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TRANSITION FROM STEADY TO OSCILLATORY CONVECTION WITH CHAOTIC FEATURE IN THERMOCAPILLARY CONVECTION

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ABSTRACT

The transition process from steady to turbulent convection via subharmonic bifurcation in thermocapillary convection of half floating zone was studied by numerical simulation and experimental test. Both approaches gave structure of period doubling bifurcations in the present paper, and the Feigenbaum universal law was checked for the system of thermocapillary convection.

INTRODUCTION

Thermocapillary convection is a typical subject of microgravity fluid dynamics, and supports also a new sort of dissipative system similar to Benard convection. The transition process such as the chaotic behavior has been studied extensively for Benard convection, there are many routes to the turbulent convection depending on the typical parameters such as Rayleigh number, Prandtl number and geometrical aspect. The transition process for thermocapillary convection will be discussed in the present paper.

Most research works of floating zone convection were concentrated on the transition from steady flow to oscillatory convection, especially the onset of oscillation in the experiments /1-8/ and the instability analyses in theory /9-13/, these studies concerned only the starting period of a complete route to turbulence. Kazarinoff and Wilkowski analyzed numerically the chaotic feature of axisymmetric floating zone /13/, and Tang and Hu discussed numerically the instability for asymmetric model of half floating zone /14/. On the one hand the route to turbulent convection of the new sort of dissipative system is attractive from the view point of non-linear science, and on the other hand, it may be also interesting from the view point of application of space materials science.

NUMERICAL SIMULATION

The unsteady and two-dimensional model of half floating zone /15/ was applied to study the transition from steady to turbulent convection. The liquid bridge with D_o in width and infinite extension suspended between two planes. The Prandtl number (Pr) of modeling medium is 105.6. There is an applied temperature difference ΔT between two planes with the upper plane heated. The transition process could be completed by numerical test and experiments for asymmetric model during increasing applied temperature difference. The temperature interval in calculation should be small enough to describe accurately the onset of subharmonic oscillation, which is very sensitive to the increasing rate of temperature.

The geometrical parameters such as D_o, geometrical aspect $A = L/D_o$ and volume ratio

of liquid bridge, or width ratio D_m/D_o, are important for the onset of oscillation and the transition process /16, 17/, where L and D_m are, respectively, the height and the minimum width of the liquid bridge, and in the present paper A = 1.0, $D_m/D_o = 0.9$ and $D_o = 4mm$. The critical applied temperature difference, corresponding to the onset of oscillation, is $(\Delta T)_c = 40^oC$. The ratio of temperature difference $R = \Delta T/(\Delta T)_c$ is introduced, and R = 1 associates to the onset of oscillation. Bifurcation may appear when the ratio R is increased.

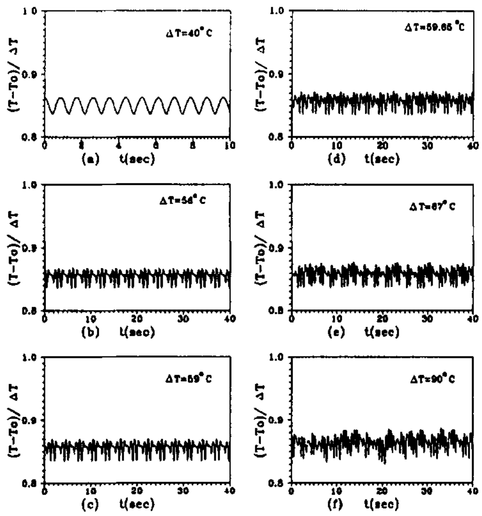

Fig.1 The temperature profiles

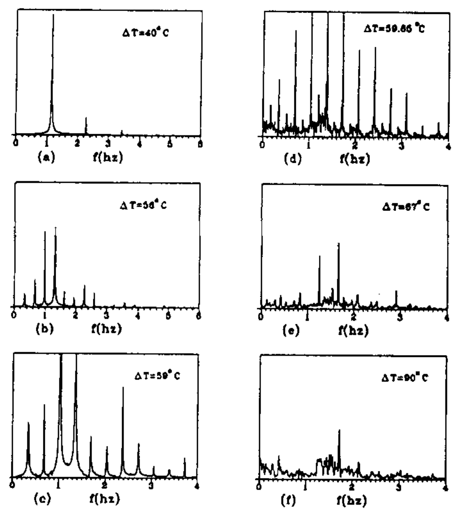

Fig.2 The spectrum of temperature profile associated by Fourier transfer with the cases of Fig. 1

Typical profiles of temperature oscillations and the associated spectrums of Fourier transforms at a point of free surface near the lower plane are given, respectively, in Figs. 1 and 2. The chaotic feature could be seen also in plane (T, dT/dt) as shown in Fig. 3. The transition from onset of oscillation to turbulence is clear. There are three typical R ranges of the transition process:

1. the transition of periodic subharmonic bifurcations with locking frequency at $1/2^n$ of basic frequency ($n \leq 4$) in the range $1 < R < 1.49$;

2. the transition of bifurcation with locking frequency at 1/m of basic frequency (m = 18, 24,...) in range $1.49 < R < 2.25$;

3. the region of random spectrum appeared in the range of larger R, for example, $R > 2.25$.

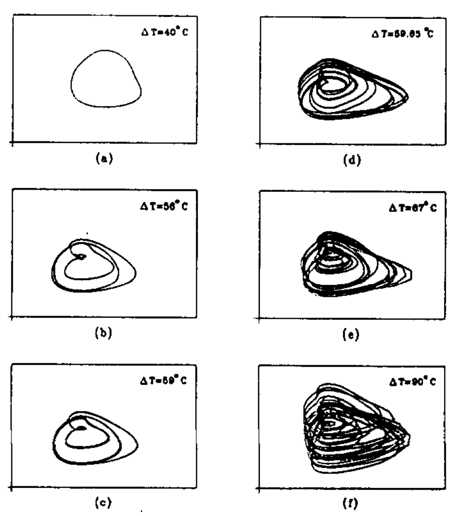

Fig. 3 The trajectories of temperature distribution in plane (T,dT/dt) for cases associated to Fig. 1.

EXPERIMENT AND THE RESULTS

In the experiment of the half floating zone the applied temperature difference for bifurcation behavior should be more higher than the critical temperature value at the onset of oscillation. The liquid bridge with several millimeters in diameter is difficult to be persisted for the case of a fat liquid bridge and higher applied temperature difference. Therefore, it is difficult to complete experimentally a whole route of transition, but the transition from onset of oscillation to bifurcation behavior may be possible under suitable condition.

In the present experiment, the liquid bridge with $A = l/d_o = 0.95, d_o = 3mm$ and $d_m/d_o = 0.7$ is adopted, where l, d_m and d_o are, respectively, the height, the minimum or maximum diameter of the liquid bridge, and the diameter of rod. The liquid bridge is consisted of 10 cst silicon oil with Prandtl number $P_r = 106$, and the case of upper rod heated is analyzed. The evolution of temperature, flow pattern and free surface may be measured, respectively, by the inserted thermocouple, the tracer particle trajectory, and the optical method of grid mask /8/.

A thermocouple of 0.03mm in diameter was inserted through the free surface into the liquid bridge at the position 1.1mm in radius and 0.4mm below the upper rod. A harmonic oscillation with basic frequency $f_c = 1.1$ Hz is given by the spectrum analyses of Fourier transformation at the applied temperature difference $(\Delta T)_c = 29.3^oC$. The fractal frequencies are locked at 1/4 and 3/4 of the basic frequency at $\Delta T = 81.8^oC$, and the integral fractals of n/4 (n = 1, 2, 3) at a bit higher applied temperature difference 83.4^oC as shown in Fig. 4 . The typical modes of temperature profile were given in the left and the associated spectrum distributions in the right of Fig. 4 . The liquid bridge was broken for more higher value of ΔT. The experiment for other typical parameters shows that the bifurcation feature is sensitive to the geometrical parameters such as A, d_m/d_o , and there are different bifurcation features for different geometrical parameter range.

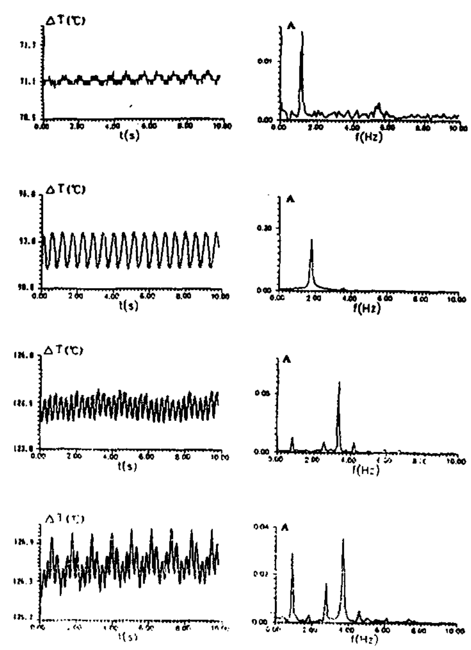

Fig. 4 Experimental result of temperature profile inside liquid bridge (left) and the spectrum distribution (right) for typical cases: (a) critical oscillation, $\Delta T = 23^oC$, (b) harmonic mode, $\Delta T = 51.7^oC$, (c) part subharmonic mode, $\Delta T = 81.8^oC$, (d) whole quarters subharmonic mode, $\Delta T = 83.4^oC$

DISCUSSIONS AND CONCLUSION

The numerical simulation gave a route of transition to turbulent convection via the subharmonic bifurcations for certain conditions in the present paper. The applied temperature differences at the onset of subharmonic bifurcations gave the ratio

$$\delta_4 = \frac{\Delta T(f_b/8) - \Delta T(f_b/4)}{\Delta T(f_b/16) - \Delta T(f_b/8)} = 4.853,$$

where f_b is the basic frequency, and $\Delta T(f_b/2^n)$ means the value of ΔT at the onset of 2^n th subharmonic bifurcation. The ratio δ_4 given by the numerical test is quite close to the value of universal constant $\delta = 4.6642$ given by Feigenbaum's general theory /17/. The periodic subharmonic bifurcations were obtained from experiment of oscillatory thermocapillary convection with applied temperature difference more higher than the critical value . However, the completed transition process cannot be given by the present experiment due to the broken of liquid bridge in higher temperature difference. Both results of numerical test and experimental test are similar.

Main interesting on thermocapillary convection are confined in the process of onset of oscillation in the present time. The purpose of the present paper is to extend the interesting to cover the complete transition process. The onset of oscillation in thermocapillary convection depends on many critical parameters, and the route to turbulent convection does also true. In the present paper, a special route to turbulence was discussed under certain conditions, however, there will be many routes to turbulent thermocapillary convection depending on detailed conditions. There need many studies to be completed in the future.

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