Vol. 38 No. 15 CHINESE SCIENCE BULLETIN August 1993

Critical Bond Number in Two-dimensional Thermocapillary Oscillatory Convection

TANG Ze-Mei (唐泽眉) and HU Wen-Rui (胡文瑞)
(*Institute of Mechanics, Academia Sinica, Beijing* 100080, *PRC*)

Received August 15, 1992.

Keywords: thermocapillary convection, oscillatory convection, microgravity.

The gravity level in spacecraft may reduce to $10^{-3}-10^{-5}$ of the one on the ground, the effects such as surface tension and phase change become dominative in driving flow in the fluid. We consider the background of crystal growth in the floating zone, and study the convection driven by the gradient of surface tension in liquid bridge of the floating zone. To study the features and onset mechanism of oscillatory thermocapillary convection is important not only in the theory of fluid mechanics, but also in space materials processing.

Thermocapillary oscillatory convection has been one of the major subjects since the 1980s. Experiments were made on the ground, on board sounding rocket and space shuttle[1, 2], including the experiments by our research group[3]. However, insufficient experiments can only give limited theoretical explanation on the mechanism of oscillation. One believed that thermocapillary oscillatory convection is induced by the azimuthal instability at the free surface[4], another suggested that oscillation is produced by the unbalance of heat transfer processes[5]. We thought that the buoyancy instability may still be an important factor in exciting the oscillation of thermocapillary convection[6], and discussed the oscillatory process in the earth gravity environment in detail[7]. The present article analyzes the features of oscillatory convection in different gravity levels based on the unsteady numerical simulation, the results show that there is critical Bond number for the onset of the oscillation for fixed aspect ratio and applied temperature difference, where the relative importance of gravity and surface tension gradient is measured by Bond number defined by $B_{\mathrm{d}}=\rho g\beta L^{2}/d\ \ /dT$, where ρ, β, $d\sigma/dT$ are, respectively, the density, expansion coefficient and gradient of surface tension, g the gravity and L the height of liquid bridge. The oscillation is easily excited for liquid bridge with larger Bond number and corresponds to smaller critical temperature difference. This implies again that the Rayleigh instability associating with the buoyancy instability is an important factor for inducing the oscillation in thermocapillary convection.

We discuss a two-dimensional model of small liquid bridge with width $D=4$ mm of the upper and lower walls, gap distance $L=4$ mm, and minimum width of liquid bridge

$D_{min}=3.4$ mm. The temperature at upper wall is relatively high, and the shape of free surface is unchanged, and determined by the one without temperature difference. The direction of gravity is along the longitudinal direction (see Fig.1).

The non-dimensional and unsteady equations of vortex, stream function and energy, and the boundary conditions are the same as given in footnote 1). We assume that the configuration of free surface is unchanged since the oscillatory variation of free surface radii have only a few micrometers; the inter-surfaces of liquid-gas and liquid-solid are streaming lines; the fluid is not sliding at the liquid-solid boundary, which is not penetrated. The vortex at free surface is determined by the stress equilibrium at tangent direction. The non-dimensional temperatures are 1 and 0, at the upper and lower walls respectively. Using the hybrid method of fractional steps, the convective terms were treated by the method of characteristic lines, and the diffusion terms by the lumping finite element method. The initial state was adopted as the convergent steady solution with applied temperature difference $\Delta T=1$°C between the upper and lower walls, and then unsteady numerical simulation was proceeded by increasing temperature at the upper wall.

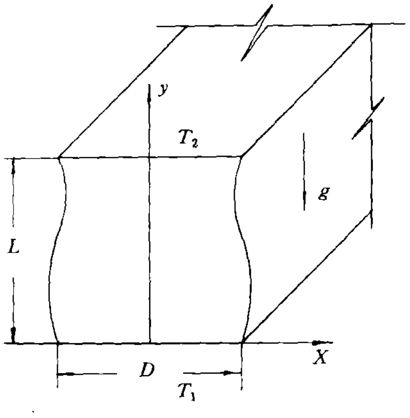

Fig.1

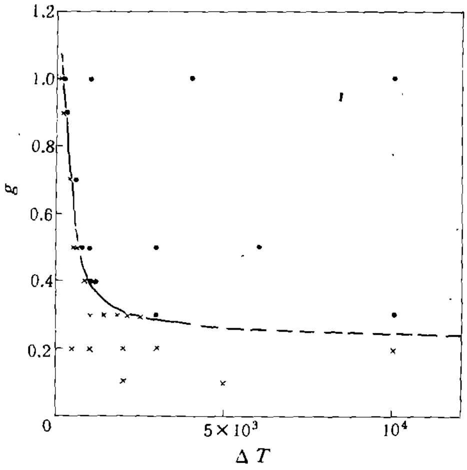

Fig.2

The instability situation for different gravity levels and applied temperature difference is given in Fig.2. It shows that the critical temperature difference for onset oscillation will be larger when the gravity level is decreased and the aspect of liquid bridge is fixed. The upper right part of the marginal stability curve associates with oscillation.

The maximum value of stream function and the temperature oscillation at one point on the free surface of liquid bridge are given in Fig.3 for a certain gravity level such as $g=1$ associating with the gravity on the ground. The perturbation of flow and temperature fields existing at $\Delta T=140$°C will develop at last into the symmetric and steady states. The oscillatory convection is onset when $\Delta T\geqslant(\Delta T)_c=200$°C, and the amplitude of oscillation

---

1) Tang, Z. M. & Hu, W. R., submitted to *Microgravity Quarterly*.

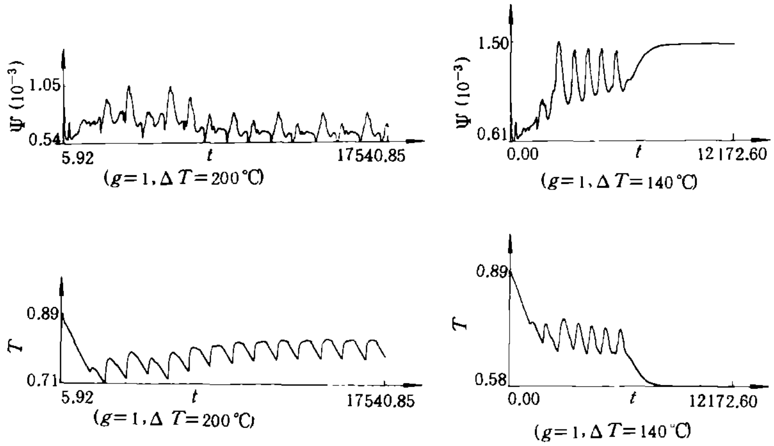

Fig. 3

will decrease with increasing applied temperature difference.

The flow features of thermocapillary oscillatory convection relatied to the decreasing gravity level are given in Fig.4 as applied temperature difference $\Delta T=1000°C$. It should be noted especially that the temperature and flow fields are no longer oscillating when the gravity level decreases from 0.4 g to 0.3 g, and it implies that there is a critical Bond number. The larger the critical Bond, the smaller the applied temperature difference in our calculating parameter ranges.

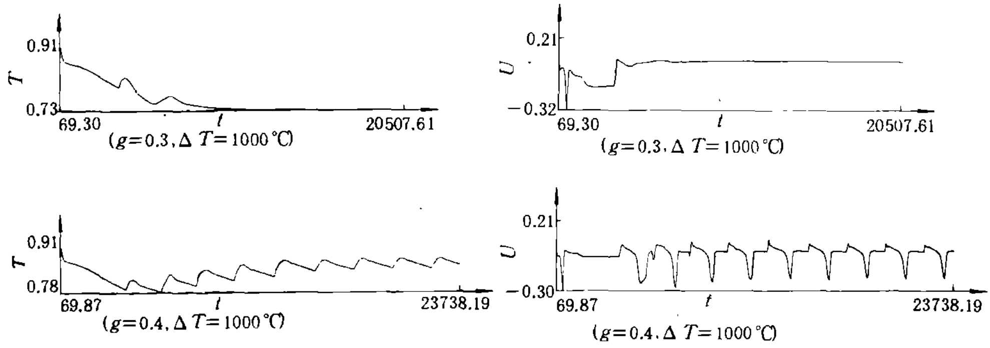

Fig. 4

The distributions of flow fields in one oscillatory period are given in Fig.5 for $g=1$ and $\Delta T=200°C$. The counter distributions of stream functions are in the time order of 1/8 period. The convections change according to the unsteady, unsymmetric and complex modes with oscillatory period of 0.85 s. The pattern and period of oscillation quite agree with the results of experiments. S-shape distribution of temperature at free surface, which has relatively high temperature at the lower part, may appear during the oscillation.

The present article points out again that there is a critical Bond number, which is pro-

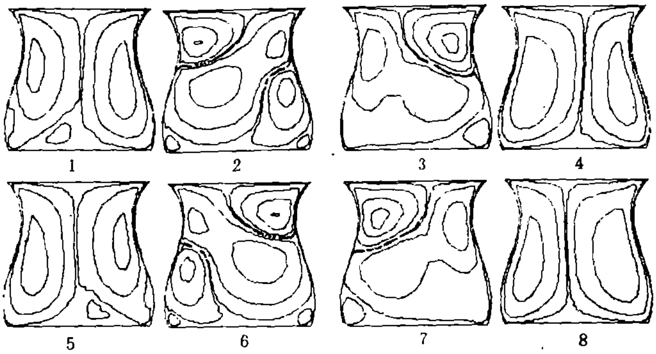

Fig. 5

portional to the gravity level for fixed aspect of liquid bridge and medium of liquid. The numerical results show that, thermocapillary convection in a small scale and upper wall heated liquid bridge may excite oscillation under certain condition of gravity level and at applied temperature difference. There is a critical gravity level or critical Bond number for fixed geometry and applied temperature difference. The larger the gravity level, the smaller the critical temperature difference, and then, the easier the exciting of the oscillation. It means that, the temperature gradient in the liquid bridge may turn to be parallel with the same direction of gravity if the applied temperature difference is large enough even for the case of upper heated wall, which is usually believed to be of stability. Therefore, the oscillation in thermocapillary convection may be excited by buoyancy instability if there is gravity, and the buoyancy may still be an important reason for exciting the oscillation in this flow.

References

1 Monti, R. & Fortezza, R., *Microgravity Quarterly*, 1991, **2**: 163.
2 Schwabe, D., Preisser, F. & Scharmann, A., *Acta Astronautica*, 1982, **9**: 265.
3 Cao, Z. H., Xie, J. C., Tang, Z. M. & Hu, W. R., *Science in China* (Series A) (in Chinese), 1991, (9): 964.
4 Preisser, F., Schwabe, D. & Scharmann, A., *J. Fluid Mech.*, 1983, **126**: 545.
5 Ostrach, S., Kamotani, Y. & Lai, C. L., *PCH Physicochemical Hydrodynamics*, 1985, **6**: 585.
6 Hu, W. R. & Tang, Z. M., *Science in China* (Series A), 1990, **33**: 934.