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Effects of *g*-Jitter on the Critical Marangoni Number

A half floating zone is fixed on a vibrational deck, which supports a periodical applied acceleration to simulate the effect of g-jitter. This paper deals with the effects of g-jitter on the fluid fields and the critical Marangoni number, which describes the transition from a forced oscillation of thermocapillary convection into an instability oscillatory convection in a liquid bridge of half floating zone with top rod heated. The responses of g-jitter field on the temperature profiles and flow pattern in the liquid bridge were obtained experimentally. The results indicated that the critical Marangoni number decreases with the increasing of g-jitter effect and is slightly smaller for higher frequency of g-jitter with fixed strength of applied gravity.

1 Introduction

Low- or micro-gravity environment in space may provide better conditions for space materials processing than on the ground, and considerable attention has been paid in the last decades to grow crystal by the floating-zone-method in space. However, the convection induced by the gradient of surface tension influences the floating zone processing in space. The relevant problems of fluid flow have been discussed comprehensively [1]. *Fu* and *Ostrach* analysed numerically the influence of Marangoni number, surface tension, Reynolds number (*Re*), and Prandtl number (*Pr*) on surface tension convection [2]. A somewhat related work was done by *Tang* to include the shape variation of free surface [3]. Furthermore some experiments have given the oscillatory features of thermocapillary convection in a liquid bridge, this oscillation may contribute influences on the quality of materials processing in space.

Moreover, there is *g*-jitter even in reduced gravity environment. The *g*-jitter in space can arise from internal and external factors such as astronaut movements and spacecraft maneuvers. Space processing experiments have indicated that the orientation and magnitude of *g*-jitter varied with time may give important influence on results of space experiments [4]. *Richardson* concluded that the effects of such vibration on heat transfer are strong [5]. *Kamotani* et al. discussed thermal convection in an enclosure including the effects of space vibration [6]. *Spardley* analysed the influence of *g*-jitter on a heated container of fluid in lower gravity by using the finite-difference-method [7]. These results indicated that *g*-jitter can induce significant temperature oscillation, change the local heat transfer and produce oscillatory patterns. Undoubtedly, *g*-jitter can influence the processes of fluid motion in space.

The small scale liquid bridge with Bond number smaller than 1 is usually used on the ground experiments to study the thermocapillary convection. An eccentric vibration machine, whose travel length and frequency could be adjusted, is utilized to supply typical *g*-jitter environment in our experiment, and then the effects of *g*-jitter on thermocapillary convection can be studied.

In the next section, the physical model and experimental method are described. Some results about the effects of *g*-jitter on thermocapillary convection and critical Marangoni number are given, respectively in sects. 3 and 4, while discussions for the results are contained in sect. 5.

2 Experimental Instrument

The simple-harmonic vibration was supplied by the vibration machine for simulating the *g*-jitter environment. The travel length A and the frequency f of this machine could be adjusted from 0.08 to 0.40 m and 0.3 to 1.5 Hz, respectively. The moving orientation of the vibration machine gave an applied acceleration parallel to the earth gravity, so the periodic variation of the acceleration applied is

$$\Delta g = A\omega^2 \sin(\omega t + \phi_0), \tag{1}$$

where $\omega = 2\pi f$ is the circular frequency, A is the travel length, ϕ_0 is the initial phase, relative to the initial position of the vibration machine. So the strength of *g*-jitter can be obtained by changing the travel length A and the frequency f of the machine. The experiment facility of half floating zone was fixed on the deck of the vibration machine, the scheme is shown in fig. 1. Experimental medium was a 10 cSt silicon oil filled in the gap between the upper and lower coaxial rods of pure copper. The upper rod is heated by electric resistance wires to give the applied temperature difference ΔT. The temperatures of upper and lower rods were measured by thermal couples. In addition, a thermal couple was inserted in the liquid bridge to measure the temperature variation of the liquid. A light sheet of 0.3 mm in diameter produced by a He–Ne laser generator passed vertically through a cross-section of the cylindrical liquid bridge and the trajectories of tracing particles mixed

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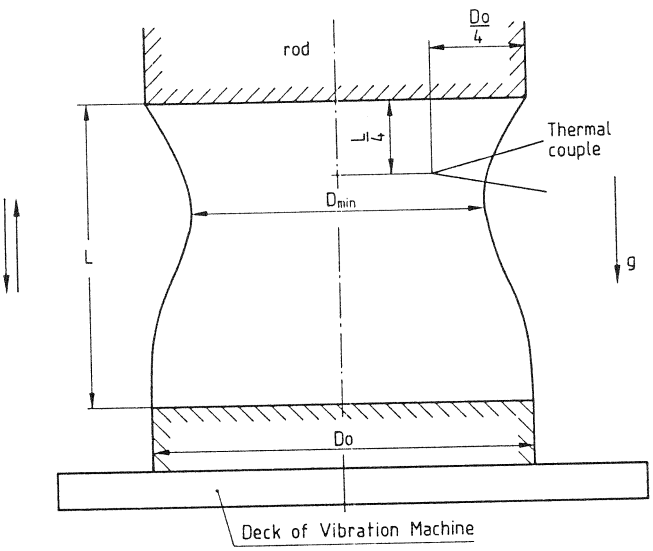


Fig. 1. Scheme of liquid bridge

in the medium showed us the flow pattern. The diameter D and height L of the liquid bridge are 3.0 mm and 2.4 mm, respectively, and the Bond number

$$Bo = \frac{\varrho g \beta l^2}{|d\sigma/dt|} = 0.58, \tag{2}$$

where ϱ, t, σ are the density, temperature, and surface tension respectively; β is the thermal expansion coefficient, g is the gravity. In this case, the effect of surface tension is dominated in comparison with the buoyancy due to the smaller Bond number. Previous works have indicated that the critical parameters include at least Marangoni number and also the volume of liquid bridge measured by the ratio of the minimum diameter D_{min} to the rod diameter D_o [8]. In the present paper, we adopt the ratio $D_{min}/D_o = 0.72$ and define $g^* = A\omega^2/g_o$.

3 Influence of g-jitter on Thermocapillary Convection

Firstly, the upper rod was heated gradually to increase the temperature difference between the upper and lower rods, and then a g-jitter field was applied on the liquid bridge by adjustment the travel length A and frequency f of the vibration machine. There were steady gravity of the earth g_o and the unsteady g-jitter gravity Δg, so the body force per unit mass acting on the liquid was given by

$$g = g_o + \Delta g = g_o + A\omega^2 \sin(\omega t + \phi_0). \tag{3}$$

The temperature measured by inserted thermal couple in the liquid bridge depended not only on the applied temperature difference ΔT but also on the g-jitter field. We defined the temperature as

$$T = T_o + \hat{T} \sin(\omega_1 t + \phi_1), \tag{4}$$

where T_o is the steady temperature, $\hat{T}$ and ω_1 are the amplitude and frequency response to applied acceleration. Different temperature variations at the fixed point measured by inserted thermal couple could be obtained for different travel length A, frequency f, and the applied temperature difference ΔT.

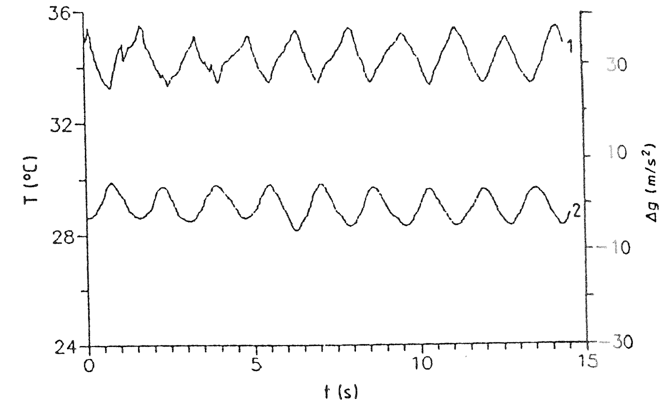


Fig. 2. (1) Temperature; (2) response to g-jitter; $\Delta T = 40$ K, $f = 0.68$ and $g^* = 0.48$

Fig. 2 shows the conditions of the g-jitter and the response of temperature at the fixed point in the liquid bridge. The results show that the response temperature frequency ω_1 equals the vibration (g-jitter) frequency ω, and the vibration phase ϕ_0 opposes to the temperature response phase, $\phi_0 = \phi_1 + 180°$.

Fig. 3 shows the relation between the steady temperature T_o and the applied temperature difference ΔT. It seems that, in the condition of present experiment, the steady temperature depends mainly on the applied temperature difference ΔT and is not sensitive to the applied g-jitter fields.

Fig. 4 presents the relation between the unsteady amplitude of temperature $\hat{T}$ and the frequency of g-jitter when the applied temperature difference ΔT and the amplitude of g-jitter are fixed. We can see from the curve that the frequency of g-jitter has little effect on the unsteady amplitude of temperature, which decreased slightly when the frequency of g-jitter increased from 0.5 Hz to 1.4 Hz.

Fig. 5 presents the relation between the unsteady amplitude of temperature $\hat{T}$ and the applied temperature difference ΔT for different levels of g-jitter. It shows that the unsteady amplitude of temperature increases not only with

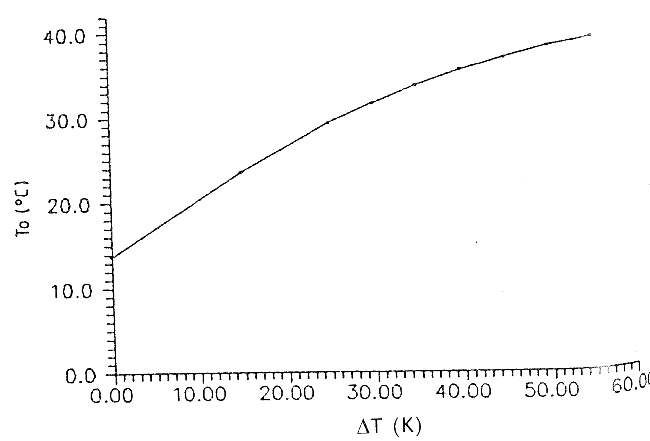


Fig. 3. Relation between the steady temperature and the applied temperature difference ΔT

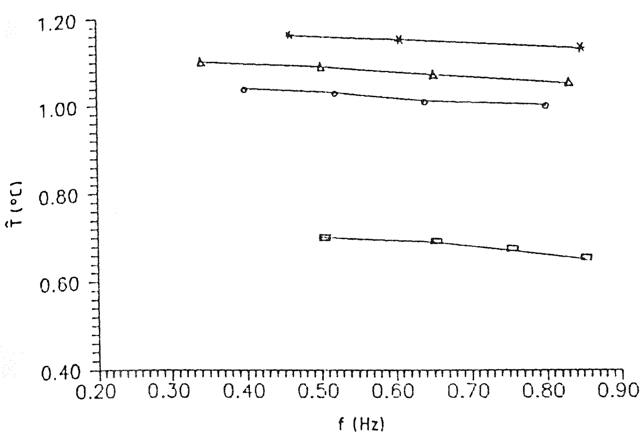


Fig. 4. Relation between unsteady amplitude of temperature response to the frequency for different levels of g-jitter and applied temperature difference; $g^* = 0.614$, (*) $\Delta T = 40\,K$, (△) $\Delta T = 35\,K$, (○) $\Delta T = 35\,K$, (□) $\Delta T = 15\,K$

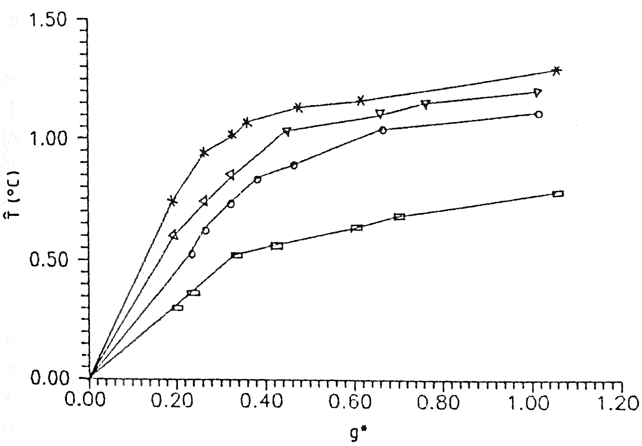


Fig. 5. Relation between unsteady amplitude of temperature and the strength of g-jitter for different applied temperature difference; (*) $\Delta T = 40\,K$, (△) $\Delta T = 35\,K$, (○) $\Delta T = 25\,K$, (□) $\Delta T = 15\,K$

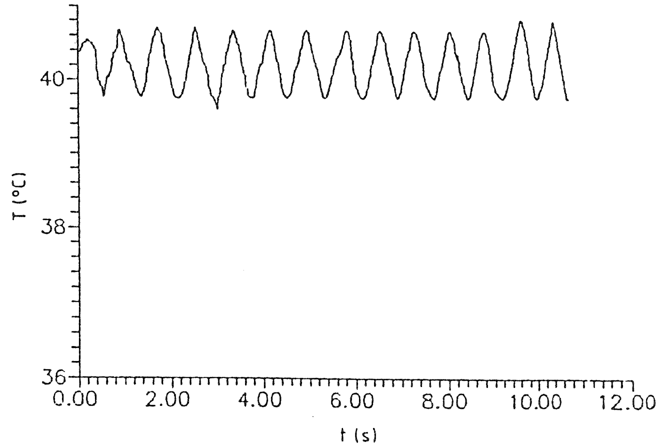


Fig. 6. Typical temperature oscillatory curve for $L = 2.4\,mm$, $D = 3\,mm$, $\Delta T = 62\,K$, $D_{min}/D_o = 0.72$

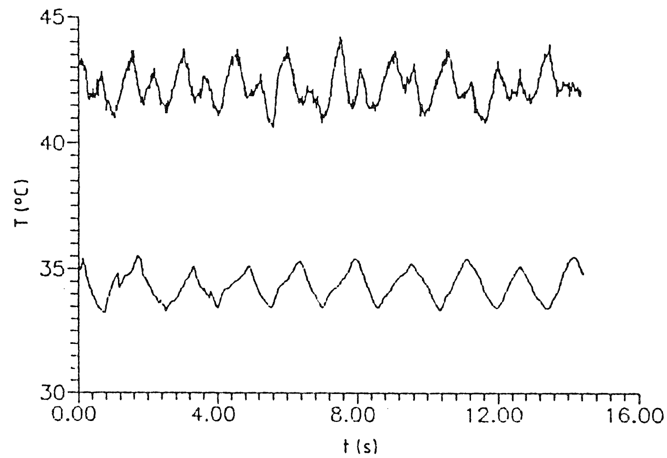


Fig. 7. Typical temperature profiles for higher (upper) and lower (lower) applied temperature ΔT for $g^* = 0.28$

the increasing of applied temperature difference ΔT but also with the increasing of applied acceleration level.

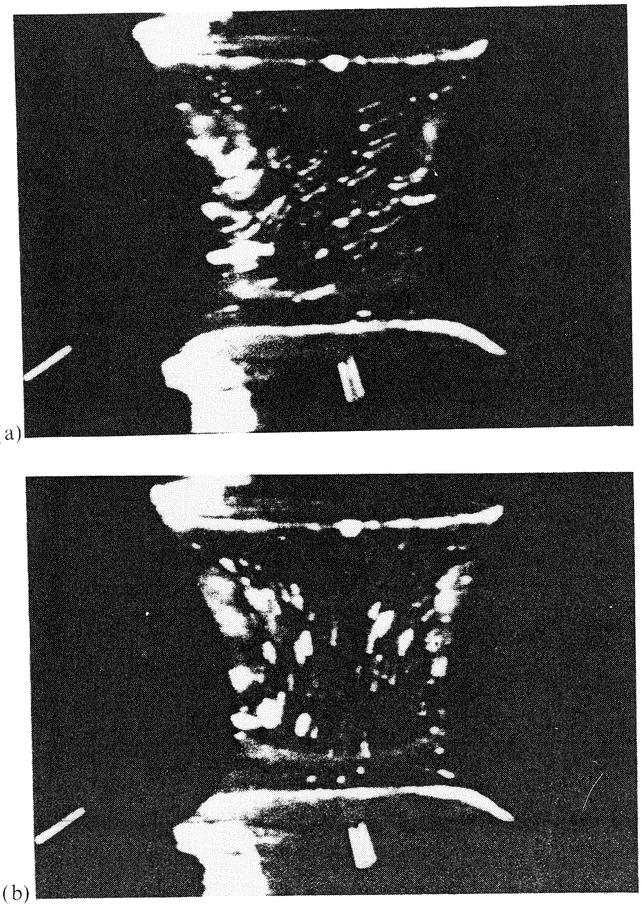
4 Effects of *g*-jitter on the Critical Marangoni Number

The transition from the steady flow into oscillatory convection in a liquid bridge under $1g_o$ is a typical problem for the case of absent applied acceleration. The critical applied temperature difference $\Delta T_c = 59$ K and the temperature oscillation measured by the inserted thermal couple is shown in fig. 6. The temperature had a periodic change and the flow pattern was unsteady for the case of applied acceleration, but the temperature curve is a hamonic wave and the flow pattern is symmetric as seen in fig. 8a if the applied temperature difference is smaller than a critical value.

We heat the top rod to get a high applied temperature difference. When the applied temperature difference ΔT is larger than a critical value, the temperature profiles and the flow pattern have a distinct change. The temperature curve as shown in fig. 7 has an oscillatory part in addition to its periodic response to *g*-jitter. Fig. 8b shows that the flow pattern is no longer symmetric when the applied temperature difference is higher. We attribute all these significant changes to its internal instability being motivated due to thermocapillary oscillatory convection in the liquid bridge. In the present experiment, inspite of its unsteady behaviour, the flow is symmetric in the main for lower applied temperature difference. However, internal instability makes the flow field asymmetric when oscillations of thermocapillary convection appear at higher applied temperature difference. Coincidently with the change of flow field, the temperature curve transmitted from harmonic wave as response to *g*-jitter into overlapping of two harmonic waves which are the superposed curve from the temperature variation as response to *g*-jitter and the internal temperature oscillation caused by thermocapillary instability.

In our experiment, the appearance of overlapped harmonic waves in temperature curve and asymmetric flow pattern were used as the criterion for determining whether there had thermocapillary oscillation in liquid bridge with applied acceleration. We could conclude the effects of

(a)



(b)

Fig. 8. Typical symmetric ((a) $\Delta T = 61$ K) and non-symmetric ((b) $\Delta T = 30$ K) flow pattern

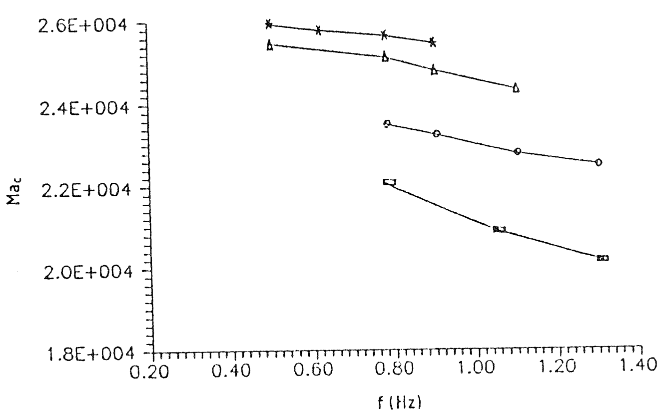


Fig. 9. The relation between frequency of g-jitter and critical Marangoni number with different amplitude of g-jitter; (∗) $g^* = 0.32$, (△) $g^* = 0.44$, (○) $g^* = 0.73$, (□) $g^* = 1.01$

different amplitude and different frequency of g-jitter on the critical Marangoni number by changing the travel length A and the frequency f of the vibration machine, and obtain the different critical Marangoni numbers depending on the different amplitude and different frequency of g-jitter.

Fig. 9 shows the influence of the frequency of g-jitter on the critical Marangoni number when the amplitude of g-jitter is fixed. The cirtical Marangoni number decreases

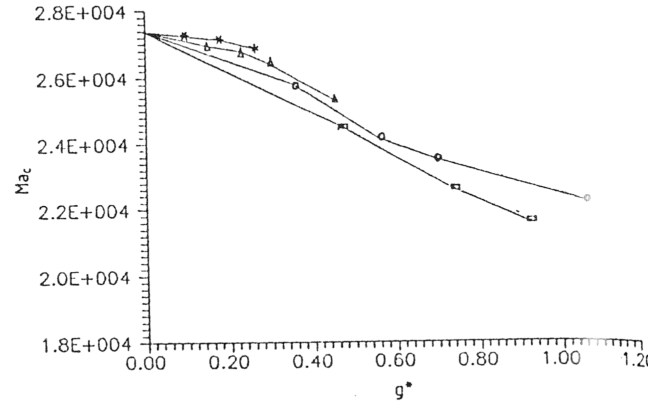


Fig. 10. The relation between amplitude of g-jitter and critical Marangoni number with different frequency of g-jitter; (∗) $f = 0.41$, (△) $f = 0.50$, (○) $f = 0.78$, (□) $f = 0.90$

with increasing frequency of g-jitter, but the range of decrease is small.

Fig. 10 shows the influence of the amplitude of g-jitter on the critical Marangoni number when the frequency of g-jitter is fixed. We can obtain that the critical Marangoni number will decrease in the g-jitter environment and the decrease is obviously depending on the amplitude of the increasing g-jitter.

5 Conclusion

Convection driven by the gradient of surface tension is one of the important problems of the space materials processing, and g-jitter is also an inevitable problem in microgravity environment. The results from our ground-based experiment indicate that the temperature profiles have a response to applied acceleration. The amplitude of response temperature depends mainly on the strength of applied acceleration. g-jitter could make the critical Maragoni number decreasing with the strength of increasing g-jitter and the internal instability could make the flow field asymmetric and take the temperature curve overlapped in g-jitter environment. All these may be responsible for the inhomogeneities in the crystal structure.

g-jitter will influence not only the distribution of surface temperature field but also the shape of free surface in a liquid bridge. All these can affect the shearing action in Marangoni boundary layer which can change the convection in a liquid bridge. Many experiments indicated that those actions may be important factors for the onset of thermocapillary oscillation. The coupling of these actions will change the critical Marangoni numbers in g-jitter environment.

This paper studies the effects of g-jitter on thermocapillary convection experimentally, the applied acceleration is given parallel to the earth gravity. Because the residual accelerations in space have variable magnitude and orientation, other orientations of applied acceleration and larger range of frequency of applied acceleration will be used to simulate the g-jitter environment in space for our further experiment.

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