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SPACE EXPERIMENTS ON BOARD THE SHENZHOU SPACESHIP ON MARANGONI DROP MIGRATIONS

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Abstract: Space experiments on Marangoni drop migrations had been conducted on board the Chinese SHENZHOU spaceship in December 2002. The purpose of the space experiment is to investigate the behavior of drop migration at large Reynolds numbers in microgravity condition. FC-75 Fluorinert liquid and KF-96L 5cst silicone oil is used as drop phase and matrix phase in the experiment, respectively. Different temperature gradients had been applied to the liquid fields in the test cell of 50mm×40mm×30mm for series of drops with different diameter from 2.5mm to 9mm. Several experiments with more than thirty drop migrations had been completed. The space experiments went on about 3 days (not continuous) and the experimental hardware is proved to be successful. A new equal-thick optical interferential system is particularly designed to observe the precise structures of the migrating tracks. Several interferential images had been clearly obtained. The interferential fringes showing the information around the moving drops through the variations of the refractive index are processed and analyzed in the paper. Also some other results of the space experiments are presented in the paper.

Keyword: Marangoni drop migration, space experiment, interferential fringes

Introdction

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, that is called the Marangoni drop migration[1]. In the present paper only the Marangoni migration driven by temperature gradient is discussed. On the ground, the effect of capillary tension is coupled with the buoyancy, in microgravity environments, the buoyancy can be neglected and the Marangoni migrations driven by variations of surface tension turns to be the dominating process. The space experiments in sustaining microgravity environments are the best chance to study the Marangoni drop migrations.

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

Recently, Research of drop Marangoni migration focus on larger Reynolds numbers and larger Marangoni numbers. For instance, a ground-based experiment shows that the coupling migration velocities at moderate Marangoni numbers are not consistent with that given by the linear model. [11] Another experiment of drop Marangoni migration at large Marangoni number performed during the short microgravity duration offered by drop shaft facility in 1996 obtained the drop migration velocities much smaller than the ones according to the YGB model [2] .Another successful space experiments on bubbles and drops migration were carried out aboard the IML-2 mission of the Space Shuttle [3]. In 1996, by using the apparatus named BDPU, the drop migration experiments were performed aboard the LMS mission of the Space Shuttle of NASA [4]. Air and Fluorinert FC-75 were used for the bubble and drop phases, respectively, 10cst silicon oil was employed for the continuous phase. Results were found to be generally consistent with that of IML-2 but still lower than the YGB model.

Space experiments on Marangoni drop migrations had been conducted on board the Chinese SHENZHOU spaceship in December 2002. FC-75 Fluorinert liquid and KF-96L 5cst silicone oil is used as drop phase and matrix phase in the experiment, respectively. Different temperature gradients had been applied to the liquid fields in the test cell of 50mm×40mm×30mm for series of drops with different diameter from 2.5mm to 9mm. An unmanned space experimental apparatus was used in the space experiments. An optical interferential system is installed especially in the apparatus to acquire information of both the background temperature field and the fine structure of the tracks of the drop migration. The interferential fringes were processed and the results were discussed in the present paper. The results of migration velocity were introduced in other paper. The interferometer and the space experiments were also briefly introduced.

Apparatus of the experiments

The apparatus consists of optical diagnostic system、drop injecting system、 control system and scientific data processing system. The functions of them were introduced in Zhang, P., et al (2001).[5] For discussing the process of interferential fringes, only the optical diagnostic system are introduced here. The optical system can observe the background temperature field, fluid flow field and the interference field. There's a test cell in this system, it is both the site for drop migration and the core element of interferential system. The photo of the apparatus is in figure 1.

Figure1. photo of the apparatus of the drop migration for space experiment

Optical diagnostic system

The optical system consists of two parts: drop track camera system and interferential system. Two CCD cameras and two VTR devices respectively collects and records the flow field and interference images in real time. In order to improve the efficiency 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°C from the other system, in order to prevent the laser beam from producing a bright speckle at the image plane center of the track system.

The CCD is the image receiver of the drop track camera system. Four LEDs are used for illuminating from the backside of the test cell. It can clearly image and track the drops in the whole angular view. The drop migration velocity could be obtained according the tracks of the drop migrations.

The interferential system detects the change of the interferential fringes produced by drop migrations. The illumination source is a laser (λ=650nm). It is designed as an interferometer without maladjustment to satisfy the stability demand for the space experiments. It is a Fizeau interferometer, the equal-thick interferential field is made up of two beams reflecting from the front and the rear surfaces (optical glass) 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. The flow by the drop migrations could induce the variation of the temperature field around it. So it can indirectly measure the wake's fine structures through the change of the interferential fringes due to the variations of the refractive index distribution of the experimental fluid.

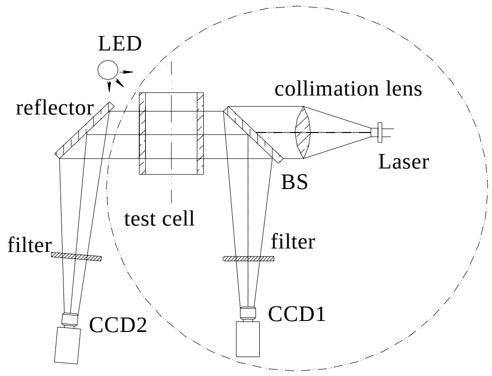


Fig2 sketch of optical system

The sketch of the optical system is shown in Fig.2, the part in the circle is the fizeau interferometer.

Test cell

The four 8mm-thick walls of the rectangular test cell are stick together by glue, and the interior is 40×30×42mm^3(length×width×height). The wall is made of K9 glass. Two Aluminum boards in the height dimension bound the cell, and an electro thermal 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 respectively and four on one not-pass-light side glass wall with the interval 8mm.Special pastern for preventing the leakage of the liquid inseparably glues the inlets of the four thermocouples across the glass wall.

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 equal-thick interferometer without maladjustment is composed of the front and rear surfaces of the test cell.

Space experiments

The space experiments went on about 3 days (not continuous) and the experimental hardware is proved to be successful. The purpose of the space experiment is to investigate the behavior of drop migration at large Reynolds numbers in microgravity condition. To obtain higher migration velocity, and therefore, larger Reynolds numbers and larger corresponding Marangoni numbers, relative big interfacial tension of the experimental liquids, lower viscosity of the matrix liquid, lager drop sizes and higher temperature gradients should be selected. In the experiments, FC-75 Fluorinert liquid and KF-96L 5cst silicone oil is used as drop phase and matrix phase in the experiment, respectively. The pair of experimental fluid has relative big interfacial tension gradient with temperature. The interfacial tension was measured over a temperature range from 20.9 ^{o}C to 68.8 ^{o}C. The results were fitted and the value of σ_T' is -0.044±0.002 dyn/cm for the silicone oil - Fluorinert interface. Three different temperature gradients $|\nabla T_\infty|$=0.9K/mm, 1.2K/mm and 1.3K/mm had been applied to the liquid fields for series of drops. Limited by the space experimental conditions, the drop sizes are selected as $D = 2.5 \sim 9$ mm. Several experiments with more than thirty drop migrations had been completed. The Reynolds number can be calculated by the following definition:

Interfacial tension Reynolds numbers

$$\mathrm{Re} = \frac{V_0 R}{\nu_i}, \qquad (1)$$

Marangoni numbers

$$M_a = \frac{V_0 R}{\kappa_i} \qquad (2)$$

Here, the reference velocity is defined as $V_0 = -\frac{\sigma_T' R |\nabla T_\infty|}{\mu_i}$, 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 ν_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 [6].

In the paper, Only the experiments with temperature gradient $|\nabla T_\infty|$ =0.9K/mm is discussed, the relevant information of the experiment is given in table 1.

Table1. The parameter range of the experiment

Temperature Gradient	R (cm)	Re
9 K/cm	0.125~0.45	8.7 ~113

Process of the interferogram

To analyze the interferogram, the first thing is to fit the interferometric data to get the expression represents the wavefront function. The wavefront function has the information of the flows due to the drop migrations. The goal of data fitting is to obtain a two-dimensional function that closely represents and interpolates the digitized fringe positions and orders of an interferogram. The data fitting is done by means of a least squares procedure[7]. It has been shown that the matrix resulting from the normal least squares procedure is almost singular. Polynomials that are orthogonal over the data points have the advantage that the matrix becomes diagonal, thus yielding the coefficients with no need to invert the matrix. So, a set of base polynomials is need to be chosen. For this application the well-known Zernike polynomials were selected [8].

The wavefront function can be expressed as a linear combination of Zernike polynomials as follows:

$$W(x,y)=\sum_{n=0}^{k} a_n z_n(x,y)$$
$$=a_0+a_1z_1+a_2z_2+\cdots+a_kz_k$$

where the polynomials $z_n(x,y)$ are the Zernike polynomials, the a_n are the coefficient of Zernike polynomials, k is the degree of the polynomials. These coefficients represent the wavefront in place of the measured data have useful property. Since the Zernike polynomials are orthogonal over the unit circle, the process of finding best focus, or removing the tilt of the reference wavefront, can be carried out by setting the appropriate coefficients to zero. The aberrations can be found from the coefficients respectively without the need to find a new least-squares fit.

Result

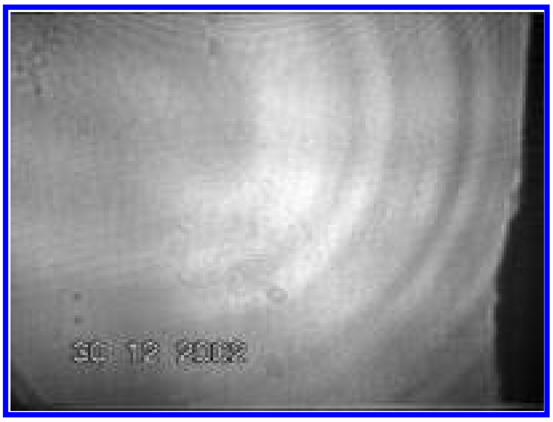
In the space experiments, only the first drop migration has clearer fringes, although the fringe space is so small that the order must be finished by manual in computer. The special method was developed to process the interferogram. The results are shown in figure (3)~(5).

Fig3. (a) shows the temperature fields in the test cell on space experiments, the temperature had been set up for more than 2 hours, but the fringes are not flat, it indicate that the temperature field is not even very well. Fig3.(b) shows the wavefront of Fig3.(a), it shows that the temperature field in the test cell is high in the middle and low around. It is because of the different thermal diffusivity of glass and 5cst silicon oil.

Fig4.(a) shows a drop migration on ground experiment. The ground-based experiments cannot be performed in 5cst silicon oil-FC75 medium because the density of drop liquid is much higher than the matrix liquid 5cst silicon oil and then the migrations driven by the interfacial tension are greatly covered by the buoyancy driven by gravity on ground. The FC-75 is hardly to shaping as a droplet. The 5cst silicon oil and vegetable oil are selected as the drop and matrix phase liquid as ground experiment medium to replace the medium for the space experiment.

Fig4. (a) shows the change of the interferential fringes in the test cell when the drop is migrating to the topside. There’s a trail after the migration. Fig4. (b) is the wavefront of Fig4.(a), no fringes could be found in the droplet and in the trail because the variations of the temperature field in them are too much to present the fringes, that is to say, the fringes are two much to be distinguish.

Fig5.(a) shows a drop migration on ground experiment. The temperature difference is 45°C, the diameter of the drop is about 2.5mm. Fig5. (b) is the fitting wavefront of Fig5.(a). Notice that the fringes surround and after the drop are curving downwards and its fitting wavefront curving upwards. The wavefront express the variations of OPD, the OPDs change bigger indicate that temperature there change higher, it is because the flow send the liquid with high temperature downwards. It proved the presence of the flow of the Marangoni migration. Fig4. (a) and (b) shows the opposite changes of the fringes and OPDs, it is because the buoyancy induce the flow around the drop.



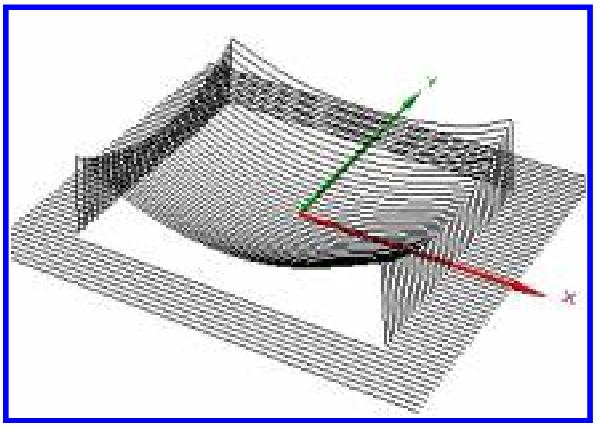


Fig3.(a) Fig3. (b)

Figure3. temperature field on space experiments

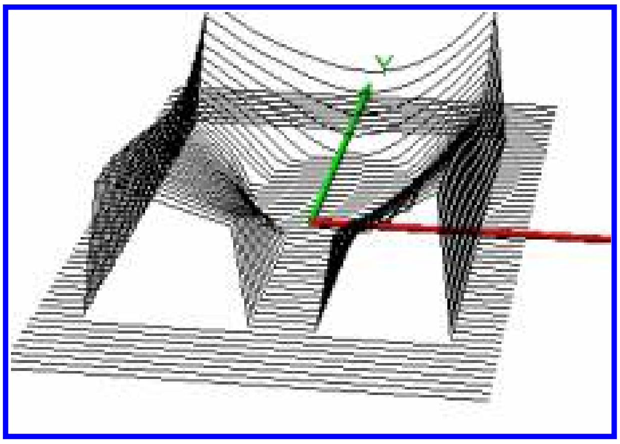


Fig4. (a) Fig4. (b)

Figure4. a drop migration on ground experiment

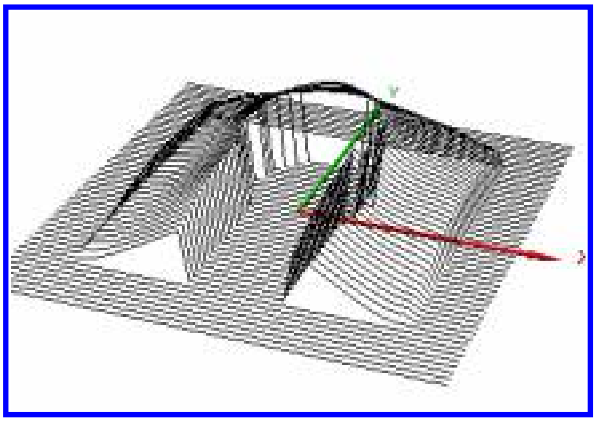


Fig5. (a) Fig5. (b)

Figure5. a drop migration on space experiment

Discussion

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 fringes contrast can be ensured only with appropriate temperature difference. The refractive index of the liquid will vary so much for 45°C 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 the influence of the temperature. The value of the wedge angle is determined by the temperature difference and the coefficient of temperature refractive index. So the interferential system is effective only in such temperature range that 45°C±1°C. The reason of no fringes could be read inside the drop and trail is because of the small valid temperature range.

The temperature field is not even inside the test cell on space experiment, and the temperature gradients in the test cell are also different. All these will take influence on migration velocity.

Although the valid temperature range is small, the interferometer is advantage in detecting the more precise temperature field and flow field in the test cell. It's a pity that the interferometer couldn't find the fine structure behind the drop for the trails, the interferential method is useful on such experiment. It needs to be improved later. The analysis of the interferograms in detail will be finished later. Other results of the experiments are in other paper.

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