$Ma = \frac{\gamma \Delta T R}{\mu \alpha}$	Marangoni number
$\vec{n}$	the outward-directed normal vector of the free surface
N_z	number of the grid points in axial direction
N_r	number of the grid points in radial direction
P	pressure
$\mathrm{Pr} = \frac{\upsilon}{\alpha}$	Prandtl number
(r, φ, z)	cylindrical coordinate
R	radius of the liquid bridge
S	dimensionless stress tensor $S = \nabla\vec{U} + (\nabla\vec{U})^T$
t	dimensionless time
$\vec{t}_\varphi$	the unit vector tangent to the free surface in the (r, φ) plane
$\vec{t}_z$	the unit vector tangent to the freesurface in the (r, z) plane
T	dimensionless temperature
T_0	mean temperature of the upper and lower ends
T_{amb}	dimensionless ambient temperature
T_{cold}	dimensionless temperature on the cold rod
$\vec{U} = (u, \ \ v, \ \ w)$	dimensionless velocity vector
x	vector composed of disturbance velocity, pressure and temperature $(u', iv', w', p', T')^{\mathrm{T}}$
X	the basic steady axisymmetric state
V_0	the liquid volume with cylindrical shape
Greek symbols	
α	thermal diffusivity coefficient
β	thermal expansion coefficient
ΔT	applied temperature difference
γ	negative temperature gradient of surface tension
$\Gamma = \frac{L}{R}$	aspect ratio
μ	dynamic viscosity coefficient
υ	kinematic viscosity coefficient
ρ_0	mean density
$\sigma(m)$	the complex growth rate of the corresponding perturbation mode
μ	dynamic viscosity coefficient
Ω	volume domain occupied by the liquid bridge
ε	thermal radiation

near future, and the corresponding preliminary theoretical studies are necessary due to the scarce space experiment opportunities. In the present study, linear stability analyses were conducted to investigate the dependency of the critical conditions of thermocapillary flow on interfacial heat exchange in a liquid bridge of a high Prandtl number fluid in microgravity, with both constant and linearly distributed ambient temperature. Moreover, the normalized "thermal" energy balance between the basic state and the critical perturbation of thermocapillary flow was investigated. Finally, the effect of interfacial heat exchange on thermocapillary flow in a liquid bridge of low Prandtl number fluid in microgravity was investigated as a comparison.

2. Governing equations and numerical schemes

Fig. 1 shows a schematic diagram of the liquid bridge of the 1 cst silicone oil (Γ = 1.8, Pr = 16.0) adopted in the present study. The thermo-physical properties of the silicone oil are listed in Table 1. With the unitary volume ratio usually adopted in the space experiment, the liquid column is cylindrical. The length, velocity, pressure and time are scaled by R, $\frac{\gamma\Delta T}{\mu}$, $\frac{\gamma\Delta T}{R}$ and $\frac{R^2}{\upsilon}$, respectively. The temperature measured with respect to T_0 is scaled by ΔT. In the cylindrical coordinates $(r, \ \ \varphi, \ \ z)$, the non-dimensional governing equations are as follows:

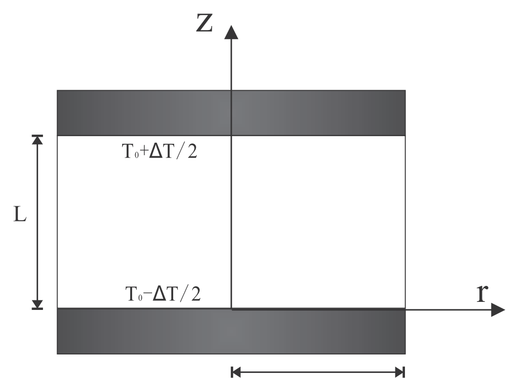

Fig. 1. Schematic of a cylindrical liquid bridge in microgravity.

$$\nabla\vec{U} = 0, \tag{1}$$

$$\frac{\partial\vec{U}}{\partial t} + \frac{Ma}{Pr}(\vec{U}\nabla)\vec{U} + \nabla P = \Delta\vec{U}, \tag{2}$$

$$\frac{\partial T}{\partial t} + \frac{Ma}{Pr}(\vec{U}\nabla)T = \frac{1}{Pr}\Delta T \tag{3}$$

The corresponding boundary conditions are as follows:

$$z = 0, \quad \Gamma: \ \vec{U} = 0, \quad T = \mp\frac{1}{2}, \tag{4}$$

$$\begin{aligned} &r = 1: \ \vec{n}\vec{U} = 0, \quad \vec{t}_z S\vec{n} = -\vec{t}_z\nabla T \\ &\vec{t}_\varphi S\vec{n} = -\vec{t}_\varphi\nabla T, \quad \vec{n}\nabla T = -Bi(T - T_{amb}). \end{aligned} \tag{5}$$

For the linear stability analysis, the basic axisymmetric steady state, $X = \{\vec{U}(r, \ \ z) = U\vec{e}_r + W\vec{e}_z, P(r,z), T(r,z)\}$, is first determined for a given set of parameters (Ma and Bi). Then small three-dimensional disturbances are imposed on the basic state, and the corresponding equations are linearized by neglecting high orders of the disturbances. The disturbances are assumed to be in the normal modes:

Table 1
Thermophysical properties of 1 cst silicone oil.

ρ_0	818 (kg/m^3)	β	0.00129 (K^{-1})
υ	10^{-6} (m^2/s)	γ	5.63×10^{-5} (kg/s^2)
K	2.4×10^{-2} (cal/m · s · k)	Prandtl number	16.0

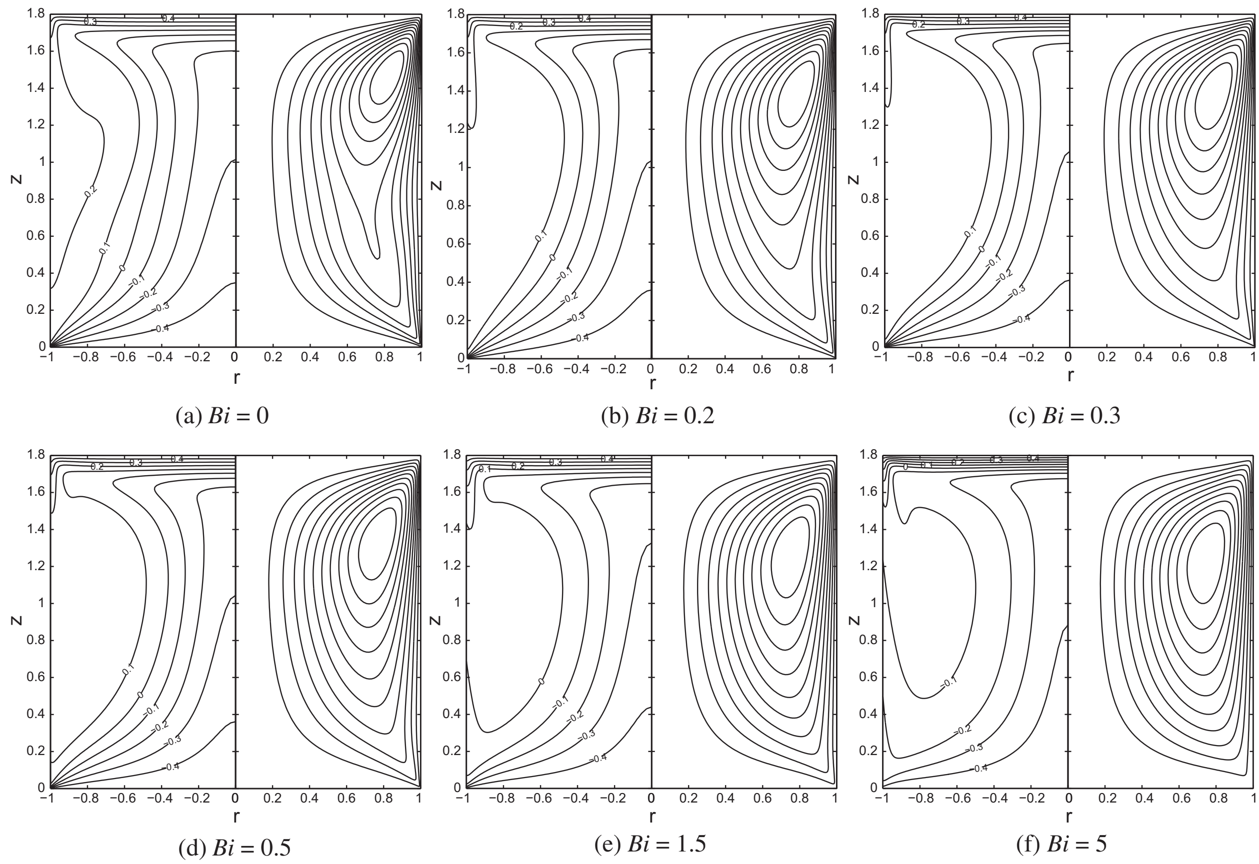

Fig. 2. Biot number dependent streamlines (right) and isothermals (left) of the basic steady flow at corresponding Ma_c for $T_{amb} = -0.5$.

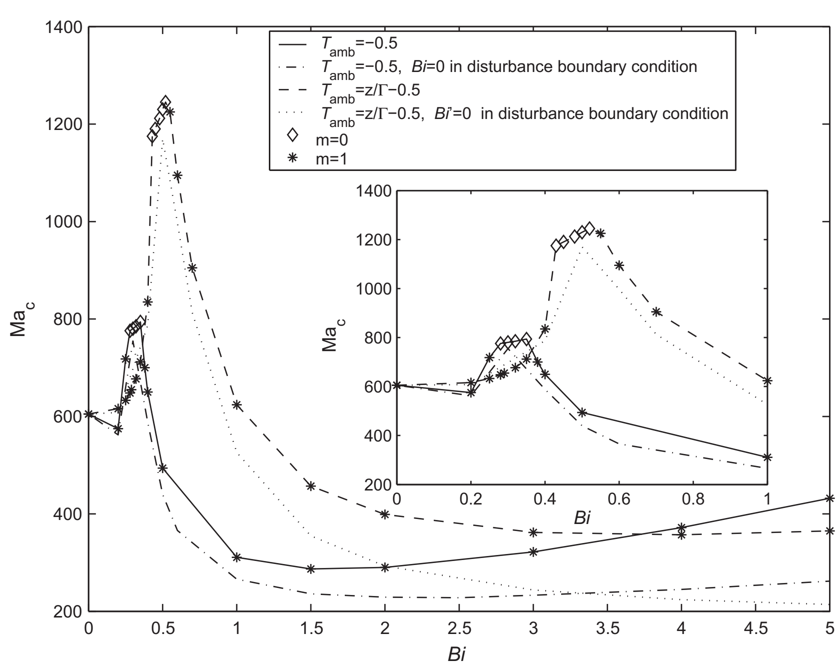

Fig. 3. Biot number dependent profiles of the critical Marangoni number.

$$\begin{pmatrix} \vec{u}' \\ P' \\ T' \end{pmatrix} = \sum_{m=-\infty}^{+\infty} \begin{pmatrix} \vec{u}'^m(r,z) \\ p'^m(r,z) \\ T'^m(r,z) \end{pmatrix} \exp\left[\sigma(m)t + jm\phi\right]. \tag{7}$$

The discrete form of the linearized equations can be written as a generalized eigenvalue problem:

$$g(x, X, Ma, m, Bi) \equiv Ax = \sigma(m)Bx. \tag{8}$$

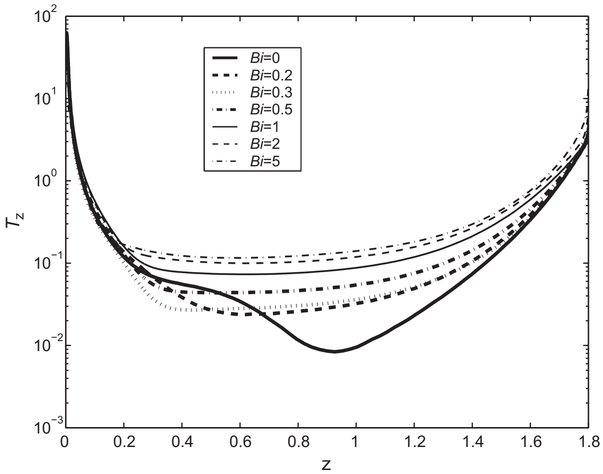

Fig. 4. Biot number dependent temperature gradient distribution at free surface at the corresponding Ma_c for $T_{amb} = -0.5$.

The eigenvalues and the related eigenfunctions of the problem are solved by the Arnoldi method [21]. For a non-symmetric eigenvalue problem, a direct method like QZ algorithm destroys the sparse structure of the problem and involves extensive computation task work which becomes impractical for large system. The Arnoldi method finds the desired eigenvalues through subspace iteration. Since we only concern about the extremal eigenvalue in our linear stability analysis, and the sparse structure of the problem, the Arnoldi method is a proper method to be adopted. And the success of its application has been demonstrated by our previous work [20,22]. The critical Marangoni number (Ma_c) is obtained when the maximum of the real part of $\sigma(m)$ for all m is zero. In practice, the azimuthal wave number m for the critical mode is not very large, and we calculated only for $0 \leqslant m \leqslant 4$. The details of the linear stability analysis can also be found in [22]. In order to properly resolve the boundary layers at both solid ends, a non-uniform mesh with denser grid points near the solid ends

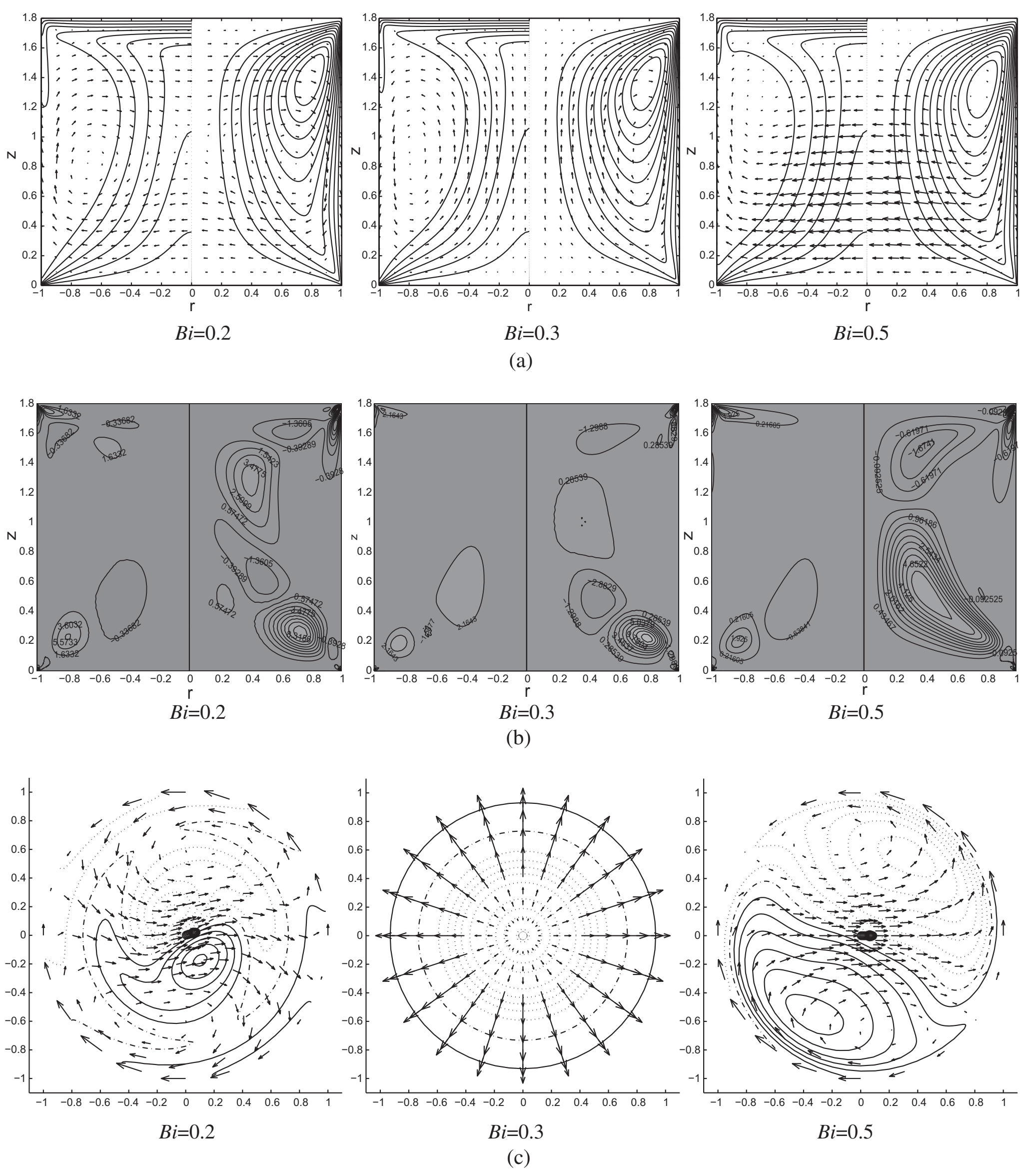

Fig. 5. (a) Streamlines (solid lines on right) and isothermals (solid lines on left) of the basic steady flow and velocity disturbances (vectors) in r–z plane; (b) distribution density j_1 (right) and j_2 (left) in r–z plane; (c) velocity disturbances (vectors) and isolines of temperature disturbances (solid lines: positive temperature disturbance; dotted lines: negative temperature disturbance; dash-dotted line: zero temperature disturbance.) at horizontal cut plane $z = \frac{\Gamma}{2}$ at the corresponding critical state at different Biot number for $T_{amb} = -0.5$.

and the free surface was adopted in this study. The total grid number is $N_r \times N_z = 81 \times 141$. The detailed code validation can be found elsewhere [20,22].

To better understand the energy balance between the basic state of thermocapillary flow and the critical temperature perturbation, the rate of "thermal" energy change (E_{th}) of the critical disturbance [7,9,10] was investigated: the thermal disturbance equation was multiplied by the temperature disturbance and integrated over the volume of the liquid bridge (Ω),

$$\frac{1}{D_{th}}\frac{dE_{th}}{dt} = Q + J - 1, \tag{9}$$

where $E_{th} = \int_\Omega \frac{T'^2}{2} d\Omega$, $D_{th} = \int_\Omega \frac{\nabla T' \nabla T'}{Pr} d\Omega$. Note that Eq. (9) is normalized by the thermal dissipation (D_{th}). $Q = -\frac{Bi}{PrD_{th}} \oint_s T'^2 ds$ is the transport of "thermal" energy through the free surface, $J = -\frac{Ma}{PrD_{th}} \int_\Omega (\vec{u}'\nabla T)T' d\Omega = J_1 + J_2 = -\frac{Ma}{PrD_{th}} \int_\Omega \left(u'\frac{\partial T}{\partial r}\right)T' d\Omega - \frac{Ma}{PrD_{th}} \int_\Omega \left(w'\frac{\partial T}{\partial z}\right)T' d\Omega$ is the interactive term between the basic thermal state and the disturbance, which indicates the energy transfer from the basic thermal field to the temperature disturbance field by the disturbance velocity. Moreover, the distribution density of J_1 and J_2 can be introduced as j_1 and j_2 through $J_1 = \int_0^\Gamma dz \int_0^1 j_1 dr$ and $J_2 = \int_0^\Gamma dz \int_0^1 j_2 dr$. A similar procedure can be used for kinetic energy balance [10,20]. However, the thermal energy balance is the focus for the liquid bridge of high Prandtl number fluids as in the present study [10].

3. Results and discussion

We studied the thermocapillary flow in a cylindrical liquid bridge in microgravity with heat transfer through the free surface. First, the case with constant ambient temperature ($T_{amb} = T_{cold}$) [17] was investigated. Fig. 2 shows the isotherms and streamlines of the basic steady axisymmetric field at the critical state for different Biot number. The isotherms crowd at the cold corner and nearly linearly distribute at the hot end except in the hot corner. In this case, the interfacial heat transfer is always heat-loss from the liquid bridge to the environment. The interfacial heat exchange pulls up the isotherms at the cold corner and enhances the axial temperature gradient at the hot end. Fig. 3 shows the Biot number dependent critical Marangoni number. In the range of intermediate and large Bi, the profile of the critical Marangoni number exhibits a convex trend, i.e. the critical Marangoni number firstly decreases with increasing Biot number up to $Bi = 1.5$, followed by an approximately linear increase. However, in the parameter range studied, the effect of heat-loss is not sufficiently intensive to stabilize thermocapillary flow with respect to the adiabatic case [17]. On the other hand, in the range of small Biot number, the critical Marangoni number increases rapidly with decreasing heat-loss, then drops sharply to that of the adiabatic case. This phenomenon is qualitatively consistent with experimental predictions [19] where Wang et al. also found that the critical Marangoni number decreases substantially when the modified average Biot number over the free surface changes from positive to zero.

Noting that the disturbances must vanish at the solid ends, the magnitude of the disturbances near the solid ends should be smaller than in the bulk region. The stability properties of the basic flow are mainly determined by the "effective" temperature difference in the middle part of the liquid bridge [23] where the largest disturbances exist. From this viewpoint, the temperature gradient at the middle part of the free surface was investigated (see Fig. 4). It was discovered that the temperature gradient at the middle part of the free surface increases with increasing Biot number in the range $Bi \geqslant 0.4$. Hence with the same applied temperature difference the effective temperature difference at the middle part of the free surface is larger for the case with larger Bi, and the corresponding basic flow tends to be destabilized. On the other hand, according to the boundary condition of the thermal perturbation at the free surface:

$$\vec{n}\nabla T' = -Bi \times T', \tag{10}$$

whenever a positive temperature disturbance arises somewhere on the free surface, it is accompanied by an increase of heat-loss through that part, and vice versa. Therefore, interfacial heat exchange restrains development of the temperature disturbance. To verify these remarks, Fig. 3 also shows the computed results with the Bi in Eq. (10) (but not in the basic state equations) set to zero. With the same basic flow, the interfacial heat exchange significantly stabilizes thermocapillary flow, and the stabilization effect becomes intensive with increasing Biot number. Practically, the major convex tendency of the Ma_c profile could be due to competition of the two mechanisms mentioned above. However, the appearance of the local maximum of Ma_c in the range of small Biot numbers, could not be explained either in experimental studies [15,19] or in the present study. Some interesting phenomena should be noted. One is that the temperature gradient distribution exhibits an undulation at the middle part of the free surface in the range of small Biot number (see Fig. 4). This configuration transition coincidentally corresponds to appearance of the local maximum of the Ma_c profile. The other phenomenon is a special axisymmetric oscillation mode with azimuthal wave number $m = 0$ that dominates the peak region of the neutral stability boundary, contrary to the other cases with $m = 1$. Fig. 5c shows the corresponding distributions of the velocity and temperature disturbances at the horizontal middle plane $z = \frac{\Gamma}{2}$. For the $Bi = 0.3$ case, the axisymmetric nature of the perturbations is obvious. There is no azimuthal velocity disturbance and the other disturbances are equally distributed azimuthally. However, the detailed relationships between the above phenomena and the local maximum of the Ma_c profile need further investigation.

To better understand energy transfer between the basic thermal field and the temperature disturbance of the thermocapillary flow, the normalized "thermal" energy balance was investigated. In all cases studied, the term Q which indicates the energy transfer through the free surface is relatively small (in the order of 10^{-2}). The temperature disturbances on the free surface are strongly restrained. Fig. 5a shows that the radial temperature gradient of the basic thermal field is significant in the center and both the hot and cold corners of the liquid bridge, while the axial temperature

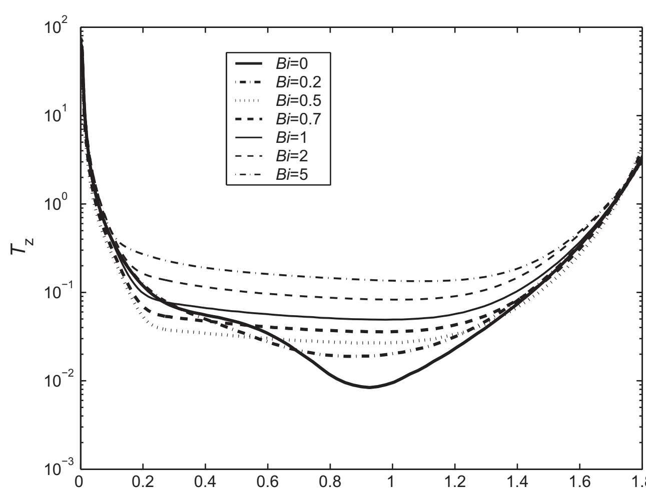

Fig. 6. Biot number dependent temperature gradient distribution at free surface at corresponding Ma_c for linear T_{amb}.

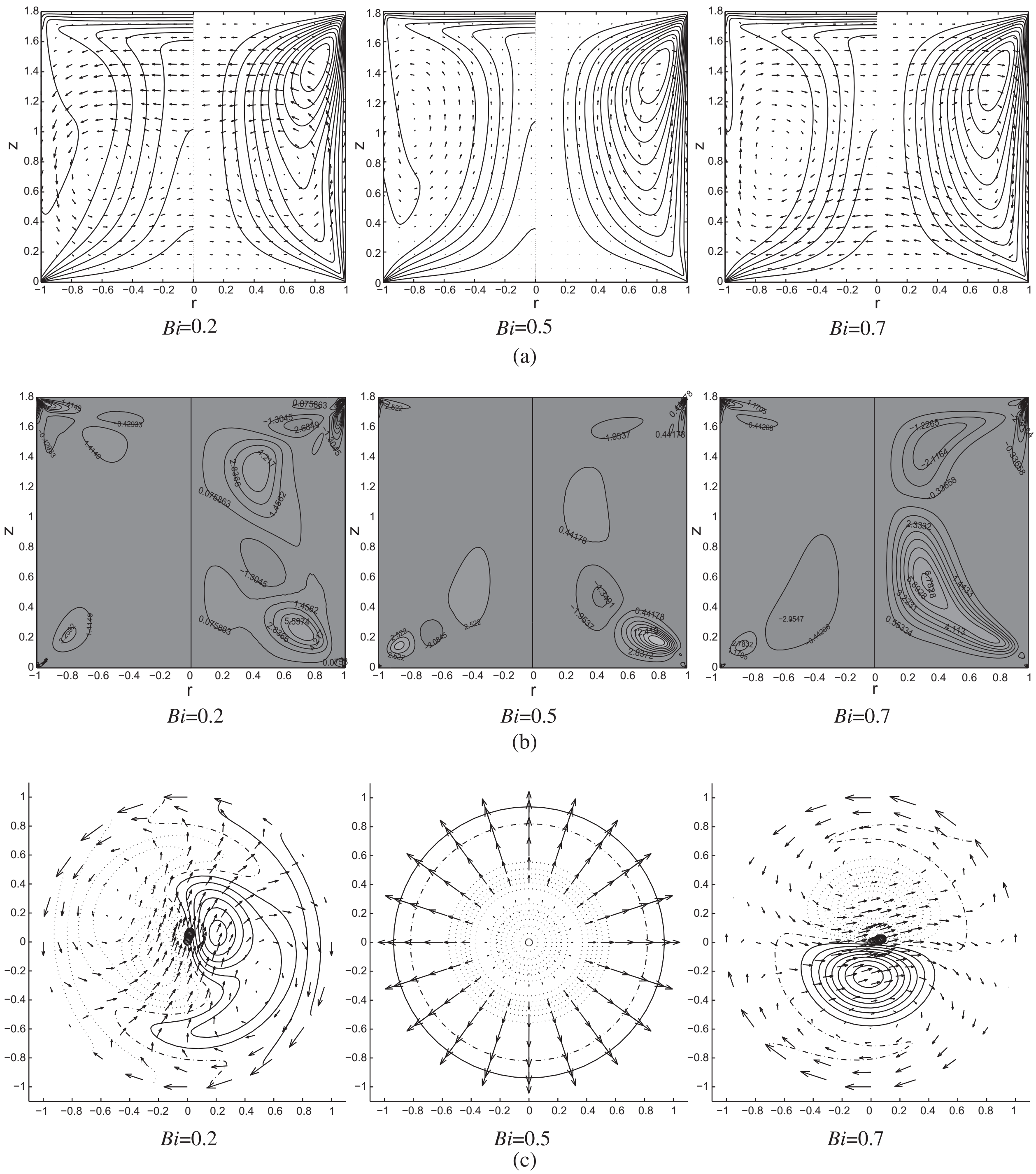

Fig. 7. (a) Streamlines (solid lines on right) and isothermals (solid lines on left) of the basic steady flow and velocity disturbances (vectors) in *r–z* plane; (b) distribution density j_1 (right) and j_2 (left) in *r–z* plane; (c) velocity disturbances (vectors) and isolines of temperature disturbances (solid lines: positive temperature disturbance; dotted lines: negative temperature disturbance; dash-dotted line: zero temperature disturbance) at horizontal cut plane $z = \frac{\Gamma}{2}$ at the corresponding critical state at different Biot number for linear T_{amb}.

gradient is significant in the hot end and cold corner. According to Eq. (9), J_1 is the energy transfer to the temperature disturbance from the radial temperature distribution of the basic thermal field by the radial velocity disturbance, while J_2 is the energy transfer to the temperature disturbance from the axial temperature distribution of the basic thermal field by the axial velocity disturbance. Therefore, for the cases with the oscillatory mode of $m = 1$ (see Fig. 5b), J_1 has its maximum distribution density in the center of the liquid bridge, and makes the major contribution to the disturbance energy which always serves as the destabilizing effect. J_2 has its maximum distribution density in the cold corner, and compared to J_1 makes a less important contribution to the disturbance energy. For instance, J_1 is 0.75 and 1.1 for Biot number 0.2 and 0.5 respectively, and correspondingly J_2 is 0.25 and -0.1, respectively. On the other hand, for the cases with oscillatory mode of $m = 0$, in the center of the liquid bridge, the velocity disturbance is nearly parallel to the basic thermal contours, and both J_1 and J_2 have maximum distribution density in the cold corner. In the case of $Bi = 0.3$, for instance, J_1 equals 0.1 and J_2 equals 0.9, so that the major contribution to the disturbance energy is from J_2 instead of J_1.

Secondly, the case with linearly distributed ambient temperature ($T_{amb} = z/\Gamma - 0.5$) [18] was investigated. In this case, heat-loss to the environment occurs at the lower part of the free surface, while heat-gain occurs from the environment at the upper part. With increasing interfacial heat exchange, the isotherms and streamlines of the two-dimensional axisymmetric convection (not shown) at the corresponding Ma_c behave quite similarly to the case with the constant ambient temperature ($T_{amb} = T_{cold}$), and likewise for the temperature gradient distributions on the free surface (see Fig. 6). Fig. 3 shows the heat transfer dependent Ma_c. (Fig. 3 also shows the computed results with Bi in Eq.(10) set to zero). The Ma_c profile exhibits a roughly similar tendency to the case with constant ambient temperature, except for the much flattened slope of the profile in the range of large Bi. Moreover, the special oscillation mode of $m = 0$ dominates the peak region of the neutral stability boundary, unlike the other cases with $m = 1$. Fig. 7 shows the computed results for the disturbances distribution. Similar to the constant ambient temperature case, in the global energy contributions of the terms in Eq. (9), energy transfer through the free surface Q is relatively small (in the order of 10^{-2}), while the major contribution to the disturbance energy for the cases of $m = 1$ is from J_1 which always serves as a destabilizing effect. J_2 also makes a contribution to the disturbance energy, but with less importance compared to J_1. On the other hand, for the cases of $m = 0$, the major contribution to the disturbance energy is from J_2, and J_1 makes a much smaller contribution to the disturbance energy.

Finally, the effect of the interfacial heat exchange on the thermocapillary flow in liquid bridge of low Prandtl number fluid in microgravity was also studied as a comparison. The details of the physical model and mathematical formulation can be found in [24]. Fig. 8 shows the computed results for a liquid bridge ($\Gamma = 2.0$) of molten tin ($Pr = 0.009$). The melting point of tin is 750 K. The ambient temperature is assumed to be 300 K, hence thermal radiation (ε is assumed to be 0.1) plays the major role in interfacial heat exchange in this case. With the adiabatic melt free surface, the critical Reynolds number is determined as $Re_c = 2819$ with critical oscillation frequency $f_c = 0.468$ Hz. When interfacial radiation is taken into account the critical Reynolds number is determined as $Re_c = 2828$ with $f_c = 0.474$ Hz. The deviation between the critical Reynolds numbers is less than 1%. Consequently, unlike the case of the liquid bridge of high Prandtl number fluids, the effect of interfacial heat exchange on the onset of oscillatory thermocapillary flow in a liquid bridge of low Prandtl number fluids in microgravity is insignificant.

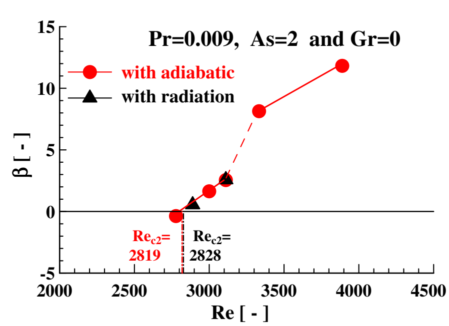

Fig. 8. Critical Reynolds number for liquid bridge of $Pr = 0.009$ with adiabatic and radiative free surface.

4. Conclusions

The effect of interfacial heat exchange on the onset of oscillatory thermocapillary flow in a cylindrical liquid bridge formed by 1 cst silicone oil ($Pr = 16.0$) with aspect ratio 1.8 in microgravity was investigated in an extended range of Biot number. With both constant and linearly distributed ambient temperatures, the computed results predict that interfacial heat exchange plays an important role in oscillatory thermocapillary flow in liquid bridges of high Prandtl number fluids. The corresponding marginal stability boundary exhibits a roughly convex trend with increasing Biot number. However, a sharp local maximum exists in the range of small Biot number where a special oscillation mode of $m = 0$ dominates, contrary to the other cases with $m = 1$. For the case of $m = 1$, the major destabilizing contribution to the disturbance energy is from the energy transfer from the radial temperature distribution of the basic thermal field in the center of the liquid bridge by the radial velocity disturbance. For the case $m = 0$ the major destabilizing contribution is from the energy transfer from the axial distribution of the basic thermal field in the cold corner of the liquid bridge by the axial velocity disturbance. Moreover, the effect of interfacial heat exchange on thermocapillary flow in a liquid bridge of low Prandtl number fluid in microgravity was also investigated as a comparison, and predicted to be insignificant.

Acknowledgments

This research is supported by the National Natural Science Foundation of China (Grant Nos. 11032011, 10872202) and the Knowledge Innovation Project of the Chinese Academy of Sciences (Grant No. KJCX2-YW-L08).

References

[1] W.R. Hu, Z.M. Tang, K. Li, Thermocapillary flow in floating zones, Appl. Mech. Rev. 61 (2008) (010803-15).
[2] Ch.H. Chun, W. Wuest, A micro-gravity simulation of the Marangoni convection, Acta Astronaut. 5 (1978) 681–686.
[3] Ch.H. Chun, W. Wuest, Experiments on the transition from the steady to the oscillatory Marangoni-convection of a floating zone under reduced gravity effect, Acta Astronaut. 6 (1979) 1073–1082.
[4] D. Schwabe, A. Scharmann, F. Preisser, R. Oeder, Experiments on surface tension driven flow in floating zone melting, J. Cryst. Growth 43 (1978) 305–312.
[5] D. Schwabe, A. Scharmann, Some evidence for the existence and magnitude of a critical Marangoni number for the onset of oscillatory flow in crystal growth melts, J. Cryst. Growth 46 (1979) 125–131.
[6] M.K. Smith, S.H. Davis, Instability of dynamic thermocapillary liquid layer Part I: Convective instability, J. Fluid Mech. 132 (1983) 119–144.
[7] G.P. Neiztel, K.T. Chang, D.F. Jankowski, H.D. Mittelmann, Linear stability of thermocapillary convection in a model of the floating zone crystal growth process, AIAA 92 (1992) 0604.
[8] M. Wanschura, V.M. Shevtsova, H.C. Kuhlmann, H.J. Rath, Convective instability mechanisms in thermocapillary liquid bridge, Phys. Fluids 7 (1995) 912–925.
[9] G. Chen, A. Lizee, B.J. Roux, Bifurcation analysis of the thermocapillary convection in cylindrical liquid bridge, J. Cryst. Growth 180 (1997) 638–647.
[10] C.H. Nienhüser, H.C. Kuhlmann, Stability of thermocapillary flows in non-cylindrical liquid bridges, J. Fluid Mech. 458 (2002) 35–73.
[11] G.P. Neitzel, C.C. Law, D.F. Jankowski, H.D. Mittelmann, Energy stability of thermocapillary convection in a model of the floating zone crystal growth process, Phys. Fluids A 3 (1991) 2841–2846.
[12] R. Savino, R. Monti, Oscillatory Marangoni convection in cylindrical liquid bridge, Phys. Fluids 8 (1996) 2906–2922.
[13] V.M. Shevtsova, J.C. Legros, Oscillatory convection motion in deformed liquid bridges, Phys. Fluids 10 (1998) 1621–1634.
[14] M. Levenstam, G. Amberg, C. Winkler, Instability of thermocapillary convection in a half-zone at intermediate Prandtl numbers, Phys. Fluids 13 (2001) 807–816.
[15] Y. Kamotani, L. Wang, S. Hatta, A. Wang, S. Yoda, Free surface heat loss effect on oscillatory thermocapillary flow in liquid bridges of high Prandtl number fluids, Int. J. Heat Mass Transfer 46 (2003) 3211–3220.
[16] M. Irikura, Y. Arakawa, I. Ueno, H. Kawamura, Effect of ambient fluid flow upon onset of oscillatory thermocapillary convection in half-zone liquid bridge, Microgravity Sci. Technol. 16 (2005) 176–180.

[17] D.E. Melnikov, V.M. Shevtsova, Thermocapillary convection in a liquid bridge subjected to interfacial cooling, Microgravity Sci. Technol. 18 (2006) 128–131.
[18] Y. Kousaka, H. Kawamura, Numerical study on the effect of heat loss upon the critical Marangoni number in a half-zone liquid bridge, Microgravity Sci. Technol. 18 (2006) 141–145.
[19] A. Wang, Y. Kamotani, S. Yoda, Oscillatory thermocapillary flow in liquid bridges of high Prandtl number fluid with free surface heat gain, Int. J. Heat Mass Transfer 50 (2007) 4195–4205.
[20] B. Xun, K. Li, P.G. Chen, W.R. Hu, Effect of interfacial heat transfer on the onset of oscillatory convection in liquid bridge, Int. J. Heat Mass Transfer 52 (2009) 4211–4220.
[21] G.H. Golub, C.F. VanLoan, Matrix Computations, Johns Hopkins University Press, Baltimore, 1996.
[22] B. Xun, P.G. Chen, K. Li, Z. Yin, W.R. Hu, A linear stability analysis of large-Prandtl-number thermocapillary liquid bridges, Adv. Space Res. 41 (2008) 2094–2100.
[23] D. Schwabe, Hydrothermal waves in a liquid bridge with aspect ratio near the Rayleigh limit under microgravity, Phys. Fluids 17 (2005) 112104.
[24] N. Imaishi, S. Yasuhiro, Y. Akiyama, S. Yoda, Numerical simulation of oscillatory Marangoni flow in half-zone liquid bridge of low Prandtl number fluid, J. Cryst. Growth 230 (2001) 164–171.