TRANSITION TO TURBULENCE IN THE FLOATING HALF ZONE CONVECTION

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ABSTRACT

The transition process to turbulence is studied experimentally in thermocapillary convection of floating half zone. The onset of temperature oscillations in the liquid bridge of floating half zone and further transitions of the temporal convective behaviour are detected by temperature measurements in the liquid bridge. The fast Fourier transform (FFT) reveals the frequency and amplitude characteristics of the flow transition. The experimental results indicate the existence of a sequence of period-doubling bifurcations that culminates in turbulence. The measured Feigenbaum numbers are $\delta_2 = 4.69$ and $\delta_4 = 4.6$. Both results can be compared with the theoretical asymptotic value $\delta = 4.669$.

INTRODUCTION

Transition to turbulent convection in dissipative dynamical systems is a subject of great interest for both its theoretical and practical aspects in the fluid mechanics. The route to turbulent convection in natural thermal convection has been the subject of fundamental research, e.g. references. [1~5] It has been studied expensively. These studies and others have shown that there are many routes to the turbulent convection depending on the typical parameters such as the Rayleigh number, the Prandtl number and geometric aspect.

There is also another interesting convection mechanism besides buoyant convection. Thermocapillary convection is a typical subject of microgravity fluid mechanics and supports also a new dissipative system similar to Rayleigh-Benard convection. The flow driven by the gradient of surface tension is called thermocapillary convection. The thermocapillary convection have received increasing attention because its relevance in the containerless method of floating-zone crystal growth and material science. The thermocapillary convection has been studied numerically and experimentally under normal gravity and microgravity. Most research works of floating-zone convection were focused on onset of oscillation in which the steady convection transits to oscillatory convection. The onset of oscillation is only the initial period of transition to turbulence. A complete route to turbulence of the new sort of dissipative system is attractive on the theoretical aspect and on the application aspect of space materials science. The transition process of thermocapillary convection will be great interesting. A route involves a series of successive period doubling bifurcations to turbulent convection has been given by the method of numerical simulation for two-dimensional and unsteady mode of the floating half zone in reference. [6]

The half-zone liquid bridge model is a typical model to study thermocapillary convection. In some ground-based studies, small scales of the liquid bridge usually are adopted in order to reduce the buoyancy effect respective to the thermocapillary one. In our present experiment, the onset of temperature oscillations in the liquid bridge of diameter d_0 = 4mm and further transitions of the temporal convective behavior are detected by temperature measurements. A route to turbulent convection is presented in present paper. Experimental study is focused on the bifurcation feature during the transition process. Period doubling bifurcation is obtained by the real time analysis of the spectra, which is accomplished by Fourier transforms. The Feigenbaum constants are given in the present paper. The Feigenbaum constants are closed to the theoretical value.

EXPERIMENTAL SET-UP

The liquid bridge of 10cst silicone oil was floated in the gap between two co-axial rods with the same diameter d_0 = 4mm. A temperature difference was applied between the upper and low rod, and the cases of upper rod heated are analyzed in the present paper. The temperatures were measured by thermocouples at both sides of the rods. Two PID-controllers (EUROTHERM 904 controller) were used to control the heating rate and the temperature difference between the upper and low rod. A thermocouple of 0.02mm in diameter was inserted into the liquid medium to measure the temperature. This thermocouple was located at about 0.2l from the upper rod and just beneath the free surface (l is the length of liquid bridge). Another two thermocouples were fixed at the both rods. The temperature signals were registered simultaneously by a PC-supported data acquisition system composed of KEITHELY 2182 and KEITHELY 2000. KEITHELY 2182 was used to acquire the temperature inside the liquid bridge. The temperature resolution of KEITHELY 2182 is 0.001 ℃. KEITHELY 2000, which is a multimeter, was used to acquire the temperatures of the upper and low rod. The temperature resolution of KEITHELY 2000 is 0.1 ℃. Scanning rates of F = 10 Hz and number of sampling points of n = 512 or 1024 were used. Times series of temperatures were transformed in the frequency domain by Fast-Fourier-Transformation (FFT) in real time. The experiments were controlled by a computer and any time plots of thermocouple-data and the temperature spectra could be observed on the computer monitor online or at any time. The liquid bridge, temperature controller and data acquisition system used in the experiments are shown schematically in Fig.1

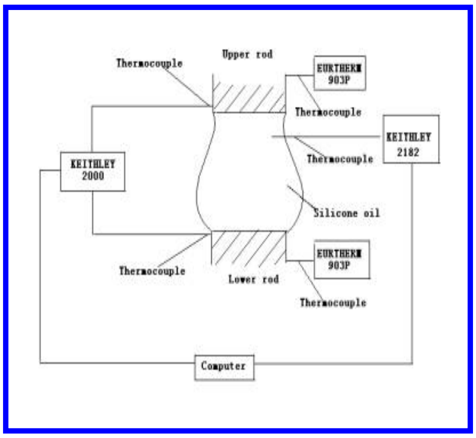

Fig.1 schematic sketch of experimental configuration

EXPERIMENTAL RESULTS

The geometrical parameters such as the diameter of two rods d_0, aspect ratio A = l/d_0 and volume ratio of liquid bridge are important for the onset of oscillation and transition process. The volume ratio of liquid bridge also be described the relative radii ratio $d_m/\ d_0$, where d_m is the minimum diameter of the liquid bridge. The liquid bridge with d_0 = 4mm, A = l/d_0 = 0.96 and $d_m/\ d_0$ = 0.9 was adopted in our experiment. The applied temperature difference ΔT between two ends of liquid bridge was increased slowly with time. It is necessary for finding the accurate moment corresponding to the onset of oscillation and the appearance of a subharmonic bifurcation. When the subharmonic bifurcation appeared, the temperature ramp profile was stopped and temperature difference between the rods was held constant. The typical heating rates were 0.1℃/s and 0.01℃/s and typical holding time between two steps is 5-8 min in present experiments. By the analysis of time series of temperatures acquired by thermocouples positioned at one point in the liquid bridge onset of oscillation was observed, and then subharmonic bifurcations of $f/2^n$ (n = 1, 2, 3, 4) successively appeared as increasing applied temperature difference. Fig.2 ~ Fig.6 shows a series of temperature signals with oscillations measured at a at a distance of (0.8 ±0.1) mm below the upper rod beneath the free surface. The applied temperature difference across the liquid bridges acquired simultaneously and the corresponding Fourier spectrum are plotted at the bottom and in the middle.

In experiment as increasing the applied temperature difference, when ΔT = 36.55℃ ± 0.05℃, the fluctuation appears in the curve of temperature (see the upper picture on Fig. 2). Simultaneously a peak appears on the curve of spectrum (see the middle picture on Fig. 2). It means an oscillatory convection with a single frequency appeared already in the liquid bridge.

Carry forward, when ΔT = 48.01℃± 0.05℃, one more peak of $f/2$ appears in the spectrum (see Fig.3). When ΔT = 61.65℃± 0.05℃, one more peak of $f/4$ appears in the spectrum (see Fig.4). When ΔT = 64.56℃± 0.05℃, one more peak of $f/8$ appears in the spectrum (see Fig.5). When ΔT = 65.15℃± 0.05℃, one more peak of $f/16$ appears in the spectrum (see Fig.6).

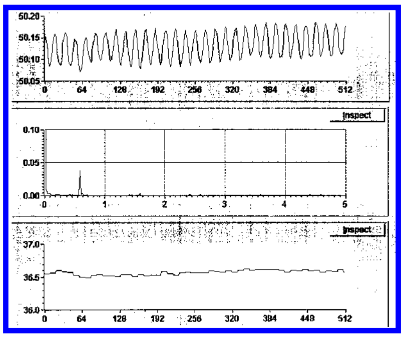

Fig. 2 The evolution of the temperature (top) and the corresponding spectrum (middle) at one point in liquid bridge and applied temperature difference (bottom) when onset of oscillation

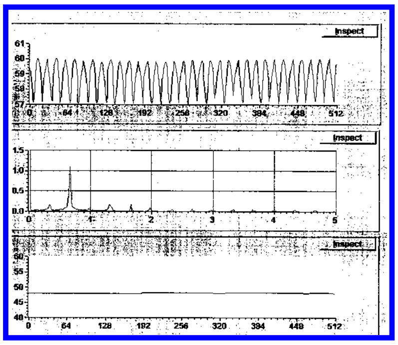

Fig. 3 The evolution of the temperature (top) and the corresponding spectrum (middle) at one point in liquid bridge and applied temperature difference (bottom) when $f/2$ appear

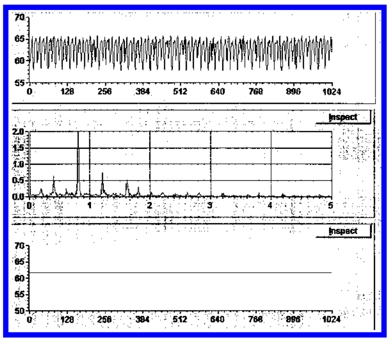

Fig. 4 The evolution of the temperature (top) and the corresponding spectrum (middle) at one point in liquid bridge and applied temperature difference (bottom) when *f*/4 appear

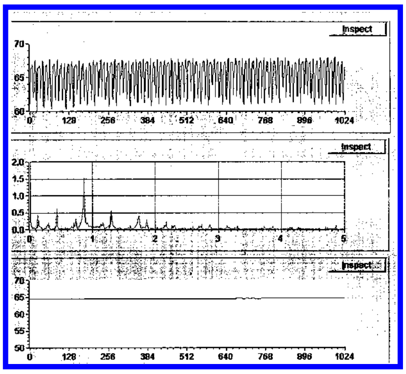

Fig.5 The evolution of the temperature (top) and the corresponding spectrum (middle) at one point in liquid bridge and applied temperature difference (bottom) when *f*/8 appear

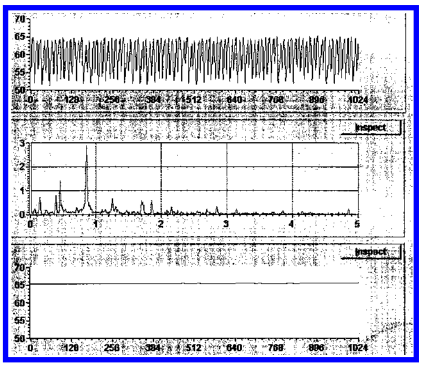

Fig. 6 The evolution of the temperature (top) and the corresponding spectrum (middle) at one point in liquid bridge and applied temperature difference (bottom) when *f*/16 appear

From Feigenbaum's general theory for the fluctuation spectrum of the route to turbulence, value a_n of the constraint should asymptotically approach to following relation

$$\delta_n = (a_{n+1}-a_n)/(a_{n+2}-a_{n+1}) \rightarrow \delta$$

where δ = 4.6642016. According to present experiment results, the Feigenbaum numbers computed for the bifurcation to the frequencies f_2, f_4, f_8 and f_{16} are If we compute the Feigenbaum number δ for the last three bifurcations, we get

$$\delta_2 = (f_4 - f_2) / (f_8 - f_4) = (61.65 - 48.01) / (64.56 - 61.65) = 4.69 \pm 0.05$$

$$\delta_4 = (f_8 - f_4) / (f_{16} - f_8) = (64.56 - 61.65) / (65.19 - 64.56) = 4.6 \pm 0.1$$

The present results are very conforming to the theoretical values given by Feigenbaum.

CONCLUSION

The floating half zone on earth base is a special type of mechanical dissipative system. In it the convection is a mixture of the thermocapillary convection which driven by the non-uniformity of surface tension and the Benard convection which driven by the buoyancy. Since we used small typical scale liquid bridge in our experiment, hence the thermocapillary convection is a dominant one. Early in the liquid bridge experiments, the most interest concentrates on the onset of oscillation, which concern only the start of the route to turbulence. There are many routes to turbulence, depending on the Prandtl number. Rayleigh number and geometric aspect of the floating half zone, and a fixed route will be determined for fixed parameters. In the present paper, we used a 10cst silicone liquid with d_0 = 4mm, A = l/d_0 = 0.96 and $d_m/$

d_0 = 0.9 and obtained a route from steady convection to turbulence via the f / 2, f / 4, f / 8, f / 16 period doubling bifurcation. The Feigenbaum constant obtained by our experiment is just very close to the theoretical value. It means that the route of subharmonic bifurcations is typical in the transition process of thermocapillary convection. The results of the subharmonic bifurcations support the idea that the oscillation in the liquid bridge of floating zone is induced by internal instability.

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