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Experimental investigation on Marangoni drop migrations using drop shaft facility

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Abstract—Experimental hardware has been developed to perform the experiments of drop Marangoni migration in the case of intermediate Reynolds numbers in a microgravity environment. The experiments were completed using the drop shaft free fall facility with a 4.5 s microgravity period in the Microgravity Laboratory of Japan. A special experimental method was designed for experimenting with a short microgravity period. In this experiment, the thermocapillary velocity of drop migration, driven only by the thermocapillary effect, was obtained. Experimental results show that Marangoni migration velocity depends on the temperature gradient and the drop diameter for fixed experimental mediums; the thermocapillary velocity of this present experiment is obviously smaller than the one suggested by YGB linear theory. This conclusion agrees, in general, with that of the ground-based experiment. © 1998 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

Yong, Goldstein and Block presented the linear perturbation model of drop or bubble migration as the YGB model [1]. The YGB model linear theory for the cases with a small Reynolds number and small Peclet number omitted the inertia influence and convective energy transport, respectively. The YGB model assumes that the applied temperature gradient is parallel to the direction of gravity and the migration velocity of a drop is the sum of two terms due to gravitational effect and thermocapillary effect, respectively. That is,

$$V=\frac{2g(\rho-\rho')(\mu+\mu')}{3\mu(2\mu+3\mu')}R^2-\frac{d\sigma}{dT}\frac{2\kappa}{(2\mu+3\mu')(2\kappa+\kappa')}\Gamma R, \quad (1)$$

where R is drop radius. σ, μ, ρ, and κ are the interfacial tension, the dynamic viscosity, the liquid density and the thermal conductivity of continuous phase, respectively. $d\sigma/dT$ and $\Gamma = dT/dz$, respectively, the gradient of interfacial tension and vertical temperature gradient at infinite. Superscript ′ represents the quantities of the drop phase. Analytical solutions were extended to include the influence of inertia [2, 3], or the influence of heat convective [4–6]. However, the case of large Reynolds numbers and large Peclet number can only be solved by the method of numerical simulation (see refs. 7, 8).

A few microgravity experiments on thermocapillary drop migration have been performed on board the microgravity sounding rocket and spacelab. The experimental results agree with the YGB model for small drops with a diameter of 11 ± 1.5 μm [9]. However, the migration velocities are smaller than the ones given by the YGB model for larger drops (0.69–2.38 mm in diameter) [10]. More experiments have been completed on the ground, and the migration velocity of drop coupled with the effects of both gravity and thermocapillarity have been obtained. Marangoni effects may be nearly separated from the coupled effects only in the case of very small drops size and a small applied temperature gradient [1, 11, 12].

Ground-based experimental results show that coupled drop migration velocities are much smaller than those of the linear model [13]. At present, the drop shaft microgravity experiment gives similar results. In general, both conclusions agree with the microgravity sounding rocket experiment [10] and the numerical simulation, to be discussed elsewhere. It should be noticed that although different experimental medium systems were used in the present experiment and in the sounding rocket experiment, conclusions are the same, but with a slight difference in quantity.

2. EXPERIMENT MEDIUMS

In this experiment, immiscible vegetable oil and 5 cst silicon oil were used as experiment mediums for

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Table 1. Physical parameters of liquids

	Temperature			
Fluid properties	15°C	35°C	50°C	70°C
μ' (cp = 10^{-2}dyn·s/cm^2)	5.09	3.61	2.86	2.17
κ' (mW/m·K)	112	111	107	105
ρ' (g/cm^3)	0.919	0.902	0.887	0.869
β' (1/K)	0.00118	0.00118	0.00118	0.00118
μ (cp = 10^{-2}dyn·s/cm^2)	92.2	39.7	23.7	13.67
κ (mW/m·K)	176	175	173	171
ρ (g/cm^3)	0.919	0.907	0.897	0.886
β (1/K)	0.00081	0.00081	0.00081	0.00081
σ (dyn/cm)	1.51†	1.18	0.722	0.422
$d\sigma/dT$(dyn/cm·K)	−0.0339†	−0.0322	−0.0172	−0.0152

† Data given by extrapolation.

the matrix liquid and drop, respectively. The vegetable oil had nearly the same density as 5 cst silicon oil at about 15°C and is immiscible at room temperature. Virtually all the necessary liquid properties were measured especially for the drop shaft experiment. Measurement errors are within 2% for σ, and smaller than 5% for other physical parameters. The parameters of this liquid system were measured by the same methods as those used for the ground-based experiment [1]. The major properties of the liquid system used in the present experiment are summarized in Table 1.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus, as shown in Fig. 1, was developed to satisfy the requirements of the drop shaft experiment. Figure 1 shows a vertical cut through the test cell, which is a configuration similar to the one of ground-based experiment. The test cell is 30 × 30 mm^2 in cross section and 3.3 mm in height. Its upper and lower walls consist of two red copper blocks, which are fixed in place with a polisulfone (PSF) frame. Three side glass windows permit optical observation and image recording. The remaining wall is a PSF plane with a sealed hole for drop injection. Five thermocouples are located in the cell through the plane for measurement of vertical temperature distribution. Two small holes on the PSF plane connect with pipes which fill the test cell with continuous liquid and allow for air exhaustion. The test cell is heated via electric coils by the upper copper block and cooled by the lower copper block via peltier element with fans radiating heat. Two thermocouples are fixed in upper and lower blocks to control a steady temperature difference between the two blocks by the EUROTHERM 818 temperature controllers.

A special device was developed to inject drops into the continuous phase liquid. The main part of the drop injector consists of two slender co-axial steel pipes, which can be conveniently inserted or withdrawn from the test cell through the side PSF planes. The injector is connected to two syringes which are full of drop liquid and continuous phase liquid, respectively. The syringes, driven either by computer-

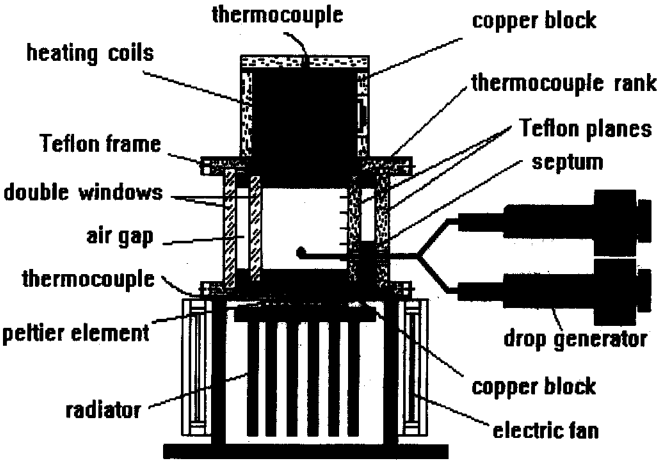

Fig. 1. Schematic diagram of the experimental apparatus.

regulated step motors or by hand, inject liquid drops in a range from 0.1–10 mm in diameter. Drops can be generated and suspended successfully in the matrix liquid and the drop size can be controlled exactly as required.

In the present drop shaft experiment, the drop capsule is divided into three levels for integrating the experiment facility. Two drop migration systems were packed in the capsule so that two experiments can be performed simultaneously during each free fall. The experimental procedure is designed to be automatically controlled by computer system, though the system may also be over-ruled by hand operation. Experimental conditions, such as drop size and drop numbers, can be controlled by tele-operation according to the requirements. Moving drops were monitored and recorded on-line by a CCD video camera; drop diameters, drop migration trajectories and velocities can be obtained by analysis of image data. Figure 2 shows the capsule arrangement of the experimental apparatus. The matrix liquid was preheated more than one hour to keep the temperature gradient before the free fall, and a nearly linear temperature profile was obtained. The short microgravity period of 4.5 s is limited. The drop is injected before the free fall, and migrates upward slowly due to both buoyancy and thermocapillary effects. After several seconds, the capsule is released, and the drop continues to migrate in microgravity environment during the free fall. In this way, the migration in microgravity condition begins from a specific initial velocity but not from the rest. This may partly overcome the disadvantage of short microgravity period. In the present experiment, the migration velocity is much higher due to joint buoyancy and thermocapillary effects than when the drop was driven only by thermocapillary effect in microgravity, because the density of drop liquid is less than that of matrix liquid. The initial acceleration process of the drop driven by both effects is used to shorten the acceleration period in a microgravity environment.

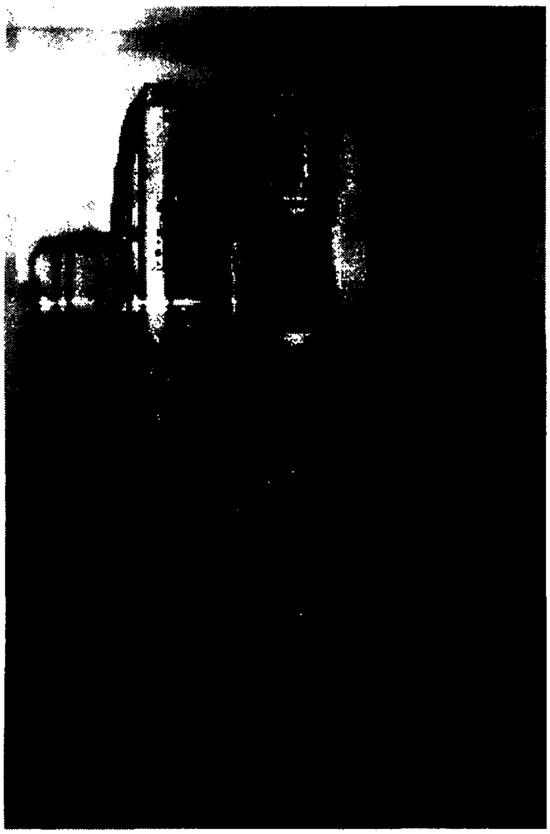

Fig. 2. The capsule arrangement of the experimental apparatus in drop shaft experiment.

4. EXPERIMENT RESULTS

The velocity feature of drop migration during the free fall was observed in the present experiment. Figure 3 gives the velocity histories of drop migration during the 4.5 s microgravity period under a temperature gradient of 32°C cm^{-1}. Microgravity began when the drop moved from the bottom to a height of 2/3 of the test cell. Because the vertical temperature gradient was persistent in the test cell, the thermocapillary force always acted on the drop from the time of injection and throughout the free fall. In addition to the thermocapillary force, a buoyancy acted on the drop before the free fall. Figure 3 shows that the migration velocities of all three drops almost reached their steady value, the thermocapillary velocity, when the microgravity period was over. It

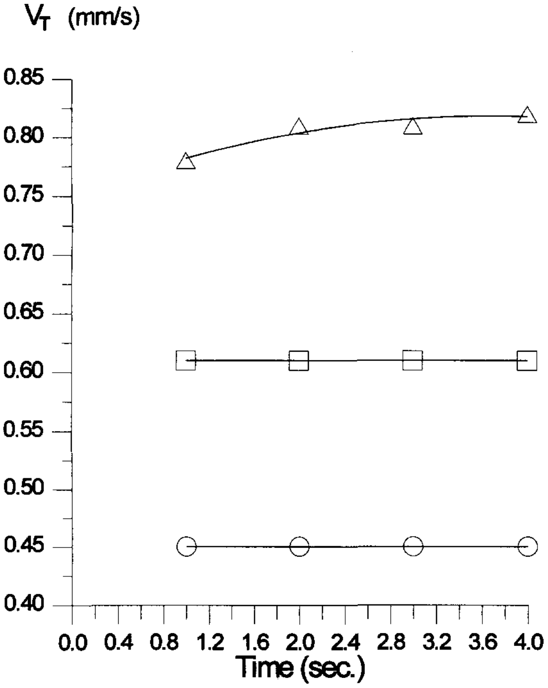

Fig. 3. The time history of drop migration velocity in microgravity environment.

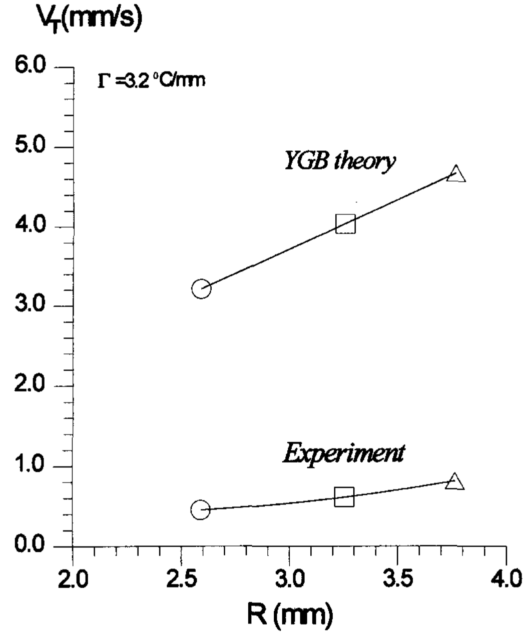

Fig. 4. The experimental result of thermocapillary velocities vs drop diameters and the corresponding data given by YGB linear theory for temperature gradient 3.2°C mm^{-1}.

can also be seen in this figure that smaller drops, compared to larger drops, can reach their steady value of thermocapillary velocity earlier for the fixed temperature gradient.

The experiments were completed for different drop sizes. The results of a set of thermocapillary velocities with variable drop diameters for a temperature gradient of 32°C cm^{-1} is shown in Fig. 4. The larger the drops, the higher the thermocapillary velocities for the fixed temperature gradient. According to equation (1), the YGB model gives a linear relation between thermocapillary velocity and drop radius for fixed temperature gradient, and the thermocapillary velocities given by the linear theory are much higher than their counterparts obtained in these present experiments. These conclusions agree with the ground-based experiment results [1]. The measured thermocapillary velocities of drop migration and the corresponding Reynolds numbers are reported in Table 2.

Table 2. Migration feature of present experiment for $\mathrm{d}T/\mathrm{d}z = 32°\mathrm{C}\ \mathrm{cm}^{-1}$

Drop diameter D (mm)	Thermocapillary velocity V_T (mm/s)	Reynolds number Re
5.18	0.45	0.88
6.51	0.61	1.50
7.53	0.07	2.18

Table 3 shows the experimental data (V_{exp}) and theoretical data (V_{YGB}) of thermocapillary velocities, in which both the present experimental data and the data obtained from Wozniak's experiment [10] are given. Different liquid systems are used in the two experiments, but both of them show that the experimental velocity data are remarkably lower than those given by YGB model.

5. DISCUSSION

The experiment in a microgravity environment may produce a drop migration driven only by a thermocapillary effect. In the present free fall experiments, the thermocapillary velocities were obtained in a microgravity environment, and the thermocapillary velocity features of drop migration for intermediate Reynolds numbers were studied. The experimental results show that the drop migrations in the case of intermediate Reynolds numbers of 0 (10^1), in order of magnitude, differ largely from the simplified linear theory given by YGB model, and the drop thermocapillary velocities of the present experiments are much smaller than those suggested by the linear case. In general, this conclusion agrees with the previous ground-based experiment [13] and the sounding rocket experiment [10]. Because both the temperature gradient and the drop size in the present experiment are larger than those in the sounding rocket experiment [10], the difference of thermocapillary velocities between experimental data and theoretical ones is greater in the present experiment (Table 3). This implies that non-linear effects should be considered in the drop migration for Reynolds numbers larger than one. When the Reynolds numbers are larger, the inertial and convective effects cannot be neglected. Furthermore, non-linear effects need to be considered, which complicates the drop migration feature. The thermocapillary effect cannot be simply de-coupled from the influence of gravity in the ground-based experiments for a non-linear model.

The present experiment clearly shows that the Marangoni migration velocity depends on the drop diameter and the applied temperature gradient for fixed experimental mediums, even in the case of drop migration for intermediate Reynolds numbers. This conclusion agrees with ground-based experimental results and the sounding rocket experiment. It can also be observed that the drops had deformations when they migrated in normal gravity due to their relatively large diameters. This means that there was a difference in the distribution of density, vertically, between the drop liquid and matrix liquid, which resulted in the deformation of the drop due to buoyancy. When the free-fall began and buoyancy disappeared, the drop deformation was reinstated (Fig. 5).

According to the experimental results, 4.5 s of microgravity period is not long enough for a larger drop approaching its steady thermocapillary velocity in the present experiment. So the special experiment

Table 3. The experimental and theoretical data

	Γ (°C cm^{-1})	R (mm)	V_{exp} (mm s^{-1})	V_{YGB} (mm s^{-1})	V_{exp}/V_{YGB}
Present drop shaft experiment	32	3.77	0.77	4.67	0.16
		3.26	0.61	4.04	0.15
		2.59	0.45	3.21	0.14
Sounding rocket experiment [11]	9.3	2.38	4.12×10^{-2}	1.72×10^{-1}	0.24
		2.12	3.42×10^{-2}	1.53×10^{-1}	0.22
		1.98	3.36×10^{-2}	1.43×10^{-1}	0.23
		1.82	2.83×10^{-2}	1.32×10^{-1}	0.21
		1.74	2.50×10^{-2}	1.26×10^{-1}	0.20

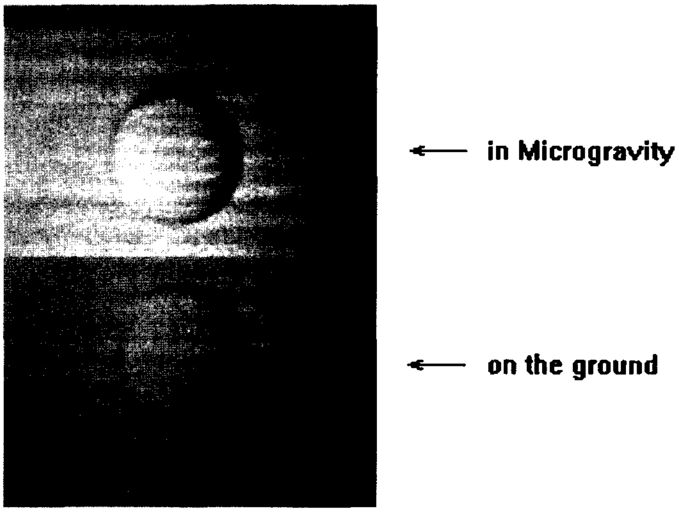

Fig. 5. Drop deformation in normal gravity (lower drop) and reinstatement in microgravity (upper drop).

method, as used in the present experiment, must be considered to overcome the disadvantage of a short microgravity period. Apparently, a longer microgravity period, such as 10 s supported by JAMIC drop shaft facility, will be more better for the drop migration experiment.

In the present experiment, the thermocapillary velocities of drop migration were obtained. Future experiments will contribute to further understanding of migration features. Furthermore, comparison of experimental results with numerical simulation is necessary and will be discussed elsewhere in the future.

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