CHAPTER V

CONCLUSIONS

5.1 Conclusions

In this thesis, we have examined thermocapillary migration of bubbles and drops in zero gravity by full numerical simulations. We have extended the front tracking method developed by Unverdi and Tryggvason (1992) to include the energy equation as well as temperature dependent surface tension. The results have been verified to be quantitatively and qualitatively reliable by comparison with theoretical results.

We studied the thermocapillary migration of a single bubble in Chapter III and confirmed the effect of the governing parameters on the migration velocity, by showing that the migration velocity of the bubble decreases with an increasing Reynolds and Capillary number. Then, we studied the interaction of two bubbles and drops in detail. The major finding of the two-bubble study, reported in Chapter III, is the tendency of the bubbles to line up, side by side, perpendicular to the temperature gradient. This tendency to form bubble layers could be of considerable significance for, for example, material processing in microgravity where layers like these might affect the bulk properties of solidified materials. Drops, on the other hand, behaved somewhat differently. In the low Re and Ma number region, they act similar to bubbles; however, they tend to line up in tandem when both the Re and the Ma

are high. Drops also deform more than bubbles, along the direction of temperature gradient.

In Chapter IV, we examined the behavior of a bubble cloud, for both mono-dispersed and polydispersed cases. The numerical simulations of mono-dispersed systems show that the bubbles form horizontal layers. As soon as the bubbles form one layer that fills the channel horizontally, the rest of the bubbles form another layer. Although we saw, in the two-dimensional sixteen bubble simulation, that this layer can break up by instability waves, the layer is eventually regenerated. Three dimensional simulations confirm the formation of layers while simulation of bubbles in polydispersed systems show the same behavior. In contrast to two dimensional simulations of polydisperse systems, where bubbles of different size form a horizontal layer, a three dimensional simulation of a polydisperse system shows that different sizes of bubbles form different layers. Each layer moves with a different velocity and the larger the bubbles, the higher the migration velocity of each layer. This results in a layer of large bubbles that moves ahead of a layer of small bubbles. While the prominent feature of layer formation is a persistent characteristic in these simulations, only bubbly flows are explored here. In the light of Chapter III, where two dimensional drops were examined, we do not expect drops to form layers at high Re and Ma.

The thermocapillary interactions of two bubbles and drops as well as many bubbles reported in this thesis are the first full simulations calculated at non-zero Reynolds and Marangoni numbers, allowing for full deformations. The computatations presented here represent a significant advance in the state of the art of numerical modeling of thermal migration of bubbles and drops. Previously, no fully three-dimensional simulations have been reported, and only axisymmetric and asymmetric calculations of spherical two-bubble or two-drop interactions have been done by Wei and Subramanian (1993), and Keh and Chen (1993) at zero Reynolds and Marangoni numbers. In additon to advances on the computational side, our results show a previously unknown behaviour for multi bubble systems. No experimental evidence exists yet, but Balasubramaniam (personal communication) and collaborators expect to investigate two bubble behavior on future Space Shuttle flights. The observed layer formation appears to be very robust, and could have important consequenses for both material processing in space as well as thermal management in gas-liquid systems.

5.2 Suggestions for future work

The surface tension between two fluids depends on the properties of both fluids as well as the temperature. In addition, it also depends on adsorbed surface active materials and the electrical charge on the surface. For bubbles where the temperature is not the only factor determining the surface tension, these effects should be included also.

Although it is a good assumption that the surface tension decreases linearly with increasing temperature, the relation is not linear when the temperature varies over a large range. Non-linear relations will be needed to account for this. This could easily be changed in our current code.

Even though the magnitude of the gravity in space is small, it is still on the order of $10^{-5} g\ m/s^2$. The effect of low levels of gravity, where surface tension forces are comparable to buoyancy forces, should be considered. This, again, is easily added to our code.

If the temperature variation in the system considered are not large, the material properties do not depend on temperature. When this requirement is not satisfied, variation of properties with temperature should be taken into account.

Although some polydisperse systems are considered in this thesis, engineering systems usually involve many different-sized bubbles or drops. To simulate such systems by fully resolving the flow field accurately will be a challenging issue for future work. One way of achieving calculations along this lines is to parallelize the code. Although we attempted to do this by using the domain decomposition method, the final code has not been fully tested as yet. This extension, however, has the potential of allowing simulations with as many as 256^3 grid points.