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Investigation on a simulation model of floating half zone convection—II. Experiment

J. H. HAN, Y. R. ZHOU and W. R. HU
Institute of Mechanics, Chinese Academy of Science, Beijing, China

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Abstract—A simulation model of floating half zone with non-uniform temperature distribution at the upper rod and uniform temperature distribution at lower rod was discussed by numerical investigation in a previous paper. In the present paper, the experimental investigation of the simulation model is given generally. The results of the present model show that the temperature profile is quite different and the critical applied temperature difference is lower than the one of usual model with same geometrical parameters in most cases. The features of critical Marangoni number depending on the liquid bridge volume are also different from the ones of usual model. © 1997 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

The convection driven by the gradient of surface tension or interface tension often dominates the process in the microgravity environment. Thermocapillary convection in the liquid bridge of floating zone or floating half zone is one of the typical subjects in microgravity fluid physics. Usual model of floating half zone deals with the convection in the liquid bridge bounded by two rods with constant temperatures, and gives the temperature profiles quite different from the one in half part of a full floating zone, where the temperature distribution at the heater plane of liquid bridge is non-uniform. Therefore, a simulation model of floating half zone with temperature distribution of positive radial gradient at the upper rod was suggested, and the basic features of the simulation model were generally discussed by the numerical approach in ref. [1]. The main features of the simulation model are more close to the ones of half part of a full floating zone in comparison with the ones of the usual model.

Similar ideas have been suggested experimentally by Hirata and his colleagues in the Waseda University of Japan [2, 3], Lees and Korea [4], and recently by Shu and Legros [5]. Their main interest seems in the measurement of azimuthal velocity due to the optical transparency of the upper disk of sapphire or glass. The temperature distributions of these models in the liquid bridge at the upper disk is nearly constant but have small negative gradient in radial direction due to the larger heat conductivity of the disk materials in comparison with the one of the fluid medium such as the silicon oil. This means that the heat and mass transfers of these floating half zone models are close to the one of usual model, but still quite different from the one of half part of a full flosating zone. The usual models, ideal simulation model with positive temperature gradient and simulation model with negative temperature gradient in radial direction are shown, respectively, in (a, b and c) of Fig. 1.

In the present paper, the simulation model close to the one of Fig. 1(b) was studied by the experimental approach. The basic experimental features of the steady convection agree with the ones of numerical results described in ref. [1]. The onset of oscillation of the simulation model is studied also in the present paper, and compared with the one of usual model. The critical Marangoni number of the simulation model is obviously smaller than the one of usual model in most cases. This conclusion implies that the oscillation in liquid bridge of simulation model, which is close to the situation of the full floating zone, is more easy to be excited than the one expected by the usual model of floating half zone in most cases, and this conclusion is not beneficial to the application of materials processing.

The experimental facility is described in the next section and the main features of the simulation model, including distributions of temperature and flow pattern, the azimuthal velocity, are discussed in Section 3. The onset of oscillation and the dependence of critical Marangoni number on the liquid bridge volume are analyzed in Section 4. The last section is discussion and conclusion.

2. EXPERIMENTAL METHOD

Liquid bridge of the simulation model is floated between a lower copper rod and a transparent upper disk, which materials has a coefficient of heat conductivity less than the one of experimental medium of liquid bridge. In this case, a positive temperature gradient in radial direction could be constructed in liquid bridge at the boundary of the upper disk [1]. Usually, silicon oil is selected as the experimental

NOMENCLATURE

d	diameter	σ	surface tension of liquid
d_0	minimal radius of liquid bridge	g	acceleration of gravity
l	height	T_h	temperature at upper copper ring
A	geometrical aspect ratio	T_0	temperature at lower rod
B_d	dynamic Bond number	T_{ub}	temperature at the upper boundary of liquid bridge.
ρ	density		
β	thermal expansion coefficient		

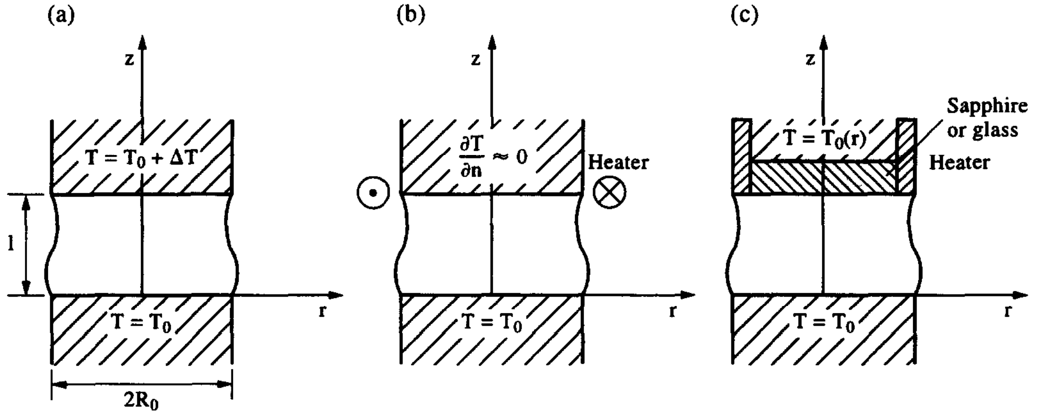

Fig. 1. Models of floating half zone: (a) usual model with constant temperatures at both rods; (b) ideal simulation model with nearly zero temperature gradient in normal direction at upper rod and constant temperature at lower rod; (c) simulation model with negative temperature gradient in radial direction at upper disk and constant temperature at lower rod.

medium as in the present paper, and its coefficient of heat conductivity is 1.34×10^4 erg cm$^{-1}\cdot$s$^{-1}\cdot$K^{-1}. It should be noted that the coefficients of heat conductivity of sapphire [2, 3] and glass [4, 5] are at least one order of magnitude larger than the one of silicon oil, and the models by using these materials as upper disk can only support a temperature distribution with negative gradient in radial direction at the boundary of upper disk. The simulation model requires that a materials of upper disk should be optical transparency for measurement of flow pattern in horizontal cross-section of liquid bridge and should have smaller coefficients of heat conductivity in comparison with the one of experimental medium to satisfy condition of temperature distribution at upper boundary of liquid bridge. In the present paper, the polycarbonate is selected as upper disk, and its heat conductivity is 1.59×10^4 erg cm$^{-1}\cdot$s$^{-1}\cdot$K^{-1}, which is a little larger than the one of silicon oil.

The upper disk of polycarbonate is surrounded by the heater of a copper ring, and configuration of the experimental facility is shown schematically in Fig. 2, where 10 cst silicon oil is used as the experimental medium. The lower rod and upper disk are co-axial, and have relatively large same diameter of $d = 5$ mm. The height of liquid bridge l is smaller than the diameter d for persistence of the liquid bridge, so the geometrical aspect ratio $A = l/d$ is smaller than l, and cases $A = 0.55$ will be discussed especially in the present paper. The dynamic Bond number B_d is usually introduced to measure the relative importance between gravity effect and thermocapillary effect, and the definition of the dynamic Bond number is $B_d = (\rho g l^2 \beta / |\partial\sigma/\partial T|)$, where g is the acceleration of gravity, ρ, β and σ are, respectively, the density, thermal expansion coefficient and surface tension of the liquid, and $\partial\sigma/\partial T$ is the differential of surface tension to the temperature. In the present experiments, the dynamic Bond number is $B_d = 0.74$ for $A = 0.55$ and this implies that the thermocapillary effect is relatively important in comparison with the effect of gravity.

Seven thermocouples are fixed through the upper transparent disk at different radii of 0, 0.76, 1.08, 1.38, 1.77, 1.95 and 2.08 mm with different azimuthal angles to measure the temperature distribution at the upper boundary of liquid bridge. Another thermocouple inserted into the liquid medium through the free surface is used to measure the temperature distribution in the liquid bridge. The light-sheet method is applied to show the flow patterns, and the particle tracers are aluminum powder of 3–5 micrometer in diameter. Two perpendicular sheet lights pass independently through the liquid bridge to show the flow patterns in the vertical and horizontal cross-sections, respectively, as shown in Fig. 2. The optical transparency of the upper disk permits to measure the velocity pattern in

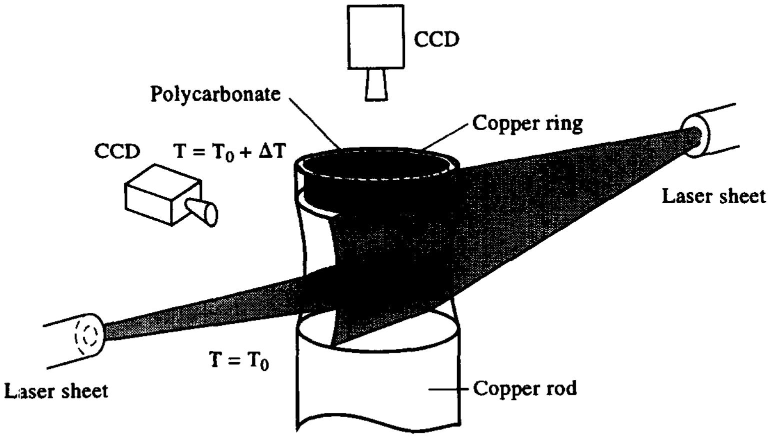

Fig. 2. Schematic diagram of experimental facility of simulation model.

a horizontal cross-section of liquid bridge [2–5], and is beneficial to understand the three-dimensional distribution of velocity field.

The basic features of the simulation model were experimentally obtained in the present paper. The experiments of a usual model with same geometrical parameters were also completed for comparison with the simulation model. There is obviously difference between two models.

3. EXPERIMENTAL RESULTS

The temperature distributions at upper boundary of liquid bridge are a typical feature of floating half zone models, and depend on the applied temperature difference. Temperature distributions are measured by thermocouples and all the profiles have positive gradient in the radial direction in the present experiments. The temperature difference between the outer edge and center may be as large as 10°C. Non-dimensional temperature distributions $(T_{\mathrm{ub}}-T_0)/(T_{\mathrm{h}}-T_0)$ depending on radii are given in Fig. 3 for cases of steady convection, where $T_{\mathrm{ub}}(r)$ is the temperature at the upper boundary of liquid bridge and applied temperature difference is defined by the temperature difference ΔT between the hot one T_{h} at upper copper ring and cold one T_0 at lower rod. All the distributions have similar profiles except the case $\Delta T = 66°\mathrm{C}$, which is a case close to the critical state. This feature of boundary temperature distribution is different from the one of other model of floating half zone such as shown in Fig. 1(a) or the ones given in refs. [2–5], and is similar to the one in the horizontal cross-section near the heater plane of a full floating zone.

Temperature profiles in the liquid bridge determine the heat and mass transfer, and then the convective process. The temperature gradient in the longitudinal direction should be nearly zero at the heater plane of a full floating zone in the microgravity environment, and this condition cannot be satisfied at the upper boundary of liquid bridge for the usual floating half zone. The temperature profiles in the liquid bridge of simulation model are given in Figs. 4(a, b) for $\Delta T = 35.1$ and 41.7°C as the examples. It could be seen that the profiles are different from the one of usual model [4], and has distribution which is similar to the half one of a full floating zone. In comparison with the usual model of floating half zone, there is a larger temperature gradient near the upper corner of liquid bridge where the heater ring is located, and this larger temperature gradient may induce easily the onset of oscillation in some cases. The experimental results of temperature distributions agree well with the ones of numerical simulation given in ref. [1].

The velocity patterns in horizontal cross-section and vertical cross-section are given, respectively, in the lower and upper part of Fig. 5 for steady convection. Two cells are steady and axial symmetric in the vertical cross-section before the onset of oscillation. Experimental results show that the cell center of zero velocity is relatively close to the free surface for simulation model in comparison with the usual model.

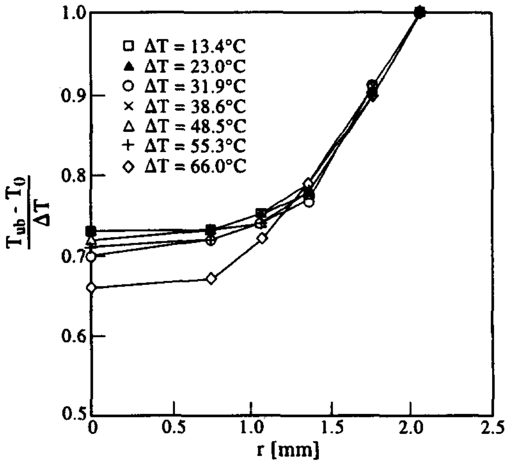

Fig. 3. Non-dimensional temperature distribution at upper boundary of liquid bridge for simulation model of $A = 0.55$ and $d/d_0 = 0.9$.

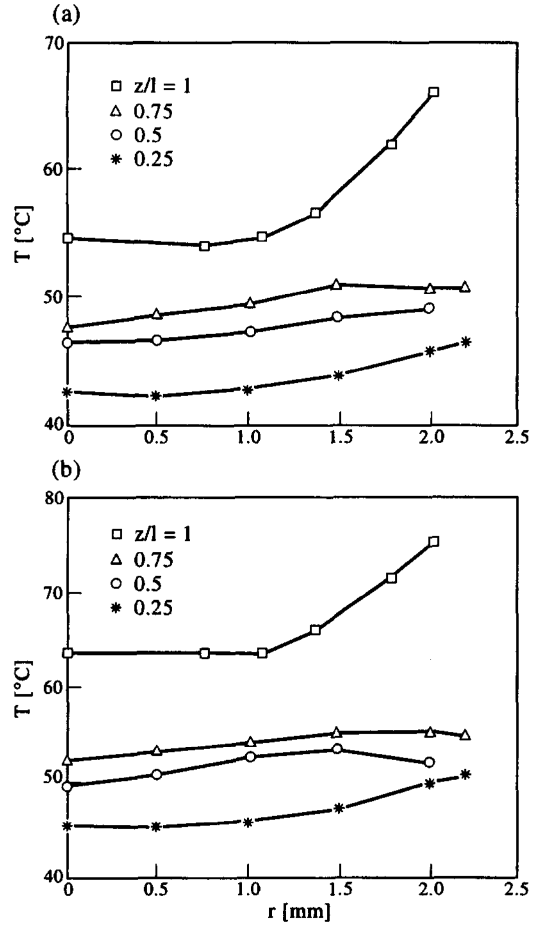

Fig. 4. Temperature distributions in the liquid bridge for applied temperature difference $\Delta T = 35.1$°C (a) and 41.7°C (b), where $A = 0.55$ and $d/d_0 = 0.84$.

4. ONSET OF OSCILLATION

Onset of oscillation is an important subject for thermocapillatory convection. The critical applied temperature difference may be determined at the moment of onset oscillation during the increasing of applied temperature difference. The basic features of onset oscillation could be seen by either the temperature measurement at a position inside liquid bridge or the flow pattern changed from nearly steady to oscillation. These features are similar for all models of floating half zone.

The velocity patterns of different modes depend on the geometrical aspect ratio [3, 4]. It was suggested that the flow pattern in the horizontal cross-section was rotated and the rotation frequency was the same frequency of oscillation [4]. On the other hand, the PIV method was used to measure the azimuthal velocity near the free surface of liquid bridge and gave an average component of zero velocity in addition to an oscillatory component [6]. These two conclusions are different. The flow patterns in vertical cross-section of oscillatory convection for $A = 0.55$ are given in Fig. 6. Figure 7 gives the sequence of flow pattern of horizontal cross-section in one period of oscillation at middle height as shown in the small figure of upper-right corner. There is a dark sink region in the center part of the cross-section and the dark means low speed flow with fewer tracers. The dark region rotates with an angular frequency, which is nearly the same as the frequency of temperature oscillation. However, the rotation of dark region does not mean the rotation of medium mass. The trajectories of tracers show clearly that there is azimuthal velocity of zero in average in a period, in addition a component of periodical fluctuation. This conclusion agrees with the results of ref. [6], but is different from the one of ref. [4]. Based on the present experiments, it could be seen that the PIV method can give clear flow pattern for the steady convection and shows the temporal variation of flow pattern for unsteady convection in the small liquid bridge of floating half zone. However, the detailed variation of the flow pattern is not clear for oscillatory convection, and can be observed qualitatively sometimes but cannot be described quantitatively due to the rapid change. It should be emphasized that the flow pattern in the horizontal cross-section is especially complex, and some patterns depending on the geometrical aspect ratio have been considered as instability modes [4, 7]. It seems to us, how to explain the flow pattern should be studied further.

It is noted that the critical applied temperature difference or the critical Marangoni number depends on the volume of liquid bridge [8, 9], and the dependence was given for the smaller liquid bridge of a few millimeters in diameter. The upper disk requires a relative large diameter, for example 6 mm in refs. [2–6] and 5 mm in the present experiment, and a smaller geometrical aspect ratio is needed for persistence of the liquid bridge. Figure 8 summarizes the experimental results of critical applied temperature difference depending on the volume of liquid bridge for simulation model (full lines), and the results of the usual model (broken lines) are also presented for comparison. Two curves of marginal state are quite different, two groups of slender liquid bridge and fat liquid bridge are shown clearly in the usual model, but this grouping phenomenon does not appear in the simulation model. It could be seen from Fig. 8 that the critical applied temperature of simulation model is smaller than the one of usual model in most important parameter range of liquid bridge volume ($0.72 < d/d_0 < 0.94$), except for very slender and very fat liquid bridge. This means that the oscillatory convection is more easily excited for simulation model.

5. CONCLUSION

The simulation model was suggested numerically in ref. [1] and analyzed experimentally in the present paper. This new model is relatively close to half part

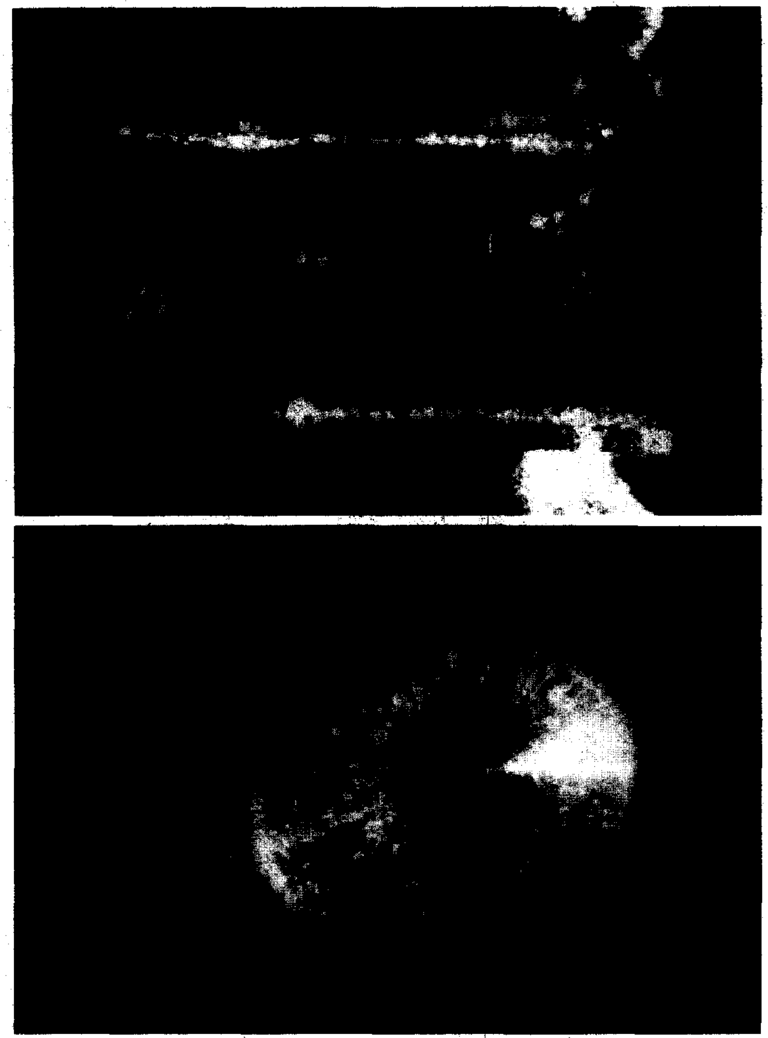

Fig. 5. Axi-symmetric flow patterns in the vertical cross-section (a) and horizontal cross-section (b) for steady convection, where $\Delta T = 36.1°\text{C}$ and $d/d_0 = 0.76$.

Fig. 6. Asymmetric flow pattern in the vertical cross-section for oscillatory convection, where $\Delta T_c = 53.7°\text{C}$ and $d/d_0 = 0.76$.

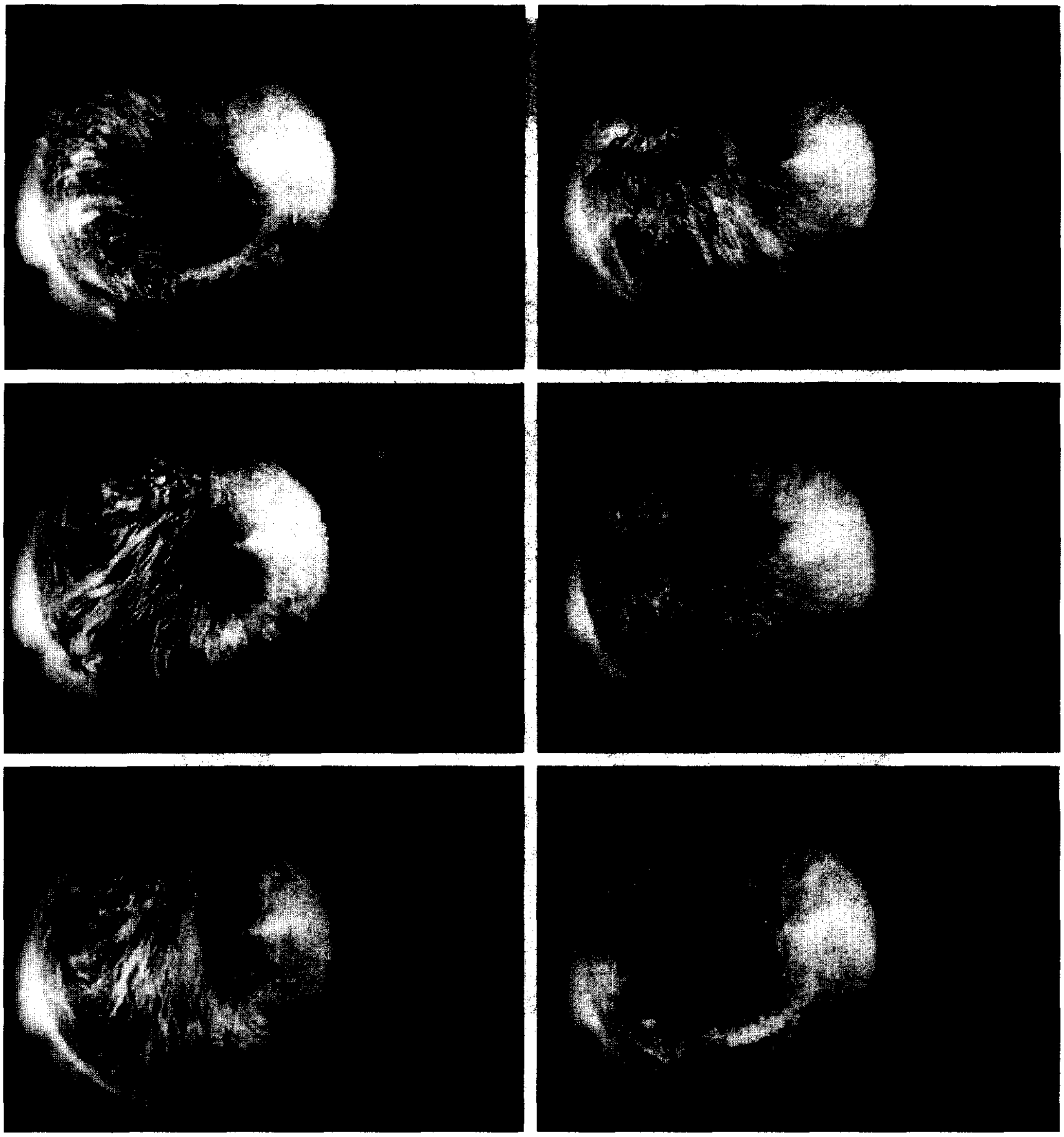

Fig. 7. A sequence of flow pattern in the horizontal cross-section in one oscillatory period in a condition the same as Fig. 6. The time step is 0.25 and oscillatory frequency is 0.78 Hz.

of full floating zone in comparison with the usual model, and may shed light on the mechanism studies of full floating zone process via the study of simulation model of floating half zone. On the one hand, the simulation model is a new system of thermocapillary convection, and every system may give contribution for studying the thermocapillary process and may be helpful to understand the mechanism of floating zone process in general. On the other hand, the simulation model may give relatively more information associated closely with the full floating zone especially.

The experimental results in the present paper agree with the ones of numerical simulation presented in ref. [1]. There are many differences of fundamental features between the simulation model and usual model. The oscillation is more easily excited for simulation model in comparison with the usual model in most liquid bridge except very slender and very fat

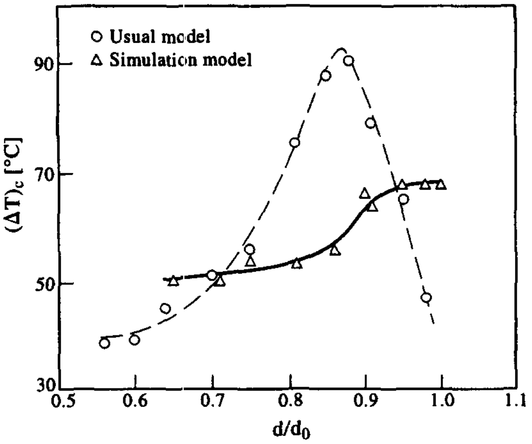

Fig. 8. Marginal curves for onset of oscillation show the critical applied temperature difference depending on the non-dimensional liquid bridge volume for simulation model (full line) and usual model (broken line).

ones. In the present paper, the preliminary features of the simulation model have been discussed experimentally. Systematic studies should be continued by both theoretical and experimental approach in the future, and the dependence of the basic feature on the parameter ranges will be analyzed.

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