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On Coherent Dynamic Structures of Oscillatory Thermal Convection in Liquid Bridges due to Free Surface Heat Gain under Microgravity

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Abstract **-** Present study investigates the coherent dynamic structures developed at the supercritical state of thermo-capillary flow in a cylindrical liquid bridge (LB). Unsteady and three-dimensional computations are carried out in a domain consisting of a LB of 5 cSt silicone oil (Prandtl number, $Pr = 67$) suspended between two differentially heated co-axial disks of similar diameter. The LB has a diameter of 4 mm and a height of 2 mm, such that the aspect ratio is fixed at 0.5. Computations are carried out under microgravity conditions to predict the onset of oscillatory instability by monitoring the liquid temperature oscillations at the free surface of the LB. To capture the threshold of instability, the temperature difference between the two solid disks has been increased in small steps up to the emergence of surface temperature oscillations. The obtained results confirm that for the cylindrical LB (volume ratio, $VR = 1$) with free surface heat gain condition described by the average Biot number, $Bi = -0.55$, the critical Marangoni number, Ma_{cr} for the onset of bifurcation from the basic state to oscillatory state is observed to be 7712. The heat gain situation occurring at the free surface of LB is found to destabilize the thermo-capillary flow substantially compared to that of the heat loss conditions reported in our previous study.

Keywords**:** Thermal convection, Free surface heat gain, Microgravity, Liquid bridge, Instability

1. Introduction

A scientific model in the form of half floating zone (HFZ) or LB is a simplified configuration that is normally used to simulate the floating zone (FZ) method of crystal growth. It is considered to be an ideal geometry for conducting experiments and to study the onset of oscillatory behavior in thermo-capillary convection (TC) [1]. Many investigations [2,3] on FZ technological processes have immensely used this simplified model due to the complexity associated with the fluid-dynamic field of thermo-capillary flow. In the context of TC, this configuration has been widely used to predict the characteristics of nonlinear systems. Various researches conducted over the years have aided in developing a typical theoretical framework for studying the fundamental properties of thermo-capillary flows which is popularly known as 'LB problem' [4]. It is a well-known fact that for sufficiently higher values of Marangoni number, $Ma > Ma_{cr}$, thermal convection inside the LB undergoes a transition from a steady axisymmetric and laminar flow into a very complicated oscillatory and three-dimensional pattern [5]. This is due to the occurrence and amplification of the temperature disturbances appearing on the liquid free surface. In high Prandtl number (Pr) liquids like 5 cSt silicone oil, the emergence of the supercritical state is found to be due to Hopf bifurcation [6,7] The underlying mechanism for the onset of oscillatory instability is found to be due to the flow and thermal coupling inside the non-linear flow system and hence known as hydrothermal wave (HTW) instability [8].

2. Problem Statement

The physical model considered for the present study is a straight/cylindrical LB of 5 cSt silicone oil ($Pr = 67$) suspended between two flat concentric and circular disks of similar diameter under microgravity conditions as depicted in Fig. 1. To yield thermal convection at the free surface of the LB, both the differentially heated disks are kept at isothermal conditions such that $T_H > T_C$. The chosen LB set up has a fixed diameter and height of $D = 4$ mm and $L = 2$ mm respectively such that the aspect ratio, AR is 0.5. Due to the assumed microgravity conditions and AR also being very small, the free surface is considered to be rigid and non-deformable [9].

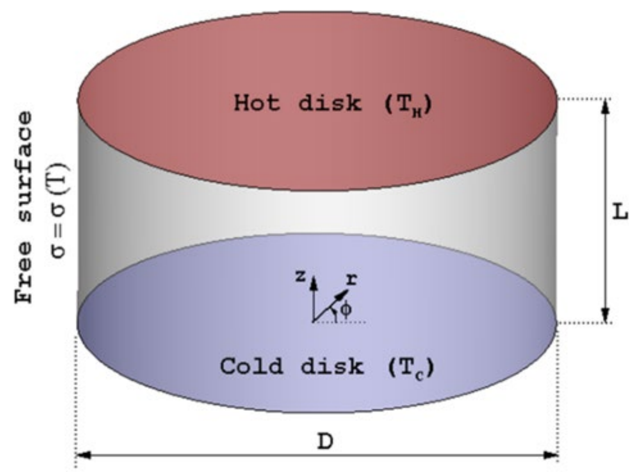

Fig. 1: Sketch of the 3D computational domain of LB configuration

3. Numerical Aspects

The fundamental unsteady and three-dimensional field equations (continuity, momentum, and energy equations) that govern the thermal convection in the present LB system are solved in polar coordinates (r,φ,z) under microgravity conditions. Furthermore, surface tension (σ), density (ρ) and kinematic viscosity (υ) are approximated to exhibit a linear dependence on the local temperature. No-slip, isothermal and impermeable boundary conditions are imposed at the interface between solid disks and liquid. At the free surface of liquid, kinematic condition is imposed due to the assumed negligible free surface deformation of LB. Taking into account of the capability of the CFD solver in handling the tangential stress balance explicitly, the influence of surface tension is incorporated into the model through tangential stress balance at the free surface. A convective heat transfer boundary condition is imposed at the free surface of LB. Furthermore, the value of Biot number, Bi depends on Re of the air, k of both liquid and air, and weakly depends on the Pr of the air [10]. Nevertheless, all the governing equations and boundary conditions associated with this particular problem is elaborately discussed in our previous research [3].

It is to be noted that the dynamical free surface fluctuations that can occur due to thermo-capillary and buoyant convection in LB are experimentally found to be in micron and sub-micron orders of magnitude [11,12]. Moreover, a recent research [13] reported that the occurrence of dynamic free surface deformation at the onset of oscillatory convection has negligible effect on the Ma_{cr} (threshold of instability). Owing to the afore-mentioned reasons, a rigid boundary approximation is incorporated to the free surface of the LB. In the present unsteady computations, structured grids are generated with the help of commercial software ANSYS ICEM CFD 17.2 and the present LB problem is also investigated using commercial CFD solver ANSYS Fluent 17.2. The working liquid is assumed to be Newtonian and incompressible. The flow and thermal fields in the LB domain are solved in dimensional variables and by choosing an incompressible laminar model. However, the present computational domain consists of only one fluid which is the working liquid as it is the major region of interest for capturing the onset of oscillatory thermo-capillary flow. Furthermore, computations are carried out with the help of widely adopted pressure based segregated algorithm SIMPLE (Semi-Implicit Method for Pressure-Linked Equations). The spatial discretization is performed using second-order upwind scheme. Similarly, the transient formulation is implemented using a second-order implicit scheme which is known to be unconditionally stable. For all the thermal convection equations solved in the liquid domain, the absolute iterative convergence is considered to be 10^{-6}. Grid and time independence study is also done by monitoring the magnitude of the local axial velocity at various locations along the liquid free surface. The percentage variation in axial velocity predicted by various numerical grids is checked and found to be less than 1.5%. Anyhow, a grid size of $50 \times 120 \times 60$ and a time step of $dt = 0.0025$ are found to to have an optimum convergence and thus adopted for further study and results discussed in the succeeding sections.

4. Validation of Computations

To establish the capability of the adopted numerical scheme for monitoring the onset of instability of thermo-capillary flow in LB, Ma_{cr} has been predicted and compared with the experimental results [14]. However, the boundary conditions used for validation of numerical procedure are similar to that considered for the present study. For a LB of 5 cSt silicone oil (Pr = 39.3 and volume ratio, VR = 1), the critical point for the onset of bifurcation corresponding to T_{amb}= 300K is found to be approximately 29516 which is merely 1.7% more than that predicted by experimental study ($Ma_{cr} \cong 29000$). Nevertheless, another comparison with the experimental results [15] is also performed for a LB with D = 3 mm, Pr = 39 and Bi = +0.30. For this comparison, Ma_{cr} predicted by the present numerical scheme is found to be 46950 which is 2.1% higher than that observed from the experiments ($Ma_{cr} \cong 46000$). The validation of the present LB problem is already discussed in detail in our previous research [3, 16].

5. Results and Discussion

In the present unsteady computations, the threshold of instability (ΔT_{cr}) is predicted for a particular value of ambient temperature, T_{amb} in each case. Then a sufficiently small increase in ΔT is applied along the free surface for every iteration until temperature fluctuations at the free surface arise. In the present case of free surface heat gain conditions characterized by Bi = -0.55, the threshold of oscillatory thermal convection is observed to be ΔT_{cr} = 20 K. The corresponding value of Ma_{cr} for the onset of bifurcation from the basic state to oscillatory state is 7712. The heat gain condition emerged at the free surface of LB is observed to destabilize the thermal convection considerably compared to that of adiabatic and heat loss conditions prescribed at the free surface [16].

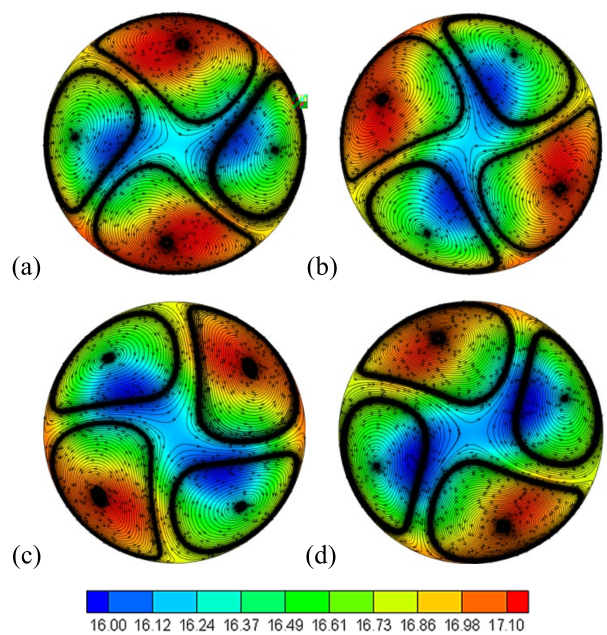

Fig. 2: Disturbance temperature and velocity fields in the generic cross-section at z = 0.5 within one oscillation period corresponding to (a) t = τ, (b) t = τ/4, (c) t = τ/2 and (d) t = 3τ/4

Here, the 3D oscillatory flow and thermal structures are computed for the present case also as depicted in Fig. 2. Once the instability steps in, the oscillatory multi-cellular regime developed in liquid zone is found to possess a couple of hot and cold thermal spots in the cross-section at a location z = 0.5. The spatio-temporalmode of convection in the present case is observed to be a rotating pattern with an even mode, m = 2. Furthermore, the number of azimuthal convective cells in the considered generic section are also found to be the same as that of the thermal spots as the temperature gradient is the driving force for the velocity field. As it is observed to be a travelling wave (TW) moving around the perimeter of the LB instead of a pulsating one, the intensity of the thermal spots generated on the generic cross-section remains unchanged with an increase in time as shown. As the azimuthal vortex cells formed in this particular section also never observed to disappear like the case of a standing wave (SW), their strength is found to be constant for a complete oscillation period. From the hydrothermal mechanism discussed in our previous and latest study [16], the major role of the radial and azimuthal velocity components in the propagation of HTWs generated at the onset of instability becomes quite evident. Moreover, it can also be inferred from the above observations that the hot liquid from the free surface is pulled into the bulk of the liquid zone and eventually it is found to enhance the continuous amplification of the interior hot spot. Meanwhile, thermal conduction causes the hot thermal spots developed in the bulk of the liquid to heat the free surface thermal spots.

Furthermore, as it is found to be an even mode of convection, the velocity and temperature fields in the meridional section are confirmed to be symmetric w.r.t. the axis of LB as presented in Fig. 3. Two counter-rotating toroidal motions are observed and these symmetrical toroidal vortices are observed to pulsate synchronously w.r.t. the LB axis during an oscillation period. This is a major characteristic feature of the even mode of spatio-temporal convection established at the supercritical state due to the time dependence.

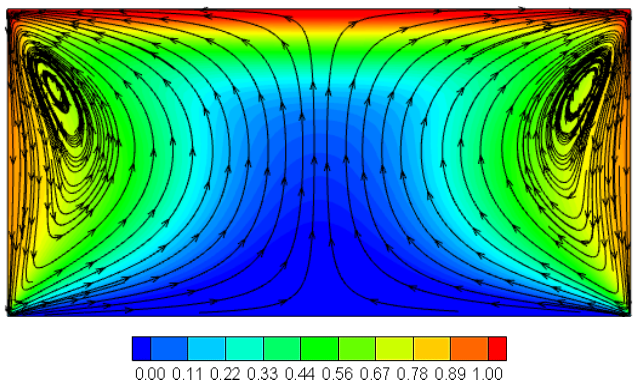

Fig. 3: Thermal and flow fields in the meridional section of LB

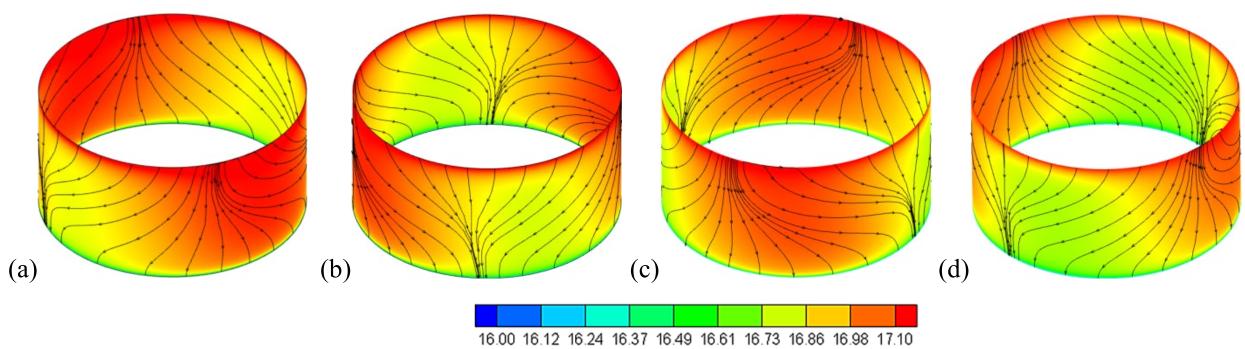

Fig. 4: Disturbance temperature and velocity fields along the free surface of LB within one oscillation period corresponding to (a) $t = \tau$, (b) $t = \tau/4$, (c) $t = \tau/2$ and (d) $t = 3\tau/4$

The evolution of the oscillatory flow state causes the flow and thermal fields on the free surface of the LB to get distorted as shown in Fig. 4. The temperature spots (2 hot and 2 cold) on the free surface are found to be accountable for the thermo-capillary stresses induced along the azimuthal direction as well. The developed supercritical state exhibits a coupling between the thermocapillary flow in the axial and azimuthal direction of the LB. However, it is also worth mentioning that the hot thermal spot and point at which the maximum temperature occurs are located in such a way that it results in the previously observed rotating pattern of the entire flow structure. The time series of the surface liquid temperature fluctuations is already presented in Fig.5. The super critical state emerged in the present case as a result of dynamic Hopf bifurcation [6] (steady to oscillatory state) also indicates a periodic solution near the onset of transition. For the present case of Bi = -0.55**,** the analysis of the monitored temperature signals using Fourier series is shown in Fig. 6. The frequency and amplitude of liquid temperature oscillations are displayed to be f = 0.38 Hz (F = 0.231) and 0.27 K.

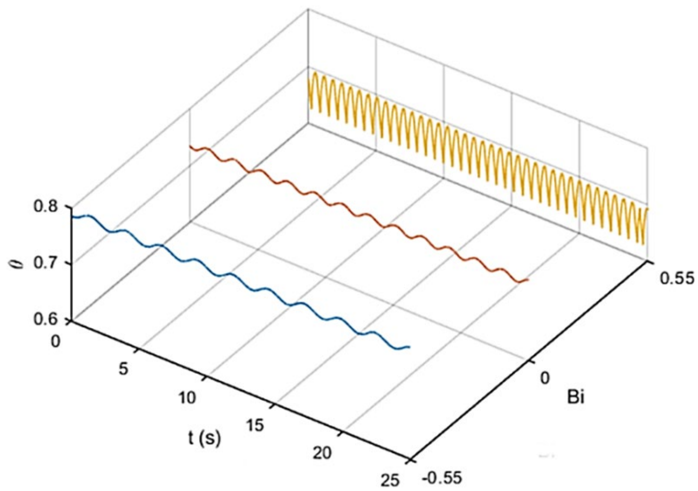

Fig. 5: Time series of temperature signals monitored at the free surface of LB for different values of Bi

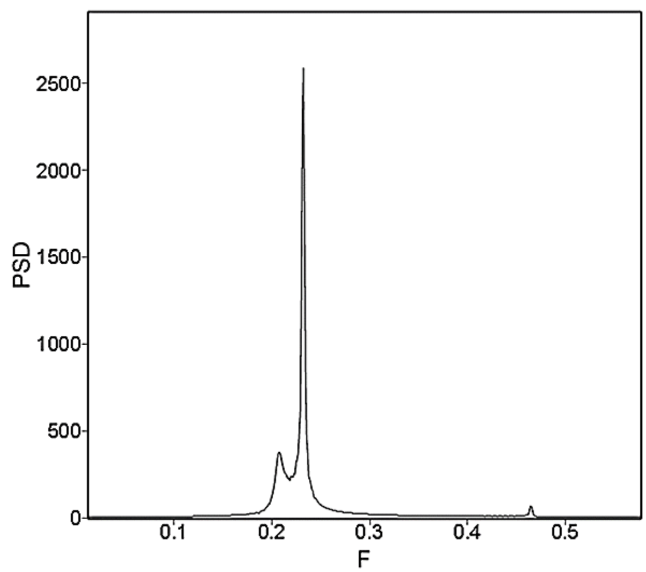

Fig. 6: Oscillation frequency analysis using Fourier series

Concerning the heat gain conditions prescribed at the free surface, with an increase or decrease in the value of Bi, any indications of a bifurcation from m = 2 solution to any other solution like m = 1, 3, 5… etc. are not observed in the present study. Meanwhile, the value of threshold of instability, Ma_{cr} is observed to be not much sensitive to the free surface heat gain as compared to that of the free surface heat loss condition as shown in Fig. 7. The afore-mentioned variation is confirmed to be in full agreement with the experimental observations [5]. When the free surface heat transfer conditions change from heat loss to heat gain, the increase in temperature gradients is noticed to be in the bulk of the liquid and the thermal convection appears very active in this certain region. Thus the significance of hot corner gradually decreases and the overall LB dimension becomes the major length scale for the occurrence of oscillatory instability. It is also worth highlighting that the range of considered value of *Bi* is less 1. As a result, Ma_{cr} is comparatively less sensitive to the present free surface heat gain conditions. However, in the present case, a sudden increase in the value of Ma_{cr} is experienced beyond a value of *B*i = -0.45. Nevertheless, in the range -0.45 ≤ *Bi* ≤ 0, the value of Ma_{cr} is observed to be not appreciably affected by the parametric variation.

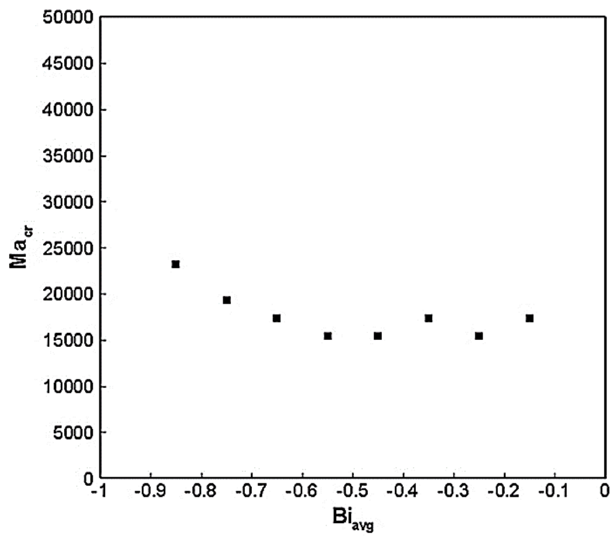

Fig. 7: Variation of Ma_{cr} vs *Bi* or free surface heat gain conditions

6. Conclusions

The canonical geometry selected for the present numerical study regarding the onset of 3D oscillatory thermal convection is a flat/cylindrical LB of 5 cSt silicone oil (*Pr* = 67). Unsteady and 3D simulations are performed out in the liquid domain under microgravity conditions to exclusively elucidate the influence of various free surface heat gain condition described by *Bi* = -0.55. The attention has been focused on the various complex 3D spatio-temporal structures and critical modes of convection developed inside LB system after the onset of oscillatory instability. An accurate estimation of the critical point for emergence of bifurcation from steady to oscillatory state (ΔT_{cr}) has been carried out and the obtained trends revealed by the various numerical computations showed that ΔT_{cr} is quite susceptible to the heat gain conditions prescribed at the free surface of the LB. Moreover, described by *Bi* = -0.55, the critical wave number, *m* is also observed to be 2. In fact, for the case of free surface heat gain described by *Bi* = -0.55, the stabilization of thermo-capillary flow is experienced only beyond a value of *B*i = -0.45. But, for the range of -0.45 ≤ *Bi* ≤ 0, the influence of *Bi* on the stability characteristics of LB is found to be comparable.

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