Space experiments of thermocapillary convection in two-liquid layers

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Received August 1, 2001

Abstract In 1999, the space experiments on the Marangoni convection and thermocapillary convection in a system of two immiscible liquid layers in microgravity environment were conducted on board the Chinese scientific satellite SJ-5. A new system of two-layer liquids such as FC-70 liquid and paraffin was used successfully, with the paraffin melted in the space. Two different test-cells are subjected to a temperature gradient perpendicular or parallel to the interface to study the Marangoni convection and thermocapillary convection, respectively. The experimental data obtained in the first Chinese space experiment of fluid are presented. Two-dimensional numerical simulations of thermocapillary convections are carried out using SIMPLEC method .A reasonable agreement between the experimental investigation and the numerical results is obtained.

Keywords: space experiment, microgravity fluids, two-layer liquids, Marangoni convection, thermocapillary convection.

The study of convective flow and heat transfer in a system of immiscible liquid layers has numerous engineering applications. In microgravity environment, where the buoyancy is greatly reduced, the convection induced by the Marangoni effect, i.e. by a surface stress due to the variation of surface tension with temperature along an interface or a surface, is of major importance[1]. In the process of crystal growth, encapsulation of an electric melt is used to control melt stoichiometry when the melt contains a volatile component[2]. In addition, encapsulation can be useful for a better control of heat transfer as shown by Jonhson[3]. It also has the advantage of reducing or even eliminating the convective flow in the melt, hence drastically reducing the unwanted inhomogeneities in solidifying materials. The liquid encapsulated floating zone technique for space processing of highly pure semiconductors has been proposed by Barocela and Jalilevand in 1987[4].

The flow driven by a temperature gradient perpendicular to the interface is called Marangoni convection. On the other hand, thermocapillary convection is driven by the gradient of interfacial tension induced by the temperature gradient on the interface. In order to realize fluid encapsulated crystal growth in space, the convection in a two-liquid-layer system has been studied experimentally and theoretically. Liu and Roux have carried out a numerical investigation into the influence of viscosity ratio and diffusivity ratio on the flow of the melt[5]. Some instability behavior and the instability critical parameters of Marangoni convection and thermocapillary convection in a system of two-layer liquids were obtained by Liu using linear stability analyses[6]. In 1994 and 1996, Legros et al. performed the space experiments of thermocapillary convection in a system of multilayer fluids on board the space shuttle. They proved that a free interface would possibly lead to the onset of convection in microgravity environment[7,8]. In China, theoretical analyses and ground-based experiments had been completed before space experiments. In 1999 the space experiments of two-layer liquids were performed on board the Chinese satellite SJ-5[9,10]. A reformed two-liquid system of paraffin and Fluorinert FC70 liquids was used in the space experiments by melting solid paraffin in the orbit. The melting process of paraffin wax from solid state under the microgravity environment was observed and compared with the theoretical results[11]. Both steady Marangoni convection and thermocapillary convection were observed in the space experiments.

In this paper, the space experiment process is described briefly. The preliminary results of the experiments in microgravity on Marangoni and thermocapillary convection in both heating cases are presented. A new model system of two-layer liquids with the effect of the bubble observed in the space experiments is presented. Numerical simulation of the model system is completed using SIMPLEC method. The numerical velocity fields are basically similar to the experimental results for Marangoni and thermocapillary convection.

1 Physical and mathematical models

The experimental facility consists of two rectangular tanks for observation, the Marangoni convection in test-cell A and the thermocapillary convection in test-cell B (fig. 1). The applied temperature difference $\Delta T(=T_h-T_c)$ is perpendicular to the interface in test-cell A, and parallel to the interface in test-cell B.

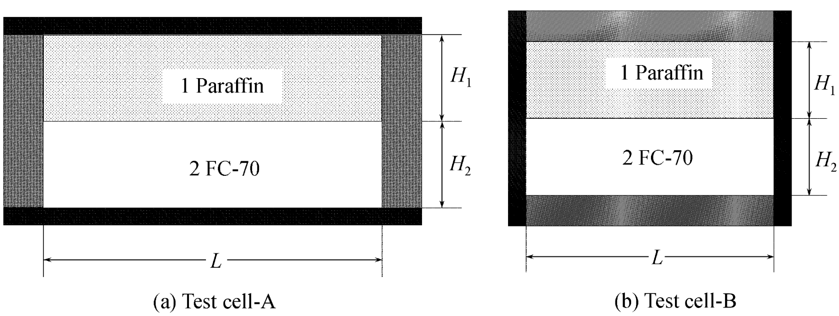

Fig. 1. Schematic diagrams of two cavities: (a) temperature gradient perpendicular to interface; (b) temperature gradient parallel to interface.

In each cavity, a bubble of about 10 mm diameter appears. The interfaces between the bubbles and the fluids are approximated as flat in the models of computation (fig. 2). This is a simplified numerical model that approximates the position and shape of the bubbles formed in the space experiment, where the thermocapillary effect due to the surface tension gradient at the interfaces can be simulated. In this paper, some assumptions are as follows: (i) the two different fluids are perfectly immiscible; (ii) the interfaces are not deformable; (iii) the simulation of convection is in two dimensions; (iv) the fluids are incompressible and meet Boussinesq approximation.

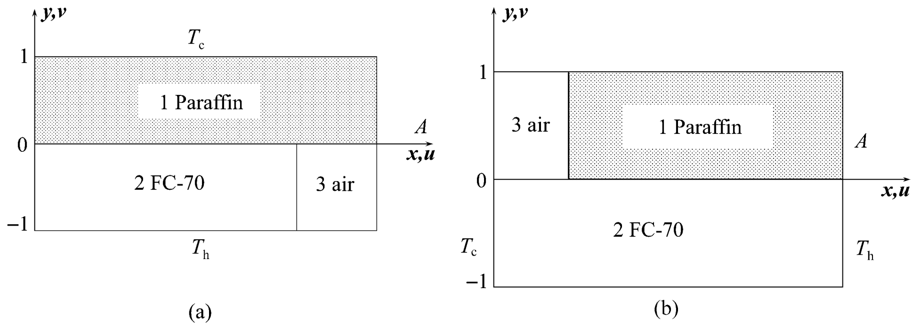

Fig. 2. Configuration of numerical simulation. (a) A, temperature gradient perpendicular to interface; (b) B, temperature gradient parallel to interface.

In microgravity environment, the flow is governed by the following dimensionless equations written in the form of primitive dependent variables:

$$\nabla \bullet V_i = 0, \tag{1}$$

$$V_i \bullet \nabla V_i = -C^{\rho_i} \nabla \rho_i + C^{\nu_i} \nabla^2 V, \tag{2}$$

$$V_i \bullet \nabla \theta_i = C_i^{\alpha} \nabla^2 \theta_i, \tag{3}$$

where i =1 represents the upside liquid; i =2, the downside liquid; and i = 3, the air. $V_i=(u_i, v_i, 0)$ is the dimensionless velocity, $\theta_i = (T_i - T_c)L/\Delta TH_2$, dimensionless temperature, and p_i, dimensionless pressure. We denote by α_2/H_2, H_2^2/α_2, H_2, $\Delta TH_2/L$ and $\alpha^2{}_2\rho_2/H^2{}_2$ the scales for time, velocity, length, temperature, and pressure, respectively. Then the 'constants' on the right-hand side of dimensionless equations (1)—(3) are

$$C_1^{\rho} = \rho_2/\rho_1, C_1^{\nu} = Pr\nu_1/\nu_2, C_1^{\alpha} = \alpha_1/\alpha_2,$$
$$C_2^{\rho} = 1, \qquad C_2^{\nu} = Pr, \qquad C_2^{\alpha} = 1,$$
$$C_3^{\rho} = \rho_2/\rho_3, C_3^{\nu} = Pr\nu_3/\nu_2, C_3^{\alpha} = \alpha_3/\alpha_2,$$

where ρ_i, ν_i and α_i are the density, the kinematic viscosity and the thermal diffusivity of fluid i, respectively. $Pr=\nu_2/\alpha_2$ is the Prandtl number of liquid 2.

On the solid walls of cavity, we take a no-slip boundary condition. At the interfaces, the normal components of velocities are vanishing and the continuity conditions of temperature, heat flux, tangential components of velocities and stresses are satisfied. The heating side-walls of each test-cell are maintained at constant temperatures T_c and T_h, $T_c<T_h$. We assume that other side-walls are adiabatic. The surface tension is assumed to vary linearly with temperature. At the interfaces, for liquid-liquid and liquid-gas, we have $\sigma = \sigma_0 - \gamma(T - T_0)$, with $T_0 = (T_c + T_h)/2$ and $\gamma = -\partial\sigma/\partial T$, which is the temperature coefficient of surface tension. Then, these boundary conditions can be expressed as follows:

(i) On the two vertical walls (x=0 and x=A)

$$u_i = v_i = 0. \tag{4}$$

$$\partial\theta_i/\partial x = 0 \quad \text{test-cell A,} \tag{5a}$$

$$\theta_i = 0 \quad (x = 0), \quad \theta_i = A \quad (x = A) \quad \text{test-cell B.} \tag{5b}$$

(ii) On the horizontal side walls:(y=–1 and y=1)

$$u_i = v_i = 0, \tag{6}$$

$$\theta_i = A \quad (y = -1), \quad \theta_i = 0 \ (y = 1) \quad \text{test-cell A,} \tag{7a}$$

$$\partial\theta_i/\partial y = 0 \quad \text{test-cell B.} \tag{7b}$$

(iii) At the interfaces

The equations of conservation satisfied at the interfaces 1-2, 1-3, and 2-3 can be derived with the same method. So here we give the relations satisfied at the interface 1-2 (y = 0) only:

$$u_1 = u_2, \tag{8}$$

$$v_1 = v_2 = 0, \tag{9}$$

$$\frac{\partial u_2}{\partial y} - \frac{\mu_1}{\mu_2}\frac{\partial u_1}{\partial y} = -Ma\frac{\partial\theta_2}{\partial x}, \tag{10}$$

$$\frac{\chi_1}{\chi_2}\frac{\partial\theta_1}{\partial y} = \frac{\partial\theta_2}{\partial y}, \tag{11}$$

$$\theta_1 = \theta_2, \tag{12}$$

where χ_1/χ_2 is the ratio of thermal conductivities of liquid-1 and liquid-2. The Marangoni number in eq. (10) is defined as

$$Ma = \gamma\delta T H_2^2/\mu_2\alpha_2 L .$$

Eqs. (8)—(12) represent the continuity of tangential velocity, kinematic condition, the lateral stress balance, continuity of heat flux, and the continuity of temperature, respectively.

2 Experimental and numerical methods

2.1 Experimental facility

Two experimental tanks have been designed according to the physical model and theoretical analyses. The internal dimensions of the experimental tanks are 48×32×20 mm^3 (TC-A), 35×32×20 mm^3(TC-B), respectively. They are sealed with the fluids consisting of two immiscible liquid layers such as the melt Paraffin (mixture of paraffin oil 7160 and paraffin wax of Merck) and Flourinert liquid (FC-70), and each layer is 10 mm thick[9]. In test-cell A, a temperature difference perpendicular to the interface is used to observe Marangoni convection, and in test-cell B, the temperature gradient is parallel to the interface in order to observe thermocapillary convection.

The experimental setup consists of the fluid tanks, the optical diagnostic system, the temperature-controlling system, and the data acquisition system. The flow visualization is realized using PIV method. The tracer particles are about 100 μm in diameter and illuminated by a laser light sheet 1 mm in thickness oriented parallel to the longest side of test container. The images of flow pattern are recorded using a CCD camera in 512×512×8 bit and transmitted to the ground laboratory in real time. Because of the sedimentation of the most part of tracer particles in FC-70, the images visualize mainly the flow patterns of paraffin liquid in the upper layer. Six Peltier elements (thermometers) inside one lateral sidewall in TC-A and inside the lower plate in TC-B are used to measure the temperature profile in the direction of the applied thermal gradient of liquids including the temperature difference ΔT between the heating plates.

The fluid system consists of the FC-70 liquid layer and the layer of paraffin wax. The paraffin layer had been kept solid before the satellite was launched in the orbit and then was melted in the space to form a system of two immisible liquid layers. The ratios of physical properties of paraffin liquid to FC-70 are ρ_1/ρ_2=0.431, ν_1/ν_2=0.958, χ_1/χ_2=2.207, and α_1/α_2=2.405. Their Prandtl numbers are Pr_1=160.2, and Pr_2=402.3 respectively. The paraffin mixture of the melting point was adjusted to 28℃, higher than the ambient temperature inside the satellite. The temperature coefficient of surface tension between paraffin and FC-70 liquids is $\gamma = -\partial\sigma/\partial T = 3.63\times10^{-5}$(N/m°K). It is an important property that causes the thermocapillary convection. While this parameter increases, the thermocapillary convection becomes stronger under the same temperature difference.

2.2 Space experiment

The satellite provided two different gravity levels, 1×10^{-4}g for five days and 1×10^{-2}g in self-rotating state of the satellite for four days. The space experiments obtained about twelve thousand frames of flow images and the related temperature data. The space experiment lasted about 12 min each time when the satellite passed over the mainland of China. The heating process had started two hours prior to the experiment. The information of the experimental process was directly downlinked to the ground station of the laboratory and the experimental procedure responded to the commands via tele-operation.

In this work, all the experimental results were acquired under the microgravity environment of 1×10^{-4}g.

2.3 Numerical methods

Numerical simulation was carried out for both test-cells in microgravity environment, by a finite difference method in two dimensions. SIMPLEC method was used in the solution of nonlinear partial differential equations. The details can be found in ref. [12]. The equations are discretized on a staggered grid using upwind difference for convective term and central difference for diffusive terms. (31+31)×121 meshes were used in the work.

3 Comparative of experimental and numerical results

3.1 Marangoni convection (Test-cell A)

Test-cell A was subjected to a temperature gradient perpendicular to the interface, and heated from FC-70 liquid layer (below). Fig. 3 shows numerically the structure of Marangoni convection and the profile of the thermal field in the respective theoretical model (without the effect of gas bubble) for ΔT=23℃ and Ma=1841. There is one pair of counter-rotating convective cells with the same size in each layer of the Paraffin-FC-70 liquids. The corresponding isotherms indicate that in the center region of the FC-70 liquid layer the heat is transported from below to the interface, and the colder liquid in Paraffin liquid layer moves down to the interface.

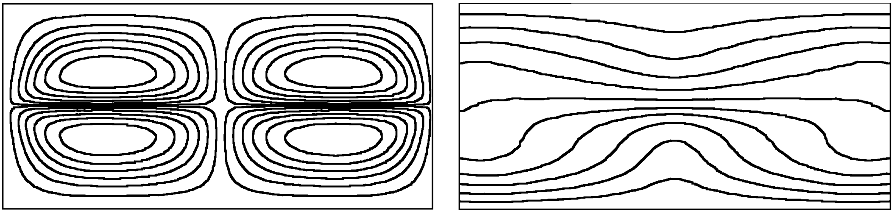

Fig. 3. Numerical streamlines (left) and isotherms (right) for Marangoni convection in the respective theoretical model (without the effect of gas bubble).

The observed convective flow in the system at temperature difference of ΔT = 23℃ is shown in fig. 4(a) which was obtained by long time exposure photography. A bubble with a diameter about 10 mm appeared obviously in the right lower corner of the cavity, due to the a small amount of fluid escaping out of the container. The video picture of convective flow traces shows that only one typical thermocapillary convective cell appeared in full part of the paraffin (upper) liquid layer. The flow pattern in the lower liquid layer was not visible because there were few trace particles floating inside the FC-70 liquid, but the convective structure of the lower liquid layer can be deduced according to the velocity continuity of the liquids along the interface.

Fig. 4(b) shows that bubble appeared at the right corner of the Paraffin liquid layer. Here, the bubble is approximated as a rectangular one, and the deformation of the gas-liquid interface is neglected. So the boundary condition at the gas-liquid interface is the same as at the liquid-liquid interface. The approximation numerical simulation of the system, with the effect of the bubble considered, around which the gas-liquid interface appears, shows good agreement between numerical and experimental results. They are the same in flow pattern .A full convective vortex appears in the upper layer because there is a larger temperature gradient along the perpendicular gas-liquid interface than horizontal interfaces, which drives Marangoni convection mainly. And the core of the vortex is upside the bubble. Comparing with the flow pattern of Marangoni convection in a ideal two-layer system (fig. 3), the onset characteristic and symmetrical pattern no longer exist due to the appearance of the bubble. Therefore, the experiment also verifies the theory of Marangoni convection in a two liquid-layer system with the effect of a bubble, and agrees well with numerical simulation.

Table 1 lists the amplitude of the velocity measured in experiment at four different points in test-cell A, for comparison with the numerical simulation. They have the same order of amplitude. Besides, they differ by not more than 43 percent in horizontal velocity component. All this demonstrates the reliability of the experiment of Marangoni convection.

3.2 Thermocapillary convection (Test-cell B)

Test-cell B is designed to observe thermocapillary convection under microgravity environment heating from right side with a temperature difference $\Delta T = 41$℃ and Ma=4922. Fig. 5 shows numerical prediction, streamlines and isotherms of thermocapillary convection in test-cell B without the effect of bubble. There is a counter-rotating convective cell in each liquid layer and these two cells are almost symmetrical.

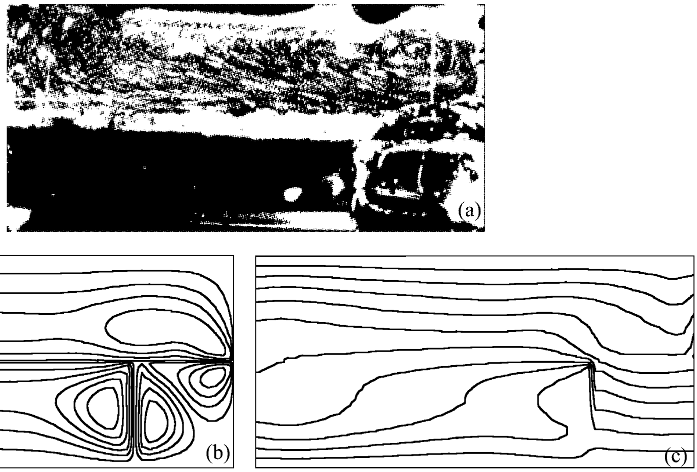

Fig. 4. Marangoni convection in test-cell A heated from the lower side. (a) Image of streamlines of space experiment; (b) simulating streamlines with the bubble; (c) simulating isotherms.

Table 1 Comparison of experimental and numerical velocity of Marangoni convection

Point N.O.	1		2		3		4	
$(x, y)(\times 10^{-3}$m)	(2.1, 6.9)		(21.5, 2.0)		(25.1, 2.4)		(27.5, 2.5)	
method	exp.	comp.	exp.	comp.	exp.	comp.	exp.	comp.
$U(\times 10^{-6}$m/s)	18.7	10.5	–46.7	–61.4	–54.5	–42.6	–54.5	–37.8
$V(\times 10^{-6}$m/s)	27.5	13.6	0.0	–1.3	11.5	–1.4	11.5	6.8

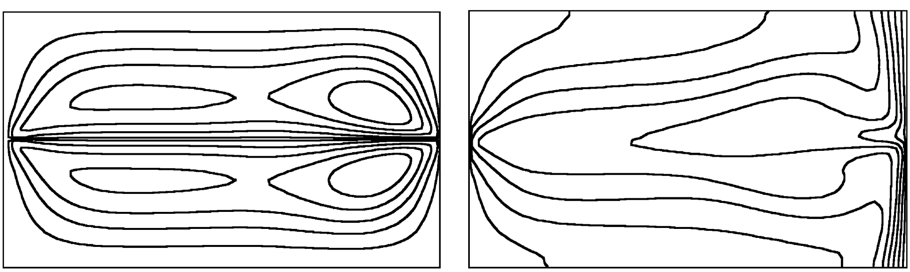

Fig. 5. Numerical streamlines (left) and isotherms (right) for thermocapillary convection (free from the effect of gas bubble).

One of the observed thermocapillary convections of the Paraffin-FC70 system in test-cell B is shown in fig. 6 where the applied external temperature gradient is parallel to the Paraffin-FC70 interface. In this case, the video pictures show that the thermocapillary observed in space is steady. There is a bubble about 10 mm in diameter at the left upper corner of paraffin liquid and the flow structure in both layers is on longer symmetrical with respect to the interface. Obviously, one convective cell appears in the paraffin liquid layer with the center of the vortex near the hot right sidewall. In the lower FC-70 liquid layer some traces of liquid movement distinguished near the liquid-liquid interface show that there is a similar convective cell opposite to the one in the upper layer. The typical thermocapillary convection in microgravity observed in space has the same profile as the numerical result shown in fig. 6(b). And the agreement between the velocity of the space experiment and numerical simulation identifies the reliability of the physical model in this paper (table 2).

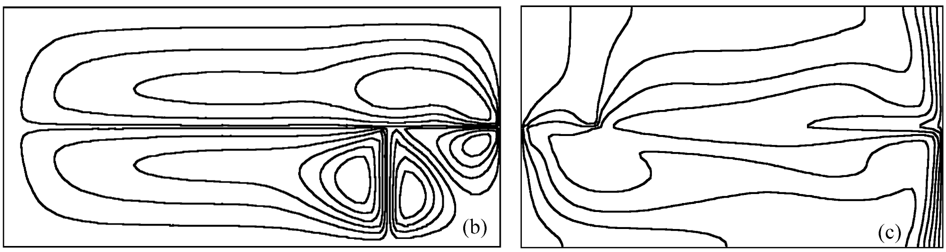

Fig. 6. Thermocapillary convection in test-cell B heated from the right side. (a) Image of streamlines of space experiment; (b) simulating streamlines with a bubble; (c) corresponding simulating isotherms.

Table 2 Comparison of experimental and numerical velocity of thermocapillary convection

Point N.O.	1		2		3		4	
$(x, y)(\times 10^{-3}$m)	(22.1, 0.4)		(23.0, 0.5)		(23.9, 0.5)		(30.5, 5.7)	
method	exp.	comp.	exp.	comp.	exp.	comp.	exp.	comp.
$U(\times 10^{-6}$m/s)	–343	–479	–445	–461	–480	–471	240	215
$V(\times 10^{-6}$m/s)	–26	–3.4	26	1.9	26	8.7	–419	–110

4 Conclusion

The space experiment performed on board the Chinese Satellite SJ-5 and the preliminary results of thermocapillary convection in two-layered liquids have been presented in this paper. The Marangoni convection and thermocapillary convection of two-liquid layers in microgravity condition have been studied numerically in different heating cases. The flow patterns and quantitative velocity of convective flow have been obtained by the treatment of long-time exposure photography of flow images. A new model related to the space experiment where both liquid-liquid interface and liquid-gas free surface are considered due to the appearance of the bubble is simulated numerically to study the Marangoni convection and thermocapillary convection with the effect of bubble. Good agreement between the space experimental results and numerical simulation on the flow structure and velocity of thermocapillary convection has been obtained for both heating cases in space. The space experiment confirmed the theoretical model and thermodynamic behavior of interfacial-tension-driven thermocapillary convection in multi-layer liquids in microgravity, even in the appearance of bubble in the experimental system.

This is the first space experiment of fluid dynamic performed successfully in China. Some typical phenomena of steady thermocapillary convection have been observed clearly in this experiment in space. The onset of Marangoni convection and the oscillatory phenomena of thermocapillary convection need to be investigated experimentally in the future on other space experiments.

Acknowledgements We thank F. Liu, P. Zhang and X.Q. Dong for performing the space experiments. This work was partly supported by the 95-yu-34 of the Department of Science and Technology and the National Natural Science Foundation of China (Grant No. 19789201). Q. S. Liu wishes to thank Prof. J. C. Legros and Dr. Ph.Gerios for their helpful discussion during his visit in ULB (Belgium).

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