International Journal of Heat and Mass Transfer 99 (2016) 182–191

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effect of ambient gas flow on the instability of Marangoni convection in liquid bridges of various volume ratios

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ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form 1 March 2016
Accepted 23 March 2016

Keywords:
Marangoni convection
Instability
Liquid bridge
Volume ratio
Heat transfer
Ambient gas flow

ABSTRACT

Instability of Marangoni convection in liquid bridges (LBs) of high Prandtl number (*Pr*) fluids has been studied by focusing on the effect of ambient gas flow on the LBs of various volume ratios. The working fluids are 2 cSt ($Pr = 28$) and 5 cSt ($Pr = 67$) silicone oils. The LB is suspended in a gap between the upper heating rod and the lower cooling rod and it is surrounded by a coaxial cylindrical wall to form an annular passage between the LB and the inner wall surface. The ambient gas motion is given to this annular passage in the range from −35 mm/s (vertically downward) to +35 mm/s (vertically upward). The ratio of the LB volume to the gap volume is varied from 0.80 (slender LB) to 1.10 (slightly fat LB). The critical temperature differences for the onset of instability are measured and corresponding critical Marangoni numbers are determined. Numerical computations are carried out to understand the flow and temperature fields both in the LB and in the ambient gas at each measured critical temperature difference. The computation results are used to evaluate the convective and the radiative heat transfers from the LB. The effect of the ambient gas motion on the relationship between the critical Marangoni number and the volume ratio is revealed. The effect is discussed in terms of the Biot number defined using the heat transfer and the critical temperature difference. It is shown that the Biot number increases with the ambient gas velocity for slender LBs while it is nearly constant for slightly fat LBs. It is found that the critical Marangoni numbers plotted as a function of the Biot number for various volume ratios and ambient gas velocities fall on a single profile corresponding to each *Pr*. Such a behavior is shown to be in accord with the previous data taken under various ambient gas temperatures and cooling rod temperatures.

1. Introduction

The instability of Marangoni convection in a liquid bridge (LB, hereafter) suspended in a gap between differentially heated rods has been studied extensively as reported by Ostrach [1], Kuhlmann [2], and Kawamura and Ueno [3]. The instability appears as an onset of time-dependent oscillatory variations of the flow and temperature fields in the LB at a critical temperature difference between the rods. This critical value, ΔT_c, is dependent on the LB conditions (refer to Fig. 1): i.e., the Prandtl number of the liquid, *Pr*, the aspect ratio, *AR*, the volume ratio, *VR*, and the rate of heat transfer between the LB and its ambient gas. The last condition is often expressed in terms of the Biot number, *Bi*.

Compared to the effects of *Pr*, *AR* and *VR* on the instability, the effect of *Bi* has not yet studied well and therefore understood less. A significant sensitivity of ΔT_c on *Bi* for the LBs of high *Pr* fluids was first experimentally found by Kamotani et al. [4]. They changed the ambient gas temperature, T_a, relative to the cooling rod temperature and observed that ΔT_c increased by a factor of two to three with increasing temperature difference between the ambient gas and the cooling rod. Based on their separate experiments using a thin plastic plate to alter the ambient gas motion (Kamotani et al. [5]), they ascribed this significant change of ΔT_c to the heat transfer between the LB and the ambient gas near the heating rod. Furthermore, Wang et al. [6] studied the effects of both heat loss and heat gain on the instability to find that the heat gain, in which T_a was raised to a level higher than the heating rod temperature, destabilized the Marangoni convection. They also found that the instability was much less affected by the heat transfer for concave LBs. Shevtsova et al. [7] studied the effect of heat transfer by considering two different situations: i.e., an LB either placed in an open-air environment or surrounded (or shielded) by a water-cooled cylinder. Considering also the effect of *VR*, they concluded that the fat LB of $VR = 1.20$ was strongly stabilized with increasing T_a while the slender LB had the opposite tendency. Similar

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.085
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Nomenclature

A	surface area [m^2]
AR	aspect ratio (=H/D)
Bi	Biot number (=$QR/(k^{(l)}A\Delta T_c)$)
D	disk diameter [m]
D_{ES}	inner diameter of the external shield [m]
$\vec{e}$	unit vector
F	body force [N/m^3] or view factor
g	acceleration of gravity [m/s^2]
H	gap between heating and cooling rods [m]
I	identity matrix
J	radiosity [W/m^2]
k	thermal conductivity [W/(m K)]
p	pressure [Pa]
Pr	Prandtl number (=ν/α)
q	heat flux [W/m^2]
Q	heat transfer rate [W]
R	disk radius (=$D/2$) [m]
Re	Reynolds number (=$U_a(D_{ES} - D)/\nu^{(g)}$)
m	azimuthal mode number
Ma	Marangoni number (=$\lvert\sigma_T\rvert\Delta TH/\rho\bar{\nu}\alpha$)
S	viscous stress tensor [Pa]
T	temperature [°C] or [K]
T_a	ambient gas temperature [°C]
T_c, T_h	cooling rod temperature and heating rod temperature [°C]
ΔT	temperature difference (=$T_h - T_c$) [°C]

$\vec{u}$	velocity vector [m/s]
U_a	ambient gas velocity [m/s]
V	liquid volume [m^3]
V_0	gap volume (=$\pi D^2 H/4$) [m^3]
VR	volume ratio (=V/V_0)
α	thermal diffusivity [m^2/s]
β	coefficient of volume expansion [1/K]
ε	emissivity
η	tangential direction to the liquid bridge surface [m]
μ	viscosity [Pa s]
ν	kinematic viscosity [m^2/s]
ξ	normal direction to the liquid bridge surface [m]
$\Delta\xi$	width of the thin layer on the liquid bridge surface [m]
ρ	density [kg/m^3]
σ	surface tension [N/m]
σ_{SB}	Stefan–Boltzmann constant (=5.67×10^{-8}) [W/(m^2 K^4)]
σ_T	temperature coefficient of surface tension [N/(m K)]

Superscript

(g)	gas
(l)	liquid

Subscript

c	critical condition or convection
r	radiation

stabilization due to the increase of T_a was observed by Watanabe et al. [8] in their LB of n-decane ($Pr = 13.5$) for $VR = 0.92$–1.05.

The effect of the ambient gas motion on the heat transfer at the LB surface was numerically studied by Tiwari and Nishino [9]. They considered a partition block as a device to alter the gas motion around the LB and reported that the presence of the partition block suppressed the ambient gas motion and thus reduced the magnitude of the heat transfer to a level that would be seen in microgravity environment. Tiwari and Nishino [10] studied experimentally the combined effect of the partition block and the heating of ambient gas and reported that the resultant suppression of the heat loss substantially stabilized the Marangoni convection in the LB of high Pr fluid. Ueno et al. [11] studied the effect of ambient gas motion by providing a forced convection of air into an annular gap that was formed between the LB and an external shield made of glass. They used 2 cSt silicone oil to generate an LB with $AR = 0.32$ and $VR = 1.00$ between an upper heating rod and a lower cooling rod. They changed the ambient gas velocity, U_a, in the range from −80 mm/s to +80 mm/s, where the negative and the positive values correspond to the downward and the upward flows, respectively. They showed that ΔT_c, which was reported in the dimensionless form (i.e., the critical Marangoni number, Ma_c), decreased with U_a. Their results imply that the Marangoni convection is destabilized (or stabilized) by the increase (or decrease) of the heat transfer from the LB to the ambient gas. The ambient gas flow through the annular gap was studied in detail by Gaponenko et al. [12] and Shevtsova et al. [13], in which the effects of both interfacial heat transfer and viscous shear acting on the LB surface were considered under the conditions of relatively high velocities of the ambient gas flow. Shevtsova et al. found numerically a new oscillatory instability when the gas was blown from the cooling rod side and presented the stability diagrams for n-decane ($Pr = 12$) and 5 cSt silicone oil ($Pr = 68$). Their stability curve for $Pr = 68$ and $AR = 1.0$ showed a drastic destabilization of the Marangoni convection when the ambient gas velocity reached a threshold. The importance of the ambient gas motion for better understanding of the instability mechanisms as well as for the possible manipulation of the Marangoni convection was discussed by Shevtsova et al. [14] to provide the basis for the planned space experiment called “Japanese and European Research Experiment on Marangoni Instabilities (JEREMI)”.

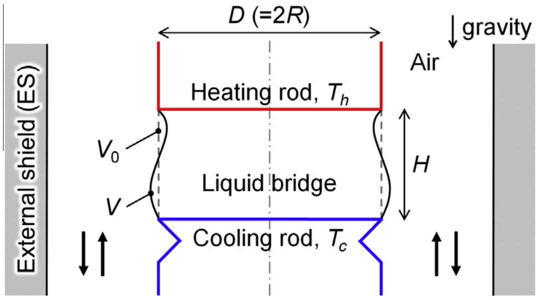

Fig. 1. Liquid bridge configuration.

As described by Kuhlmann [2], the knowledge about Bi at the LB surface is necessary for reliable numerical simulations and analyses because those computations need to define an appropriate thermal boundary condition. An often used thermal boundary condition is the heat transfer condition that assumes a constant Bi along with an appropriate profile for the ambient gas temperature. Melnikov and Shevtsova [15] studied the effect of ambient temperature on the instability of the Marangoni convection in LBs of 1 cSt silicone oil ($Pr = 18$) for $VR = 1.00$ and a wide range of AR. Their results indicated that both Bi and T_a affected the instability in a coupled and complex way. In fact, Melnikov et al. [16] demonstrated that a careful definition of the magnitude of heat transfer at the LB surface was essential to gain good agreement between their numerical simulations and the experimental data taken in microgravity. Such a careful definition was also shown to be