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Oscillatory thermocapillary flow in liquid bridges of high Prandtl number fluid with free surface heat gain

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Abstract

Oscillatory thermocapillary flow in liquid bridges of high Prandtl number fluid is studied. The effect of free surface heat transfer, especially heat gain, on the oscillation phenomenon is investigated experimentally and numerically. It is shown that the critical temperature difference (ΔT_{cr}) changes substantially when the free surface heat transfer changes from loss to gain in the case of nearly straight liquid bridges. In contrast, ΔT_{cr} is not affected by the free surface heat transfer with concave liquid bridges. The free surface heat transfer rate is computed numerically by simulating the interaction of the liquid and the surrounding air. The oscillatory flow is also investigated numerically by analyzing the liquid flow in three-dimensions for straight bridges. The computed results agree well with the experimental data. The simulation shows that the free surface heat gain enhances the surface flow and that the oscillatory flow is a result of interactions between the convection effect and buoyancy. The flow does not become oscillatory if there is no net heat gain at the free surface in the range of Marangoni number of the present work ($\leqslant 1.8 \times 10^4$), so the present cause of oscillations is different from that in the free surface heat loss case we investigated in the past.

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1. Introduction

Much work have been done on oscillatory thermocapillary flow in the half-zone, or liquid bridge, configuration, in which a liquid column is suspended between two differentially heated walls (e.g. [1–3]). It is known that the flow becomes oscillatory for a wide range of Prandtl number (Pr). However, the cause of oscillations for high Pr fluid ($Pr > 20$) is not yet fully understood. One reason for this lack of understanding is that available experimental data are somewhat confusing and contradictory due to various effects, as pointed out in [3]. The shape of the liquid bridge is known to play an important role in oscillatory thermocapillary flow of high Pr fluids (e.g. [3,4]). Buoyancy is not completely negligible in ground-based experiments. Oscillatory buoyant–thermocapillary flow in liquid bridges has been investigated [5] and some experiments were conducted in microgravity (e.g. [6]). In the configuration where the liquid is heated from above, buoyancy tends to stabilize the flow. It has recently been found that the onset of oscillations in high Pr fluids is very sensitive to the heat transfer at the free surface. Heat is lost from the free surface in typical room temperature experiments. The heat loss is associated mainly with natural convection of the surrounding air induced by the heating and cooling arrangement used in the experiment. Under typical conditions, the natural convection is relatively week, so its effect has been neglected in the past. However, Kamotani et al. [7,8] and Shevtsova et al. [9] have shown that the onset of oscillations is very sensitive to the heat loss: the critical temperature difference changes by a factor of two to three when the surrounding air

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Nomenclature

Ar	liquid bridge aspect ratio, L/D
Bi^*	modified average Biot number over free surface
Bi^*_{loc}	local modified Biot number, $qR_0/(k\Delta T)$
Bo_{d}	dynamic Bond number, $Gr/R\sigma = \rho g \beta L^2/\sigma_{\mathrm{T}}$
Bo_{s}	static Bond number, $\rho g L^2/\sigma$
D	diameter of liquid bridge base
D_0	diameter of liquid bridge neck (see Fig. 1)
Dr	diameter ratio, D_0/D
g	gravitational acceleration
Gr	Grashof number, $g\beta\Delta T L^3/\nu^2$
k	thermal conductivity
L	liquid bridge height
Ma	Marangoni number, $\sigma_{\mathrm{T}}\Delta T L/\mu\alpha$
Ma_{cr}	critical Ma for onset of oscillations
Pr	Prandtl number, ν/α
q	local heat transfer rate at free surface
R_0	radius of liquid bridge base
$R\sigma$	surface tension Reynolds number, Ma/Pr
T	temperature
T_{C}	cold wall temperature
T_{H}	hot wall temperature
T_{R}	ambient air temperature
$\overline{T}$	azimuthally averaged temperature defined in Eq. (1)
T'	disturbance temperature, $T - \overline{T}$
u	velocity component in z direction
(r, z)	coordinates for liquid flow defined in Fig. 1
(R, Z)	global coordinates defined in Fig. 2

Greek symbols

α	thermal diffusivity
β	coefficient of thermal expansion
ΔT	imposed temperature difference, $T_{\mathrm{H}} - T_{\mathrm{C}}$
ΔT_{cr}	critical temperature difference
θ	azimuthal coordinate
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension
σ_{T}	temperature coefficient of surface tension
ψ	stream function in cylindrical coordinates

temperature is varied. Therefore, we have to take this sensitivity into account when we explain the oscillation mechanism for high Pr fluid. Since this heat loss experiment gave us significant insight into the oscillatory thermocapillary flow, we have extended the work to include free surface heat gain. Our earlier results [8] indicated there is a difference between the cause of oscillations with heat loss and that with heat gain.

In addition to the experiment, three-dimensional numerical simulation of the oscillatory flow is performed. Oscillatory thermocapillary flows in liquid bridges have been simulated in the past for various Pr fluids (e.g. [10–13]). Sim and Zebib [14] investigated the effect of heat loss on the instability. However, oscillatory buoyant–thermocapillary flow with free surface heat gain has never been simulated in the past. The present simulation shows that the experimentally observed oscillations with free surface heat gain are induced by the interaction between thermocapillarity and buoyancy. The free surface heat gain makes the flow active over a wider region, which makes it easier for the flow to become oscillatory.

Because of the fact that there is some work to be done in order to fully the understand oscillatory thermocapillary flows of high Prandtl fluids, JAXA (Japan Space Exploration Agency) organized a research group to conduct a comprehensive study of the subject. The group is preparing a microgravity experiment to be conducted aboard the Space Station in the near future. The present work is done in conjunction with this effort. The present paper is based partially on the thesis by Wang [15].

2. Experimental work

The liquid bridge configuration is illustrated in Fig. 1. The experimental setup is similar to the ones used and described in our various earlier experiments ([3,7,8,15]). The top and bottom rods are made of copper. Two and 3 mm rods are used in the present work. The rod temperatures are monitored by inserted thermocouples. Two and 5-centistokes (cSt) silicone oils are used as the test fluid. The bottom rod is cooled by cooling water from a constant temperature bath. The main difference from our earlier systems is the top rod. The top rod was heated by a nichrome wire in our past experiments. In the present experiment with heat gain, in which the ambient temperature is kept above the hot wall temperature, the top wall must be

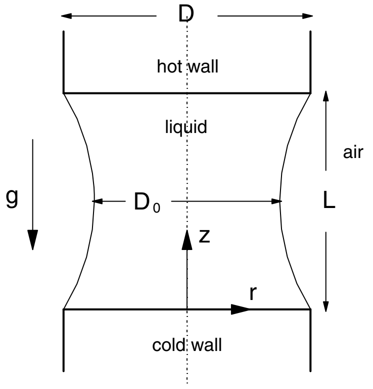

Fig. 1. Liquid bridge configuration.

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