TR 32 CT

AXISYMMETRIC THERMOCAPILLARY CONVECTION IN LIQUID BRIDGES WITH DYNAMIC FREE-SURFACE DEFORMATIONS

Bok-Cheol Sim*, Young-Deuk Kim*, Woo-Seung Kim*, Abdelfattah Zebib**
* Department of Mechanical Engineering, Hanyang University,
Seoul, 133-791, Korea
** Department of Mechanical and Aerospace Engineering, Rutgers University,
Piscataway, New Jersey, 08854-8058, USA
corresponding e-mail:wskim@hanyang.ac.kr

Thermocapillary convection is a surface tension driven flow due to a temperature gradient along an interface. It is steady and axisymmetric when the driving temperature difference in an open cylindrical cavity, or a liquid bridge, is sufficiently small. This steady convection undergoes transition to oscillatory, three-dimensional flow as the temperature difference increases beyond a critical value. Because surface forces dominate body forces in space, understanding these transitions is important to material processing in microgravity. Although a few numerical studies with deformable surfaces have been performed in two-dimensional rectangular cavities, there is no work available for cylindrical liquid bridges. Here we report on a numerical study of axisymmetric thermocapillary convection in liquid bridges with deformable surfaces. The interface is determined as part of the complete solution. The influence of capillary number, Reynolds number and aspect ratio on the dynamics is explored.

MATHEMATICAL AND NUMERICAL MODEL

The physical system considered is a liquid bridge with a deformable free surface as shown in Fig. 1. A Prandtl number (Pr) of 1 is assumed, and the aspect ratio (Ar) is defined by R/H, where R and H are, respectively, the radius and height of the liquid bridge. The upper and lower disks have nondimensional temperatures $T_{hot}=1$ and $T_{cold}=0$. The Biot number, Bi, which gives free-surface heat loss is assumed zero.

The free-surface shape, g(t,z), is unknown and is determined as part of the solution to the coupled governing equations. In order to solve the problem, the physical domain is mapped into a rectangular computational domain. The transformed governing equations and boundary conditions are solved by a finite volume method employing a SIMPLER algorithm. Nonuniform grids are constructed with finer meshes in the regions near the free surface and the upper and lower walls where the boundary layers develop. A brief summary of the computational procedure is as follows:

1. Start with initial conditions for temperature (T), velocity (**v**) and free-surface shape (g),
2. The rectangular computational domain is generated numerically,
3. Solve the transformed governing equations to find T and **v** with the transformed boundary conditions,
4. Calculate g to satisfy the normal stress balance and conserved liquid volume equations,
5. Steps (2)-(4) are repeated at each time step until all conditions for T, **v** and g are satisfied with the desired accuracy,
6. Return to step (1) for the next time.

Because no data with deforming liquid bridges are available in the literature, the numerical is validated against known results for a flat surface in Table 1. Our results with zero capillary number (Ca=0, flat nondeformable surface) are in good agreement with those from other studies[1,2].

RESULTS AND DISCUSSION

We have investigated convection up to Re=5000 with Pr=1, Ar=0.5, 1 and 2 and various $Ca \leq 0.1$, and have found no oscillatory axisymmetric states. Assuming nondeformable flat interfaces, the critical Re for transition to oscillatory states is about 2500 from linear theory[2,3] and three-dimensional numerical simulations[4]. Since Ca is in the range $O(10^{-2})$-$O(10^{-3})$ in most experiments[5], we conclude that dynamic free-surface deformations do not induce transition to oscillatory axisymmetric convection. Thus only azimuthal waves can generate oscillations in a liquid bridge with either non-deformable or deformable surfaces. This is consistent with studies of convection in other cylindrical geometries[4,6].

Figure 2 shows free surfaces with Ar=1, Ca=0.05 and various Re. These are convex near the lower cold wall, and change from concave to convex with increasing Re near the hot wall. At sufficiently low Re, the free surface is almost asymmetric about its mid point. It has two peaks and is elevated near the cold stagnation point where surface pressure achieves its maximum value. As Re increases, the free surface develops three peeks. The surface deformations are $O(10^{-4})$, and its maximum value is 1.2×10^{-3} with Ca=0.1. The effect of Ca on surface deformations is shown in Fig. 3. Surface elevations and depressions increase with increasing Ca, while its shape is independent of Ca at a fixed Re. Four peaks are observed on the free surface at a high Re. Figure 4 shows stream function minima, surface temperatures and velocities at various Ca and Re=2500. They are independent of Ca. Thus dynamic free-surface deformations with $Ca \leq 0.1$ do not influence the convection in the liquid bridge. Figure 5 shows surface deformations with Ar=0.5, Re=2500 and various Ca. The free surface is almost asymmetric about its mid point with its shape independent of Ca..

CONCLUSIONS

Steady axisymmetric thermocapillary convection phenomenon in a liquid bridge heated from the upper wall is examined. Two-dimensional simulations with either non-deformable or deformable surfaces predict steady convection even at very high Re and Ca. Thus, dynamic free-surface deformations do not induce transitions to oscillatory axisymmetric convection. Free surfaces are convex at the cold corner. At the hot corner they change from concave to convex with increasing Re at fixed Ca. At low Re, surface deformations are determined by surface pressure variation. Two peaks may be observed at low Re and the number of peaks increases to four with increasing Re. Normal viscous stresses become important with increasing Re in particular near the hot corner where consecutive free surface elevation and depression occur. Surface deformations are larger with increasing Ca and are $O(10^{-4})$ with Ar=1 and $Ca \leq 0.1$. With decreasing Ar at fixed Re and Ca, surface deformations are larger. Thermocapillary convection inside the liquid bridge is insensitive to variations in Ca.

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Table 1: Comparison of stream function minima ($\psi_{\min} \times 10^2$) in a 2D liquid bridges (Bi=0.3, Ar=1 and Ca=0)

Re	Pr	Sumner et al. [1]	Wanschura et al. [2]	Present results
100	0.1		-1.02	-1.031
100	10	-0.4221	-0.425	-0.4216
10	100	-0.4205		-0.42

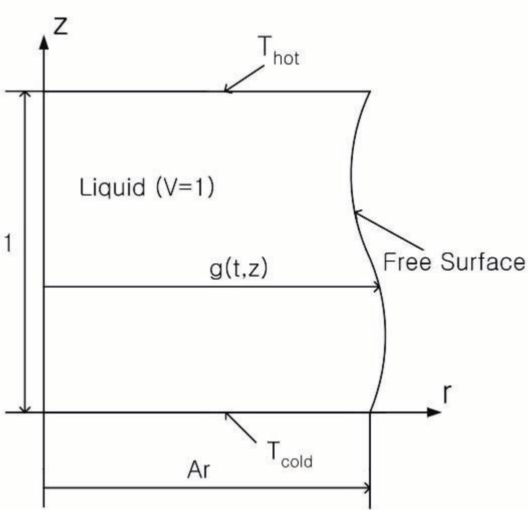

Fig. 1: Physical System.

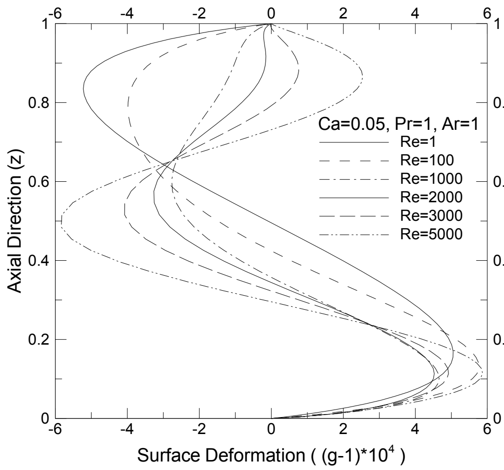

Fig. 2: Free surface shapes with Ar=1, Bi=0, Ca=0.05 and various Re.

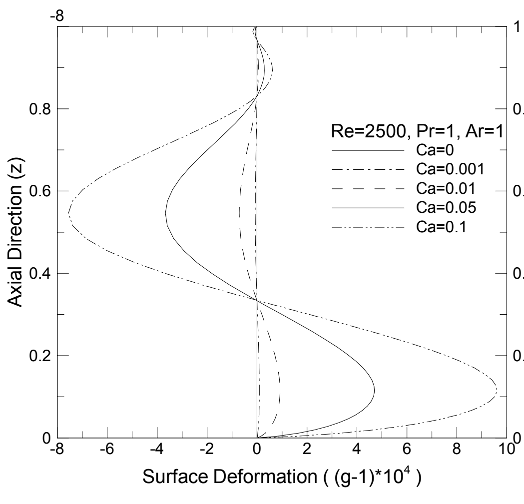

Fig. 3: Free surface deformations with Ar=1, Bi=0, Re=2500 and various Ca.

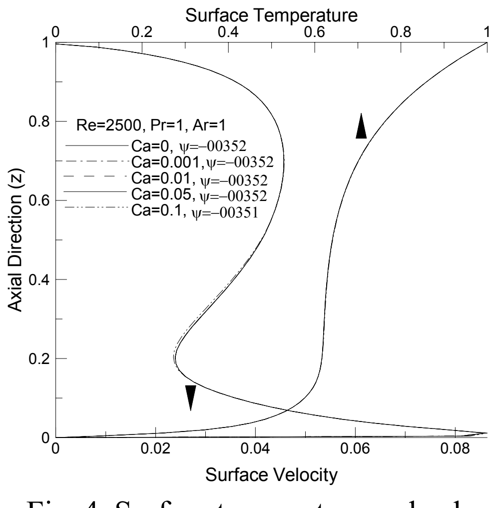

Fig. 4: Surface temperature and velocity distributions corresponding to Fig. 3.

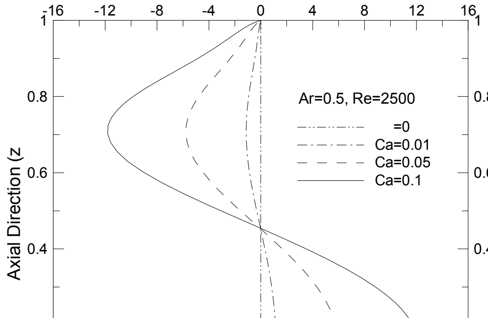

Fig. 5: Free surface shapes with Ar=0.5, Bi=0,
Re=2500 and various Ca.