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強制対流熱伝達とふく射伝熱が高プラントル数液柱内表面張力流に及ぼす影響の数値シミュレーション

Numerical Simulation of the Effect of Forced Convective and Radiative Heat Transfer on Thermocapillary Convection in a High-Prandtl-Number Liquid Bridge

矢野大志 [1]，西野耕一 [2]
Taishi YANO[1], Koichi NISHINO[2]
1　神奈川大学，Kanagawa University
2　横浜国立大学，Yokohama National University

1. Introduction

The interfacial heat transfer—the heat transferred through the liquid-gas interface—is one of the most important parameters for the thermocapillary convection in a liquid bridge exposed to the ambient gas. A liquid bridge is a column of the liquid suspended between a pair of parallel rigid walls, which are, in this study, circular in shape, with one having a higher temperature than the other (**Fig. 1**). Since the strength of surface tension σ of many liquids, such as silicone oil, is a monotonically decreasing function of temperature T (i.e., $\partial\sigma/\partial T < 0$), the inhomogeneous temperature distribution on the liquid bridge free surface and the resultant tangential surface stress (i.e., the so-called thermocapillary stress) drives the thermocapillary convection. The net flow direction in the vicinity of the liquid bridge free surface is from the warmer side toward the cooler side due to negative $\partial\sigma/\partial T$, while that in the interior region reverses in order to satisfy the mass conservation in the liquid bridge. The interfacial heat transfer can change the temperature of the liquid bridge; therefore, it has notable impact on the flow pattern as well as the instability of thermocapillary convection. For this reason, many researchers[1–3] paid attention to the interfacial heat transfer, and its effects have been investigated over the past few decades. Currently, a Japanese-European joint project in the Japanese Experiment Module Kibo on the International Space Station (ISS), which is called the Japanese-European Research Experiment on Marangoni Instability (JEREMI), is planned for execution within a few years.[4–5] One of the main research targets in JEREMI is to understand the effects of interfacial

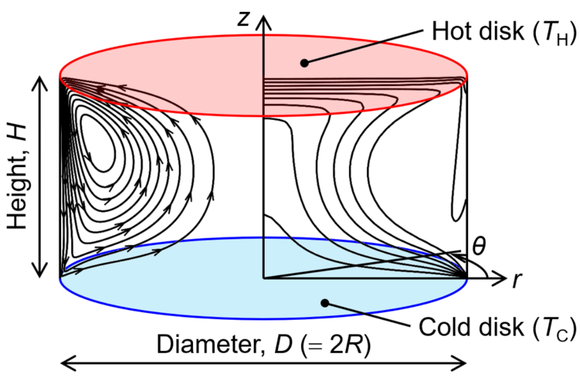

Fig. 1　Geometry of the liquid bridge suspended between a pair of circular disks with different temperatures. The typical flow and temperature patterns of thermocapillary convection are illustrated in the left and right halves of the diagram, respectively.

heat transfer on the thermocapillary convection. The present study is positioned as a prior research of JEREMI project, and the effects of interfacial heat transfer due to the forced ambient gas flow (i.e., the convective heat transfer) and the radiation (i.e., the radiative heat transfer) on the flow and temperature patterns of axisymmetric steady thermocapillary convection are investigated through numerical simulations.

2. Numerical Simulation

In the present study, the commercial computational fluid dynamics (CFD) software STAR-CCM+ ver. 14.02 is used to simulate the axisymmetric steady thermocapillary convection. As mentioned above, the present study focuses on the JEREMI project; therefore, the simulation domain geometry, working fluids, boundary conditions, and other conditions are selected to reflect those in JEREMI. The substance of the present liquid bridge is silicone oil with the Prandtl number (Pr) of 67. The liquid bridge has a perfect cylindrical shape with D = 10 mm and H = 5 or 10 mm; therefore, the target aspect ratios (i.e., $A = H/D$) is A = 0.5 and 1.0 (see **Fig. 1** for the definitions of D and H). The liquid bridge is suspended between the 10.5 mm-height disk at temperature T_C and the 3.5 mm-height disk at temperature T_H, where diameters of both disks are 10 mm. Hereinafter, the former disk is referred to as the cold disk and the latter one is referred to as the hot disk, because the relation $T_C < T_H$ always holds through the present study. The liquid bridge and these disks are placed inside a cylindrical chamber with diameter of 30 mm, which is filled with argon gas.

The flow and temperature fields both in the liquid bridge and in the ambient gas are simulated simultaneously through the following time-independent continuity, momentum, and energy equations of incompressible Newtonian fluids under zero-gravity conditions:

$$\nabla \cdot \boldsymbol{u} = 0 , \tag{1}$$

$$(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \boldsymbol{u} , \tag{2}$$

$$(\boldsymbol{u} \cdot \nabla)T = \alpha \nabla^2 T , \tag{3}$$

where $\boldsymbol{u}$ (= u_r, u_θ, u_z) is the velocity vector, p is the pressure, ρ is the density, ν is the kinematic viscosity, and α is the thermal diffusivity. On the liquid-gas interface, the balances of the tangential stress and the heat flux density can be expressed as

$$\mu^{(l)} \frac{\partial u_z^{(l)}}{\partial r} - \frac{\partial \sigma}{\partial z} = \mu^{(g)} \frac{\partial u_z^{(g)}}{\partial r} , \tag{4}$$

$$-k^{(l)} \frac{\partial T^{(l)}}{\partial r} = q_c + q_r , \tag{5}$$

respectively, where μ is the dynamic viscosity, k is the thermal conductivity, q_c and q_r are the heat flux densities due to convection and radiation, respectively, and superscripts (l) and (g) denote the quantities for the liquid and the gas, respectively. We note that a cylindrical coordinate system (r, θ, z) with its origin at the center of the cold disk is adopted as illustrated in **Fig. 1**. The major components of the interfacial heat transfer considered in the present study are twofold: the convective component, and the radiative component. The effect of former component is investigated by inducing the forced gas flow around the liquid bridge, and that of latter component is investigated by changing the temperature of the chamber wall. The method, boundary conditions, and other conditions were reported in more detail by Yano and Nishino.[6)]

3. Results and Discussion

Some examples of the flow and temperature fields inside and in the vicinity of the liquid bridge obtained from the present numerical simulations are shown in **Fig. 2**. In these results, the temperatures of the cold disk and the hot disk are assumed to be constant at T_C = 20°C and T_H = 40°C, respectively. The temperature difference between the hot disk and the cold disk ΔT (= $T_H - T_C$) is therefore ΔT = 20 K, which yields $Ma = 1.93\times10^4$, where Ma is the Marangoni number defined as

$$Ma = \frac{\left|\partial\sigma/\partial T\right| \Delta T \left(D/2\right)}{\rho \nu \alpha} . \tag{6}$$

The temperature of the chamber side wall is denoted by T_W and it is varied in the range from T_C to T_H. The no-slop boundary conditions are applied on the surfaces of the cold disk, hot disk, and chamber side wall. If the forced ambient gas flow enters from the cold/hot disk side, the constant temperature ($T = T_C/T = T_H$) and the constant velocity ($\boldsymbol{u}$ = (0, 0, U_0)) conditions are applied on the chamber bottom/top wall, and the adiabatic and the pressure outlet conditions are applied on the chamber top/bottom wall. If there is no forced ambient gas flow (i.e., results with $U_0 = 0$), the no-slip conditions are applied for both chamber bottom and top walls, and the constant temperature conditions $T = T_C$ and T_H are applied for chamber bottom and top walls, respectively. We note that the negative or positive U_0 stands for the upward or downward gas flow in **Fig. 2**, respectively.

In **Fig. 2(a)**, the effects of convective heat transfer are investigated by varying U_0 from (1) +100 mm/s to (2) −100 mm/s, where T_W is kept constant at 30°C. As shown in these figures, the temperature in the vicinity of the liquid bridge free surface (referred to hereinafter as the surface temperature) for U_0 = +100 mm/s is basically lower than that for U_0 = −100 mm/s because the liquid bridge is surrounded by cooler ambient gas when the forced ambient gas flow enters from the cold disk side. Such drop in temperature increase the magnitude of thermocapillary stress near the hot disk and the resultant velocity on the liquid bridge free surface (referred to hereinafter as the surface velocity) is also increased in magnitude. It is confirmed that the contribution of viscous shear stress from the ambient gas flow to the convection inside the liquid bridge is insignificant compared with that of thermocapillary stress. Therefore, the primary effect of forced ambient gas flow is convective heat transfer rather than the viscous shear stress. **Figure 2(b)** compares the effects of radiative heat transfer for $U_0 = 0$, where T_W are (1) 20°C and (2) 40°C. The lower the temperature of chamber side wall is, the greater the amount of heat lost from the liquid bridge and vice versa; therefore, the surface temperature and the resultant surface velocity change with T_W. The results in **Fig. 2** indicate that both convective and radiative heat transfer appreciably affect the temperature and flow patterns of thermocapillary convection. It is interesting to point out that these effects appear not only in the vicinity of the free surface but also in the interior region.[6)]

The net heat transfer rates due to (1) convective heat transfer Q_c, (2) radiative heat transfer Q_r, and (3) both Q (= Q_c+Q_r) are evaluated for various combinations of U_0 and T_W, and they are mapped as a function of U_0 and T_W in **Fig. 3**. We note that the net heat transfer rates are evaluated as $Q_c = \int_S q_c dS$, $Q_r = \int_S q_r dS$, and $Q = \int_S (q_c + q_r) dS$, where the integration is performed over the liquid bridge free surface. We also note that the liquid bridge loses heat for $Q > 0$ and it gains heat for $Q < 0$. It is obvious from these results that the amount and direction of interfacial heat transfer (i.e., magnitude and sign of net heat transfer rate, respectively) are sensitive to both U_0 and T_W. As shown in **Figs. 3(1)** and **3(2)**, the amount of Q_c monotonically increases with increasing U_0, and that of Q_r monotonically increases with decreasing T_W. As a result, as

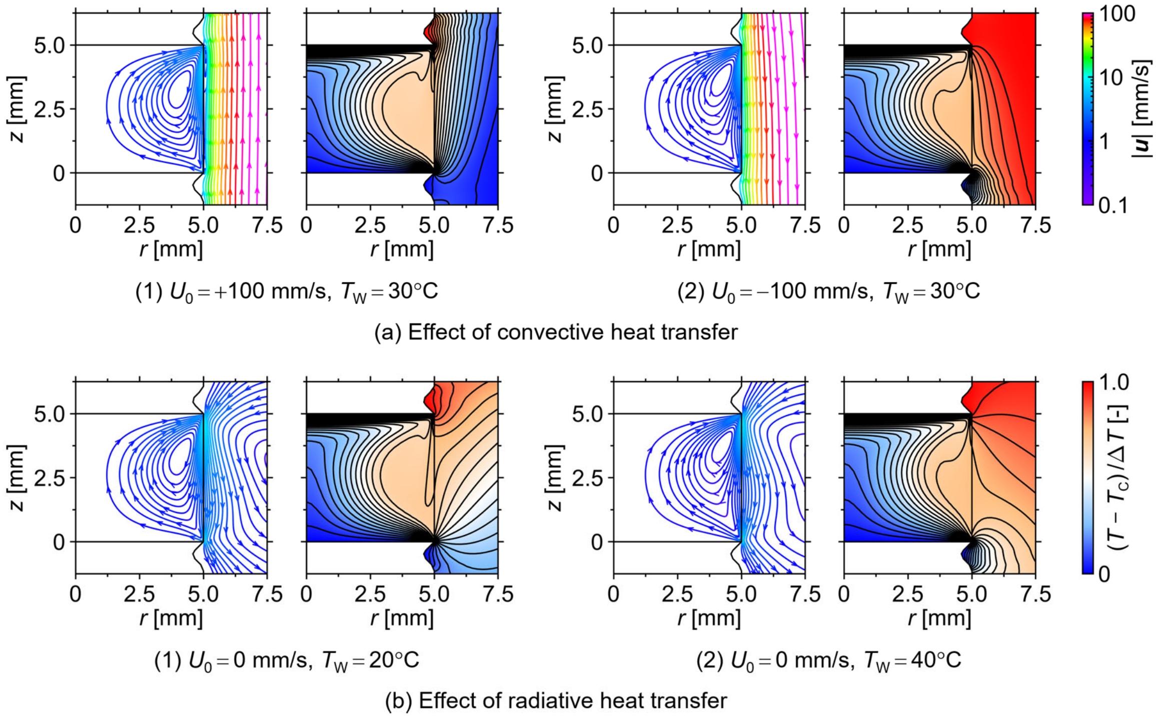

Fig. 2 Effect of (a) convective and (b) radiative heat transfer for $A = 0.5$ and $\Delta T = 20$ K: the flow field (each left) and the temperature field (each right).

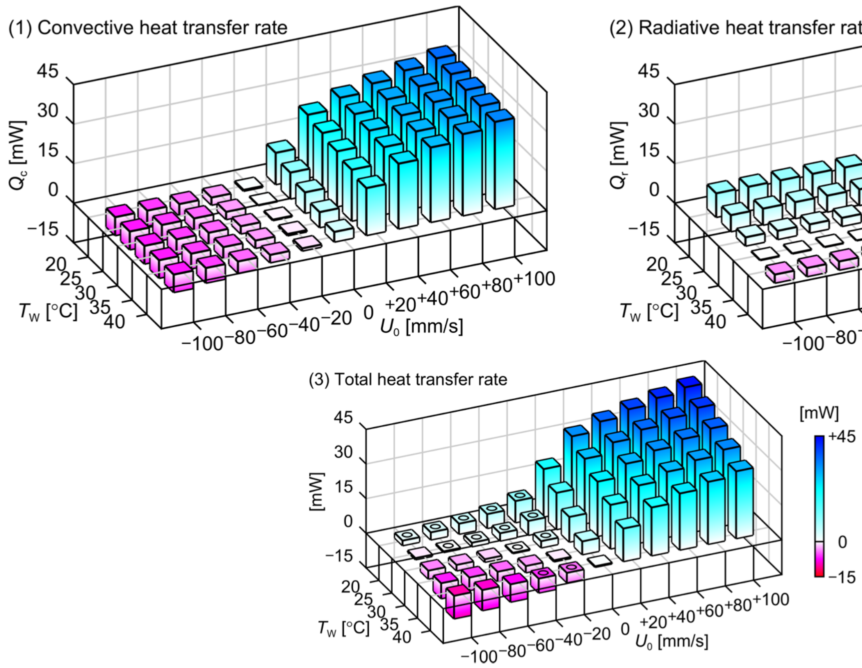

Fig. 3 Maps of net heat transfer rate through the liquid-gas interface for A = 0.5 and ΔT = 20 K: (1) convective component, (2) radiative component, and (3) total amount. Bars marked with circles in (3) indicate the conditions where $|Q_c| < |Q_r|$.

shown in **Fig. 3(3)**, the amount of Q increases with increasing U_0 and decreasing T_W and vice versa. It is important to note that bars marked with a circle in **Fig. 3(3)** indicate the conditions with $|Q_c| < |Q_r|$. The magnitude of Q_c is greater than that of Q_r for many cases, especially for $U_0 \geq 0$, meaning that the convective heat transfer is the primary component of the heat transfer for such cases. However, when the forced ambient gas flow enters from the hot disk side, the radiative heat transfer can be the primary component of the interfacial heat transfer. Such situation is peculiar to the zero-gravity or microgravity conditions because the buoyancy and associated natural convection heat transfer must exist on the normal-gravity condition and the contribution of the radiative heat transfer becomes relatively weak. The present results indicate that both convective and radiative heat transfer are important to the thermocapillary convection under reduced-gravity condition.

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