Wall Effects on the Thermocapillary Migration of Single Fluorinert Droplet in Silicon Oil Liquid

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1 Introduction

Fluid particle (bubble or drop) will move to the hotter side when placed in another immiscible fluid under a temperature gradient. Surface tension generally decreases with increasing temperature and the non-uniform surface tension at the fluid interface leads to shear stresses that act on the outer fluid by viscous forces. This causes droplets in the fluid to move in the direction of the thermal gradient. The flow from a region of low surface tension to a region of higher surface tension is referred to as Marangoni flow.

A few microgravity experiments on the thermocapillary droplet flow in zero gravity have been performed on board the microgravity sounding rocket and Space laboratory, and noted that there are no numerical results with which to evaluate their data [1] mentioned the complex behaviour of thermocapillary droplet migration, confirming that further studies were still needed. They also confirmed that a longer experimental time in microgravity conditions is necessary for a droplet approaching its steady thermocapillary velocity. It is also difficult to obtain complete information about the behaviour of bubbles/droplets in space, and Computational Fluid Dynamics (CFD) studies have been undertaken by many researchers in order to compare and analyse their experimental results [2]. In recent years and with advances in numerical calculation, knowledge of thermocapillary flow has undergone a considerable change and new calculated results could be used to revise and adjust some previous results. On the other hand, numerical simulations have consequently become an

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important tool in studies of two-phase flows in a microgravity environment and can help to clarify the basic fluid physics, as well as to assist in the design of the experiments or systems for the zero-gravity environment. Understanding thermocapillary droplet flow is very important for future research and for designing useful experiments; indeed, an understanding of these phenomena is highly desirable for the future design of space shuttles and equipment that might be employed in space condition. There is still much to be understood about two-phase flows in general and especially in zerogravity conditions. As a result, this paper will investigate the sensitivity of various parameters and/or scenarios that could not be investigated or fully covered previously, i.e. walls effect.

2 Methdology

The thermocapillary motion of a drop was first examined experimentally by Young, Block, and Goldstein [3], when Reynolds number (Re) and Marangoni number (Ma) are small, which means that both convective momentum and energy transport are negligible, who also found an analytical expression for its terminal velocity in the creeping flow limit:

$$V_{\mathrm{YGB}} = \frac{2|\mathrm{d}\sigma/\mathrm{d}T|r_d\lambda\mathrm{d}T/\mathrm{d}x}{(2\mu + 3\mu')(2\lambda + \lambda')} \tag{1}$$

commonly called the YGB model, which is suitable for small Reynolds and Marangoni numbers:

$$\mathrm{Re}_T = \frac{r_d V_T}{\nu} \tag{2}$$

$$\mathrm{Ma}_T = r_d V_T/\alpha = \mathrm{Re}_T . \mathrm{Pr} \tag{3}$$

where Prandtl number is the ratio of kinematic viscosity to thermal diffusivity:

$$\mathrm{Pr} = \nu/\alpha \tag{4}$$

and ν is the kinematic viscosity in m^2/s:

$$\nu = \mu/\rho$$

The velocity V_T derived from the tangential stress balance at the free surface is used for scaling the migration velocity (m/s) in Eqs. (2) and (3):

$$V_T = \frac{(\mathrm{d}\sigma/\mathrm{d}T).(\mathrm{d}T/\mathrm{d}x).r_d}{\mu} \tag{5}$$

where μ and μ', λ, and λ' are the dynamic viscosity and thermal conductivity of continuous phase and droplet, respectively. ρ is the density and r_d is the radius of the droplet. The constant $\mathrm{d}\sigma/\mathrm{d}T$ or σ_T is the rate of change of interfacial tension and $\mathrm{d}T/\mathrm{d}x$ is the temperature gradient imposed in the continuous phase fluid.

3 VOF Model and Computational Procedure

The governing continuum conservation equations for two-phase flow were solved using the ANSYS-FLUENT commercial software package [4], and the volume of fluid (VOF) method was used to track the liquid/gas interface. This method deals with completely separated phases with no diffusion. The geometric reconstruction scheme, based on the piece-wise linear interface calculation (PLIC) method of Young's [5] in Ansys-Fluent, was chosen for the current investigation. Geo-reconstruction is an added module to the already existing VOF scheme that allows for a more accurate definition of the free surface [6]. The movement of the gas/liquid interface is tracked based on the distribution of the volume fraction of the gas, i.e. α_G, in a computational cell, where the value of α_G is 0 for the liquid phase and 1 for the gas phase. Therefore, the gas/liquid interface exists in the cell where α_G lies between 0 and 1. A single momentum equation, which is solved throughout the domain and shared by all the phases, given by:

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla p + \nabla.[\mu(\nabla\vec{v} + \nabla\vec{v}^T)] + \vec{F} \tag{6}$$

In Eq. 6, $\vec{F}$ represents volumetric forces at the interface, resulting from the surface tension force per unit volume. The continuum surface force (CSF) model proposed by Brackbill et al. [7] is used to compute the surface tension force for the cells containing the gas/liquid interface:

$$\vec{F} = \sigma\frac{\rho k\vec{n}}{\frac{1}{2}(\rho_L + \rho_G)} \tag{7}$$

where σ is the coefficient of surface tension,

$$\sigma = \sigma_0 + \sigma_T(T_0 - T) \tag{8}$$

and σ_0 is the surface tension at a reference temperature T_0, T is the liquid temperature.

4 Results

This section presents the results of an extensive numerical investigation of the thermocapillary flow of a Fluorient droplet, $d_b = 9$ mm, rising in stagnant silicon oil. The size of the computational wall bounded domain was chosen as 60×30 mm with zero permeability "no inflow or outflow" from the sides. For the simulations, silicone oil properties were taken as the ones given from Hadland et al. [8]. A numerical prescription for the viscosity, density, and surface tension variation against temperature is provided via user defined functions (UDFs). These UDFs are dynamically linked with the FLUENT solver. The initial rise velocity for the droplet is set to zero. The upper surface (top wall) of the model is hotter than the bottom surface (bottom wall); both top and bottom walls are set to no-slip solid walls. The final numerical results for a range of thermal Reynolds numbers and thermal Marangoni numbers are compared to the experimental measurements of SZ-4 Space Shuttle IML-2 Experiment and Space Shuttle LMS Experiment [1] as seen in Fig. 1 which are found to be in decent agreement.

The size and aspect ratios of the cylinders were varied by using three different columns with diameters of 15, 20, and 30 mm to test the effect of column width only on the time and speed of the droplet migration. Figure 2 shows that when the ratio of the droplet diameter to the column diameter is less than 0.45, the influence of the column diameter on the ascension velocity is negligible; however, as the AR increases, there is a significant reduction in the droplet's velocity. The results obtained here were considered as a factor having crucial effect on the droplet speed; consequently, the wall effect was removed from the calculations. Note that in all thermocapillary droplet flow calculations, the migration velocity is taken as the droplet migration in the radial direction, as seen in Figs. 3 and 4; moreover, the droplet remained spherical in shape and no deformation was noticed for any of the ARs.

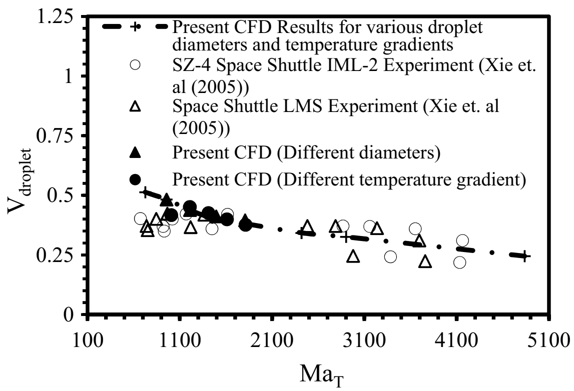

Fig. 1 Validation of present CFD with experimental data

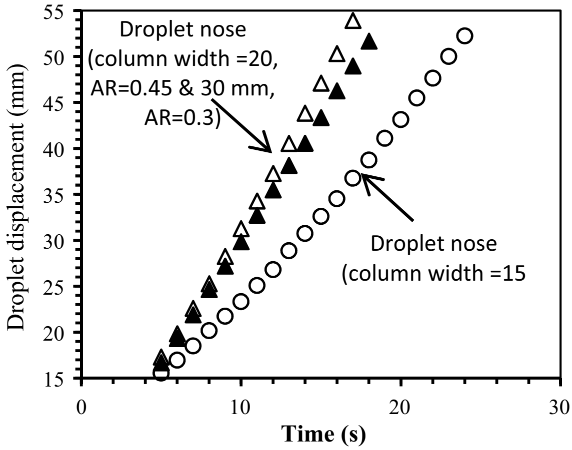

Fig. 2 Compares the *y*-coordinates of 9 mm droplets

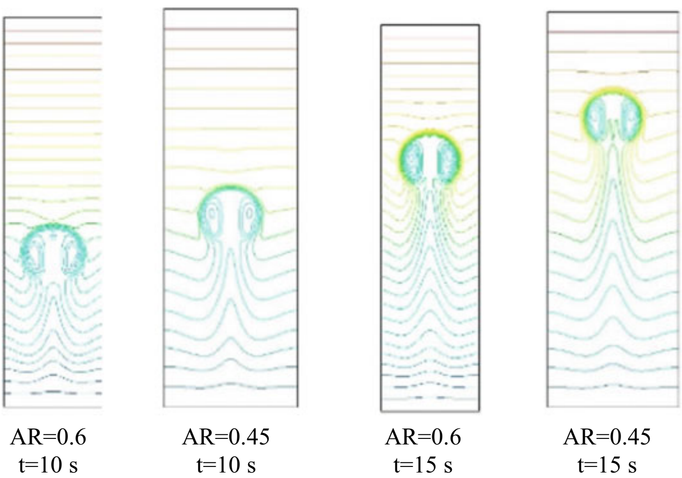

Fig. 3 2d-axis contours of temperature illustrate the effect of two ARs upon droplet migration at time = 10 s and 15 s

5 Conclusions

Two- and three-dimensional VOF simulations of two-phase (liquid/liquid) transient flow were performed using a multiphase flow algorithm based on the finite-volume method. The current results show conclusive existence of Marangoni droplet flow phenomena in a zero-gravity environment. The present CFD results show that the thermocapillary droplet rise velocity is effected by the column diameter. The results show that when the ratio of the droplet diameter to the column diameter (AR) is less

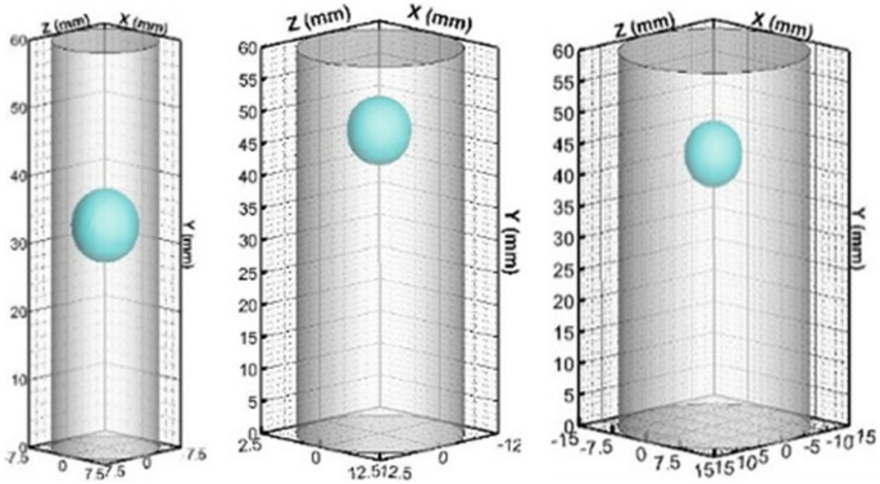

Fig. 4 Three-dimensional droplet migration towards the hotter side of three different column width (15, 20, and 30 mm), at $t = 15$ s

than 0.45, the influence of the column diameter on the ascension velocity is negligible; however, as the AR increases, there is a significant reduction in the droplet's velocity. The VOF model with the UDF was examined properly and results show that the surface tension coefficient was well coded due to the fact that it is based on the geo-reconstruct algorithm, suggesting that it is an appropriate choice to solve thermocapillary and zerogravity problems.

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