ACTA MECHANICA SINICA, Vol.19, No.2, April 2003 ISSN 0567-7718
The Chinese Society of Theoretical and Applied Mechanics
Chinese Journal of Mechanics Press, Beijing, China
Allerton Press, INC., New York, U.S.A.

EXPERIMENTAL STUDY ON THERMOCAPILLARY CONVECTION

SHU Jizu (束继祖)
(*National Microgravity Laboratory, Institute of Mechanics, CAS, Beijing* 100080, *China*)

ABSTRACT: In the present paper, the experimental studies on thermocapillary convection are reviewed. The author's interest is mainly focused on the onset of oscillatory thermocapillary convection, the features of oscillatory flow pattern, and the critical Marangoni number related with temperature and free surface oscillation. The coordinated measurement in a microgravity environment of a drop shaft is also addressed.

KEY WORDS: microgravity fluid dynamics, thermocapillary convection, liquid bridge, floating zone, oscillatory process, free surface wave, experiment in drop shaft

1 INTRODUCTION

The experiment of floating zone convection plays an important part in the study of Thermocapillary Convection (simplified as TC), which is one of gravity-independent type of natural convection. The experiments were carried out mostly in the ground based laboratory, and some in the microgravity environment. It is known that only a liquid bridge of small diameter can be utilized on the ground, and the liquid bridge should be kept in a small Bond number $B_0 = \beta g l^2/\sigma < 1$, which is a criterion for larger thermocapillary effects in comparison with the gravity effect.

The onset of TC, the transition from the motionless state to the laminar convection state, is induced by an infinite simal temperature gradient. The first critical Marangoni number Ma_0 is nearly equal to zero[1]. The laminar TC may become time-dependent (oscillatory) convection by increasing the Marangoni number (i.e. increasing the temperature difference between the two rods of the liquid bridge) beyond a certain critical Marangoni number Ma_C. It is important to avoid such kind of transition for applications in crystal growth in a floating zone. An unsteady flow in the liquid phase causes a considerable deterioration in the quality of grown crystal and is also important in the non-linear fluid dynamics. The oscillatory TC is one of the complex hydrodynamic problems, associated with the oscillation of temperature, velocity of the flow field and the free surface wave. However, most previous experimental studies on the TC[2,3] only use thermocouples to measure temperature, which is hardly enough to understand such complex fluid dynamic process. In the present paper, the experimental methods for the measurement of the oscillation in the liquid bridge related to the temperature, flow field and free surface wave are presented. And the experimental results are further discussed. The results by coordinated measurements in the experiment of the liquid bridge in the microgravity environment of drop shaft are also addressed.

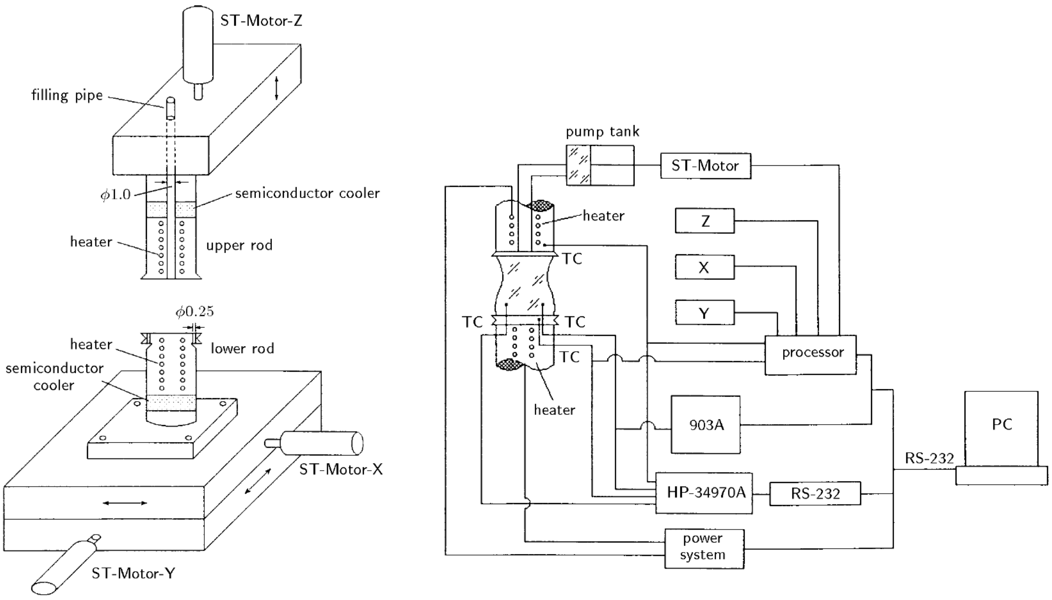
2 THE EXPERIMENTAL SYSTEM

The liquid bridge of a floating half zone in the experiment is sketched in Fig.1(a). It consists of two cylindrical rods. The edges of two rods are sharpened and the waterproof barrier is coated on the surface of the rods to prevent the experimental liquid from seeping over the edges of the two rods. Two small holes are located in each rod for installing the thermocouples to measure the applied temperature difference ΔT of the liquid bridge. The thermocouples for the measurement of temperature in the flow field of the liquid bridge are inserted into the liquid bulk through the two small holes ($\phi 0.25$ mm) on the lower rod at different azimuthal angles. The upper and lower rods are usually axis-symmetrical, and have a tolerance of 10 μm. Either the upper or the lower rod can be moved along the z-axis by a stepping motor, which is controlled by the PC computer to adjust the length of the liquid column. For controlling the volume of the liquid bridge, a feeding system operated also by the

---

Received 12 June 2001, revised 29 July 2002

PC computer was designed. The heater is installed into the upper and lower rods separately, to establish a temperature gradient field on the liquid bridge. The heat rate and the applied temperature difference ΔT are controlled by a temperature controller and could be present before the start of the experiment via the PC computer. The thermocouples, used to measure the temperature of rods and the temperature fluctuation in the liquid bulk, are connected with a data acquisition/switcher unit HP-34970A, and then via the cable RS-232 linked with the PC computer. The measuring temperatures are displayed on the monitor in real time. In the experiment, various measurements, for example, the flow pattern, the free surface oscillation etc., can be equipped with the experimental system, and the coordinated measurement, which means that the multi-physical quantities can simultaneously be measured in real time, can be made available, in order to meet the optimal correlation for the analysis of the flow phenomena of the TC. A practical arrangement for the experiment on ground is shown in Fig.1(b).



(a) The schematic diagram of a liquid bridge

(b) The measurement system for the measurement of onset of oscillatory thermocapillary convection by thermocouples

Fig.1

3 THE ONSET OF THE OSCILLATORY CONVECTION

The onset of the oscillatory TC is the process of transition from steady (laminar) TC into unsteady (oscillatory) TC, which is generally detected by using a thermocouple inserted into the flow field of the liquid bridge to measure the history of temperature fluctuation. A typical result of an experimental run is shown in Fig.2. The temperature oscillation starts at $\Delta T_{\rm C}$, and the amplitudes of the temperature oscillation grow continuously in a certain range as ΔT

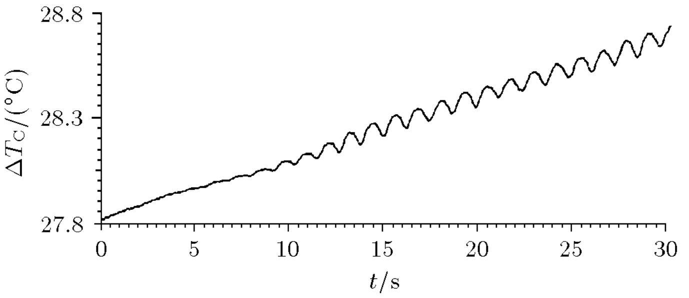


Fig.2 A typical run process of temperature oscillation in flow field of a liquid bridge

increases within a certain value. Here, ΔT_{C} is the critical value of the applied temperature difference, which is related directly to the critical Marangoni number Ma_{C}, and it is an important physical parameter in the study of floating zone convection.

The flow pattern of TC is useful for the analysis of the oscillatory TC, which is visualized by the method of light sheet[4]. A typical flow pattern of the stationary TC is shown in Fig.3(a) and the schematic diagram of the liquid bridge of floating half zone in a steady flow is shown in Fig.3(b). The features of laminar TC roll are independent of the azimuthal angle. As the applied temperature difference ΔT exceeds a critical value ΔT_{C}, the TC begins to oscillate. The flow pattern shows to be periodical both in space and in time, and the motion is three-dimensional. The oscillatory TC in a floating zone can be visualized in an half period sequence as shown in Figs.4(a)~(c), and described schematically in Figs.4(d)~(f). The streamlines of the oscillatory TC on the free surface and in a vertical cross-section of the liquid bridge are sketched at a fixed time. The moment is depicted when the vortices in the light sheet reach extreme positions(Fig.4(d)). The oscillatory TC is characterized by a sinusoidal distortion of the roll cross-section. The time dependence is caused by the propagation of this distortion around the zone axis.

(a) The flow pattern

(b) The schematic diagram of the liquid bridge of a floating half zone in steady (laminar) flow

Fig.3

The oscillatory TC shows some of the modes for the symmetrical zone, as an integer number m of the periodical roll distortions that can be developed on the circumference of the zone[5,6]

$$m\lambda = \pi d_0$$

where λ is the real wavelength of the instability in the azimuthal direction. The integer m is called the mode (or wave) number and the d_0 is the diameter of the rod. It is found experimentally that the mode number and wavelength are functions of aspect ratio $A = l/d_0$, where l is the length of the liquid bridge. The flow pattern of the lowest mode $m = 1$ (as $A > 0.65$) is shown in Fig.4. If the aspect ratio is decreased by reduction of zone length l for a constant d_0, the flow patterns for higher number m have been observed. For zones of various diameters, the modes depend on the aspect ratio in a unique way, and an empirical correlation is given as

$$2mA \cong 2.2(\text{constant}) \qquad (\text{for } A < 0.5)$$

for all zones, and it shows that the critical azimuthal wave number increases when the aspect ratio is decreased. The wavelength λ of the oscillation is proportional to l and independent of d_0. The zone length l seems to be the only proper characteristic number in the description of oscillatory TC in the zones with $l \leq d_0/2$. With the product mA, a constant non-dimensional parameter of oscillatory TC is obtained, which provides a possibility for calculating the mode number as A is given. The non-dimensional wave number K of the developed oscillatory TC is determined as

$$K = 2ml/d_0 = 2mA \leq 2.2$$

In all zones, the unstable TC develops a wavy structure with this wave number, as is demonstrated experimentally by the measurement of the free surface wave[7,8].

As the applied temperature difference ΔT is increased beyond a certain value, the chaotic feature of TC is observed, and the transition from onset of oscillation to the turbulence via sub-harmonic bifurcation was obtained by both the experimental and numerical studies[9]. The evolution of the temperature, the flow

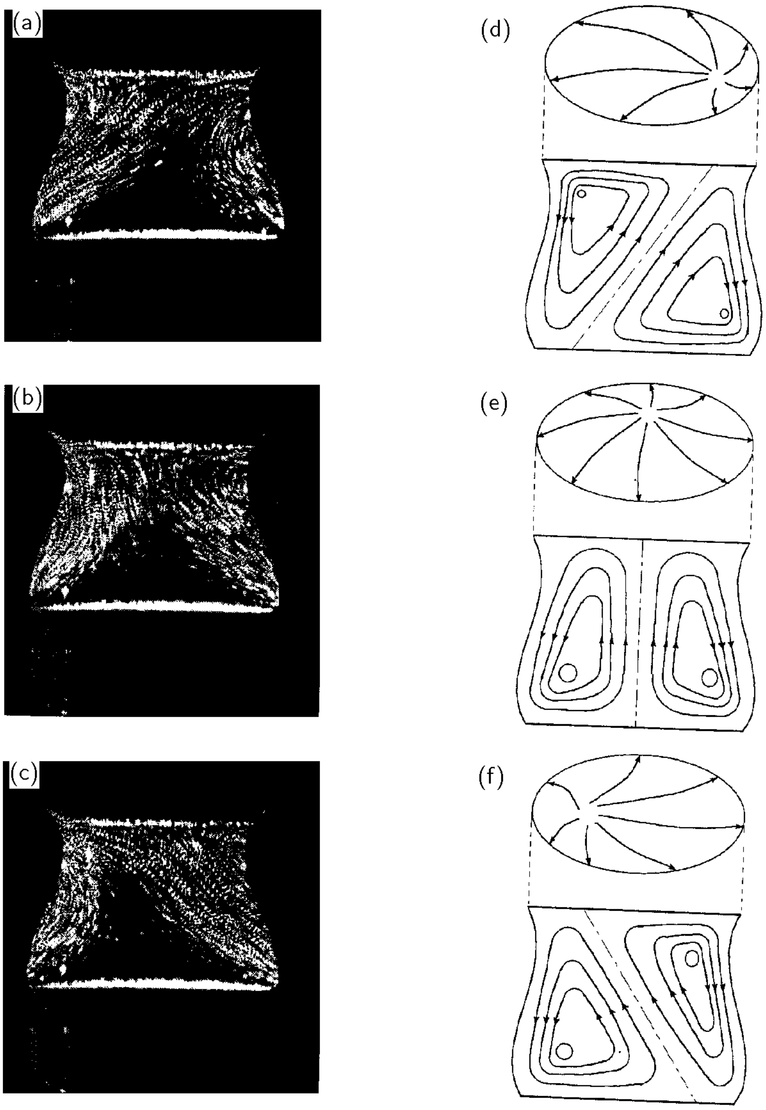


Fig.4 The oscillatory flow patterns in a periodic sequence (a)~(c) and qualitative picture of oscillatory thermocapillary convection with $m = 1$ (d)~(f)

pattern and the free surface deformation were measured, respectively. The experiments show that the bifurcation feature is sensitive to the geometrical parameters, such as the aspect ratio, non-dimensional volume $(d_{\min}/d_0)$. And there are different bifurcation features for different geometrical parameter ranges. The periodic sub-harmonic bifurcation is obtained from oscillatory TC with an applied temperature difference higher than the critical value. It is known that the very complicated oscillatory structures can be observed, as the driving force (i.e. the applied temperature difference ΔT) is gradually increased. The typical appearances, that might indicate chaos, are the quasi-periodic flow state, period-doubling phenomena and spatio-temporal intermittence, due to the nonlinearity of the system.

4 THE CRITICAL MARANGONI NUMBER

The critical value of the transition from steady (laminar) TC into unsteady (oscillatory) TC is determined generally by measuring the onset of the thermal oscillation, i.e. ΔT_C, by the method of inserting thermocouples into the flow field of the liquid bridge. It is well known that the critical Marangoni number Ma_C is directly proportional to the critical value of ΔT_C. The experimental studies pointed out that the critical Marangoni number Ma_C depends on a number of parameters, such as the geometric aspect ratio[5], the volume of the liquid bridge[10], the heating rate[11], the gravity level or g-jitter condition[12], and the influence of the inserted thermocouple was also investigated[13,14].

The coordinated measurement is one of the useful and important methods in the research of TC in the floating zone. The relationship of the temperature and free surface oscillation in the onset process was established experimentally[15]. The experimental result shows that the onset of the free surface oscillation comes earlier than that of the temperature oscillation, and the offset of the oscillation for a free surface comes later than that of the temperature at a proper heating. A typical experimental result is shown in Fig.5. Obviously, the critical Marangoni number defined by the critical temperature Ma_{CT} will be larger than that defined by the temperature of onset free surface oscillation Ma_{CA}. An empirical formula from the experiments for the liquid bridge of $d_{\min}/d_0 = 0.8$, at a normal heating rate is given as

$$Ma_{\mathrm{CT}} = (1 + 0.07)Ma_{\mathrm{CA}}$$

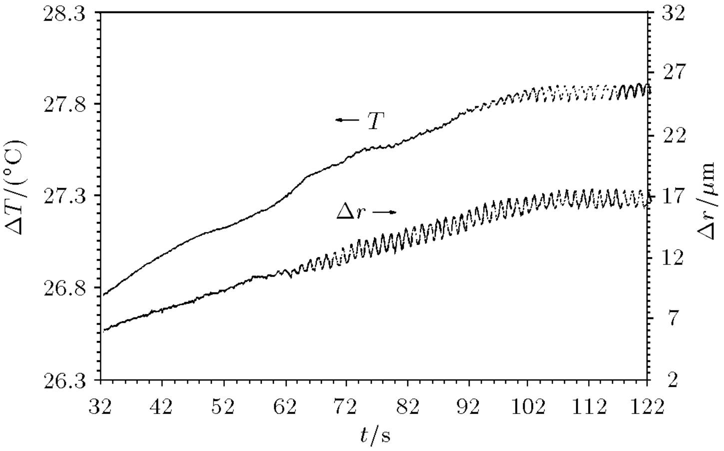


Fig.5 The onset processes of temperature (T) in flow field and free surface radii (Δr) of a liquid bridge

The critical Marangoni number defined by onset of temperature oscillatory has been studied for more than two decades. Many theoretical models were based on the assumption that the free surface was not deformed and not oscillated. However, the free surface oscillation is really an important physical parameter which is more sensitive as defined by the critical Marangoni number than that defined by the temperature oscillation. The temperature oscillation and free surface variation satisfy the perturbation condition, and the ratios of their oscillatory components to their mean components are $10^{-1} - 10^{-2}$ and 10^{-3} in order of magnitude, respectively. However, the ratio of velocity oscillation to its mean value is 1 in order of magnitude. So, the transition process is a strong non-linear problem, although the temperature and free surface are small in perturbation. It seems that after the free surface is firstly excited into an oscillation, there needs to be a relatively longer time delay for exciting the temperature oscillation in the liquid bridge, because of the small amplitude of the free surface oscillation in order of magnitude.

The oscillatory features of TC depend on the dissipative behavior of the system, which is related to the gravity level. The systems of a half-floating zone convection in 1-g and micro-g may have different dissipative features. Gravity effect may induce convection, and lead the system towards more disorder in comparison with the system in micro-g. This means that the critical Marangoni number Ma_{C} on the ground may probably be smaller than that in a micro-g condition. Some space experiments showed that the critical Marangoni number was at least one order of magnitude larger in the micro-g state than that on the 1-g condition[16]. It must be pointed out that the liquid bridge in a micro-g experiment can be of a relatively larger scale. Furthermore, the small bond number $B_0 \ll 1$ requires that the scale of the liquid bridge must be as small as a few millimeters for the experiments on the ground. It implied that the comparison on the critical values between the state of 1-g and micro-g will be better with a small liquid bridge of a few millimeters, which can be measured experimentally based on both states, 1-g and micro-g. Therefore, the experiments in the microgravity environment of the drop shaft were carried out[17,18]. It is known that the microgravity period time of the drop experiment is too short to study the onset process of the oscillation. The experiments were designed to check indirectly the critical state of the onset oscillation. The applied temperature difference in 1-g state, before the dropping on the ground, was adjusted to be very close to the critical value, either a bit larger or a bit smaller, and then the response in the microgravity environment was studied. The experimental result of the transition from the oscillation, close to the critical state in 1-g, into the non-oscillatory state in micro-g for a slender liquid bridge is shown in Fig.6. An opposite result was also obtained for a wide liquid bridge as shown in Fig.7, the transition from non-oscillation state, close to the critical state in 1-g, into the oscillatory state in the micro-g condition. The experimental results show that the microgravity response of the oscillation depends on the geometrical parameters, such as the volume of the liquid bridge, especially. A comparison is made for the liquid bridges with the same geometrical parameters, which satisfy the condition of small Bond number in both 1-g and micro-g conditions.

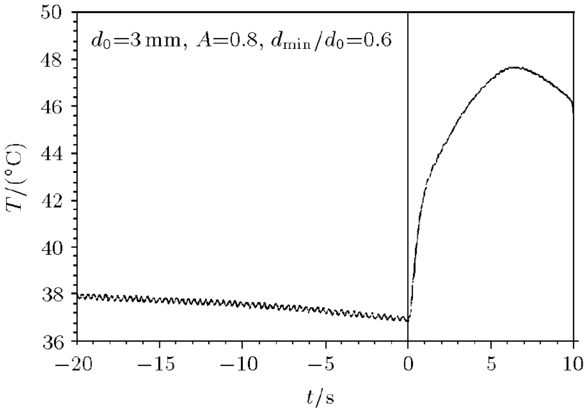


Fig.6 Near the critical point(ΔT is 1°C above the ΔT_C) in l-g condition (in the time of 20 s to 0) from oscillation transited into non-oscillation in micro-g condition (in the time of 0 to 10 s) for a slender liquid bridge

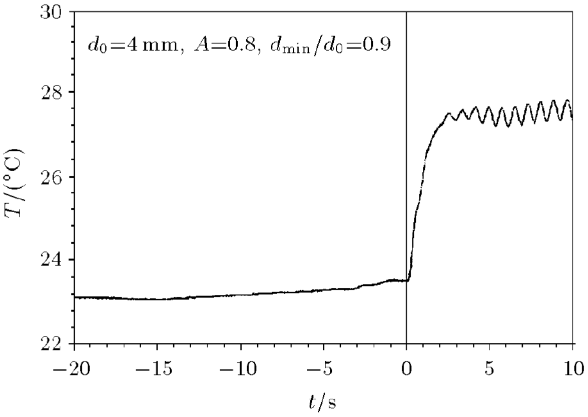


Fig.7 Near the critical point(ΔT is 1°C smaller than ΔT_C) in l-g condition (in the time of −20 s to 0) from non-oscillatory state transited into oscillation in micro-g condition (in the time of 0 to 10 s) for a wide liquid bridge

5 CONCLUSION

The development of spacecraft application in material preparation promotes the research on thermocapillary convection, in particular, on the onset of oscillation. The laboratory experiment is an alternative significant approach in revealing implied essentials and shedding light on mechanism of induced convection relevant to the crystal growth in semiconductor industry. The evolution of oscillatory TC is a complicated process associated with flow, heat transfer and free surface deformation. The critical parameters, the oscillatory modes and free surface deformation are important factors for understanding the mechanism of convection onset process. The coordinated experiment is proved to be a useful method in the study of thermocapillary convection in the half floating zone.

REFERENCES

1 Schwabe D, Scharmann A. In: Proc of 5th Euro Sym on Material Science under Microgravity (ESA SP-222) 1984. 281
2 Schwabe D, Scharmann A, Preisser F, et al. *J Crystal Growth*, 1978, 43: 305
3 Chun CH, Wuest W. A microgravity simulation of the Marangoni convection. Acta Astronaution, 1978, 5: 681
4 Merzkirch W. Flow Visualization. New York: Academic Press, 1987
5 Preisser F, Schwabe D, Scharmann A. Steady and thermocapillary convection is liquid columns with free cylinduical surface. *J Fluid Mechanics*, 1983, 126: 545
6 Lee J, Lee DJ, Lee JH. On the mechanism of oscillation in a simulated floating zone. *J Crystal Growth*, 1995, 152: 341
7 Shu JZ, Yao YL, Hu WR. Free surface vibration in oscillatory convection of half floating zone. *Science in China*, 1993, 36(3): 326
8 Shu JZ, Yao YL, Zhou R. Experiment study of free surface oscillation of a liquid birdge by optical diagnostics. *Microgravity Science & Technology*, 1994, 7(2): 83
9 Tang ZM, Hu WR, Xie JC, et al. Transition from steady to oscillatory convection with chaotic feature in thermoeapillay convection. *Adv Space Research*, 1995, 16(7): 67

10 Hu WR, Shu JZ, Zhou R, et al. Influence of liquid bridge volume on the onset of oscillation in floating zone convection, I. Experiment. *J Crystal Growth*, 1994, 142: 379

11 Xei JC, Hu WR. Influence of heating rate on onset of oscillation in liquid bridge of half floating zone. *J of Thermal Science*, 1994, 3(2): 122

12 Tang H, Cao ZH, Lui F, et al. Effect of g-jitter on the critical Marangoni number. *Microgravity Science & Technology,* 1994, 7(1): 137

13 Cao ZH, You XT, Tang ZM, et al. Experimental investigation of thermocapillary convection in half floating zone. *Adv Space Research*, 1991, 11(7): 229

14 Cao ZH, Xei JC, Tang ZM, et al. Experimental study on oscillatory thermocapillary convection. *Science in China*, 1992, A35(6): 725

15 Yao YL, Lui F, Hu WR. How to detemine critical Marangoni number in half floating zone convection. *Int J Heat Transfer*, 1996, 39(12): 2539

16 Monti R. On the onset of the oscillatory regimes in Marangoni flows. *Acta Astronautica*, 1987, 15: 557

17 Yao YL, Shu JZ, Tang ZM, et al. Handware development and ground-based studies for drop sheft experiment on oscillatory convection in half floating zone. *Adv Space Research*, 1995, 16(7): 215

18 Yao YL, Shu JZ, Xei JC, et al. Transition of oscillatory floating half zone convection from Earth's gravity to microgravity. *Int J Heat Transfer*, 1997, 40(11): 2517