International Journal of Heat and Mass Transfer 125 (2018) 1121–1130

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effect of interfacial heat transfer on basic flow and instability in a high-Prandtl-number thermocapillary liquid bridge

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ARTICLE INFO

Article history:
Received 29 December 2017
Received in revised form 7 March 2018
Accepted 25 April 2018

Keywords:
Thermocapillary convection
Basic flow
Instability
Liquid bridge
Interfacial heat transfer

ABSTRACT

The effects of interfacial heat transfer on the basic flow and instability of thermocapillary convection in high-Prandtl-number (Pr) liquid bridges are investigated experimentally and computationally. Liquid bridges of silicone oil ($Pr = 28$) are formed in a gap between the lower cooled rod and the upper heated rod, both with a diameter of 5 mm, where the rods are surrounded by a cylindrical enclosure made from an acrylic block. The instability data are collected experimentally for $AR = 0.30–0.50$ and a wide range of $(T_C - T_a)$, where AR is the aspect ratio (= height/diameter) of the liquid bridge, T_C is the cooled rod temperature, and T_a is the ambient gas temperature. The data indicate the appreciable effect of interfacial heat transfer on the instability and basic flow pattern of thermocapillary convection in liquid bridges. Each instability curve for $AR = 0.35–0.50$ shows a local peak of the critical temperature difference and the oscillation frequency at a certain $(T_C - T_a)$, where such a peak is associated with the transition of the azimuthal oscillation mode. The heat transfer ratio Q_{LB}/Q_{HR} is evaluated from the numerical simulation to discuss the effect of interfacial heat transfer, where Q_{LB} and Q_{HR} are the heat transfer rates at the liquid bridge surface and at the heated rod surface, respectively. It is found that the instability conditions for different AR values are well correlated with Q_{LB}/Q_{HR}. This correlation is consistent with the effect of Q_{LB}/Q_{HR} on the basic flow and temperature fields, both in the liquid bridge and in the ambient gas. The resultant change in the basic flow and temperature field inside the liquid bridge leads to the change in the onset conditions of oscillatory thermocapillary convection.

1. Introduction

The thermocapillary convection in a liquid bridge (LB, hereafter) is driven by the surface tension difference induced by the temperature gradient along the LB free surface. The surface is exposed to an ambient gas whose temperature is usually different from the temperature of the LB. The heat transfer through the liquid-gas interface therefore plays an important role in the basic mechanisms and associated instability of the convection. Fig. 1 depicts a half-zone LB of high-Prandtl-number (Pr) fluid filling the gap between coaxial rods with a temperature difference of $\Delta T = T_H - T_C$. The convection exhibits a transition from a steady axisymmetric state to a variety of time-dependent oscillatory states at a certain critical temperature difference ΔT_c [1,2]. The relationship between such instability mechanisms and interfacial heat transfer has become an important subject for better understanding of thermocapillary convection.

The importance of interfacial heat transfer was noted by Kuhlmann and Rath [3] in their linear stability analysis for the LB of $Pr = 7$, where they showed better agreement with experimental data by considering the heat loss from the LB free surface. A significant effect of interfacial heat transfer on ΔT_c was shown experimentally by Kamotani et al. [4,5], Shevtsova et al. [6,7] and Wang et al. [8], who varied the heat transfer rate at the LB free surface by changing the temperature difference between the ambient gas and the cooled rod. These experimental studies showed that the free surface heat loss destabilizes the thermocapillary convection in straight or convex LBs. Wang et al. [8] also showed that ΔT_c becomes rather insensitive to the magnitude of heat transfer rate when the LB is warmed by the ambient gas (i.e., heat gain). Yano et al. [9] studied the effect of interfacial heat transfer on the thermocapillary convection in microgravity and revealed that the traveling direction of the hydrothermal wave is directed from the cold side toward the hot side under the heat-gain condition and is opposite under the heat-loss condition. Shevtsova et al. [6,7] reported an interesting finding in that the critical azimuthal oscillation mode (m) can switch from $m = 1$ to 2 with increasing heat loss for a certain LB condition.

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.132
0017-9310/

Nomenclature

AR	aspect ratio (=H/D)
Bd	dynamic Bond number (=$\rho g\beta H^2/\lvert\sigma_T\rvert$)
Bi	Biot number (=$\{Q/(2\pi RH)\}R/(\Delta T\cdot k)$)
D	rod diameter [m]
f	oscillation frequency [Hz]
F	dimensionless oscillation frequency (=$H^2 f/(\alpha\sqrt{Ma})$)
H	liquid bridge height [m]
k	thermal conductivity [W/(m·K)]
m	azimuthal oscillation mode number
Ma	Marangoni number (=$\lvert\sigma_T\rvert\Delta TH/(\rho\bar{\nu}\alpha)$)
Nu	Nusselt number (=$\{Q/(\pi R^2)\}R/(\Delta T\cdot k)$)
Pr	Prandtl number (=ν/α)
q	heat flux [W/m^2]
Q	heat transfer rate [W]
$Q_{\mathrm{LB}}/Q_{\mathrm{HR}}$	heat transfer ratio
r	radial direction [m]
R	rod radius (=$D/2$) [m]
T	temperature [°C] or [K]
T_{a}	ambient gas temperature [°C]
T_{C}, T_{H}	temperatures of cooled rod and heated rod [°C]

ΔT	temperature difference between rods (=$T_{\mathrm{H}}-T_{\mathrm{C}}$) [K]
V	liquid bridge volume [m^3]
V_0	volume of the gap between rods (=$\pi D^2H/4$) [m^3]
VR	volume ratio (=V/V_0)
z	axial direction [m]
α	thermal diffusivity [m^2/s]
β	volumetric thermal expansion coefficient [1/K]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
σ_T	temperature coefficient of surface tension [N/(m·K)]

Subscript

c	critical condition or convective component
CR	cooled rod surface
HR	heated rod surface
LB	liquid bridge free surface
r	radiative component

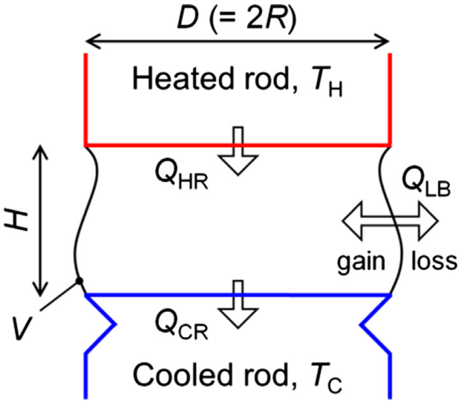

Fig. 1. Configuration of the half-zone liquid bridge.

Another approach to varying the interfacial heat transfer experimentally is to alter the ambient gas flow. A partition plate (or block) placed near the LB can change the ambient gas motion and the resultant interfacial heat transfer [10–12], and its strong effect on the onset condition of instability was reported in previous experiments [4,5,10]. As reported by Kamotani et al. [5], the partition plate located near the heated rod affects ΔT_{c} significantly, whereas that located near the cooled rod does not, indicating that the interfacial heat transfer near the hot corner is more important to the onset condition of instability. The effect of convective heat transfer exerted by the forced gas flow was studied experimentally [13,14] and numerically [15]. The forced ambient flow transports the cold/hot gas to the LB free surface when the flow comes from the cooled/heated rod side. This transport of cold gas or hot gas can enhance the heat loss or heat gain, respectively, and such a change in interfacial heat transfer apparently affects the instability mechanisms of thermocapillary convection [13–15].

In previous studies, the local heat flux q_{LB} is specified as a temperature boundary condition at the interface between LB and ambient gas as follows [2]:

$$q_{\mathrm{LB}}=-k_{\mathrm{L}}\nabla T_{\mathrm{L}}=-k_{\mathrm{G}}\nabla T_{\mathrm{G}}=h_{\mathrm{LB}}(T_{\mathrm{LB}}-T_{\mathrm{a}}), \tag{1}$$

where k is the thermal conductivity, h_{LB} is the heat transfer coefficient, T_{LB} is the LB surface temperature, and T_{a} is the ambient gas temperature. The subscripts L and G denote the liquid phase and gas phase, respectively. Xun et al. [16] and Melnikov and Shevtsova [17] considered h_{LB} and $(T_{\mathrm{LB}}-T_{\mathrm{a}})$ to study the effect of interfacial heat transfer in their numerical simulations, whereas Kamotani et al. [5] and Wang et al. [8] used Q_{LB}, which is the integral of q_{LB} over the LB free surface, to evaluate the effect of interfacial heat transfer experimentally. It is evident from Fig. 1 that Q_{LB}, Q_{HR} and Q_{CR} are the quantities representing heat transfer in the basic flow in the LB, where Q_{HR} is the heat transfer rate at the interface between the LB and the heated rod surface and Q_{CR} is the heat transfer rate between the LB and the cooled rod surface. Considering $Q_{\mathrm{LB}}=Q_{\mathrm{HR}}-Q_{\mathrm{CR}}$ (or $Q_{\mathrm{LB}}/Q_{\mathrm{HR}}=1-Q_{\mathrm{CR}}/Q_{\mathrm{HR}}$), the quantity $Q_{\mathrm{LB}}/Q_{\mathrm{HR}}$ (the heat transfer ratio, hereafter) is a possible dimensionless parameter used to describe the effect of interfacial heat transfer on the basic flow and also on the instability of thermocapillary convection in the LB [9]. The present paper reports the experimental and numerically simulated results by focusing on $Q_{\mathrm{LB}}/Q_{\mathrm{HR}}$ and the effect of interfacial heat transfer on the thermocapillary convection in LBs of high-*Pr* fluids.

2. Method

2.1. Experiment

The thermocapillary convection in the LB of silicone oil with the kinematic viscosity of 2 cSt is investigated in this work. The silicone oil (KF-96L-2cs) was manufactured by Shin-Etsu Co., Ltd., and its physical properties at 25 °C are summarized in Table 1. These values are based on the data supplied by the manufacturer except for the temperature coefficient of surface tension σ_T, which was measured by the authors. The temperature dependencies of the physical properties are considered only for σ and ν, and those values at a temperature of T [°C] are estimated as follows:

$$\sigma(T)=\sigma(25\,^{\circ}\mathrm{C})+\sigma_T\times(T-25), \tag{2}$$

$$\nu(T)=\nu(25\,^{\circ}\mathrm{C})\times\exp\left(5.892\times\frac{25-T}{273.15+T}\right). \tag{3}$$