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Influence of liquid bridge volume on the onset of oscillation in floating zone convection I. Experiments

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Abstract

The onset of oscillation in the floating zone convection driven by the gradient of surface tension was experimentally studied, and discussions were concentrated on the influence of liquid bridge volume on the onset of oscillation. Distributions of critical applied temperature difference and frequency depending on the volume of the liquid bridge were obtained, and there was a gap range of liquid volume which separated the curve of marginal stability into two parts for fixed rod diameter and aspect ratio. The results imply that the volume of the liquid bridge is a sensitive critical parameter for the onset of oscillation. The implication on the instability is also discussed in the present paper.

1. Introduction

Thermocapillary convection occurs in materials processing which involves free surface with non-uniform temperature distribution, for example, the floating zone method, which is one of the important methods for crystal growth either on the ground or in space of materials processings. The model of half floating zone as shown in Fig. 1 with small typical length scale has been studied extensively since the 1970's to simulate the effect of thermocapillary convection in microgravity environment. The onset of oscillation has been monitored in most cases by temperature [1–4], which was usually measured by the thermocouple

inserted in the liquid bridge, and the oscillation of temperature measured the onset of oscillatory convection. Recently, non-contacted measurement associated with free surface vibration was developed. This optical method gave the improved results of $(\Delta T)_c$ [5–7] and discovered the features of free surface wave in the floating zone [7–9].

The relationship between the critical applied temperature difference $(\Delta T)_c$ and the typical length scale l or rod diameter d_0 for fixed aspect ratio A has been shown by either experimental or theoretical analyses. Relative dispersive data of $(\Delta T)_c$ were given by experiments for fixed rod diameter d_0 and aspect ratio A . Recent experiments showed that the volume of the liquid bridge is also a critical parameter for the onset of the oscillation in half floating zone, that is, the criti-

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Fig. 1. Schematic diagram of half floating zone.

cal applied temperature difference $(\Delta T)_c$ depends sensitively on the volume of the liquid bridge for fixed d_0 and A [5–8,10]. This may shed light on the studies of oscillatory mechanism, in addition to explain the dispersion of experimental data of $(\Delta T)_c$. The oscillation is easily excited for both fat and slender liquid bridge, and is difficult to be excited for the liquid bridge with volume in the gap region. It shows that there are two branches of $(\Delta T)_c$ distributions separated by the gap region depending on the volume of the liquid bridge. The instability analyses of iso-temperature liquid bridge showed the dependence of liquid bridge volume and gave two stability regions for the liquid bridge with middle volume [11]; the results are similar, in some sense, to the ones given by the experiments of the present paper, although the oscillatory thermocapillary effect will be coupled with the resonant vibration, which associates with the case of zero applied temperature difference.

In the present paper, the influence of liquid bridge volume on the critical applied temperature difference and on the critical frequency of oscillation was discussed in detail. The next section will discuss the experiment facility and conditions. The experiment results for $d_0 = 2, 3$ and 4 mm were obtained and will be discussed in Section 3 for different aspect ratios A . The implication on instability is given in Section 4, and, then, the conclusion in the last section.

2. Experimental conditions

The liquid bridge of 10 CST silicon oil was floated in the gap between two co-axial rods with the same d_0 in diameter and l in height. The small typical scale of a few millimeters for d_0 and l was discussed for the enlarged thermocapillary effects. A temperature difference was applied between the upper and lower rod, and the cases of upper rod heated were analyzed in the present paper. Diameter $d_0 = 2, 3, 4$ mm and $A = l/d_0 = 0.6, 0.8, 1.0$ were adopted. The Bond number was defined as follows

$$Bo = -\rho g \beta l^2 / \sigma'_T,$$

where ρ , σ and β are, respectively, the density, surface tension and coefficient of thermal expansion, g is gravity, and σ'_T is differential respective to temperature T . Then, the Bond number $Bo = 1.58$ for $d_0 = 4$ mm and $A = 1$, and $Bo = 0.14$ for $d_0 = 2$ mm and $A = 0.6$. The thermocapillary effect is much larger or in the same order of magnitude in comparison with the gravity effect for the cases discussed in the present paper.

The volume of liquid bridge V may be characterized by the volume of cylinder $V_0 = \pi d_0^2 l / 4$, that is, the non-dimensional volume of the liquid bridge V/V_0 may be introduced. On the other hand, the diameter ratio $d_{\min}/d_0$ may also be used to describe the relative volume of the liquid bridge, where $d_{\min}$ is the minimum diameter of the liquid bridge. For example, we discuss a liquid bridge with $d_0 = 3$ mm, and the relations between V/V_0 and $d_{\min}/d_0$ are given respectively for $A = 0.6, 0.8$ and 1.0 in Fig. 2. Configurations of liquid bridge shapes are shown in Fig. 3 for $d_0 = 3$ mm and $A = 1$. The $d_{\min}/d_0$ is used to describe the relative volume in the following discussion, and it denotes the ratio of maximum diameter of liquid bridge to rod diameter if $d_{\min}$ is larger than d_0 .

The applied temperature difference ΔT was increased gradually in the experimental procedure, and the critical value of $(\Delta T)_c$ could be determined if convection transited from steady into oscillation, and the onset of oscillation was monitored by free surface vibration. An optical system to measure directly a small local region of

Fig. 2. Relationship between relative volume and relative diameter of liquid bridge.

free surface by CCD camera gives the radii variation if the magnifying power is $10^3:1$ in order of magnitude [7,8]. The onset of free surface vibration occurs at the same time of temperature oscillation measured by thermocouple inserted in the liquid bridge; however, the contacted measurement by thermocouple will interfere with the heat transfer process of the liquid bridge and may increase 20% of the critical value $(\Delta T)_c$, more than the one given by the non-contacted method of the optical system [5], which is applied in the present paper. The applied temperature was measured by two thermocouples which were contacted, respectively, at the upper rod and the lower rod near the interfaces with the liquid

Fig. 3. Free surface shapes of $d_0 = 3$ mm for different volumes of liquid bridge.

Fig. 4. Critical applied temperature difference depending on volume of liquid bridge for $d_0 = 3$ mm.

bridge, but no thermocouple was inserted in the liquid bridge. The onset of oscillation was determined by the appearance of free surface oscillation.

3. Experimental results

We discuss in detail the cases of $d_0 = 3$ mm. The relationship of critical applied temperature difference $(\Delta T)_c$ depending on $d_{\min}/d_0$ was summarized experimentally as the full lines in Fig. 4 for aspect ratio $A = 1.0, 0.8$ and 0.6 . The broken lines gave sharp increment of critical value $(\Delta T)_c$ according to the experimental results that the liquid bridge could not be persisted and was broken when the volume of the liquid bridge had a small increment or decrement from left or right side into the gap region, which separated the curve of marginal stability into two parts, i.e., the fat group and the slender group. On the one hand, the sharp increase of critical value of $(\Delta T)_c$ means that there are relatively higher values of $(\Delta T)_c$ in the gap region, which associates a relative stability region depending on the volume of the liquid bridge for the onset of oscillation. On the other hand, the liquid bridge is difficult to persist when the volume of the liquid bridge falls in the gap region; this means, in some sense, that the dynamical state is instability. Therefore, the gap region could be considered to be the abnor-

Fig. 5. Distributions of critical frequency for $d_0 = 3$ mm.

mal region of the stability. Now, we analyze the dependence of critical frequency f_c on the volume of the liquid bridge, where the critical frequency f_c is defined as the frequency associated with the onset state of oscillation. Generally, it was shown experimentally that the larger the critical applied temperature difference $(\Delta T)_c$, the higher the oscillatory frequency f_c [8]. Therefore, the profiles of frequency f_c will have similar distributions as those of $(\Delta T)_c$, i.e., the distribution of f_c was separated by a gap region into two groups associated respectively with fat and slender liquid bridge, as given in Fig. 5.

The dependence of $(\Delta T)_c$ on the volume of the liquid bridge and the dependence of critical frequency f_c on the volume were obtained for the cases $d_0 = 2$ mm and 4 mm, which are associated with Bo smaller than and larger than 1, respectively, and were also obtained experimentally. Separate distributions of profiles occurred and the gap regions of abnormal feature on stability were there for both cases of thermocapillary effect dominant ($Bo \ll 1$) and gravity effect dominant ($Bo \gg 1$). These features are important not only for theoretical research, and also for application of materials processings.

4. On the stability region

According to the results for $d_0 = 2, 3$ and 4 mm, the gap region of liquid bridge volume asso-

ciated with abnormal features depends on the diameter d_0 and aspect ratio A . From the view point of experiment, the stability region of onset oscillation is difficult to be determined accurately. From the view point of experiment, we can obtain a gap region by cutting the marginal curves extended to the higher value of $(\Delta T)_c$ as the broken lines in Fig. 4 for fixed d_0 and A with a line of constant high value of $(\Delta T)_c$, for example $(\Delta T)_c = 120^\circ\text{C}$. The distributions of the gap regions obtained experimentally by this definition were sensitive to the aspect ratio A , but not sensitive to the Bond number Bo , as shown in Fig. 6.

Langbein studied the stability of the liquid bridge with iso-temperature in static basic state, and found that the marginal stability depended on aspect ratio A , volume of liquid bridge $d_{\min}/d_0$ and the Bond number Bo . The results showed also that there was a stability region of liquid volume for fixed aspect ratio A depending on Bond number Bo [11], for example the region located in $d_{\min}/d_0 \in (0.2, 1.0)$ for $A = 1$ and $Bo = 0.1$ and $d_{\min}/d_0 \in (0.25, 1.0)$ for $A = 0.5$ and $Bo = 1$. The case of iso-temperature requires

Fig. 6. Distributions of gap range of liquid volume associated with stability region. The solid, dashed and dash-dotted lines are related, respectively, to $d_0 = 4$ mm, 3 mm and 2 mm; the value of geometric aspect A is noted by the numbers above the line.

Fig. 7. Typical stability range of half floating zone; the shaded region is associated with the stability region.

$\Delta T = 0$, and relates to the abscissa of state $(\Delta T)_c = 0$ in Fig. 4. It is expected that the conclusion about the dependence of stability on the liquid volume and aspect ratio for the case of iso-thermal liquid bridge could be extended to the thermocapillary case of the liquid bridge. Combining the results of both cases, we have the typical stability diagram as shown in Fig. 7 for fixed d_0 and A , and a stability region exists from the iso-temperature case for linear disturbance of the static basic state, and then evolves to oscillatory thermocapillary convection via the stability region of steady thermocapillary convection. The stability region is convergent from a relatively larger extension in the static state to a small extension in the state of thermocapillary convection. Theoretical explanation of the stability region will be very interesting.

On the view point of application, it is of great benefit to design the floating zone with the liquid volume fallen in the gap region for fixed rod diameter and aspect ratio, and, in this case, the onset of oscillation in the liquid bridge could be delayed or even avoided.

5. Conclusion

In the present paper, the dependence of critical applied temperature difference on the volume of the liquid bridge was analyzed in detail for half

floating zone with Bond number from much smaller than 1 to larger than 1. The results show that the influence of the liquid bridge volume is obvious, the experimental values of critical $(\Delta T)_c$ may disperse in a range more than three times larger, depending on the volume of the liquid bridge for fixed diameter d_0 and aspect ratio A . This implies that the volume of the liquid bridge is one of the critical parameters for the onset of oscillation in the liquid bridge of floating zone. A gap region of abnormal features on the stability was given experimentally for fixed d_0 and A of the liquid bridge with Bond number either much small than 1 or larger than 1, and the gap region of liquid volume is relatively larger for the case of larger aspect ratio $A = 1$. The experiments of a larger liquid bridge with $d_0 = 5.5$ mm were completed also, and similar results of profile distributions were obtained.

It should be pointed out that, in some sense, the ranges of gap region given by experimental method in the present paper are arbitrary. The results cannot be given by experiment if two broken lines of marginal curves may or may not be crossed. It is not certain if the cause of the broken liquid bridge with the volume fallen in gap region comes from the instability of the dynamical state or from others sources. However, the higher value of $(\Delta T)_c$ in the gap region implies the relative stability from the view point of instability analyses.

The critical parameters are important for mechanism studies of the oscillation. Many physical parameters in addition to the geometrical parameters have been suggested as the critical parameters from view points of both experimental and theoretical sides. It was proved that geometrical parameters such as the typical length scale d_0 and aspect ratio A are sensitive parameters for the onset of oscillation, and it was proved also that the volume ratio of the liquid bridge V/V_0 or $d_{\min}/d_0$ is another sensitive parameter for the onset of oscillation. Furthermore, the existence of a gap range of liquid volume which associates with the stability region of oscillation implied that the volume parameter may be more important in the stability analyses.

The experiments were completed in the labo-

ratory on the ground, the results may be applied to the floating zone proceedings on the ground. The ground experiments with Bond number much smaller than 1 may shed light on the microgravity experiment, which results will be greatly attracted in the future. On the other hand, theoretical analyses of volume influence in comparison with the experimental results are interesting, and will be discussed by numerical simulation in Paper II.

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