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SPACE EXPERIMENTS OF CONVECTION IN A SYSTEM OF TWO IMMISCIBLE LIQUID LAYERS

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ABSTRACT

The space experiments of the fluid physics were performed on board the Chinese scientific satellite *SJ-5* in the Mai of 1999. A special system of two-layer liquids such as FC-70 liquid and paraffin were used successfully in space where the paraffin was melted in the space. Two different test-cells are subjected to a temperature gradient perpendicular to or parallel to the interface for studying the Marangoni convection and thermocapillary convection, respectively. The temperature data and the PIV pictures of flow motion in the system were obtained quite clear, and each experimental case including the heating rate was adjusted by the tele-operation. The preliminary results of microgravity experiment are presented for the thermocapillary convective flows and the melting process of solid paraffin of the system. A new model of multilayer fluids related to the space experiment is suggested for considering the effect of gas bubble on the Marangoni and thermocapillary convection.

1. Introduction

In the multi-layer fluid systems, the Marangoni convection is driven by a temperature gradient perpendicular to the interface. On the other hand, the thermocapillary convection is driven by the gradient of interfacial-tension induced by the temperature gradient on the interface. The ground-based experiments of the Marangoni convection and the thermocapillary convection are affected obviously by the buoyancy effect, and the studies of the Marangoni convection related to the buoyancy effect on the ground are concentrated in the Marangoni-Benard instability.

The space experiments of the fluid physics were performed on board the Chineses scientific satellite *SJ-5* in the Mai of 1999. The purposes of this Multi-layer Experiment Mission in space were to study both the thermocapillary convection and the Marangoni convection in a system of two immiscible liquid layers in different microgravity environment 10^{-5}g – 10^{-3}g. The buoyancy effect is difficult in general to eliminate in the ground-based experiments of investigation of Marangoni convection and thermocapillary convection. The microgravity environment gives an opportunity to study the pure thermocapillary and Marangoni convections. The convection in the new system is also important for development of new theories and mechanisms in the fluid mechanics. Space experiments on the subject have obtained progress and the onset of Marangoni convection in two liquid layers was observed in space [1]. Recently, the investigation of thermocapillary convection in a 3 liquid-layer system is presented [2]. Both steady Marangoni convection and thermocapillary convection in the system were observed successfully in the space experiments. The non-linear and time dependent convective feature of thermocapillary convection in multi-layer fluids subjected to a temperature gradient parallel to the interfaces needs specially to be studied theoretically and experimentally [3].

The process of heat transfer in imcrogravity is dominated generally by the pure heat conduction, diffusion and mass transfer without the buoyancy convection. The melting process of the paraffin wax from solid state was observed one time in space during the SJ-5 experiment. This process under the microgravity environment is a typical heat transfer problem. From the point of science, it is very valuable to analyze the pure conductivity melting process and compare the space experiment with the theoretical calculation [4].

In the present paper, the space experiment process and some techniques realized in the development of experimental facility are described briefly. The preliminary results of the experiments in moicrogravity devoted to the Marangoni and thermocapillary convection in both heating cases are presented. The melting process of solid paraffin of the system in microgravity is analyzed in comparison with the numerical simulation. A new model system of two-layer liquids with the effect of the bubble observed in the space experiment is discussed and the more details study will be presented in the other paper.

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2. Experimental Facility

The experiment facility consists of two rectangular tanks for observing the thermocapillary convection in *Test-cell A* and the Marangoni convection in *Test-cell B* (see Fig. 1). The internal dimensions of these experimental tanks are respectively 48×32×20mm^3 (TC *B*) where the applied temperature difference ΔT is perpendicular to the interface, and 35×32×20mm^3 (TC *A*) where the applied temperature difference ΔT is parallel to the interface.

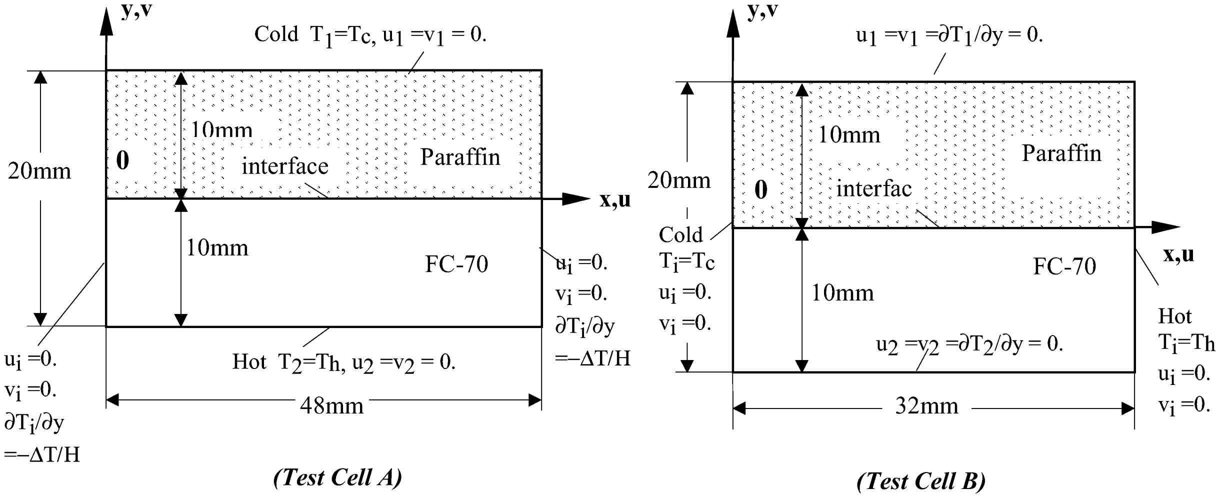
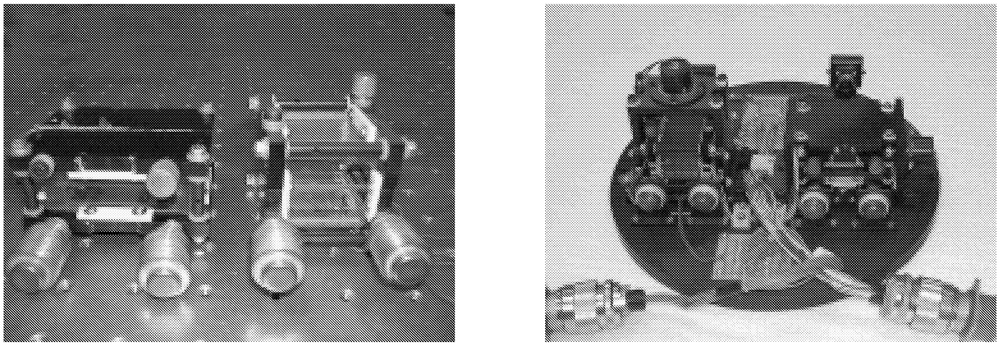


Figure 1. Schematic diagrams of two test cavities



(a) (b)

Figure 2. Experimental facility (a) before assemble: Test-cell *A* (left) and Test-cell *B* (right); (b) integration of the set up.

The fluid system was consisted of a FC-70 liquid layer and a layer of paraffin. The physical properties of the two liquids and the solid paraffin are listed in Tab. 1. The ratios of the paraffin liquid to Fc-70 are respectively ρ^*=0.4313, ν^*=0.9584, χ^*=2.2072 and α^*=2.405. The paraffin wax of the melting point adjusted to 28°C, which is higher than the ambient temperature of the satellite. The paraffin layer had been kept in solid before the satellite was launched in the orbit and then was melted in the space to form a system of two immiscible liquid layers. In order to prevent the creeping of interface along the quartz wall, the side quartz walls of the tanks were manufactured with a round cave of 1mm in width and 1mm in depth. FC-725 is coated in the groove due to it is wetted better by the Fluorinert FC-70 than by the paraffin. These approaches are successful in the microgravity experiments for both test tanks.

The tracer particles were mixed into fluids respectively in two layers for flow visualization and were illuminated by a laser light sheet of 1mm in thickness. The images of flow patterns were recorded by CCD camera in 512×512×8bit. The thermal data were measured by using six Peltier elements inside each test cell. The external temperature difference was applied gradually before two hours when the satellite had been entry the mainland of China. During the experimental run, the image data are transmitted to the ground laboratory in real time for every 2 minutes, and then the temperature data are downloaded alternately for 2 seconds and packed into image data.

Table 1. Physical properties of the fluids used in the SJ-5 experiment

	Melting Paraffin	Fluorinert (FC-70)	Solid Paraffin	Ratio of Paraffin to FC70
Density (kg/m^3)	8.324×10^2	1.93×10^3	8.324×10^2	0.4313
Specific heat (J/kg°K)	2.2×10^3	1.045×10^3	2.2×10^3	2.102
Thermal cond. (W/m°K)	1.523×10^{-1}	6.9×10^{-2}	2.879×10^{-1}	2.2072
Thermal Diffusivity (m^2/s)	8.3698×10^{-8}	3.48×10^{-8}		2.405
Coef. expansion (°K^{-1})	7.4743×10^{-4}	1.0×10^{-3}		0.7474
Dynamic viscosity (kg/ms)	1.117×10^{-2}	2.702×10^{-2}		0.4134
Kinetic viscosity (m^2/s)	1.3418×10^{-5}	1.4×10^{-5}		0.9584
Interface tension (N/m)	2.8574×10^{-2}	1.8×10^{-2}		
Int. Ten. gradient (N/m°K)	-5.37×10^{-5}	-6.7×10^{-5}		-3.63×10^{-5}
Melting point (°C)			28	
Latent heat (w·s/kg)			1.6×10^5	
Prandtl number	160	402.3		0.3977

3. Experimental Operations

The satellite provided two different gravity levels, five days in 10^{-5}g and four days in 10^{-3}g in the self-rotating state of the satellite. The facility was mainly controlled and the heating rate was adjusted by the tele-operation technique. The experiments obtained about twelve thousand frames of the PIV flow images and the related temperature data. The space experiment started when the satellite passed over the mainland of China, and the period is roughly 10 minutes. The heating process started at the moment 2 hours before the experiment had started.

Tele-operation technique plays important role in the space experiment to operate the experimental process [5], especially for the non-recoverable spacecraft such as the scientific satellite SJ-5. The information of the experimental process is directly down link to the Ground Station of the laboratory and to other domestic stations which transmit the information to the laboratory via the Internet. Principal investigators (PI) in the laboratory make decisions to interfere the experimental process in the real time when the satellite passes over the mainland of China. The experimental procedure was responded to the commands via teleoperation.

4. Theoretical Preparation and Numerical Methods

Linear instability

As the theoretic preparations, the linear instability analyses by using the means of small perturbation method were performed and developed to predict the onset of Marangoni convection and the onset of thermocapillary convection in the two-layer fluids in space. In the last case, an asymptotic solution of convection flow in an infinite cavity ($A\rightarrow\infty$) as the basic return-flow solution of two-layer fluids is used to give the linear instability analysis of thermocapillary convection between two parallel planes. The detailed methods and analysis results are presented in our previous paper [6-7].

Melting problem

The melting problem is solved in a 2-D rectangular domain ($0\le x\le 48$, $-10\le y\le 10$) in test cell *A* (see Fig.1) where the x-axis is perpendicular to the applied temperature gradient, and the origin position of the interface locates at the center of test container. The simulation domains include all of the liquid paraffin (i=1), the liquid FC-70 (i=2), solid pararffin (i=3) and the walls of the K-9 glass (i=4) by a finite difference method with the grids moving to meet the moving melting interfaces and two layers D-R scheme. The heat transfer equations in each of the four kinds of regions will be solved, and then matched by the conditions connecting with the regions. The thermal conductivity condition would be satisfied at the liquid-liquid interface and the lateral sides. At both the upper and lower plates (y=10 and y=-10mm) the constant heat power is assumed to be subjected

$$\lambda_i \frac{\partial T_i}{\partial y} = \frac{Q}{S}, \qquad (i = 1,2,3)$$

where Q (10 watts) and S (32×48 mm^2) are respectively the power on each plane and the area of each plate.

At the melting interfaces (y= $b_1(x, t)$ and $b_2(x, t)$), the latent heat during the melt of solid paraffin is considered and

$$T_i = T_m \qquad (i = 1,2)$$

where T_m is the melting point of the solid paraffin; $b_1(x, t)$ and $b_2(x, t)$ are the two melting interfaces.

The initial constant temperature T_{ini} for all calculating regions is the environmental temperature in the beginning of the heating process.

2D simulation of convection

Convective structures of the liquids system are presented numerically for both test cells in microgravity environment, by a finite difference method in two dimensions. The details numerical method used and the boundary conditions can to be found in [8].

5. Main Results of Microgravity experiment

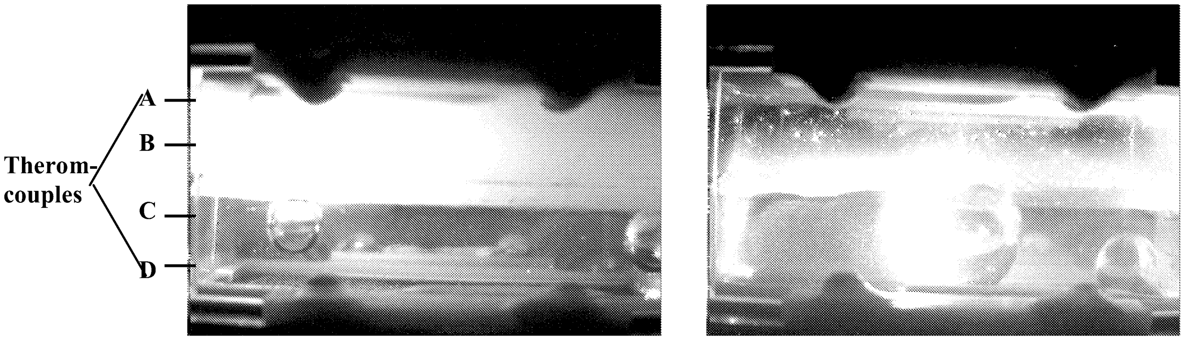
5.1 Melting Process of Solid Paraffin

The whole melting process of solid paraffin in space were observed successfully in the test cell *A* while the experimental system of two layers was heated from both upper and lower heating plates. Figure 6(a) shows a photograph of the solid paraffin layer (upper) and Fluorinert FC70 liquid layer (lower) in space before the beginning of experiment. When a constant temperature higher than the paraffin melting point T_m=28 °C were applied to the upper and lower plates, the solid paraffin layer started melt toward the inside of paraffin layer from both sides and this layer became transparent continuity (see Fig. 6(b)). A clear separated interface between paraffin and FC70 liquids formed at the end of the melting process.

The melting process of paraffin in microgravity is simulated numerically and is compared with the space experiment for different thermal differences. The variation of temperature inside the paraffin during melting process are calculated for three different thermal cases:

(I) T_1=32.0°C, T_2=32.0°C, T_{ini}=12.6°C;
(II) T_1=40°C, T_2=50°C, T_{ini}=13.6°C;
(III) T_1=83.8°C, T_2=48.6°C, T_{ini}=19°C.

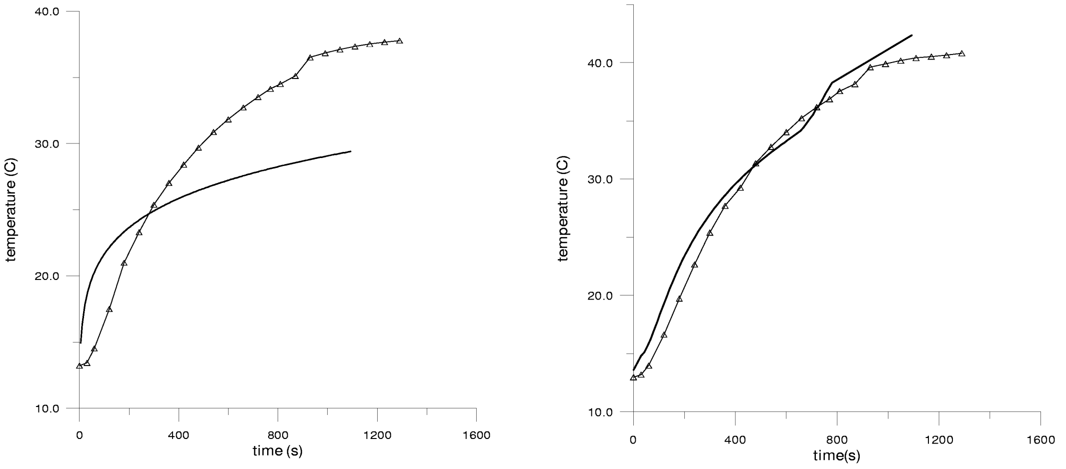
The numerical simulations show different time to melt all of the solid paraffin in above different heating case. In the case (I), it takes 2332 seconds to melt all of the solid paraffin, and 1094 sec for case (II), 713 sec for case (III), respectively. In the space experiment, the test heating process started before 2 hours of the starting of the experiment. So, both experimental process and numerical results show the pre-heating period of the system is enough for the solid paraffin to be wholly melted.



(a) (b)

Figure 3. Images of the melting process of the solid paraffin in test cell *A*: (a) before the beginning; (b) in the middle.

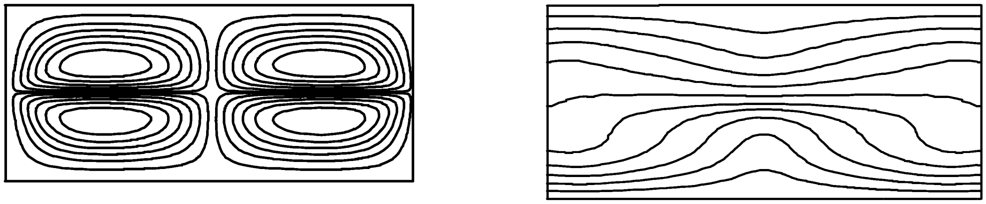
The temperature inside of the liquids are measured by four thermocouples A, B, C, and D shown in Fig. 3(a) for test cell A. The comparisons of the temperature distributions at the positions of four thermocouples A and D are given in Fig. 4 for the heating case (II). The temperature data given by the space experiment (triangle symbols) and the numerical simulations (lines) are plotted together. The temperature variations during the melting process between the numerical simulation and the space experiment are basically similar. The differences between the temperatures of the space experiment and the numerical simulation is lower than 0.3 $|T_{exp}-T_{num}|/(T_{exp}+T_{num})$. Compared with the thermocouples A and D, the temperature of the space experiment at the position of thermistor A is higher than that of the numerical results when t>300s. The reason is that some bubbles emerged in liquids in the experiment after the launch induced the local thermocapillary convection to speed up the heat transfer during the melting process.



(a) (b)

Figure 4. The variations of temperature at the positions of the thermocouples A (a) and D (d) given by space experiment (lines triangular) and the numerical simulation (solid lines), where T_{up}=40.0°C, T_{down}=50.0°C, T_{ini}=13.6°C.

5.2 Marangoni Convection in Test Cell *A*



(a) (b)

Figure 5 Analytical prediction of Marangoni convection in test cell *A* without the effect of bubble at ΔT=23°C: (a) streamlines ; (b)isotherms

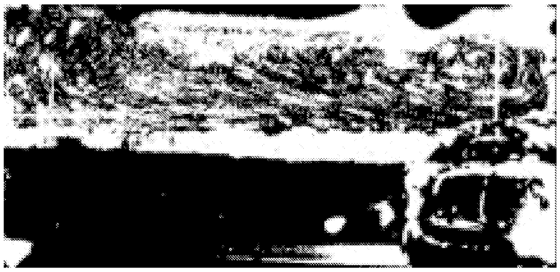


Figure 6 Photographs of streamlines of "Marangoni convection" observed in space in test cell *A* with the effect of bubble at ΔT=23°C for heating from below.

In test A subjected to temperature gradient perpendicular to the interface, the linear stability analysis indicates that when ΔT≥ 2.325°C and heated from FC-70 liquid layer (below), the Marangoni convection appears in the system of Paraffin and FC-70 liquids in microgravity condition. Figure 5 shows respectively the structure of Marangoni convection and the profiles of the thermal field given by the numerical simulation for

$\Delta T=23°C$ and Ma=. There is one pair of the counter-rotating convective cells with the same size in each layer of the Paraffin-FC70 liquids. The corresponding isotherms (see Fig. 3(b)) indicate that the heat is transported from below to the interface in the center region of the FC-70 liquid layer, and the colder liquid in paraffin layer move down to the interface.

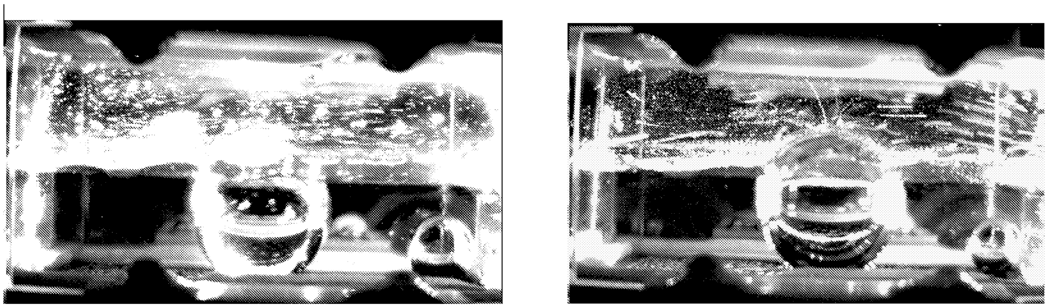
Table 2. Experimental results of Marangoni convection in test cell A at $\Delta T=23°C$

Location (x, y) ($\times 10^{-3}$m)	(2.1 , 6.9)	(21.5 , 2.0)	(25.1, 2.4)
Velocity Components	Exp. Results	Exp. Results	Exp. Results
U ($\times 10^{-6}$m/s)	18.7	-46.7	-54.5
V ($\times 10^{-6}$m/s)	27.5	0	11.5

In space experiment at the temperature difference $\Delta T=23$℃, the observed convective flow in the system is shown in Figure 6 obtained by the treatment of long time exposure photography. A bubble of about 10mm diameter appeared obviously in the right lower corner of the cavity, due to the litter escape of fluids out of the test container. Table 2 lists the amplitude of the velocity measured in experiment at three different positions in test cell *A*. The video picture of convective flow traces shows that only one typical thermocapillary convective cell appeared in full part of the (upper) Paraffin liquid layer. The flow pattern in the lower liquid layer is not visible because there are few trace particles floating inside the FC-70 liquid, but the convective structure of the liquid layer could be deduced according to the velocity continuity of liquids along the interface. The two convective cells of each layer liquid in the theoretic prediction of Marangoni convection of ideal system (see Fig.5 (a)) are already replaced by a full convective vortex in the upper layer and some different vortex in the lower layer. It is notified that due to the appearance of the bubble and the stronger thermocapillary driven-force along the interfaces between the gas bubble and FC-70 or Paraffin, the onset characteristic and symmetrical pattern of Marangoni convection in the two-layer liquids are no longer existent.

The approximate numerical simulation of the Paraffin-FC-70 liquids in considering the effect of bubble around which the liquid-gas interfaces appear [9] show an agreement between numerical and experimental results on the flow pattern is good.

The thermocapillary convections in test cell *A* when the bubble is in the center of cavity are shown in Figure 7 for different experimental cases: (a) $\Delta T=15°C$ for heating from the FC-70 liquid side and (b) $\Delta T=40°C$ for heating from the top of paraffin liquid. In both cases, the multiple convective cells of Marangoni convection are not observed experimentally. Instead of that, the typical convective pattern of thermocapillary convection similar to that in test call *B* is represented due to the stronger thermocapillary effect around the bubble. The 3D flow can be found obviously in high ΔT in Fig. 7(b).

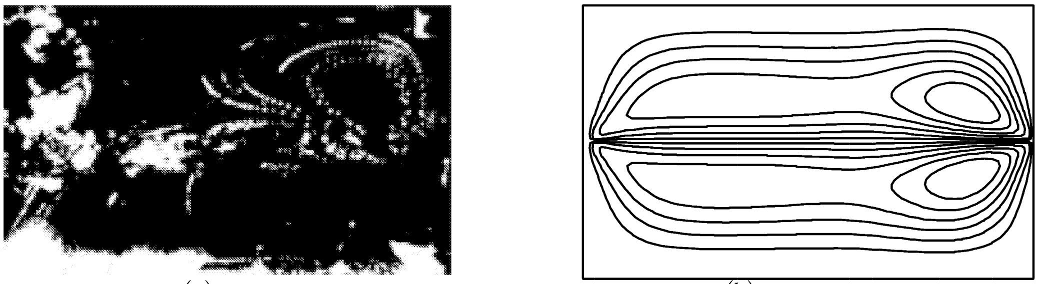


(a) (b)

Figure 7 Photographys by long time exposure (10 mimuts) for Marangoni convection in test cell *A* when the bubble is at the centre of cavity in Paraffin layer at (a) $\Delta T=15°C$ for heating from below and (b) $\Delta T=40°C$ for heating from top.

5.3 Thermocapillary Convection in Test Cell *B*

One of the observed thermocapillary convection of the Paraffin - FC70 system in test cell B is shown in Fig. 8(a) where the applied external temperature gradient is parallel to the interface in microgravity. In this case, the applied temperature difference between two lateral sides (right side hotter than the left one) is $\Delta T=43$℃, and the video pictures show the thermocapillary convection observed in space is stead. The maximum of the amplitude of velocity measured is about $480\mu ms^{-1}$in the location at x=30mm and y=5.7mm. Obviously, one convective cell appears in the paraffin liquid layer and the center of vortex is nearthe right hot sidewall. In the lower FC70 liquid layer some traces of liquid movement distinguished near the liquid interface show there is a similar convective vortex in opposition to that in the upper layer. The typical thermocapillary convection in microgravity observed in the experiment has the same profile in comparison with the numerical results shown in Fig.8 (b).



(a) (b)

Figure 8. Thermocapillary convection in test cell *B* heated at the right side wall:
(a) Photographs of streamlines of two-layer flow in space；(b) Simulating streamlines without the bubble.

6. Conclusion

The thermocapillary convection of a two liquid-layer system in both heating cases are observed during the nine days of space experiment onboard the Chinese satellite. The reformed two-liquid system of Paraffin and Fluorinet FC70 liquid was used successfully in the space experiment by melting solid paraffin in the orbit. Some melting process of the solid paraffin in space are analyzed and compared with the theoretical results. The time of full melting process of solid paraffin in this solid-liquid system is less than 40 minutes in microgravity when external temperature difference $\Delta T \geq 32°C$.

The flow patterns and quantitative velocity on the thermocapillary convection in the two-liquid layers have been obtained in microgravity condition 10^{-5} and $10^{-3}g$. The typical Marangoni convection patterns and its onset predicted theoretically in test cell *A* did not appeared, and the steady thermocapillary convective cell dominated due to the appearance of a visible bubble in the Fluorinert FC70 liquid layer of the system. Both experimental results and numerical simulations show that the intensity of Marangoni convection in test cell *A* with the effect of bubble is higher than that without the bubble.

In test cell *B* subjected to a temperature parallel to the liquid-liquid interface, the thermocapillary convections observed are similar to those obtained by numerical simulations.

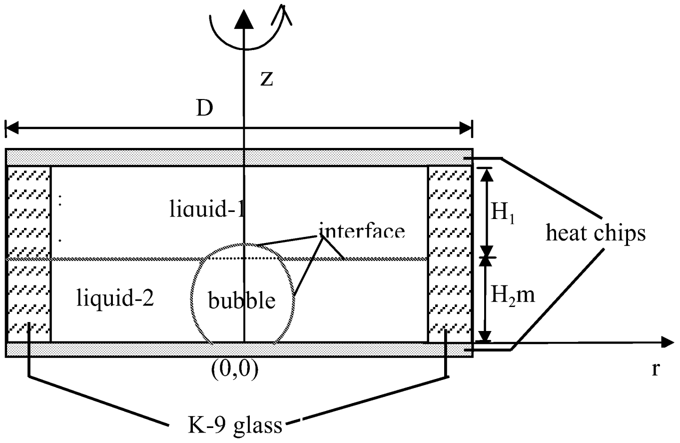


Figure 9. A new model of thermocapillary convection when the bubble appears in the two-liquid layers.

A new model related to the space experiment is being simulated numerically for studying the Marangoni convection and thermocapillary convection with the effect of bubble (see Fig. 9). The new model of multilayer fluids concerning both liquid-liquid interface and liquid-gas free surface due to the appearance of the bubble is necessary to be studied for obtaining more understands of the combined effect of multi and complex form interfaces on the Marangoni and thermocapillary convection.

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