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Thermocapillary Droplet Flow in a Rotating Cylinder: A 3D study

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Abstract

In this paper, a study is presented for Marangoni flow driven by a temperature gradient, causing a droplet to migrate from a cold to a hot region in an enclosure. Specifically, the detailed behaviour of a thermocapillary isolated droplet rising in an axisymmetric rotating cylinder in a zero-gravity environment is analyzed and numerically presented via a computational fluid dynamics (CFD) approach. The momentum and continuity equations for the multi-phase flow are solved using the commercial software package Ansys-Fluent v.13. The volume-fluid (VOF) method is used for two- phase flow tracking, a methodology that has been found to be a valuable computational tool for studying the Marangoni phenomenon regarding liquid-liquid interaction, and the validation of results are in reasonable agreement with previous experimental observations from the literature. Thermocapillary droplet flow was also implemented in a 3D geometry in a zero-gravity environment for rotational velocities ranging from 0.5 to 1 radian/sec. The study revealed that the behavior of the droplet varies significantly with the angular velocity as it heads towards the side wall with increase of the angular movement.

Keywords: droplet, two-phase, zero-gravity, thermocapillary, surface tension gradient, VOF-Ansys.

1 Introduction

The initial experimental study on thermocapillary bubble and droplet migration was conducted in 1959 by Young et al. [1] in a ground laboratory for space experiments. They successfully stabilized a small, static gas bubble and moved it down against the buoyancy force by applying a vertical temperature gradient between the bottom side and the top side of the tested liquid field. Xie et al. [2] stated the complexity of thermocapillary droplet migration process, and the need for a longer time for experiments to allow the droplet to approach steady state condition and encouraged further studies to understand the ensuing complex phenomenon. Subsequently, thermocapillary flow of bubbles/droplets was studied experimentally by various researchers using on-board zero gravity experiments conducted on space lab and sounding rockets. These researchers have noted that there are no theoretical or numerical results to compare the results of their experiments, and much remains to be understood about the two-phase flows in zero gravity [2]. The trajectory of a bubble/droplet is a new field of study that aims to support research in space applications; however, microgravity flow experiments are complex, and thus it is difficult for space researchers to design a space experiment that achieves all their goals [2]. Researching the flow patterns is very desirable for an understanding of the physics of fluid motion in an environment of zero gravity, as stated previously by [3], Kang et al. [4] who conducted an onboard experimental study on the migration of thermocapillary bubbles in a recoverable satellite, stated that most of the microgravity data available from space experiments are only available for low Reynolds and Marangoni numbers. In recent years, knowledge of Marangoni phenomenon has undergone considerable progress due to advances achieved in the numerical solution techniques. Thus, numerous researchers have conducted numerical studies to compare their results obtained [5-7].

Small vibrations and rotation on the ground although are always present but hidden due to earth gravity and there is an urgent need to elucidate this phenomenology in a zero-gravity environment, As emphasized by Alhendal et al. [8], there has not been a simulation study looking at the size distribution of a bubble under both the spin state and the zero gravity states.

2 Computational Methods

In 1959, Young et al. [1] originally investigated the thermocapillary flow of bubbles and droplets using their linear model for surface tension:

$$\sigma = \sigma_0 + \sigma_T(T_0 - T) \tag{1}$$

where σ_o denotes the surface tension at a reference temperature T_o, and σ_T is the rate of change of surface tension with temperature. The two most important parameters governing thermocapillary motion are the Reynolds and Marangoni numbers defined as [4,5]:

$$\mathrm{Re} = \frac{\mathrm{RV_o}}{\mathrm{v}} \tag{2}$$

$$\mathrm{Ma} = \frac{\mathrm{U_o.R}}{\alpha} = \mathrm{Re.Pr} \tag{3}$$

$$\mathrm{Pr} = \frac{\mathrm{v}}{\alpha} \tag{4}$$

$$V_T = \frac{\sigma_T \Delta T R}{\mu} \tag{5}$$

Here, R is the droplet radius, ν is the dynamic viscosity and α is the thermal diffusion of the surrounding fluid, and Pr is the Prandtl number.

In this study the computational domain is defined as a cavity enclosed by non-slip adiabatic walls with no velocity at the inlet or the outlet, and all calculation were started at time t=zero as seen in figure 1. Before "patching the droplet using Ansys [9] Fluent's "region" function", the matrix liquid has been heated to achieve a stable steady state temperature gradient. The density, viscosity and surface tension coefficients for silicon oil and droplet, are computed via a user defined function "UDF" facility in Fluent emphasizing due dependence on temperature. The thermophysical properties for density and viscosity for the host liquid and fluorinert (FC-75) droplet used in the present simulation were taken as those given in Table (1) from [10], as follows: The change in density with temperature of the host liquid and droplet is defined as:

$$\boldsymbol{\rho = A + BT} \tag{6}$$

and the change in viscosity with the temperature of the two liquids is taken from:

$$\boldsymbol{\mu = exp(\, C + D/T)} \tag{7}$$

Furthermore, the surface tension coefficient between the oil (DC-200) and the fluorinert (FC-75) droplet is specified as $3.6x10^{-5}$ N/m.K.

The VOF model presented in [9 and 11] with the user defined functions (UDF) for density and viscosity of both the droplet and host liquid were examined and validated appropriately. The results presented in the figures obtained in this paper show that the UDF density, viscosity, and surface tension modulus were correctly coded, indicating that they are a suitable choice for solving thermocapillary problems [4,5].

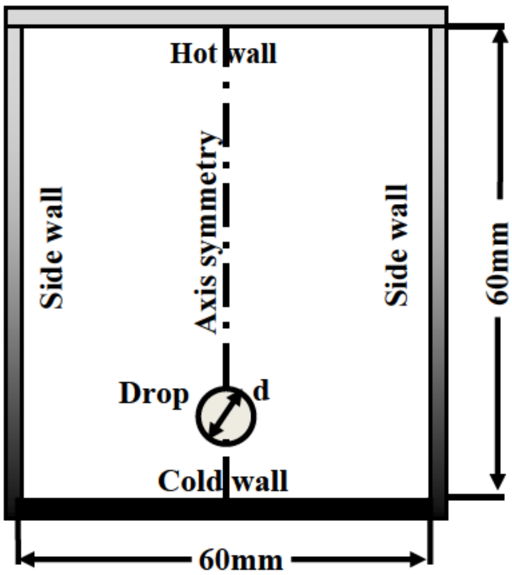


Figure 1: Schematic of droplet trajectory in a uniform temperature gradient.

3 Results and Discussion

Figure 2 displays the flow patterns and the isotherms that developed within the fluorinert droplet and the silicone oil for 2D axisymmetric simulations for the indicated times. The dynamical behaviour of the droplet as it migrates from the bottom to the top surfaces in a container maintained at temperatures of 283 and 343 K, for the upper and lower walls, respectively is clearly seen.

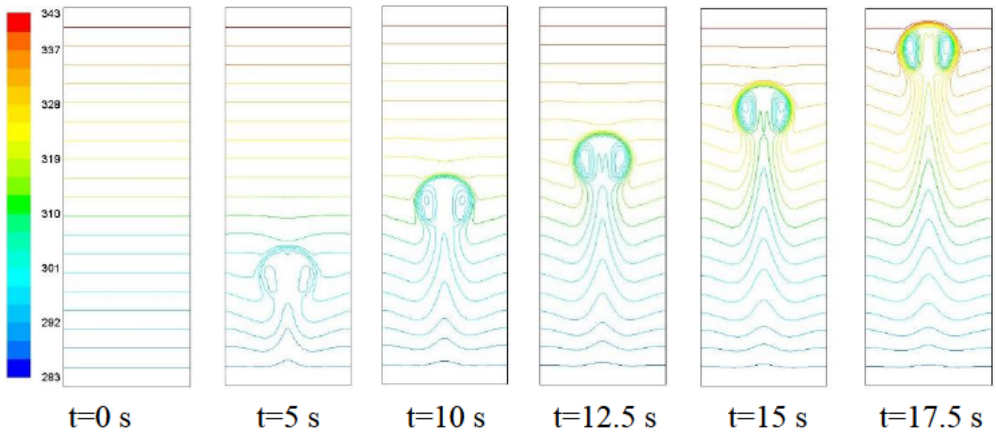


Figure 2: Contours of the isotherm flow patterns of the droplet for axisymmetric simulations.

The final computational results when compared with the thermal Reynolds and thermal Marangoni numbers obtained in the experimental case carried out via the SZ-4 IML-2 and the LMS space shuttle experiments [2] found reasonable agreement as shown in Figure. 3.

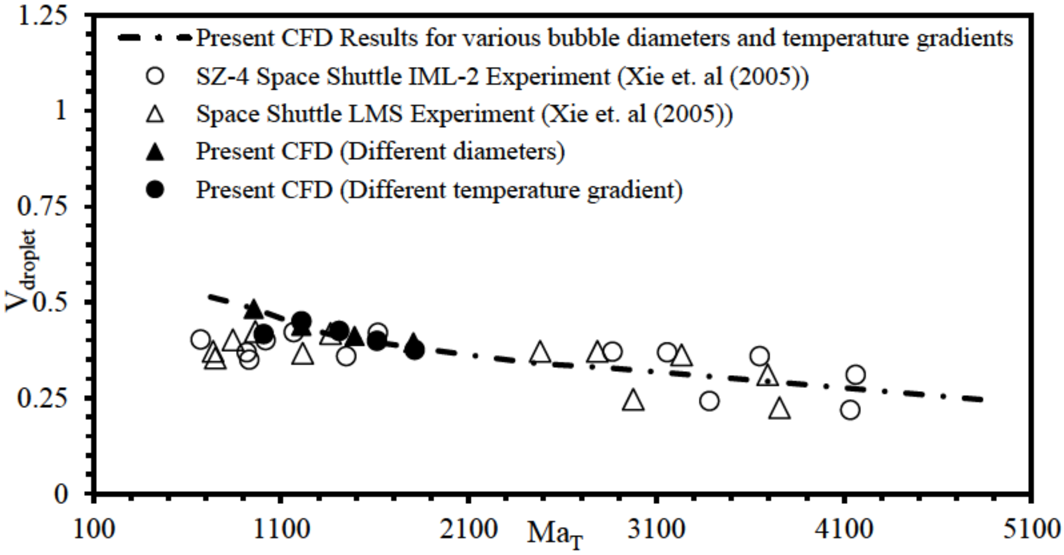
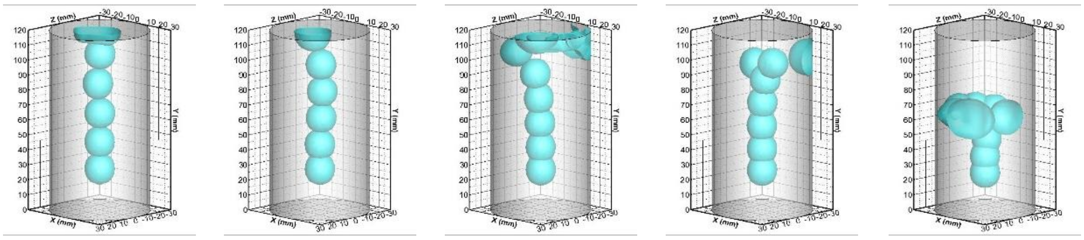


Figure 3: Validation of present CFD with experimental data of [2].

The present results are obtained for the case of a single drop of equal radius, 5 mm, located in the center of the cylinder and at a distance of 10 d from the cold bottom wall. A temperature gradient of 0.5 K/mm was prescribed for each simulation and the corresponding thermal Reynolds (Re_T) and Marangoni (Ma_T) numbers for all cases were set to 6.97 and 713, respectively.



ω =0.5 rad/s **ω =0.6 rad/s** **ω =0.7 rad/s** **ω =0.75 rad/s** **ω =1 rad/s**

Figure 4: The flow pattern results of the numerical calculations of five angular velocities (ω).

The degree of divergence of the droplet toward the side walls of the cylinder depends primarily on the angular velocity (ω) and the distance (r) from the center with respect to rotational forces, and on the thermal gradient vis-à-vis the Marangoni force, as shown in the figure 4. In the case where the angular velocity is set at (ω) = 0.5 rad/sec and less, the droplet migrates linearly toward the hotter side, is indicative of the overriding effects of the thermal force on the droplet's trajectory. With ω = 0.6 rad/sec, the thermocapillary force still dominates the droplet migration.
These flow pattern figures also show that at angular velocity ω = 0.7 rad/sec and higher, an oscillation appears, and the droplet moves away from the axis of rotation toward the side walls before it reaches the top of the cylinder. The primary difference in the droplet behaviour can be observed by increasing angular velocity to 0.75 radians/sec, resulting in a significant shift in the droplet orientation towards the outer walls. Increasing the spin rate to 1 rad/sec and higher produces a significantly higher effect on the trajectory.

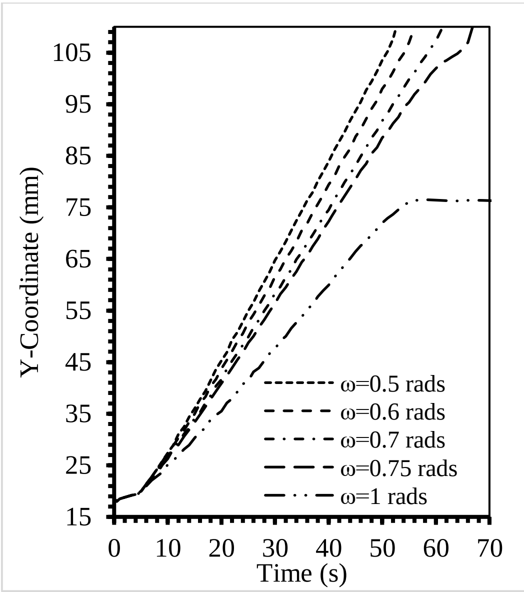


Figure 5: The distance toward the hotter side of the five angular velocities (ω).

In general, it is noted that for a low rotational velocity of ω<0.5, the motion of the droplets is mainly influenced by the Marangoni force. However, at a higher rotation speed ω> 0.6, and in the presence of a constant temperature gradient, the droplet dynamics including inertia is dominant over the rotational influences and behaves quite differently, such studies further indicate that a small rotational speed has a significant influence on the droplet dynamics and can also cause a significant decrease in the droplet velocity as it moves toward the hotter side. This is clearly shown in Figure 5, which shows that the ascent takes longer to reach the hotter upper wall in the case of higher rotational speeds.

4 Conclusions and Contributions

The existence of the Marangoni phenomenon has been demonstrated by elucidating the trajectory and shape of the droplet in zero gravity by providing numerical calculations and flow pattern.

In space, where the effect of gravity is absent, rotation can have noticeable effects on the thermocapillary (Marangoni) bubble/droplet behavior. These effects can have predominant effects on the behavior and movement of gas bubbles and liquids droplet in a zero gravity. The results in this research show that the centrifugal force arising due to angular velocity is an example of an external force that is absent in earth gravity while such effect is significant in a zerogravity space environment. In addition to demonstrating the effect of these low rotational velocities in space, a comparison was made between these velocities via the thermal Reynolds and Marangoni numbers to clarify the effect of angular velocities in the presence of temperature gradients on the behavior of droplet. Current results can used to direct the trajectory of droplets in zero gravity by changing rotational velocities or temperatures between the upper and lower walls. Also, the dynamics and collision of droplets in zero gravity conditions can be controlled by rotating the cylinder at certain speeds. Since it is difficult to achieve zero gravity in a laboratory environment, one can clearly and profitably demonstrate the relevant phenomena using numerical simulation. Simulating these phenomena also allow researchers to study the effects of changing the sensitivities of different parameters. Thus, computational fluid dynamics (CFD) has become an important vital tool for studying thermocapillary flow phenomenon to elucidate basic flow physics. It can also help design a more suitable experiment for microgravity and simulation proves its worth and potential as a valuable tool for researching and tackling challenging problems in zero-gravity conditions, and one can note the numerical modelling credentials of simulating realistic 3D Marangoni states. No previous similar work was used to compare the results obtained; however, the present study can be used in the future to validate recent results. In order to test the behavior of off-center droplets, a 3D simulation is necessary and a 2D spin axis will not be sufficient to model such flows.

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