Thermocapillary migrations of drops and bubbles

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Abstract

The transport phenomenon of drops or bubbles is a very important topic in fundamental hydrodynamics research and practical applications such as material processing and the chemical engineering. In microgravity environment, if drops or bubbles stay in a continuous phase with non-uniform temperature field, they will start to move as a result of the variance of the interface tension. This kind of movement is called the Marangoni migration. This review tries to sum up the main results in this field on theoretical analysis, numerical simulations and experiments. So far the theoretical analysis is still limited to the linear or weak nonlinear steady questions, while the current numerical simulations can already obtain the time-dependent process of the bubble/drop migration when the effect of heat convection is small. For strong heat convection problem, or when the Marangoni number is bigger than 100, no numerical result is in consistence with those of experiments so far. Some of the lastest numerical results are shown when heat convection is strong, and the main difference between strong and weak heat convection is analyzed. Finally, we also discuss the main unresolved problems in this field and some possible directions in the future.

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1 Introduction

The migration of drops and bubbles is a very common physical phenomenon in daily life, which can happen to the air bubble in water tunnel, the steam bubble in the boiling water, the drops in the oil bottle, the raindrop and so on. These drops or bubbles appear when one kind of liquid or gas is put into another kind of fluid (continuous phase), and they will start to move when there is some kind of force pushing them. The migration of drops/bubbles exists in many industrial applications such as material manufacture, crystal growth, industrial processing, chemistry, drugs manufacture and so on. Along with the fast development in space exploration, especially the increasing number of space experiments, the studies on the physical mechanism of drop/bubble migration phenomena under the microgravity environment become more and more important.

In the environment of normal gravity, the drop or bubble, if it does not dissolve into the continuous phase, will move due to the buoyancy when the densities of two fluids are different. As a matter of fact, the bubble migration driven by the buoyancy is a classical hydrodynamical problem that has been extensively discussed in many textbooks and monographs.

In space, the influence of gravity can be ignored, and buoyant effect vanishes, so some other mechanism is needed to drive the drop or bubble. In practice, people normally use the non-uniformed temperature field, the electromagnetic field [1], or electrophoresis [2] to drive the drop/bubble. In practice, most attentions have been paid to the surface tension gradient generated by temperature or concentration gradient of the continuous phase. And the drop or bubble migration caused by the gradient of temperature is the so-called thermocapillary migration. Under the normal gravitational condition, the thermocapillarity is covered by the gravitational effect, and can only become noticeable in some very small-size systems. Under the microgravity environment, we can get a undisturbed physical picture of the thermocapillary problem.

In most cases, the value of interface tension will decrease when temperature rises, so when the drop/bubble is put into the continuous phase with nonuniform temperature

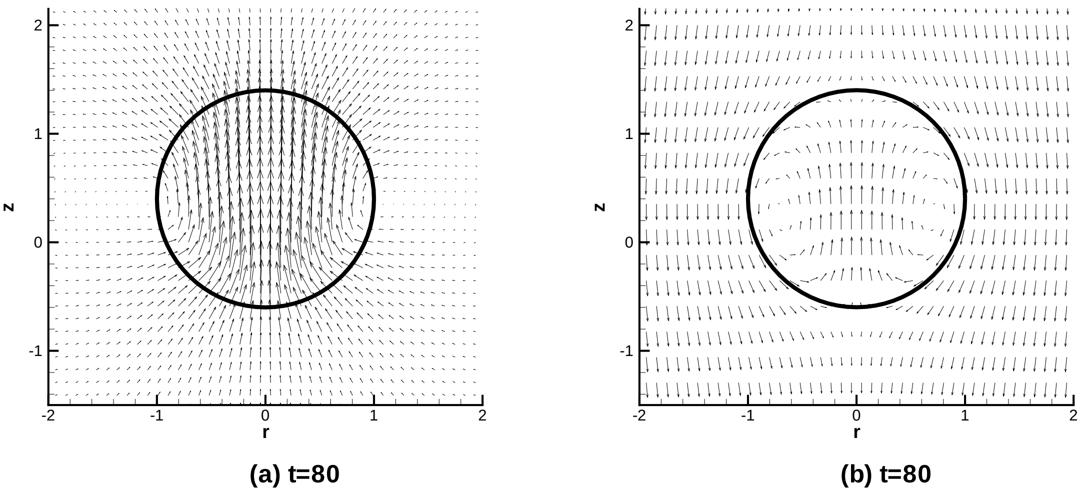

Fig. 1. The typical computed velocity field of the drop thermocapillary migration: (a) in the laboratory reference frame; (b) in the reference frame moving with the drop.

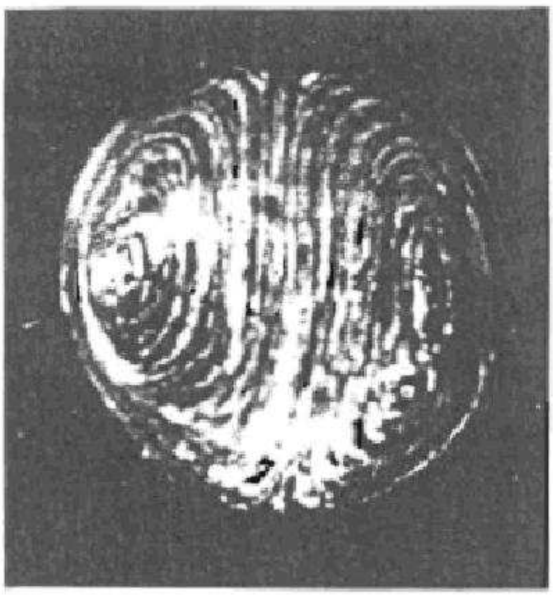

Fig. 2. The experimental picture indicating the flow inside the thermocapillary drop (from [6]).

field, the interface tension is not constance any more. The varying interface tension will drive the liquids of both sides, the liquid inside the bubble/drop will form eye-like vortices (see Figs. 1 and 2). In the meantime, the drop/bubble will start to move from the low temperature part of the continuous phase to the the hot end. Different from buoyancy-driven migration, a new physical mechanism exists behind this phenomenon and the research in this direction will help people to understand other thermocapillary problems.

In the microgravity environment, the study on the dynamics of drops and bubbles is important not only in theoretical aspect, but also in many applications related to the space exploration. For example, it is inevitable to encounter the dilemma of the mixture of two undissolved fluids during the material processing. Under the normal gravity, it is easy to separate them if their densities are different. However, this can not be done under the microgravity condition, so the thermocapillarity migration is a good choice. Along with fast space exploration, the non-mold foundry technique of spatial materials is already considered the most promising technology to get materials of high purity. In the manufacture process, the existence of drop/bubble is inevitable, and the thermocapillarity migration technique may discharge them ([3], [4]). Moreover, the Marangoni migration can also be applied to the combustion system of rockets, the cooling system of space environment ([5]), all kinds of space chemical experimental processes, space biological researches and so on.

In the following, we will mainly present the works related to the single bubble/drop migration, which is intensively studied and fruitful in the last few decades. A more detailed discussion on thermocapillary migration can be found in[7]. In section 2 of this review, we will discuss the theoretical results in this field, and introduce the symbols that we are going to use throughout this paper. Section 3 and 4 will discuss numerical simulations and experimental results respectively. Section 5 provides the summary and some proposals for future work in this direction.

2 Theoretical results

2.1 Formulation of the problem

In the zero-gravity environment, a fluid particle (bubble or drop) is placed in an ambient fluid with a temperature gradient G and generally moves toward the hot region under the thermocapillary force. The particle is assumed to keep spherical shape through the whole process. The governing equations of velocity $\mathbf{u}$, pressure $\mathbf{p}$ and temperature T can be written as

$$\nabla \bullet \mathbf{u}_i = 0,$$
$$\frac{\partial \mathbf{u}_i}{\partial t} + \mathbf{u}_i \bullet \nabla \mathbf{u}_i = -\frac{1}{\rho_i}\nabla p_i + \nu_i \Delta \mathbf{u}_i, \tag{1}$$
$$\frac{\partial T_i}{\partial t} + \mathbf{u}_i \bullet \nabla T_i = \kappa_i \Delta T_i,$$

where ρ, ν and κ are the density, kinetic viscosity and thermal diffusion, respectively. Subscripts 1 and 2 denote the continuous fluid and drop, respectively. By taking the radius of particle R_0, velocity $v_0 = -\sigma_T G R_o/\mu_1$, $\rho_i v_0^2$, GR_0 as reference quantities of position, velocity, pressure and temperature, the problem can be formulated in demensionless as

$$\nabla \bullet \mathbf{u}_i = 0,$$
$$\frac{\partial \mathbf{u}_i}{\partial t} + \mathbf{u}_i \bullet \nabla \mathbf{u}_i = -\nabla p_i + \frac{\nu_i/\nu_1}{Re}\Delta \mathbf{u}_i, \tag{2}$$
$$\frac{\partial T_i}{\partial t} + \mathbf{u}_i \bullet \nabla T_i = \frac{\kappa_i/\kappa_1}{Ma}\Delta T_i,$$

where $Re = v_0 R_0/\nu_1$ and $Ma = v_0 R_0/\kappa_1$ are Reynolds and Marangoni numbers, respectively. For the thermocapillary drop migration, a key problem is the relation of terminal velocity V_∞ to Re and Ma.

2.2 Results for small Re and Ma numbers

The first theoretical model to treat the thermocapillary bubble migration was suggested by Young, Goldstein and Block(1959)[8]. At zero limit of Re and Ma numbers, they established the Stokes equations

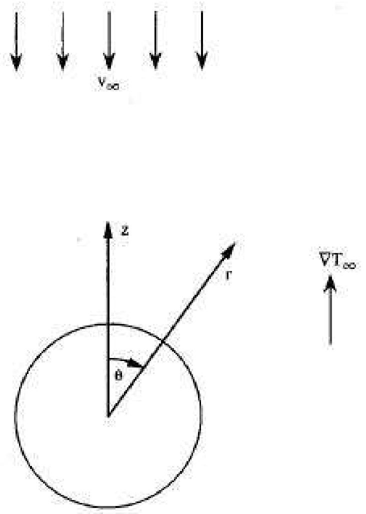

Fig. 3. Schematic figure of thermocapillary drop migration with body coordinate system.

$$
\begin{aligned}
&\nabla \cdot \mathbf{u}_i = 0, \\
&\frac{\nu_i/\nu_1}{Re}\Delta \mathbf{u}_i = \nabla p_i, \\
&\Delta T_i = 0.
\end{aligned}
\tag{3}
$$

The solution of above equations in an axisymmetric spherical coordinate system $(r,\,\theta)$ is required to satisfy the following interface boundary conditions

$$
\begin{aligned}
&v_{r1}(1,\theta) = v_{r2}(1,\theta) = 0, \\
&v_{\theta 1}(1,\theta) = v_{\theta 2}(1,\theta), \\
&\frac{\partial}{\partial r}(\frac{v_{\theta 1}}{r})|_{r=1} - \alpha \frac{\partial}{\partial r}(\frac{v_{\theta 2}}{r})|_{r=1} = \frac{\partial T}{\partial \theta}|_{r=1}, \\
&(p_1 - \frac{2}{Re}\frac{\partial v_{r1}}{\partial r})|_{r=1} - (\gamma p_2 - \frac{2\alpha}{Re}\frac{\partial v_{r2}}{\partial r})|_{r=1} = -\frac{2\sigma}{We}|_{r=1}, \\
&T_1(1,\theta) = T_2(1,\theta), \\
&\frac{\partial T_1}{\partial r}|_{r=1} = \beta \frac{\partial T_2}{\partial r}|_{r=1},
\end{aligned}
\tag{4}
$$

and the boundary conditions at far away from the drop

$$\mathbf{u}_1(r \to \infty, \theta) \to (-V_\infty \cos\theta, V_\infty \sin\theta),$$
$$T_1(r \to \infty, \theta) \to r_\infty \cos\theta, \tag{5}$$

where $\alpha = \mu_2/\mu_1$, $\beta = k_2/k_1$ and $\gamma = \rho_2/\rho_1$. μ and k are dynamical viscosity and thermal conductivity, $We = \rho_1 v_0^2 R_0/\sigma_0$ is Weber number. The linear YGB analytical solution is

$$V_{YGB} = \frac{2}{(2+3\alpha)(2+\lambda)}, \tag{6}$$

where $\lambda = \kappa_2/\kappa_1$. For the bubbler, we have $\alpha = \lambda = 0$ and $V_{YGB} = 1/2$. Usually, since the fluid particle is assumed as spheral, the normal stress balance condition above is removed.

After the YGB linear analytical solution, a series of theoretical works focus on the effect of nonlinear terms in governing equations. Generally, when the driving force on the drop is zero, the drop is in an equilibrium migration process, i.e., a steady state. However, in fact, several parameters of the continuous fluid are dependent on temperature and will be changed in the migration process of the drop. Therefore, a real steady state of the drop migration process cannot be reached. Subramanian(1981)[9] proposed a quasi-steady state assumption, which is described as the time scale of reestablishment of stable velocity and temperature fields is smaller than that of the change of parameters related to the environmental temperature. Under the assumption, all parameters related to the environmental temperature are constants. Therefore, by going over an unstable migration process from the beginning, the drop migration can arrive at a quasi-steady state, i.e., the migration speed V_∞ is a constant.

Using the coordinate transformation from the laboratory coordinate system to a coordinate system moving with the drop velocity V_∞, the governing equation can be revised as

$$\nabla \bullet \mathbf{u}_i = 0,$$

$$\mathbf{u}_i \bullet \nabla \mathbf{u}_i = -\nabla p_i + \tfrac{\nu_i/\nu_1}{Re} \Delta \mathbf{u}_i, \qquad (7)$$

$$V_\infty + \mathbf{u}_i \bullet \nabla T_i = \tfrac{\kappa_i/\kappa_1}{Ma} \Delta T_i.$$

Based on the above equations, several researches presented effects of nonlinear terms. Since the drop is assumed as spheral, the normal stress boundary condition is neglected. For small Re and Ma numbers, i.e., the inertia and convection of energy are included, Bratukhin(1975)[10] obtained the first order approximation solution $O(Re)$ by the perturbation method. Thompson(1980) gave the second order approximation solution $O(Re^2)$ and found the solution cannot satisfy the boundary condition of far away, i.e., the Whitehead paradox. For zero limit of Re number and small Ma number, i.e., the inertia is neglected, Subramanian(1981)[9] introduced the inner and outer solutions near the interface and successfully solved the problem using the method of matched asymptotic expansions. He first gave the solution for bubble up to $O(Ma^2)$, and then extended in the drop migration process and obtained the terminal velocity[11]

$$V_\infty = \frac{2}{(2+3\alpha)(2+\lambda)}[1 + O(Ma^2)]. \qquad (8)$$

Clearly, the first order term $O(Ma)$ does not appear in the solution. For the same cases of Re and Ma numbers, Haj-Hariri et al(1990)[12] discussed the effect of inertia on the terminal velocity when the drop deformation with the normal stress balance is included. They found that the migration velocity could increase, decrease, or remain unchanged depending on the value of physical parameters. For small Re number and zero limit of Ma number, i.e., the convection of energy is neglected, Balasubramaniam & Chai(1987)[13] presented an exact solution for the drop migration based on the potential flow fields in both inner and outer drop, which valid for all Re number. They further discussed the deformation of drop under the normal stress boundary condition. In order to investigate unsteady behavior of the drop migration, Dill & Balasubramaniam(1992)[14] presented an asymptotic solution of unsteady Stokes problem at $t \leq 1$ and $t \to \infty$ using Laplace transforms.

2.3 Results for the large Re and Ma numbers

For the bubble migration, without the diffusion of energy, Crespo & Manual(1983)[15] presented the solution at large Ma number based on the energy conservation as following

$$V_\infty = \frac{1}{3}. \tag{9}$$

For large Re numbers, using matched approximation method, Crespo & Jimenez-Fernandez (1991) [16] introduced a momentum boundary layer and presented the solution as

$$V_\infty = \frac{1}{3} - \frac{\ln 3}{8} = \frac{1}{5.1}. \tag{10}$$

For large Ma numbers, Balasubramaniam & Subramanian(1996)[17] introduced a temperature boundary layer and presented the higher order solution using matched approximation method as

$$V_\infty = (\frac{1}{3} - \frac{\ln 3}{8}) - 0.1369\epsilon \ln \epsilon + 0.6578\epsilon, \tag{11}$$

where $\epsilon = 1/\sqrt{Ma}$. It displays that the migration speed of bubble decreases with increasing of Ma number. The solutions agree well with the results of correspondent numerical simulation based on the steady-state Eqs. (7) [18][19] and experimental investigation[20]. At this time, the behavior of the thermocapillary bubble migration is reasonably well understood. The terminal velocity of the bubble increases very weakly with increasing Re number, and decreases with increasing Ma number.

For the drop migration, Balasubramanian & Subramanian(2000)[21] introduced inner and outer temperature boundary layers and presented a solution using matched approximation method as

$$V_\infty = \frac{4h(\delta)Ma}{\beta(2+3\alpha)^2(1+\delta)^2}, \tag{12}$$

where $\delta = \sqrt{\lambda}/\beta$ and h is a monotonous increasing function. It is noted that the temperature within the drop is lower than that of continuous fluid. The migration speed of drop increases with increasing of Ma numbers. The solution is in qualitative agreement with the correspondent numerical simulation based on the steady-state Eqs. (7)[22]. However the experimental investigation proposed by Hadland et al(1999)[20] and Xie et al(2005)[23] does not agree qualitatively with above theoretical and numerical results, i.e., the drop migration speed decreases with increasing of Ma numbers. Since the solutions of the theoretical analysis[21] are based on the potential flow field in the continuous phase and Hill's spherical vortex within the drop, Wu & Hu(2007)[24] proposed an ill-posedness thermal flux boundary condition in terms of the potential flow field.

The above qualitative difference between experimental investigation and theoretical or numerical results may be resulted from the quasi-steady state and non-deformation assumptions of the drop. In the experimental investigation, drop does not reach the steady state migration process. On one hand, short investigation time in the experiments is one reason, which will be checked in future experiments. On the other hand, whether the changing of physical parameters with temperature can satisfy the quasi-steady state assumption is a key question. Meanwhile, even the quasi-steady state assumption is satisfied, the effect of deformation of the drop on migration speed, which is neglected in theoretical and numerical modelling, is still an open question. Therefore, the thermocapillary drop migration at large Marangoni numbers has not been completely understood on its physical mechanism at this time.

3 Numerical simulations

With the fast development of modern computers, numerical simulations are already widely used in many research fields. Numerical investigations of the thermocapillarity migration problem started about thirty years ago. In 1988, Szymczyk and Siekmann used the vorticity-stream function scheme to simulate the bubble migration for the first time [25]. Later, Shankar and Subramanian solved the energy equation with the finite difference method, and adopted the velocity field from the analytical Stokes solution. They concluded that the non-dimensional velocity of the bubble will decrease with the increasing Ma number[26]. The similar scheme was used by Merritt and Subramanian [27] to study the combined effect of buoyancy and thermocapillarity, with Ma $\in [0, 5]$. Balasubramaniam and Lavery solved both the energy equation and the momentum equation with the finite difference scheme [18], with $\mathrm{Re} \in [0.1, 2000]$ and $\mathrm{Ma} \in [0, 1000]$. They found that the influence of Ma number is much larger than that of Re number. Chen and Lee took the deformation of the bubble into consideration, and concluded that the small deformation of the bubble might lead to big reduction in the migrating speed[28]. Further research in this direction showed that the reduction of interface tension will lead to bigger deformation of the bubble continuously when it reaches hotter region of continuous phase, therefore there might be no final stable migration speed[29].

There are also many numerical researches on the thermocapillary migration of drops, and situations involved also become more and more complex along with the development of the computational techenique. Ehmann *et al.* carried out the first numerical simulation on the drop migration[30]. Without any reasonable explanation, they found that the stable migration velocity of the drop for big Ma numbers is not always smaller than the YGB speed, and it will be larger than the YGB speed in the certain circumstances. Ma [22] used a steady model (in the reference frame moving with the drop) to simulate the drop migration, and what they simulated was the same as the two kinds of liquids in previous experiments[20], but with totally different conclusions. They found that only when Ma number is small, will the non-dimensional migration speed decrease for larger Ma. The velocity will become bigger for larger Ma number when $\mathrm{Ma} \in [50, 200]$, which fits the analytical solution in [21].

The two simulations above adopted the reference frame moving with the drop. A better understanding of the problem requires the study of the time-dependent process of the evolution, indicating the usage of the moving surface technique. In the recent thirty years, the numerical scheme of moving surface has attracted much attention, and maybe also the fastest developing field in the computational physics. The related methods include the VOF method, level set method, front-tracking method, phase field method, etc.

Haj-Hariri *et al.* used the level set methods to simulate the three-dimensional problem of the drop thermocapillary migration, and found that the temperature contour in the front of the drop will wrap around the drop during the evolution and reduce the varying

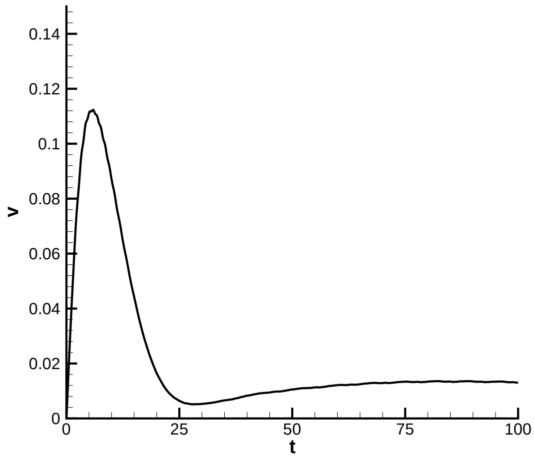

Fig. 4. The time evolution of the speed of the drop when $Ma = 500$, $Re = 10$, $\alpha = 0.3$ and $\beta = 0.3$ (from [38]).

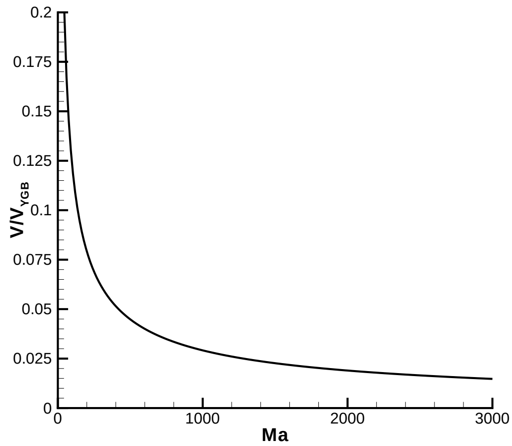

Fig. 5. The non-dimensional velocities of drops *vs* Ma number, $Re = 10$, $\alpha = 0.3$ and $\beta = 0.3$ (from [38]).

rate of interface tension. The heat convection inside the drop seems to lower speed of the drop [31]. In the case of deformation, they found the influence of inertia on drops seemed to be bigger than that on bubbles. Geng *et al.* used axisymmetric model and the front-tracking scheme to simulate experimental results in [32], and the computed final velocities of the drop were much larger than those from experiments [33]. And further study using three dimensional finite element and front-tracking method claimed a better fit with experiments[34].

Bassano and Castagnolo used the level set methods to simulate drop migration with large Re and Ma numbers, and the situation corresponded to the methyl alcohol drop and ethylamine continuous phase. They found that there is fluctuation during the time evolution of the migrating speed, but they did not give any explanation of this phenomenon [35]. One drawback of this study is that the methyl alcohol can actually be dissolved in ethylamine, which presents some other numerical challenges. Nas *et al.* used the finite difference and front-tracking scheme to study the case of multi-drop interaction in two and three dimensional situations. In their research, the bubble deformation is very small and $Ma < 100, Ca < 0.05$, and the interaction between drops can be obviously observed [36,37].

Recently, we simulated the drop thermocapillary problem with the front-tracking method and finite-difference axisymmetric model[38]. We found that there is a fluctuation of the velocity before the migration speed becomes stable when Ma number is fairly large, and the larger Ma number will lead to even larger overshoot (Fig. 3). In fact, when Ma number is large, the effect of heat convection will be stronger than that of heat diffusion. The cold liquid originally staying at the bottom of the drop will be transferred to the top before fully heated-up, and in the meanwhile, the hot liquid on the top reaches the bottom before cooling down. Hence, the temperature gap between the top and the bottom of the drop is reduced. Smaller temperature difference leads to smaller thermocapillary effect that drives the drop, and the drop will become stable at the lower speed eventually. Hence, it is clear that the overshoot of the migration speed is caused by the redistribution of the temperature along the interface. We also made some numerical comparisons between the non-dimensional velocities of drops *vs* Ma number, the trend of which fits the previous experimental study (see the references in the next section).

4 Experimental research

The experiments of Marangoni migration can only be carried out on the ground in the early stage, and most experiments are only related to the bubble in the beginning. Researchers normally use the cocurrent gradient of temperature with the gravity direction to keep the bubble stable, and the effects of different physical parameters related to thermocapillarity can then be studied. In 1959, besides the fundamental theoretical work they carried out, YGB also implemented the corresponding experiments on the ground[8]. They generated a liquid bridge using the gap within the micrometer. They tried to keep the upper end of the bridge colder than the bottom, and the bubble can be suspended inside the bridge if there is a balance between the thermocapillary force and buoyancy, which can be used to confirm the rightness of YGB theory. Later, similar technique was adopted to measure the thermocapillary force[39]. They found that the YGB theory can predict the results of the experiment with the ethyl alcohol, while the thermocapillary force in the methyl alcohol is larger than that in the YGB theory. Hardy refined the YGB's experiment[40], and gave the estimated value of σ_T in silicone oil through experiments.

Merritt and Subramanian worked on the situation when the buoyancy and the thermocapillary force of the bubble were not balanced [41], and they found that the increasing volume of the bubble during the migration will lead the bubble to move downward and then upward. Although it is obvious that the size of the bubble is not constant, but the result is still close to that of the YGB theory. Wei and Subramanian studied the multi-bubble situation. It is found that the migration of the bigger bubble, which affect the temperature field of continuous phase, will lead to nontrivial impact on the behavior of small bubbles[42,43]. Similar experiments were carried out by Barton & Subramanian [44] and Morick & Woermann [45].

In the drop migration experiments on the ground, the density of the drop can be chosen to match the density of the continuous phase to remove the effect of the buoyancy. It should also be noticed that the drop liquid should not be dissolved into the continuous phase. Despite the above limitation, the density-matching methods can perform migration mainly driven by thermocapillarity of the drop on the ground. We will only mention some of the most important works in the following: Wozniak obtained the temperature field near the drop using the technique of interference[46]; Hähnel *et al.* worked on the relation between the drop radiuses and temperature gradient, and some modification of the linear YGB theory was proposed[47]; Rashidnia and Balasubramaniam displayed the velocity field near the interface, with a good description on the influence of the thermocapillarity [48].

It should be realized that, even for density-matching methods, it is impossible to fully remove the influence of gravity on the ground. The relations between temperature and density for different liquids are quite different. It is merely possible to have the nearly close densities of two liquids for a small scope of temperature; otherwise the influence of buoyancy will become dominate. Hence, more precise experiments can only be performed in a microgravity environment. Papazian and Wilcox first performed the microgravity experiment of bubble thermocapillary migration on a rocket [49]. Thompson worked on bubble migrations in the different liquids [50]. They found that the bubble can not move

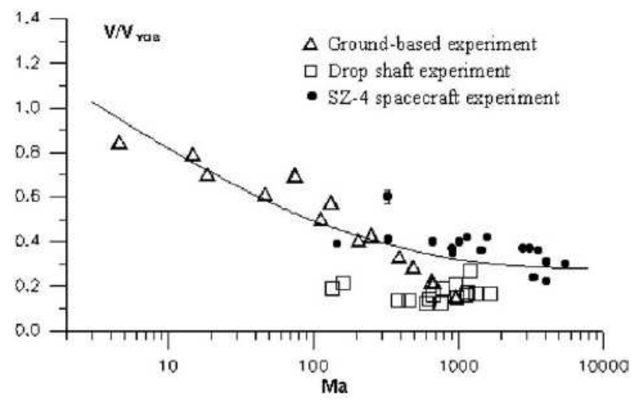

Fig. 6. The non-dimensional drop migration velocities *vs* Ma numbers (from [23], the data are from experiments on the ground (1996)[6], Falling tower (1998) [32,57] and the 4^{th} Shenzhou spacecraft (2002) [23].

in distilled water, the bubble migration speed in glycol is close to YGB speed, and the velocities in the ethyl alcohol and the silicone oil are slower than what the YGB theory predicts. There are also many other experiments on rockets [51–55] and falling towers [56], which will not be discussed here.

The microgravity experiments in China started relatively late, but with pretty fast development. In 1996, Xie *et al.* have attempted to work on the Marangoni migration with the soybean-oil drop and the silicone-oil continuous phase[6]. The Re numbers in their experiments are $O(10)$, and the final speeds of the drops are much smaller than those of YGB's. They also presented a PIV picture of the flow field inside the drop, the profile of which conformed with the theoretical results(Fig. 2). They concluded that, when Ma is big, the heat convection is the main reason leading to the gap between theory and experiment. Later, experiments with the same types of liquids are shifted to the falling tower, ending up with the same conclusion [32,57]. In fact, because of the short period of experimental time in falling towers and of the variance of viscosity with temperature, the final steady migration speed can not be reached.

The rocket and falling-tower experiments are still limited because of the relatively short experimental microgravity time. The long-time bubble/drop migration needs the platform on satellites or spaceships. In 1987, there were two sets of experiments on bubble/drop migration in the D-1 project of NASA. The first set of experiments studied bubbles and water drops with the continuous phase of silicone oil. Only the experiments with the bubbles showed the phenomena of migration, and only part of the experimental results can fit the numerical ones [58,59]. Another set of experiments studied the bubble migration in several kinds of silicone oils, and concluded that the variance of the viscosity should be considered in the energy dissipation of surface [60]). In the IML-2 space experiment of NASA (1994), Balasubramaniam *et al.* performed the migration experiments of bubble and Fluorinert FC-75 drops with the continuous phase of Dow-Corning silicone oil[61]. They concluded that the non-dimensional final speeds of both bubbles and drops will become smaller for larger Ma numbers. In 1996, the LMS project of NASA repeated the experiment of IML-2 but with the continuous phase of lower viscousity. Their conclusion was the same as that of IML-2, but with larger scopes of Re numbers and Ma numbers[20]. In 2002, Larger Ma number bubble migration was studied on the 4th Shenzhou spaceship: the continuous phase was 5cs silicone oil and the drop was Fluorinert FC-75; the highest Ma number in their experiment is 5500[23]. Besides conforming previous experimental results (Fig. 5), they also gave out the interference image around the drops. It should be stressed that, mainly due to the insufficient time for migration and to the decreasing viscosity of liquids for increasing temperature, none of the experiments above really reached the final stable migration velocity, especially for large Ma numbers.

5 Summary

There have been several decades since people started to study the thermocapillarity migration phenomena. From the case of one-bubble/drop studies in the beginning to multi-bubble/drop researches, from the simple linear analysis to the complicated non-linear analysis, researches in this field have become increasing deeper with more valuable achievements.

After the appearance of the linear YGB theoretical result, people began to focus on the non-linear effect, taking influences of inertia and heat convection into consideration. Now most people tend to believe that the effect of inertia is relatively small, but disagrees with the role of the heat convection in the Marangoni migration. From the reviewing sections above, we can see that most experiments tend to believe that the non-dimensional migration velocity will decrease with the increase value of Ma number until Ma number is fairly large (up to 5500 [23]). However, some analytical [21] and numerical [22] results

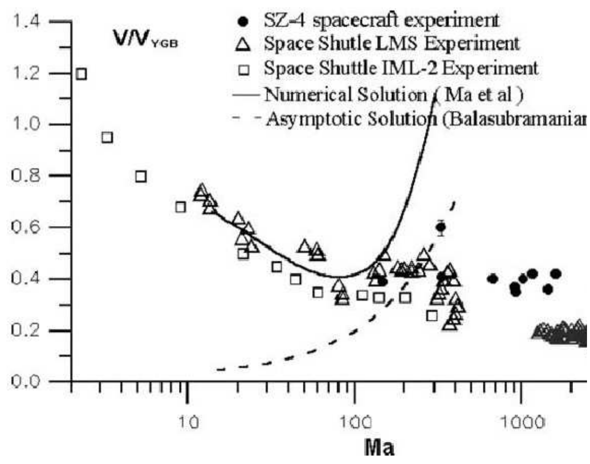

Fig. 7. Main results of non-dimensional migration speed *vs* Ma (from [23]).

tend to believe that the non-dimensional migration speed will become bigger for larger Ma number when $Re, Ma \to \infty$ (Fig. 6). Time-dependant numerical simulations on the large Ma from us, on the other hand, well fits the trend in the experiments [38,62].

Besides the research on time-dependent issue, it is also necessary to develop the theoretical model on the steady problem. Because there is no obvious deformation during the migration, the final important issue that should be addressed in this field is the research on large Ma numbers. Of course, the research should not be confined to one bubble/drop problem. In the case of multi-drop migration, the situation will be even more complicated, but maybe more valuable because of its application from the viewpoint of engineers. The deformation of the interface and three-dimensional effect can not be overlooked any more in those studies.

In general, there are relatively few opportunities for space experiments, so it is most important to know how to fully utilize ground-based techniques to remove the influences of gravity, and how to tune the space experiments with the help of falling towers, rockets, etc.

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