Vol. 44 No. 6 SCIENCE IN CHINA (Series E) December 2001

Space experimental device on Marangoni drop migrations of large Reynolds numbers

ZHANG Pu (张 璞), HU Liang (胡 良), LIU Fang (刘 方),
YAO Yonglong (姚永龙), XIE Jingchang (解京昌), LIN Hai (林 海)
& HU Wenrui (胡文瑞)

Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China
Correspondence should be addressed to Zhang Pu (email : zp@imech.ac.cn)

Received December 25, 2000

Abstract The space experimental device for testing the Marangoni drop migrations has been discussed in the present paper. The experiment is one of the spaceship projects of China. In comparison with similar devices, it has the ability of completing all the scientific experiments by both auto controlling and telescience methods. It not only can perform drop migration experiments of large Reynolds numbers but also has an equi-thick interferential system.

Keywords: Marangoni drop migrations, microgravity fluid mechanics space experimental device.

The Marangoni drop migration, which is the motion when the drop is in the uneven fields of temperature or concentration, is a classical question of fluid mechanics[1]. When the bubbles and drops are submerged in an immiscible liquid, it will produce thermocapillary or concencapillary migrations driven by variations of interfacial tension if there are uneven fields of temperature or concentration on their surface. On the ground, the effect of capillary tension is coupled with the buoyancy, which makes it difficult to research the capillary process. In microgravity environments, however, the buoyancy can be neglected and the Marangoni migrations driven by variations of surface tension turns to be the dominating factors. The microgravity experiments are the best chance to study the process. Only the Marangoni migration driven by temperature gradient is discussed in the present paper.

The Marangoni drop migration is important in both theory and applications. During the process of producing alloy, many droplets will occur inside the continued liquid in some temperature ranges. When the temperature field is not uniform, the Marangoni migrations will occur due to the gradient of the surface tension. In welding and producing materials in space, the bubbles suspending in the melting liquid can be driven out by controlling the temperature. Results of those experiments will help improve the producing process both in space and on the ground.

The model analytically dealing with the linear perturbation cases of small Reynolds numbers ($Re \ll 1$) and small Marangoni numbers ($Ma \ll 1$) is named YGB theory by Young et al.[2]. The influence of inertia term and heat convection cannot be omitted in the cases of large Reynolds number and large Marangoni numbers.

Many experiments have been performed on the ground and the results showed the coupled migration effects of thermocapillary tension and buoyancy[3—5]. The pure thermocapillary migration process can be researched only in sustaining microgravity environments.

The bubbles and drops migration experiments were carried out aboard the IML-2 mission of the Space Shuttle[6]. The experiments were performed in an apparatus named bubble drop particle unit (BDPU) which was provided by ESA. The apparatus consisted of the systems of power, optical diagnostics, illumination and imaging. The optical diagnostics system included a video camera, a motion picture camera and a point diffraction interferometer (PDI). The PDI can be used only in a small temperature range because of the influence of the gradient of the temperature-refractive index. In the core of the BDPU were two rectangular test cells with $60 \times 45 \times 45\text{mm}^3$ in the interior. In the long dimension, the cell was heated by Peltier elements through the aluminum surfaces; the other four walls were made of fused silica coated with indium tin oxide to minimize heat loss by radiation, 10 thermistors were mounted on the interior walls for temperature measurement. The injection needle of diameter 1.5 mm was covered with a small valve. Soon after the drops were formed at the tip of the needle, the injector was withdrawn rapidly to its original position to detach the drop. Liquid drops did not detach from the tip of the needle but were separated from the liquid column, so the first case failed. The continuous liquid was 50 cst silicone oil and drop liquid was Fluorinert FC-75. The diameters of drops varied from 2.0 to 14.4 mm, and those of bubbles ranged from 1.2 to 14.8 mm and the temperature gradient was 1.0 K/mm. So the Reynolds number $Re > 1$. The results showed that the migration velocity of experiments was lower than theoretical predictions, and it was a function of drop size and the applied temperature gradients, $V_{\text{exp}} = f(R, |\nabla T_\infty|)$.

In 1996, the drop migration experiments were performed aboard the LMS mission of the Space Shuttle of NASA[7]. Air and Fluorinert FC-75 were used for the bubble and drop phases, respectively, 10cst silicon oil was employed for the continuous phase. The experimental apparatus was also the BDPU. The Reynolds numbers of this experiment were larger than that of IML-2 mission due to the higher temperature difference and lower viscosity of the continuous liquid. Results were found to be generally consistent with that of IML-2 but still lower than the YGB model.

The BDPU of ESA was the main apparatus for international drop migration experiments. The experiments were operated by astronauts at space lab in the space shuttle. An unmanned space experimental device is discussed in the present paper. To obtain more information, in the device an optical interferential system is installed to acquire information of both the background temperature field and the flow field.

1 General designs of the experimental device

The device was designed for space experiments on large Reynolds numbers. Of course, it also applied to small Reynolds numbers. To study the nonlinear cases, the influence of inertia term and heat convection should be included. There are two important dimensionless parameters.

Interfacial tension Reynolds numbers
$$Re = \frac{V_0 R}{v_i}, \tag{1}$$

Marangoni numbers
$$Ma = \frac{V_0 R}{\kappa_i}. \tag{2}$$

Here the reference velocity is defined as $V_0 = -\dfrac{\sigma'_T R \mid \nabla T_\infty \mid}{\mu_i}$, R is the radius of the drop, σ'_T, the rate of change in interfacial tension with temperature, ∇T_∞, the temperature gradient imposed on the continuous phase fluid, and v_i, μ_i, κ_i, the kinematics viscosity, dynamic viscosity and thermal diffusivity. The subscripts $i = 1, 2$ stand for drop and continuous phase respectively. By formula (1), the large Reynolds numbers imply that the influence of the inertia is relatively strong, thus requiring that the drop sizes should be larger, the temperature difference higher and viscosity lower.

The main intention of the experiments is to study the thermocapillary migrations of single drop with different sizes and different temperature gradients. The chief task is to observe the track of the migrations and measure the migrations velocity. The 5 cst silicon oil and FC-75 are the continuous and drop liquids respectively. We selected the 5 cst silicon oil to obtain larger migrations velocity for its lower viscosity. Due to the space limitation, we selected the drop sizes as $R = 2$—10 mm, the temperature difference as $|\nabla T_\infty| = 1$—1.5 K/mm. We can obtain larger Reynolds numbers for the higher temperature difference and lower liquid viscosity in the space experiments than IML-2.

The duration of the space experiments is about 90 min, 60 min for establishing the temperature field and 30 min for performing the experiments. The former experiments showed that the time it took to set up steady temperature field was directly proportional to the square of the height of the test cell, so the height of the test cell was selected as 42 mm. According to the results of numerical simulation, the trajectory of drop migrations in large Reynolds numbers would be oscillated. The optical interferential system is to observe the fine structure in its wake.

Different from the international one-off apparatus in rocket, our device can be repeatedly used and inject drops for several times; the BDPU of ESA need astronaut, while ours is unmanned. The experiments can be auto controlled by the embedded program. At the same time, it has the function of telescience, the experts on ground can control and intervene the space experiments through telecommands in real time. The equi-thick interference system is so steady that it can endure the space vibration environments. The injection system has a dual-sleeve structure and had been successfully used by drop shaft. It is also simple and reliable compared with BDPU for decreasing mechanical motions. In addition, the device is universal in the functions of temperature field establishment, temperature measurement, optical diagnostics and real time image recording. One can use the device to perform different space experiments of fluid physics research by selecting different experimental objects.

The device is sketched in fig. 1. It consists of test cell, injecting system, optical diagnostic system, image system and electrical-control system. The test cell is the core of the device, and it is the site for drop migration. The injecting system is responsible for injecting different size drops to the test cell according to the time sequent demands. The optical diagnostic system can observe the background temperature field, fluid flow field and the interference field. The image and recording system collects and records the flow field and interference images on two VTRs in real time, respectively. The electrical control system has the function of carrying out the experiments according to the program sequence, storing the scientific data and communicating with ground station.

2 Optic-mechanical system

2.1 Test cell

The four 8 mm-thick walls of the rectangular test cell are sticked together by glue, and the interior is $40 \times 30 \times 42$ mm^3. The cell is bounded by aluminum boards in the height dimension, and an electrothermal film is mounted on the top surface to establish the temperature field. There are six thermocouples to measure the temperature in the test cell, two on top and bottom surfaces,

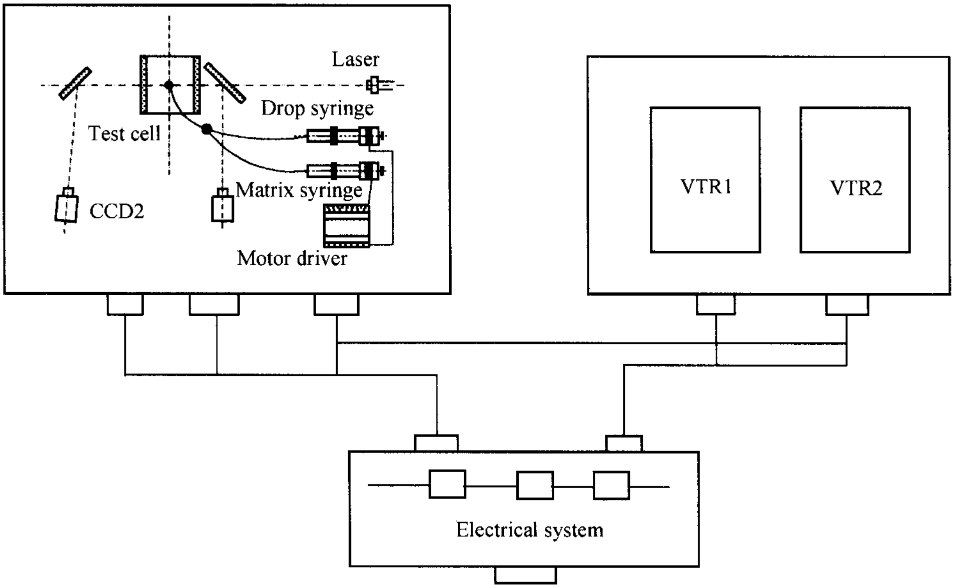


Fig. 1. Sketch of experimental device.

and four on one not-passing-light side wall with the internal 8 mm. During the space experiments, the temperature data can be downlinked to the application center on ground for display and storage. The experimenter can judge the temperature difference in the test cell according to the temperature curves.

The test cell is the key component of the whole experimental device. It was not only the site for drop migration but also the part of interferential system. In order to improve the stability, the equi-thick interferometer without maladjustment is composed of the front and rear surfaces of the test cell.

2.2 Optical diagnostic system

The space experiments require that the optical system should have the following essential functions.

(i) Showing the temperature field before injecting drops.

(ii) Continuously collecting and recording the tracks of the drop migrations for migration velocity measurement.

(iii) Continuously collecting and recording the interferential patterns of the drop migrations wakes from which the fluid fine structures can be obtained.

Hence the optical system consists of two parts: drop track camera system and interferential system. The CCD is the image receiver of the drop track camera system. Four LEDs are used for illumination from the backside, the field of vision is 56 mm × 40 mm, the object resolving power is 0.1 mm and the object depth of field is ± 2 mm. The cross section of the test cell is 40 mm × 30 mm and the drop diameters are varied from 2 to 10 mm, the system can clearly image and track the drops in the whole angular view. In order to improve the efficiency of the device and obtain more related information in an experiment, the track system is required to work with the interferential system independently and simultaneously. The optical axis of the track system is deflexed 5℃ from the other system to prevent the laser beam from producing a bright facula at the image plane center of the track system.

The interferential system detects the change of the interferential stripes produced by drop migrations. The illumination source is a laser (λ = 650 nm), and the image receiver is a CCD. Due to the stability request of space experiments, it is designed as an interferometer without maladjustment. The equi-thick interferential field is made up of two beams reflecting from the front and the rear surfaces of the test cell. The beam reflecting from the rear surface passes through the liquid twice, so it has the information of refractive index distribution related to the temperature field of the liquid. It can indirectly measure the variations of the temperature field of the experimental fluid through the change of the interferential stripes, and thus can measure the wake's fine structures.

Because the refractive index of the experimental liquid will vary greatly with temperature variation, (that is, the coefficient of the temperature refractive index is large), good stripes contrast can be ensured only with appropriate temperature difference. The refractive index of the liquid will vary so much for 45℃ temperature difference and produce such an equivalent optical wedge that the stripes are too close to read. We designed the test cell in a shape of broad top and narrow bottom to compensate for the influence of the temperature. The value of the wedge angle is determined by the temperature difference and the coefficient of temperature refractive index. The sketch of the optical system is in fig. 2.

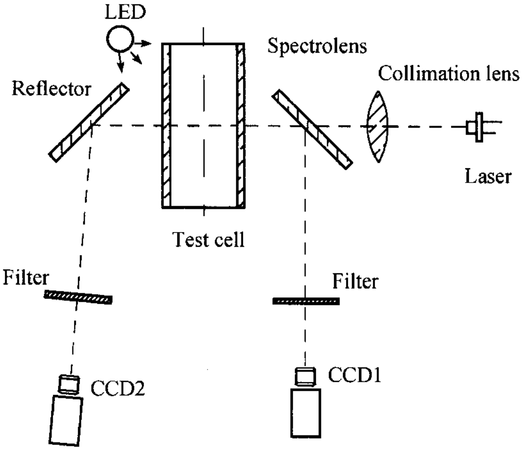


Fig. 2. Sketch of optical system

2.3 The injecting system

The injecting system is a program-controlling device with a double-pipe structure. It consists of generator, drop and matrix liquid syringes, step-motors and their drivers. The generator is based on a double-pipe structure, consisting of two co-axial steel pipes. The inner and outer pipes are connected with two syringes via flexible pipes and tie-ins respectively. There is a gap between the two pipes. FC-725 is painted as the coating on the outer wall of the inner pipe and on the inner wall of the outer pipe in order to decrease the wetting between the drop liquid and the pipe wall so that the drops could be detached from the tip of the pipe easily. The generator is connected with two syringes that are full of drop liquid FC-75 and matrix liquid 5 cst silicon oil respectively. The system is able to automatically inject drops controlled by a computer servo system.

During the drop injecting process, the drop liquid is fed through the inner pipe to form a drop at the outlet of the inner pipe first, and then the matrix liquid is supplied from the gap between the inner and outer pipes to release the drop from the tip of the inner pipe and make it suspend in the matrix. The drop size can be controlled as required. The diameter of the inner pipe is very small (0.25 mm for the inner diameter and 0.5 for the outer diameter). The injecting system is sketched in fig. 3.

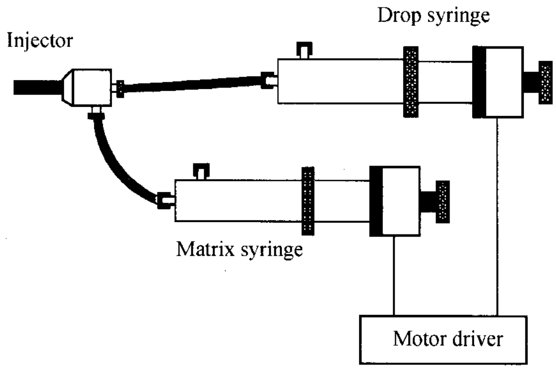


Fig. 3. Sketch of injecting system.

During the experiment, the volume of the matrix liquid in the test cell will increase due to the expansion of silicon oil when it is heated to set up a temperature gradient. The drops injected into the matrix liquid will increase the total volume of the liquid as well. In this case, the extra liquid should be stored somewhere. On the other hand, any pressure increases inside the test cell is not expected, since the increased pressure may break the test cell. Thus a flexible vessel is augmented, which is connected with the test cell and is sealed after all the air in the vessel and the test cell is exhausted. In this way, the extra liquid can be stored in this flexible vessel with little pressure increase.

3 Electrical-controlling, image collecting, image recording system and telescience

3.1 Electrical-controlling system

The temperature gradient is established by heating electrothermal film, the system controls two step-motors, a laser, two VTRs, four LEDs and the process of injecting drops. During the space experiments, when the device is let to pass through the observation regions, the electrical-controlling system downlinks the scientific telemetry datum and two channels' alternated images to the ground. At the same time, it receives the telecommands and memory load commands that are the information of changing parameters for new experiments.

3.2 Image collecting and image recording system

Two CCD are used for collecting images with resolving power of 512 × 512 × 8 bits, and two VTRs are used for recording drop migration tracks and interferential patterns, respectively. During the space experiments, two alternant images are transmitted to two VTRs respectively and downlinked to ground at the same time. Processing the images datum in VTR tapes, we can determine the migrations velocity and the fine structures of the drop wakes.

3.3 Telescience

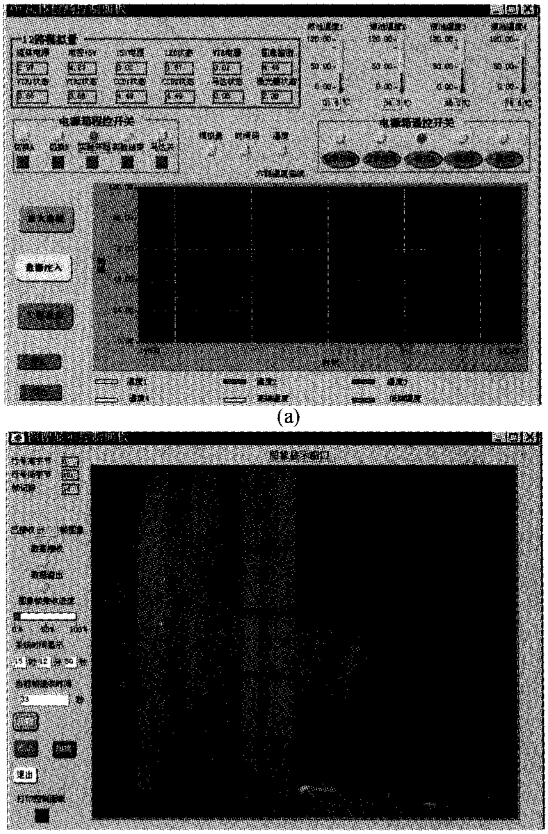
The space experimental device has the ability of telescience, it can efficiently improve the quality of the experiments without astronauts. There are 15 items of telemetries, 5 items of telecommands, 7 items of time-lapse telecommands, 64 KB memory load commands, 4 items of temperature curves and 2 channels of images. During the space experiments, the experimenters can monitor the status of the components, temperature difference and the process of the experiment through the downlinked information of telemetry, temperature curves and images. The experts on ground can make immediate or time-lapse judgments from the downloaded information by comparing it to the ground experimental models and then change the process of space experiments at ground lab. The telecommands and time-lapse telecommands can implement teleoperations in real-time and lapse-time meanings respectively. The memory load commands are the most flexible method to change the experimental parameters including temperature difference, drop size, quantity of injecting liquid, recording time of VTR, duration of the experiment and so on. The above telescience methods on ground are complementary to each other.

There are three modes in the space experimental workflow. The first one is default mode. In this mode, the experimental process is auto controlled by embedded program without ground intervening, and thus, the mode ensured the completion of experiments even if the communications between the space and ground are interrupted. The second one is memory-loading mode. The device is controlled by the memory load commands, and it can flexibly change the experimental parameters and scenarios in this case. The third is commanding mode. It can finish the experiments according to the ground instructions if the program is in trouble. The three modes are complementary to each other. They not only enhance the reliability but also improve the experimental efficiency by telescience methods. Furthermore they make the best of the valuable microgravity time. The device is the next one for space fluid experiments with telescience, following the fluid physical device aboard the SJ-5 satellite in China[9]. Obviously, it can enrich our experience in space fluid physical telescience experiments.

4 Functional tests of the device and primary results of ground-based experiments

We selected Fluorinert FC-75 and 5 cst silicon oil as the drop and matrix liquid, respectively. However, the ground-based experiments cannot be performed because the density of drop liquid is much higher than the matrix liquid and then the migrations driven by the interfacial tension are greatly covered by the buoyancy driven by gravity on ground. The 5 cst silicon oil and vegetable oil are selected as the drop and matrix phase liquid to replace the medium for the space experiment. Functional tests of the device and primary ground-based experiments had been carried out and certain results are shown in the following figures.

Fig. 4 (a) shows that the experiment was started and the laser, LED, CCD and step motors had been activated. The temperature curves are flatter and the four curves in the test cell are gradually separated from each other, implying that the temperature field have been set up and it is time to inject drops. In fig.4 (b), the fluid flow image shows that a drop has been injected. There are 4 thermocouples on the wall of the test cell and they are also simple objects for reference in measuring velocity.



(a)

(b)

Fig. 4. Status tests of the device and flow field.

In fig. 5, the two interferential patterns imply the background temperature field in the test cell. The flatness and spacing density of the interferential stripes show an even temperature field and the linear degree of the temperature gradient.

Fig. 6 shows the change of the interferential strips in the test cell when the drop is migrating to the topside. There is a trail after the migration, for there is a little solution between the drop and matrix liquid and their refractive indexes are not equal and the temperature of drop is different from that of the matrix liquid. The obvious changes of the interferential strips in the tail of the drop indicate the presence of the flow in fig. 6 (a); and the changes of the interferential strips surrounding the trail indicate the action of the interfacial tension in fig. 6 (b).

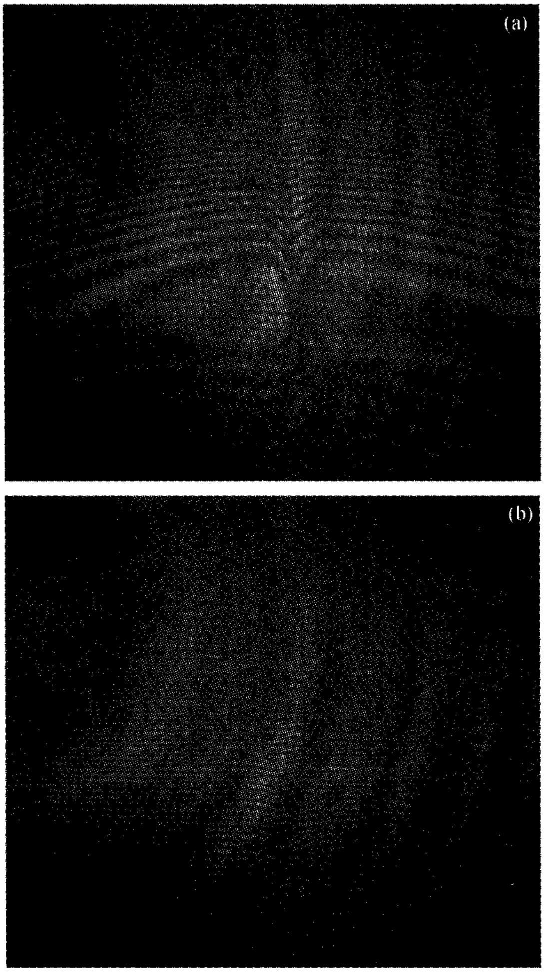


Fig. 5. Interferential pattern of the establishing process of the temperature field.

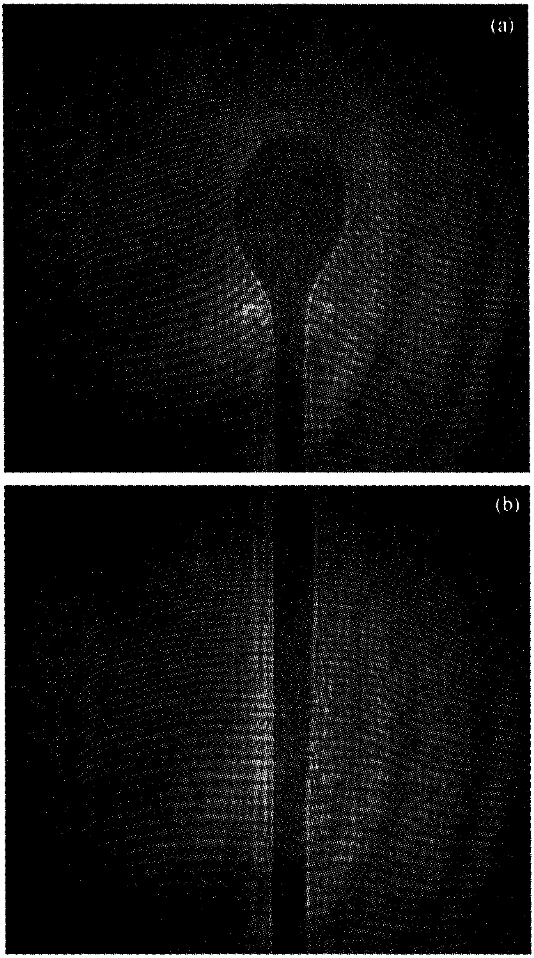


Fig. 6. Interferential pattern when the drop is migrating to upside.

5 Discussion

Numerical simulations had been carried out as the pre-study of the space experiments. Two-dimensional and unsteady model of drop Marangoni migrations were calculated for the case of large Reynolds numbers and the accelerating drop migrations was determined[10]. In numerical simulation of asymmetric model, in the case of large Reynolds numbers, the drop migration trajectory toward warmer region could be a non-straight line, and the migration velocity could be lower than those in YGB model. The oscillated drop trajectory could be due to the vortex in the wake of the drop tail[11]. An interferential system for observing the wake and vortex is designed.

The neutral suspending method could be used for researching drop Marangoni migration on the ground. In the method, the density of drop and matrix liquid were matched equal to decrease the influence of gravity. The 5 cst silicon oil and vegetable oil were used as the drop and matrix liquid. Their densities are 0.934 g/cm^3 at 0℃, the gradients of the interfacial tension with temperature variation -0.0055×10^{-5}N/(cmK), drop diameters 0.6—6 mm, the temperature gradients 5.85 and 7.5 K/mm, respectively and the experimental Reynolds numbers are 0.09—14.6. The results implied that the drop migration velocity was lower than those in YGB model[8]. Although the neutral suspending methods was used, their density were not equal in the whole temperature range because the thermal expanding coefficients of drop and matrix liquid were not the same. The influence of gravity could not be neglected. Only in microgravity environment could pure thermocapillary drop migrations be obtainable.

According to the results of certain space experiments and theoretical calculations, it takes about several seconds for drops of diameter of millimeter magnitude to obtain steady velocity. So this kind of experiments could be carried out in some short-time microgravity facility such as drop shaft. As the pre-research of space experiments, some experiments were carried out using drop shaft with 4.5 s microgravity times in Japan in 1996. The medium was the same as that in the ground-based experiment, the temperature gradient was 3.2 K/mm, and the drops diameters were 5.2—7.5 mm, belonging to the intermediate Reynolds numbers (0.88—2.18). The results implied that drop migration velocity was dependent on the drop size and the temperature gradient. The experimental velocity was obviously lower than the theoretical one, being in agreement with the results of the ground-based experiments[12].

The universal space experimental device for fluid mechanics discussed in the present paper was developed for the scientific project of drop Marangoni migrations for large Reynolds numbers. Its general design as well as its optical and injecting systems has distinct features. The device is especially applied to the unmanned space experiments. It can improve the reliability and decrease the demands and outlay of the experiments by telescience methods. The tests of the device proved that it can meet the requirements of the space experiments.

Acknowledgements We thank the Team of the 1st Dept. of Space Center of CAS and Prof. Cao for their cooperation and help.

References

1. Hu, W. R., Xu, S. C., Microgravity Fluid Mechanics (in Chinese), Beijing: Science Press, 1999.
2. Young, N. O., Goldstein, J. S., Block, M. J., The motion of bubbles in a vertical temperature gradient, J. Fluid Mechanics, 1959, 11: 350.
3. Wozniak, G., Siekmann, J., Srulijes, J., Thermocapillary bubble and drop dynamics under reduced gravity survey and prospects, Z. Flugwiss. Weltraumforsch, 1988, 12: 137.
4. Braum, B., Ikier,'C., Klein, H., Thermocapillary migration of droplets in a binary mixture with miscibility gap during liquid/liquid phase separation under reduced gravity, J. Colloid and Interface Science, 1993, 159: 515.
5. Wozniak, G., On the thermocapillary motion of droplets under reduced gravity, J. Colloid and Interface Science, 1991, 141: 245.
6. Balasubraaniam, R., Lacy, C. E., Wozniak, G. et al., Thermocapillary migration of bubbles and drops at moderate values of the Marangoni number in reduced gravity, Phys. Fluid, 1996, 8: 872.

7. Hadland, P. H., Balasubramaniam, R., Wozniak, G. et al., Thermocapillary migration of isolated bubbles and drops at moderate to large Marangoni number and moderate Reynolds number in reduced gravity, Experiments in Fluids, 1999, 26: 240.

8. Xie, J. C., Lin, H. Han, J. H. et al., Drop migration of middle Reynolds number in vertical temperature gradient, Microgravity Sci. and Teach., 1996, IX/2: 95.

9. Yao, Y. L., Liu, Q. S., Zhang, P. et al., Space experiments on thermocapillary convection and Marangoni convection in two immiscible liquid layers, J. Jpn. Soc. Microgravity Appl., 1998, 15: 285.

10. Geng, R. H., Hu, W. R., Ao, C., Axisymmetric drop Marangoni migration in different Reynolds numbers, IAF-98-J. 4. 06, AIAA, 1998.

11. Geng, R. H., Hu, W. R., Ao, C., Asymmetric drop Marangoni migration of Reynolds numbers, Acta Astronautic, 1997, 41: 757.

12. Xie, J. C., Lin, H., Han, J. H. et al., Experimental investigation on Marangoni drop migration using drop shaft facility, International J. Heat and Mass Transfer, 1998, 41: 2077.