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Space experimental investigation on thermocapillary migration of bubbles

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Results from a space experiment on bubble thermocapillary migration conducted on board the Chinese 22nd recoverable satellite were presented. Considering the temperature field in the cell was disturbed by the accumulated bubbles, the temperature gradient was corrected firstly with the help of the temperature measurement data at six points and numerical simulation. Marangoni number (*Ma*) of single bubble migrating in the space experiment ranged from 98.04 to 9288, exceeding that in the previous experiment data. The experiment data including the track and the velocity of two bubble thermocapillary migration showed that a smaller bubble would move slower as it was passed by a larger one, and the smaller one would even rest in a short time when the size ratio was large enough.

bubble, thermocapillary migration, microgravity, interaction

A bubble or drop will move to the hotter side when placed in another immiscible fluid under a temperature gradient. This motion happens as a consequence of the variation of the interfacial tension with the temperature. Young et al. first investigated the thermocapillary migration of bubbles and drops with their linear YGB model when Reynolds number (*Re*) and Marangoni number (*Ma*) are small, which means that both convective momentum and energy transport are negligible[1]. During the recent several decades, many researchers studied the thermocapillary migration of bubbles and drops. Their work was reported by Wozniak[2] and Subramanian[3−5].

The experiments on thermocapillary migration of bubbles and drops on the ground are limited by the effect of gravity. In order to decrease the effect of buoyancy and buoyancy flow on the ground, researchers had to use small drops and bubbles and could only obtain small *Re* and *Ma*. Some experimental results showed that the YGB model was reasonable at small *Re* and *Ma* number, and others showed that there were obvious differences between the predictions by the YGB model and the experimental results. Then a lot of theoretical and numerical methods were used to correct the YGB model at large *Re* and *Ma* number[4,5]. However the microgravity is necessary for ex-

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periments at large *Re* and *Ma*. Subramanian[4,5] reported the experiments on thermocapillary migration under microgravity environments with drop tower, rocket and space flight. Most the valid results were attained in the recent three space flights. The first was Space Shuttle Columbia during the International Microgravity Laboratory mission (IML-2) in 1994[6]. Bubbles and drops of Fluorinert FC-75 were injected into the cell filled with 50cSt silicone oil. The *Re* ranged from 0.0096 to 2.2, and the *Ma* ranged from 5.4 to 810 in the experiments. The second was Space Shuttle Columbia during the Life and Microgravity Science (LMS) mission in 1996[7]. The *Re* and the *Ma* were increased, because 10cSt silicone oil was used instead of 10cSt silicone oil. The extent of *Re* and *Ma* was from 0.839 to 87.2 and from 51.7 to 5780, respectively. The third was China's spacecraft ShenZhou-4 in 2002 where single drop thermocapillary migration was studied[8]. All the above experimental results were compared with the theoretical[9] and numerical[10] predictions at large *Ma*.

In most applications, drops and bubbles are not isolated. Meyyappan[11] solved the axisymmetric thermocapillary migration of two gas bubbles in the quasi-steady state with bispherical coordinate. The result showed that two bubbles with the same size will migrate with the same velocity when both the *Re* and the *Ma* are small, and the velocity is identical to that obtained from YGB model; and when a large bubble migrates after a small one coaxially before contact, the velocity of the smaller is more than that from YGB model, and the velocity of the larger is less than that from YGB model. Subsequently, Meyyappan and Subramanian[12] solved the thermocapillary migration of two bubbles at an arbitrary angle to the applied temperature gradient with zeroth-order reflection approximation. Then Anderson[13] extended the reflection solution to the first order and obtained the velocities of two arbitrarily-oriented droplets up to terms of $O\left(r_{12}^{-6}\right)$, where r_{12} is the distance between the two drops. But all of these approximate solutions are invalid when the bubbles or drops move close enough. Acrivos et al.[14] estimated the average thermocapillary migration velocity of a cloud of identical bubbles. Keh and Chen[15], Wei and Subramanian[16] used the boundary-collocation method to study the thermocapillary migration of a small number of bubbles. Sun and Hu[17,18] used successive reflection technique to obtain the analytical solution. The results indicate that the interaction between two bubbles has a significant influence on the migration of the smaller bubble. And when the larger bubble approaches to the smaller one and drives it aside, the smaller one's speed may decrease to zero and even move backwards as shown in Figure 1 (where Z_1, Z_2 are the longitudinal position, and Y_1, Y_2 are the horizontal position of small and large bubbles, respectively. The size ratio $\lambda = R_2 / R_1 = 10$, where R_1 and R_2 are the radius of the smaller bubble and the larger bubble. The temperature gradient $\nabla T_\infty = 30$ K/cm). All works on interactions of bubbles and drops above were limited at small *Re* and small *Ma*. Recently numerical simulations of the thermocapillary interaction of three-dimensional fully deformable bubbles and drops at large *Re* and *Ma* were reported by Nas[19,20]. The results show that bubbles and drops tend to line up perpendicular to the temperature gradient, which contrasts with results at small *Re* and *Ma*.

Wei and Subramanian performed the experiments on the interaction of two bubbles thermocapillary migrating at small *Re* and *Ma* on the ground[21]. Their results agreed with the predictions by Anderson[13]. Experimental research on thermocapillary migration of two interacting drops on the ground has been performed by our laboratory[22]. The influence on the velocity of the small drop by the large one consisted with the Sun and Hu's theoretical results. However, there are only a few experiments on interaction of large bubbles and drops under microgravity because of much

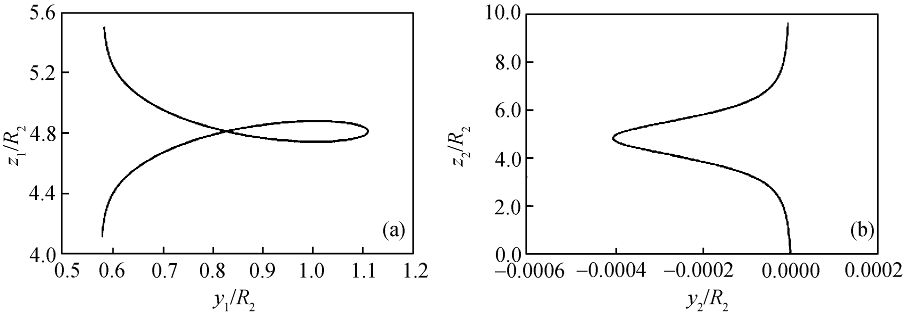


Figure 1 Motions of two bubbles. (a) Smaller bubble's track; (b) bigger bubble's track.

more difficulties than single drop or bubble. Some experimental results from Balasubramaniam in IML-2[6] and Hadland in LMS[7] showed that convective transport of energy was very important at large *Ma*. The thermal wake of the leading bubble or drop affected the trailing one obviously. The trailing bubble or drop migrated more slowly than that without the leading one and had a tendency to leave the axis which resulted in the effect of the thermal wake weakening, which induced that the trailing one ran faster and passed the leading one.

In the autumn of 2005, the experiment of bubble migration was performed aboard the Chinese 22nd recoverable satellite. The goal of the experiment was to observe single bubble thermocapillary migration and the interaction of two migrating bubbles at large *Ma*. A KF-96L series silicone oil of nominal viscosity 5cst was selected as the continuous phase. *Ma* number was expanded in this experiment, because of the smaller viscosity of continuous phase and the larger temperature coefficient of interfacial tension.

1 Experimental apparatus and procedure

As shown in Figure 2 the cell was composed of four optical glass walls and two aluminum blocks at the top and the bottom, and the rectangular test cavity was 70 mm high with the horizontal cross-section of 40 mm × 40 mm. A piece of electric heating film and a Peltier element were placed at the top and the bottom surface, respectively. A grid plate was placed near the top to keep the uniformity of the temperature distribution and let drops stay at the top from disturbing the temperature field. In order to ensure a steady applied temperature gradient, two PID temperature controllers were used to measure and maintain a constant temperature at the top and the bottom. The temperature field of continuous phase in the cell was measured with six thermocouples placed on the side wall from the top down. In order to control the radius of drop injected accurately, a small-diameter cylinder (made by FESTO in Germany) and Stepper-Mike Actuators (made by PI in Germany) were used to control the volume of the bubbles injected.

There was a flexible vessel as a buffer connected with the top of the cell, which compensated for the increase in liquid volume with the increase of the temperature and collected the exhaust bubbles. The whole process was controlled by the embedded system on board. The heating process was started 100 minutes before bubble injection in order to obtain a linear and longitudinal temperature distribution. Each group bubbles were injected at an interval of several minutes. A system with a CCD camera and a videotape was used to record the bubble tracks which would be analyzed after the flight.

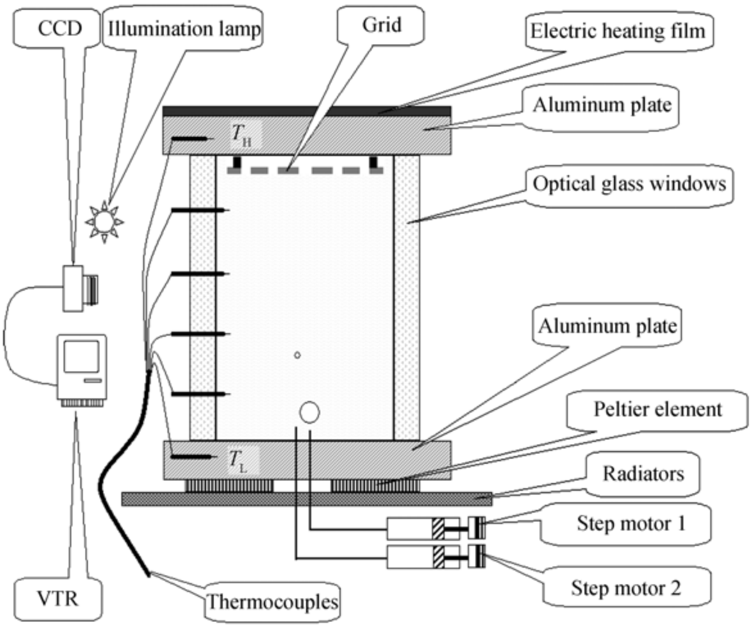


Figure 2 Schematic of the experimental apparatus.

2 Experimental results

A KF-96L series silicone oil of nominal viscosity 5cst was selected as a continuous phase. The surface tension was measured over a temperature ranging from 17.8℃ to 61.2℃ with a plate method by a kruss k12 tensiometer. The value of σ_T was (–0.078 ± 0.002) dyn/(cm·K) with the method of line fitting, and other properties of the liquid came from Xie[8]. *Re*, *Ma*, reference velocity V_0, thermal diffusivity κ and YGB model velocity V_{YGB}[1] are expressed as

$$Re = \frac{RV_0}{\upsilon}, \tag{1}$$

$$Ma = \frac{RV_0}{\kappa}, \tag{2}$$

$$V_0 = \frac{|\sigma_T||\nabla T_\infty|R}{\mu}, \tag{3}$$

$$\kappa = \frac{\lambda}{\rho c_p}, \tag{4}$$

$$V_{YGB} = \frac{2|\sigma_T|R\lambda\nabla T_\infty}{(2\mu + 3\mu')(2\lambda + \lambda')}, \tag{5}$$

where R is the radius of the bubble; ∇T_∞ is the temperature gradient; μ and μ', λ and λ' are the dynamic viscosity, thermal conductivity of air and continuous phase, respectively; υ and c_p are the kinetic viscosity and the specific heat of the continuous phase; ρ is the density of the continuous phase. The properties of liquid system used in the experiment are listed in Table 1.

Table 1 Physical property parameters of 5cst silicon oil

Temperature (℃)	15.0	25.0	35.0	50.0	57.0	70.0	75.0
ρ (kg/m^3)	919	918.5	902	887	882.3	869	864.2
λ (W/m·K)	0.1121	0.111	0.1099	0.1083	0.1076	0.1054	0.1045
μ (10^{-3} N·s/m^2)	5.09	4.27	3.61	2.86	2.67	2.17	2.01
σ_T (10^{-5} N/(m·K))				−7.8 ± 0.2			

Although there was a system designed to collect air bubbles on the top of the cell, there were some bubbles still accumulated under the grid shown in Figure 2. Figure 3 shows a 7 mm bubble staying under the grid at the 150th min. It is supposed that the bubble staying on the top of the cell would affect the temperature field of the liquid and decrease the valid distance of bubble migrating.

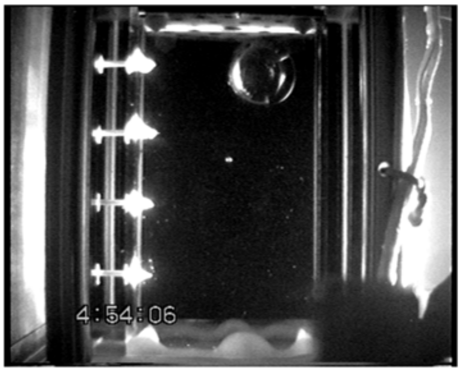


Figure 3 Accumulated bubble under the grid.

2.1 Measurement and correction of temperature field

The experiment lasted 220 min. It took the first 100 min to set up a stable temperature field. The variation of the temperature with the time at six points measured by the thermocouples was shown in Figure 4. The six curves corresponded to the temperature at six points from the top down in Figure 2. As supposed in the foregoing statement, bubbles staying on the top of the cell would destroy the uniform temperature gradient in the cell.

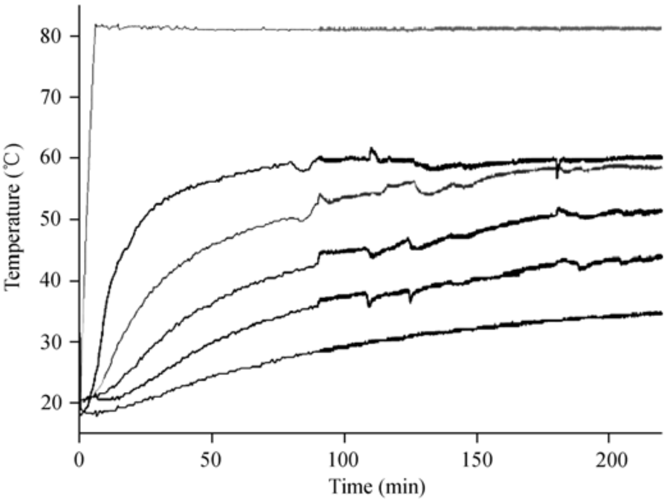


Figure 4 The temperatures measured by thermocouple.

Temperature measurements at the six points at the time of Figure 3 could be obtained from Figure 4, as listed in Table 2. The CFD software Fluent 6.0 was used to simulate the temperature field based on some assumptions. The numerical results were compared with the measurements to confirm the assumptions reasonable.

Table 2 Measurement and numerical simulation at the six points

Point number	1	2	3	4	5	6
Measurement (℃)	81.16	58.51	55.74	47.42	40.48	32.16
Numerical simulation (℃)	81.16	59.11	56.17	48.33	40.49	32.16

Fluent software is based on the finite volume method which could solve many fluid problems. Firstly, a 2D model was built as shown in Figure 5, and a 7 mm bubble was placed under the grid in the model. The six measure points in Figures 2 and 3 were used to monitor the uniformity of the temperature gradient. But the temperature data in Figure 4 showed that the temperature difference between the top side and the second point was too large. It is considered as the reason that there was some air staying between the top side and the grid. So an air layer was placed there in the model as shown in Figure 5. The numerical mesh of the model was triangle. The boundary conditions included: (1) the temperatures on the top and the bottom were set as 81.16℃ and 32.16℃ which equaled that in the experiment; (2) Convective heat transfer boundary condition was specified at the glass wall[23], and the convective heat transfer coefficient was 0.0242 W/mK which equaled the thermal conductivity of air because of little convection under microgravity. The thickness of the glass was 8 mm and the thermal conductivity of the glass was 1.207 W/mK; (3) The surface of the bubble under the grid was set as Marangoni boundary and thermal coupled boundary[22]; (4) The thermocapillary flow between the top side and the grid was neglected and the air layer was only set

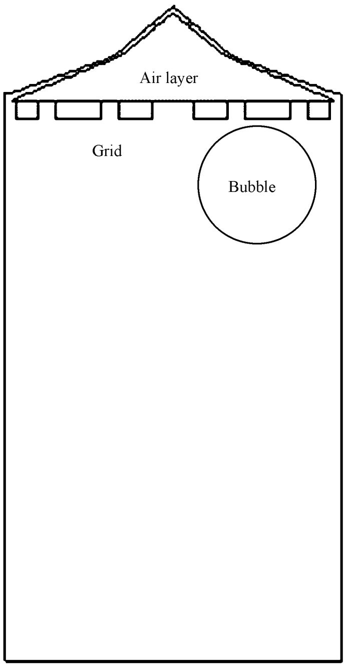


Figure 5 Computational domain.

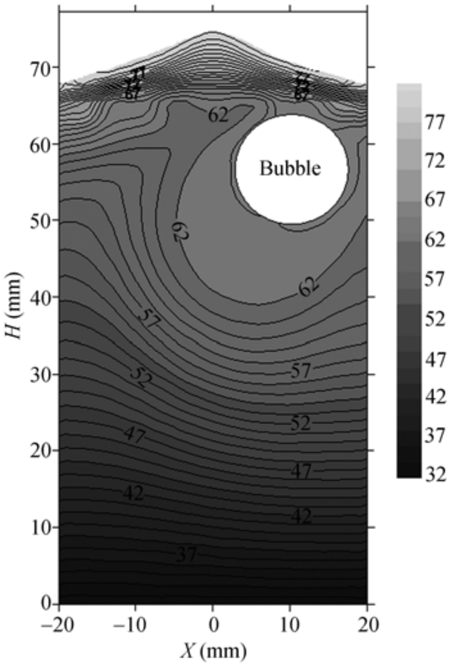


Figure 6 Numerical simulation of temperature field.

as the thermal coupled boundary because of the complicated structure of the grid and no detailed image data; (5) The grid was set as the thermal coupled boundary. The numerical simulation was shown in Figure 6 and the comparison between the measurements and the numerical results at the six points was listed in Table 2.

Table 2 shows that the numerical simulation was very close to the experimental data, which proved the assumption reasonable. The simulation showed that the real temperature gradient was less than the designed and the uniform temperature gradient was destroyed by the bubble under the grid. The important thing was that the real temperature gradient was 1.4 times that calculated from the measurements at the six points. The simulation also showed that the order of magnitude of the disturbance on the velocity field in the downside of the cell was about 10^{-2} mm/s, which was less than 1/100 of the bubble velocity. So the disturbance on the velocity field was ignored.

2.2 Experimental results of single bubble thermocapillary migrating

There was no steady migrating velocity of bubbles because the physical properties of the continuous phase especial viscosity varied with temperature. Even if the properties of the continuous phase were constant, bubbles also need some time to reach a steady velocity after being detached. Because the properties including the density, heat capacity, thermal conductivity, and temperature coefficient of interfacial tension are nearly constant and the viscosity changed with temperature instantaneously, it was assumed that the time taken for the velocity and temperature fields to accomplish steady distributions corresponding to the local conditions around the bubble was much less than that taken for the bubble to move far enough for the viscosity to change a little, which was called quasi-steady assumption. The data from the experiments were analyzed with the assumption and were compared with theoretical prediction and numerical results. Figure 7 showed the variation of velocity of four groups of single bubble with time, when the temperature gradient $|\nabla T_\infty| =$ 0.73℃/mm. The bubbles accelerated with time until they reached the top side where the temperature gradient decreased as shown in Figure 6. The middle part of the cell ranging from 20—40 mm was selected as the window for observation as ref. [7], and the velocity, *Ma*, *Re* and V_{YGB} which were calculated based on the local conditions were shown in Figure 8. Figure 9 shows the compassion between previous space experiments and theoretical prediction and numerical

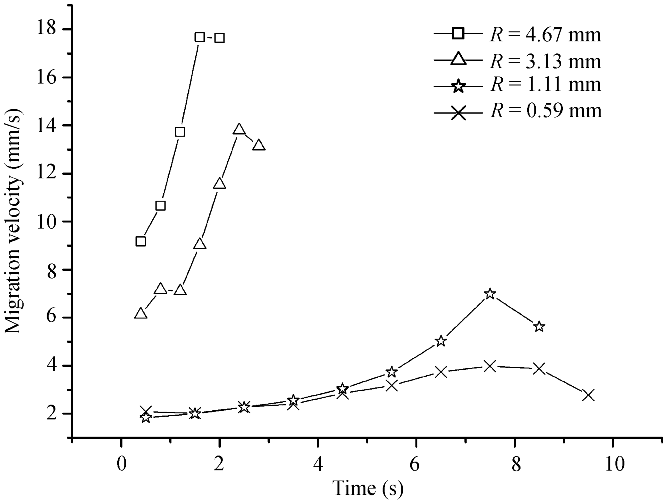


Figure 7 Migration velocity of bubble versus time.

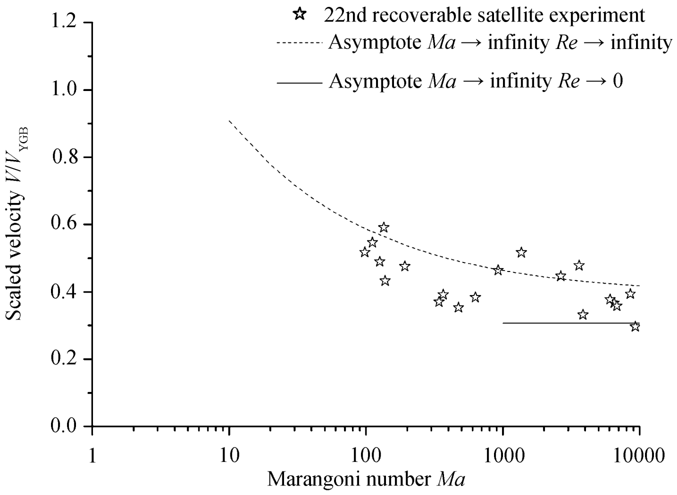


Figure 8 Scaled velocity versus *Ma*.

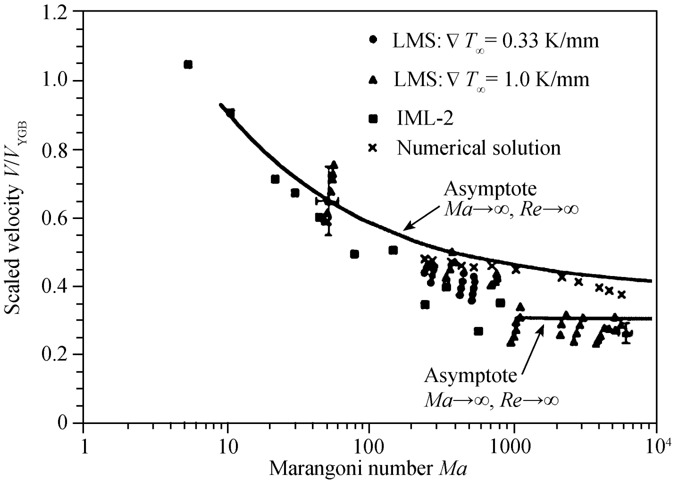


Figure 9 Previous experimental data and predictions from an asymptotic theory and a numerical solution.

results[7,9,10]. The predicting theory was based on qusi-steady assumption, where both heat convective and heat conduction inside the bubble were ignored. As *Ma* approaches infinity, the scaled velocity is shown as eqs. (6) and (7); and numerical simulation was also based on qusi-steady assumption, which was solved by the finite difference method, but heat convective and heat conduction inside the bubble were considered. In the experiment, *Ma* and *Re* ranged from 98.04 to 9288 and 2.3—217.9, respectively. The experimental results are consistent with the earlier results at *Ma* below 6000 as shown in Figure 9. When *Ma* was raised to 9300, Figure 8 showed that the experimental results still accorded with theoretical prediction[9] and numerical results[10].

$$\frac{V}{V_{\mathrm{YGB}}} = 0.3076, \quad Re \to 0, \tag{6}$$

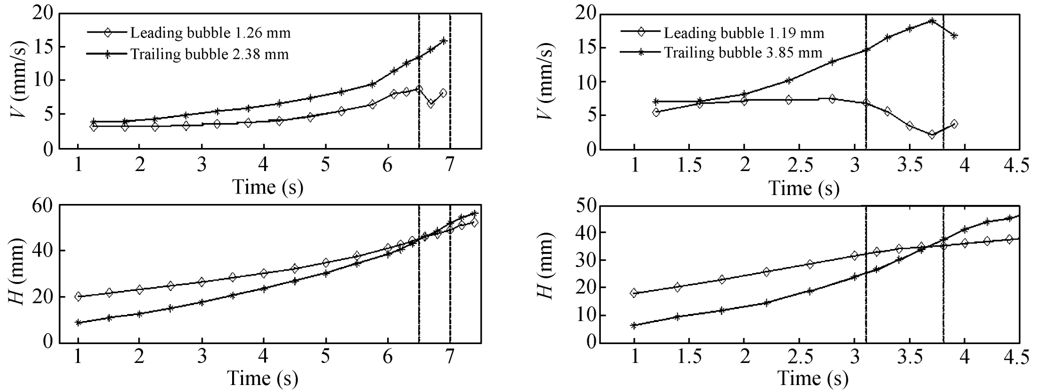
$$\frac{V}{V_{\mathrm{YGB}}} = 0.3920 + \frac{0.1369}{\sqrt{Ma}}\left[9.610 + \ln\left(Ma\right)\right], \quad Re \to \infty. \tag{7}$$

2.3 Interaction of two bubble thermocapillary migration

Some experiments on two bubble thermocapillary migration were also performed. A small bubble was injected into the cell, and then a large bubble was injected after some time. The process of the larger passing the smaller was expected to be observed. But there was only a finite distance for migrating and bubbles migrated relatively fast, so the appropriate interval between two bubbles was necessary to record a whole passing process. Bubble migrating could not be monitored without real-time video being downloaded. So the time intervals were difficult to design when the whole experiment was performed by the auto control system. The valid experimental data are shown in Table 3 and Figure 10. Four groups of two interacting bubbles are listed in Table 3, and the variation of vertical velocity and displacement with time were shown in Figure10. Figure10(d) shows a process of one large bubble surpassing two small bubbles in sequence.

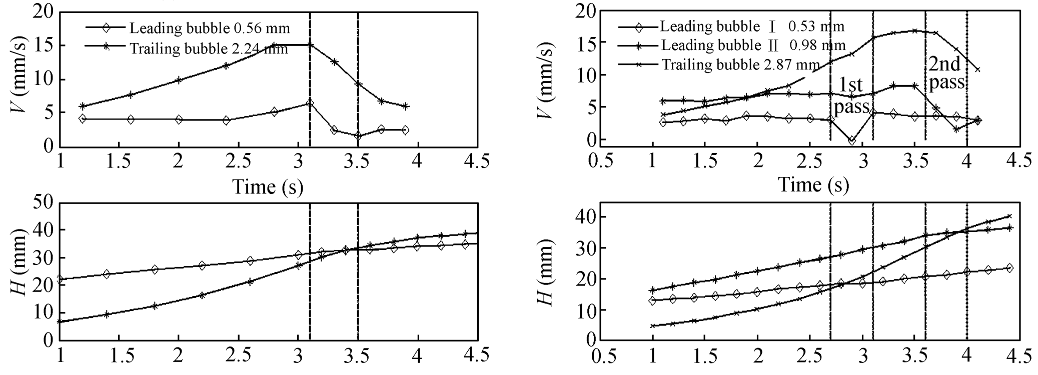
Table 3 Experimental results of two bubble thermocapillary migration

No.	Large bubble (mm)	Small bubble (mm)	*Ma*		*Re*		Coaxial	Figure
			large bubble	small bubble	large bubble	small bubble		
1	2.38	1.26	1576−2470	562−713	29.3−74.2	11.8−18.8	no	9(a)
2	3.85	1.19	4173−6264	442−547	75.8−173	9.16−13.9	no	9(b)
3	2.24	0.56	1370−2011	85.4−145	25−52.8	1.85−3.48	yes	9(c)
4	2.87	0.53	2056−3240	79.9−90.1	36.1−83.5	1.55−1.95	yes	9(d)
		0.98		292−365		5.90−9.11	yes	9(d)



(a) The size ratio $\lambda = 1.89$

(b) The size ratio $\lambda = 3.24$



(c) The size ratio $\lambda = 4$

(d) The size ratio $\lambda = 5.42$ and 2.92

Figure 10 Velocity and displacement of two bubbles.

In Figure 10(a)—(d) two vertical dashed lines were used to label the region, where one bubble was close to another and two bubbles influenced each other strongly. The length of the region was about 0.5—1.1 times the larger bubble diameter. However, the prediction of interacting region by Meyyappan[11] is 0.8—1.4 times the larger bubble diameter when the relative change of smaller bubble velocity reaches 20%. When the larger bubble approached the smaller one, the smaller would be pushed aside by the larger and move along the surface of the larger to the downside, therefore the track of the smaller bubble was affected greatly. It was the common characteristic in Figure 10(a)—(d) that a smaller bubble would move slower as it was passed by a larger one, and the effect increased with the increase of the size ratio of two bubbles. The smaller one could come to rest in a short time when the size ratio is large enough, as shown in Figure 10(d) (the radiuses of the two bubbles were 2.87 mm and 0.53 mm, and the size ratio was 5.42), which accorded with the theoretical prediction from refs. [17,18]. However, when the size ratio was more than 2, little effect on the larger bubble by the smaller could be observed. The reason why the velocity of the larger bubble decreased at last in Figure 10 was that the bubble reached the top of the cell.

It was difficult to compare the experimental results with the existing theory, because: (1) linear assumption was not tenable because of large *Ma* and *Re* as shown in Table 3; (2) the viscosity of continuous phase varied with temperature obviously as shown in Table 1, so the steady migrating velocity varied with location; (3) the single CCD camera could only record 2D information, so the velocity due to interaction in the direction parallel to the axis of the camera could not be measured; (4) the velocity of bubble decreased near the top of the cell because of the finite height of the cell.

3 Conclusions

Results from a space experiment on thermocapillary bubble migration conducted on board the Chinese 22nd recoverable satellite are presented in this paper. Considering the temperature field in test cell was disturbed by some accumulated bubbles, the temperature gradient was corrected with the help of the temperature measurement data at six points and numerical simulation. The simulation also showed that the effect of the disturbance on the velocity field of the bubble migrating could be ignored.

A KF-96L series silicone oil of nominal viscosity 5cst was selected as a continuous phase. *Ma* number was expanded to 9288 in this experiment, because of the smaller viscosity of continuous phase and the larger temperature coefficient of interfacial tension. Although the stable migrating velocity could not reach because of the physical properties including viscosity, etc. varying with the temperature, the experimental data were analyzed with the quasi-steady assumption. The experimental results are consistent with the earlier experimental results at *Ma* below 6000. When *Ma* was raised to 9300, the experimental results of V/V_{YGB} against *Ma* still accorded with theoretical predictions and numerical results.

The experiment data on the interaction of two bubble migrating showed that: the length of the interacting region was about 0.5—1.1 times the large bubble diameter; it was proved that a smaller bubble moved slower when passed by a larger one and would come to rest or move backward in a short time when the size ratio was large enough as predicted by linear theory; when the size ratio was more than two, there was little effect on the larger bubble by the smaller. However when the nonlinear effects of interaction of two bubble migrating are not neglected at large *Ma* and *Re* number, further theoretical work is needed.

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