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Numerical Investigation Regarding the Influence of 3-D Marangoni Flow on Bubble Behaviour in a Rotating Cylinder

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The migration of gas bubbles immersed in a liquid under the action of a temperature gradient and surface tension (Marangoni flow) in a zero gravity environment is numerically investigated for different Ma, Re, and Pr (Marangoni, Reynolds, and Prandtl numbers). The full Navier–Stokes equations as well as the energy equation for temperature gradients are solved incorporating a volume of fluid (VOF). Finite Volume method, and the surface tension force is modeled by a continuum surface force (CSF). The axisymmetric model is further extended for a 3-D geometry to investigate the case of a rotating cylinder to enhance bubble merging behavior in a Marangoni flow. It has been verified that the calculated results are in agreement with available experimental and numerical results. Rotational force can effect the enhancement of bubble migration and contact between the bubbles in microgravity. It is also concluded that the VOF is able to simulate two-phase flow under microgravity conditions.

1. Introduction

In zero gravity, the Marangoni effect will dominate the system as the main driving force in the determination of the gas bubble movement due to the varying liquid surface tension in a temperature gradient. Bubble dynamics has become a very important study area for fundamental research and applications in a reduced gravity environment, such as space material science, chemical engineering, space-based containerless processing of materials e.g., glass is believed to have the potential of producing very pure materials, Uhlmann (1982), and thermocapillary migration may provide mechanisms to remove bubbles from the melt. Control of vapor bubbles forming in both the fuel systems of liquid-rockets (Nas and Tryggvason, 2003) and the cooling system of space habitats may be achievable using thermocapillary migration. Experiments under normal and microgravity conditions are too costly as well as being complicated, Bozzano (2009), and hence, numerical simulations become an important tool in research studies of two-phase flows under a microgravity environment. It is uneasy to get complete information about the behavior of bubble in space and a CFD study has been undertaken by many researchers to compare and analyze their experimental results, Treuner et al. (1996). The shape and the area of the varying interface are very complex and a simulation study is required, Subramanian et al. (2009). Therefore, it is necessary to carry out appropriate numerical simulations for the behavior of bubble in microgravity.

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2. Methodology : Volume of Fluid (VOF)

Thermocapillary motion of a single bubble was first studied by Young et al. (1959). Surface tension depends on the temperature and decreases with an increase in the temperature. A shear stress on the host fluid will, due to the variation of surface tension on the interface caused by the temperature gradient push the host liquid from the hot to the cold side. This viscous force will move the adjacent fluid which will move the bubble toward the hotter side of the host fluid. (Alhendal et al. 2010):

$$\sigma = \sigma_0 + \sigma_T (T_0 - T) \quad \text{where, } \sigma_T = -(d\sigma / dT) = \text{constant} \tag{1}$$

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 Reynolds and Marangoni numbers:

$$\text{Re} = \frac{RU_b}{v} \tag{2}$$

$$Ma = \frac{RU_b}{\alpha} = \text{Re}.\text{Pr} \quad \text{where, } \text{Pr} = \frac{v}{\alpha} \tag{3}$$

Here, R is the radius of the bubble, ν and is the dynamic viscosity and α is the thermal diffusivity of the surrounding liquid, and Pr is the Prandtl number. U_b is bubble velocity. The "geo-reconstructed-VOF" based on the piece linear interface calculation (PLIC) in Fluent (2006), which is a modification of the original VOF scheme to define the free surface more accurately, (Hirt and Nichols, 1981), is used in this investigation. In the VOF model, the governing equations are solved using the volume fraction in each cell. The summation of each phase's volume fraction α_k is unity: $\sum_{k=1}^{n} \alpha_k = 1$ (4)

For α_g=1.0, α_g=0.0 and 0<α_g< the cell represents the gas region and the liquid region and the interface region respectively. In a two-phase system, if the phases are represented by the subscripts 1 and 2, and if the volume fraction of the second of these is being tracked, the density in each cell is given by: $\rho = \alpha_2 \rho_2 + (1 - \alpha_2)\rho_1$ (5)

For n-phase system, viscosity, density, and all other properties are computed in the manner as the volume-fraction-averaged on the form: $\rho = \sum \alpha_k \rho_k$ (6)

The continuity equation is $\frac{\partial \alpha_k}{\partial t} + \vec{v}\nabla \alpha_k = 0$ (7)

The momentum equation is dependent on the volume fractions of all phases through ρ and μ : $\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla.(\rho \vec{v}\vec{v}) = -\nabla p + \nabla.[\mu(\nabla \vec{v} + \nabla \vec{v}^T)] + \vec{F}$ (8)

where $\vec{F}$ represents the volumetric forces at the interface resulting from the surface tension. The energy equation, shared among the phases, is shown below, and v is treated as the mass-averaged variable. $v = \frac{\alpha_1 \rho_1 v_1 + \alpha_2 \rho_2 v_2}{\rho}$ (9)

$$\frac{\partial}{\partial t}(\rho E) + \nabla.(\vec{v}.(\rho E + P)) = \nabla.(k_{eff}\nabla T) + S_h \quad (10)$$

The VOF model treats energy, E , and temperature, T , as mass-averaged variables:

$$E = \frac{\sum_{k=1}^{n} \alpha_k \rho_k E_k}{\sum_{k=1}^{n} \alpha_k \rho_k} \quad (11)$$

E_k is based on the specific heat of each phase and the shared temperature. The properties ρ and E_{eff} (effective thermal conductivity) are shared by the phases. The source term, S_h contains contributions from radiation, as well as any other heat sources.

3. Numerical Procedure

In this simulation a bubble with a diameter of 0.6 cm was placed 1 cm from the bottom wall (cold). Hence, the size of the computational wall bounded domain was chosen as 12 cm x 6 cm with no “inflow or overflow” from the sides. For the purposes of these simulations, ethanol properties were taken to be same as the properties given in table (1) from Thompson et al. (1980). The unsteady 2-D axisymmetric and 3-D models were formulated using the commercial software package FLUENT® (2006) in modelling the rise of a bubble in a column of liquid in zero gravity (Marangoni flow). Surface tension and its temperature coefficient used in the simulations for the ethanol and N_2 are (σ =27.5 dynes/cm and σ_T =-0.09 dynes/cm°C), Kuhlmann (1999). A numerical prescription for the surface tension vs. temperature behaviour is provided via a user defined function (UDF) which can be dynamically linked with the FLUENT solver.

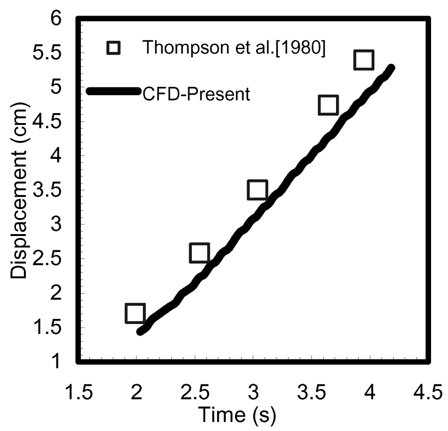

Figure 1. Comparison of the present work with Thompson et al. for N_2 diameter=0.6 cm

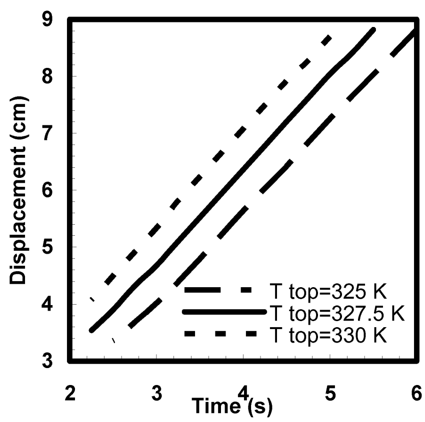

Figure 2.shows the effect of temperature on the single bubble rise velocity for d=0.6cm

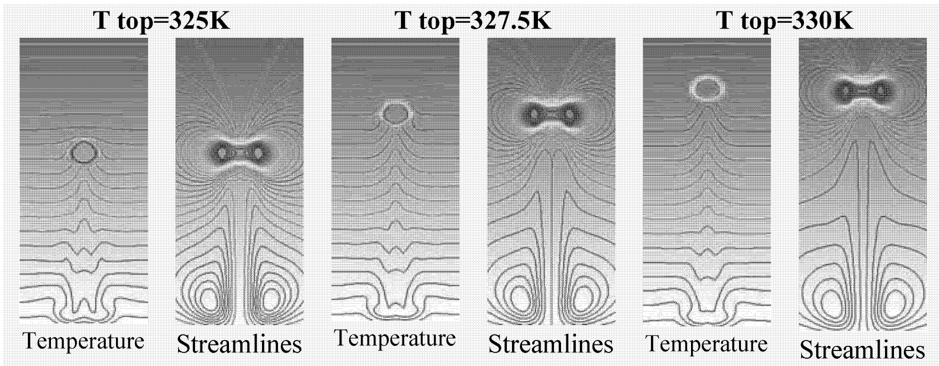

Figure 3. Sensitivity tests results for different bulk liquid temperatures (Pr=16.3) at time (t)=5 second, and bubble diameter (d) for N_2 =0.6 cm

Predicted simulations have been compared with the experimental work of Thompson et al. (1980) as shown in figure 1 and with Treuner et al. (1996) in figure 5 and agreement obtained. The effect of Prandtl number (Pr) on the migration time of single bubble was considered as shown in figure 4. In a nonuniform temperature gradient, the cold side of the bubble will have a higher surface tension than the warm side. "When ever surface is created, heat is absorbed, and whenever surface is destroyed heat is given off. Therefore a swimming bubble absorbs heat at its hot end and rejects heat at its cold end" (Nas and Tryggvason, 1993) as seen in temperature contour of figures 3 and 8. Sensitivity tests results for different bulk liquid temperatures in figures 2 and 3 show the capability of Fluent to simulate two phase flow in microgravity environment using VOF model.

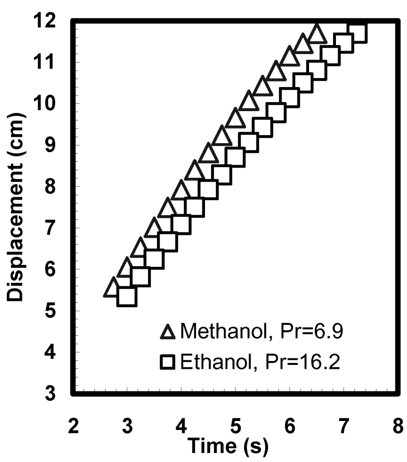

Figure 4. shows present CFD works for different fluid(Pr)

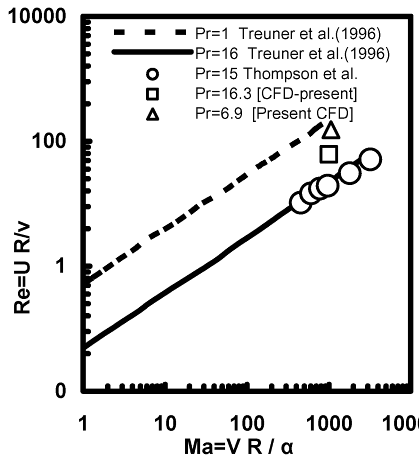

Figure 5.Comparison of present work with Thompson (1980) and Treuner (1996) for different Ma and Re

4. Results and Discussion

The fluid on the bottom is cold, and therefore has greater surface tension. The fluid on the top is hot, therefore possesses weaker surface tension. The tendency of the fluid with greater surface tension is going to pull the fluid with less surface tension towards it. This motion would be from top to bottom. The trends in figure 6 show the drop in the bubble migration time between the rotational speeds. Results show that by adjusting the rotational speed it is possible to change the gas bubble behaviour in a thermocapillary flow. The results can help determine the new migration time and speed in the rotating cylinder. Bubble rise velocity is governed by a force balance around the bubble. In the absence of gravity and rotation, there are two forces acting on a bubble: Marangoni force, which is responsible for the upward movement of the bubble and the drag force, which opposes this movement. A constant rotational speed of 0-1 rad/s is applied to the cylindrical wall which imparts an extra radial forced vortex motion to the adjacent fluid layer, the effect of which translates as a velocity towards the axis. Here, the application of rotation in thermocapillary flow imparts an additional downward force on the gas bubble which causes a reduction in the bubble rise velocity.

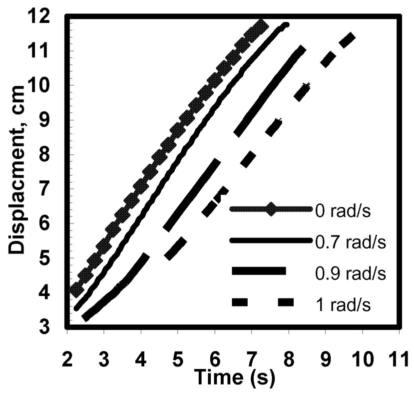

Figure 6. Rotating speed (ω) vs. bubble displacement

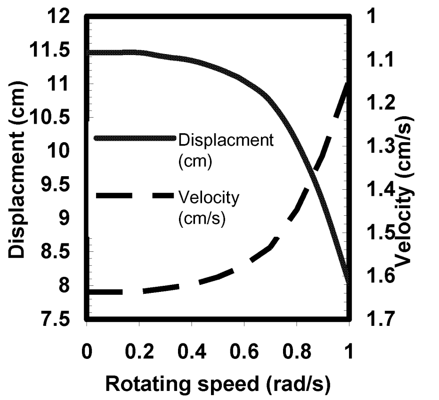

Figure 7. Rotating speed (ω) vs. Velocity and displacement of single bubble, t =7s

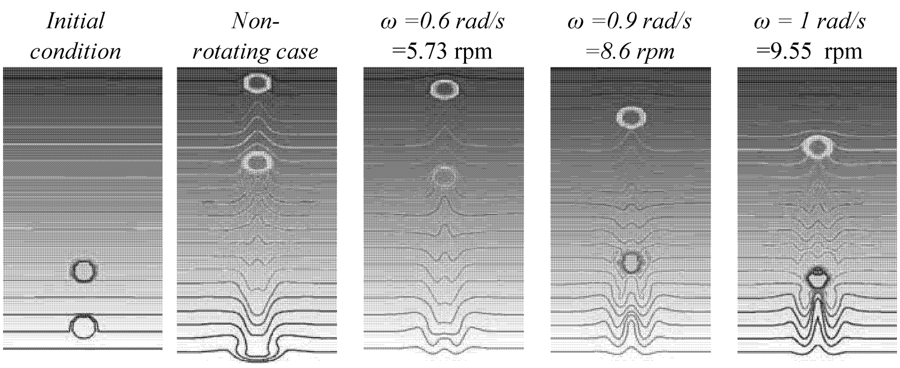

Figure 8. Effect of different rotational speed on the behaviour of two bubbles of equal size in zero gravity at time=5 s

5. Conclusion

Numerical results were presented to show the trajectory, and shape of the bubbles in a rotating liquid under zero gravity conditions. It was found that as the rotational speed increased, the time for bubble migration toward the hotter side (Marangoni) also increased. It was also shown by figures the conclusive existence of Marangoni bubble flow phenomena in a zero gravity environment. The behaviour of the compound rotational and surface tension driven motion, shapes, and trajectories of bubbles is a new area of study, and it is planned to help support research area based on space applications. Concerning the VOF solver of Fluent, the study shows that the thermal variations of the surface tension coefficient and the ability to simulate surface tension as a function of temperature (thermocapillary flow) using a UDF is possible for routine design and development engineering activities.

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