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# A generalised multiphase modelling approach extended for heat transfer with thermal phase change

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**Abstract –** The generalised multifluid modelling approach (GEMMA) was developed and implemented in the OpenFOAM code to deal with different interfacial scales in multiphase flows. The interface between two phases is tracked by adding an interface-resolving capability in the cells occupied by large interfaces, whilst the model reverts to a standard multifluid formulation in the regions of small/dispersed interfaces. In this work, the GEMMA model is further developed to predict the condensation process of a steam bubble in subcooled liquid flows and heat transfer from steam to liquid through the interface in a turbulent stratified flow. Comparison of the simulation results with experimental data demonstrates that the model predicts well the behaviour of a condensing bubble and illustrates how the initial bubble diameter and sub-cooled temperature affect the bubble shape and lifetime. Overall, the results indicate that the extended GEMMA model provides an accurate predictive tool for heat transfer in multiphase flows.

## 1. Introduction

Thermal phase change processes are effective ways of removing heat, as the latent heat of condensation and boiling provide high heat transfer rates. Direct contact condensation and heat transfer between steam and subcooled water are widely encountered in many industrial applications, for example, in nuclear reactors where the condensation occurs mainly on free surfaces. Many studies have been conducted using experiments to understand the condensation process in detail. However, it is impossible to obtain complete information about this phenomenon because the shape and area of the interface are very difficult to measure. Therefore, it is necessary to carry out numerical simulations as a complement to experimental studies.

## 2. The Extended GEMMA Model

The GEMMA model was built on top of the standard multifluid modelling framework suitable for small/dispersed interfaces contained in the OpenFOAM reactingMultiphaseEulerFoam solver. The main idea behind GEMMA is the introduction of two different formulations within the multifluid framework; in each cell of the computational domain, one of two approaches is selected, based on the local capability of the numerical grid to resolve the morphology of the interface. The two approaches are Eulerian-Eulerian for areas in the simulation that do not have interfaces above the grid scale, and a novel multifluid approach mimicking the behaviour of an interface resolving approach such as volume of fluid for those that do. A detailed description of the model can be found in [1]. In this work, the GEMMA model is extended for heat transfer with thermal phase change and applied to steam bubble condensation in subcooled flows and steam-water stratified flow. The accuracy of the model was evaluated, focusing on three parameters of the condensation process: interfacial area, interfacial heat transfer coefficients, and interfacial mass transfer. The interfacial area is estimated as a function of bubble diameter and the heat transfer between the two phases is modelled based on the Nusselt number on both sides of the interface, from the interface to the liquid and from the vapour to the interface, which is assumed to be at saturation conditions at the local pressure. The Nusselt number for the liquid phase is calculated using Hughmark's correlation, which has been implemented as a typical model to predict the condensation process based on comparisons made between different experimental correlations in the work of [2]. It was estimated that the vapour temperature will be close to the saturation temperature due to the large heat transfer coefficient on the vapour side of the interface. In terms of interfacial mass transfer, the thermal phase change model, responsible for the mass transfer between the liquid and vapour phases at an interface due to the processes of evaporation or condensation, is developed to assure that it is only active at the interface. In this model, the heat is estimated to be totally transferred over the interface. In addition, the GEMMA model was incorporated within a large eddy simulation that used a dynamic Smagorinsky model for the subgrid stresses to predict the fluid flow, including that of a sheared turbulent interface in a steam-water stratified flow with turbulence damping at the interface.

## 3. Results and Discussion

To validate the modified GEMMA model, simulations of condensing bubbles were performed and compared with published experimental results under the conditions shown in Table 1. The behaviour of an adiabatic bubble is also compared with a condensing bubble for one of the considered cases. Fig. 1 (left) illustrates the time-dependent behaviour of the condensing bubble and the adiabatic bubble for case 3, allowing for a qualitative comparison. Through the analysis of the results, it is evident that the deformation behaviour of the condensing bubble differs from that of the adiabatic bubble. In the adiabatic bubble case, the bubble rises in the water while maintaining its initial size. The hydrodynamic force is responsible for deforming the bubble, causing it to transition from a spherical shape to an elliptical shape and eventually to a hemispherical shape. A comparison of bubble diameter history is shown in Fig. 1 (right), where two-dimensional model predictions are compared with the data of Chen et al. [3]. It can be seen that the numerical results are in reasonable agreement with the experimental data. The two- and three-dimensional bubble condensation of case 3 is contrasted in Fig. 2 (left), with a comparison between two- and three-dimensional bubble diameters over time shown in Fig. 2 (right). In general, the bubble diameter history of both simulation types agree well with the experimental data and reasonably predict the bubble condensation process. Figure 3 (left) shows a comparison of the condensation process for case 4. Both simulations agree less well with the experimental data [4] because in the simulations the bubble was initialised with a spherical shape, while it was irregularly shaped in the experiment. Nevertheless, the simulated bubbles still show the same trend of volume decrease as the experiment, with simulation of bubble volume as a function of time compared with data in Fig. 3 (right). Here, although the two-dimensional simulation tends to over-predict the volume, the three-dimensional simulation under-predicts it; but both simulations are in good agreement with the experimental data. This difference is attributable to the fact that the three-dimensional model more accurately represents the bubble volume observed in the experiment.

Figure 4 (left) shows the bubble deformation process and compares predictions with the data of Kamei and Hirata [5]. In this condensation process the bubble becomes flat initially due to the effects of buoyancy, then changes to a hemispherical shape due to the effects of mass transfer. Subsequently, the top of the bubble begins to flatten, and an oval shape is reached. Eventually, the bubble returns to a spherical shape due to the increased surface tension effect. The history of the predicted bubble shape is seen to be generally consistent with the experimental results. In addition, Fig. 4 (right) illustrates the interfacial condensation rate along the two-dimensional surface of the condensing bubble at 2 ms for case 4. The simulation results demonstrate a satisfactory agreement with the experimental results of [4], both in terms of time and bubble volume. It is worth noting that the condensation rates on both sides of the bubble are the same, resulting in a symmetric shape for the bubble.

Table 1: Operation conditions of experiment and simulation.

| Case No. | Source | $P_p$ [MPa] | $\Delta T_{sub}$ [K] | m ($kgm^{-2}s^{-1}$) | $d_B$ [mm] |
|---|---|---|---|---|---|
| 1 | Chen et al. (2010) | 0.106 | 8.7 | 100.0 | 1.024 |
| 2 | Chen et al. (2010) | 0.101 | 12.8 | 118.0 | 0.950 |
| 3 | Chen et al. (2010) | 0.130 | 25.0 | 400.0 | 1.008 |
| 4 | Kim and Park (2011) | 0.105 | 12.0 | 85.0 | 4.9 |
| 5 | Kamei and Hirata (1990) | 0.200 | 10.0 | - | 8.0 |

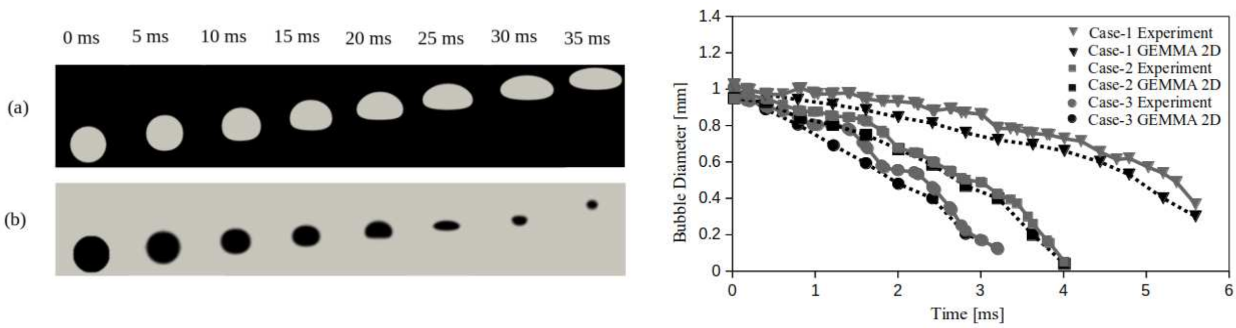


Figure 1: Two-dimensional bubble shape history comparison between (a) adiabatic bubble, (b) condensing system for case 3 (left) and comparison of bubble diameter history for cases 1, 2 and 3 (right).

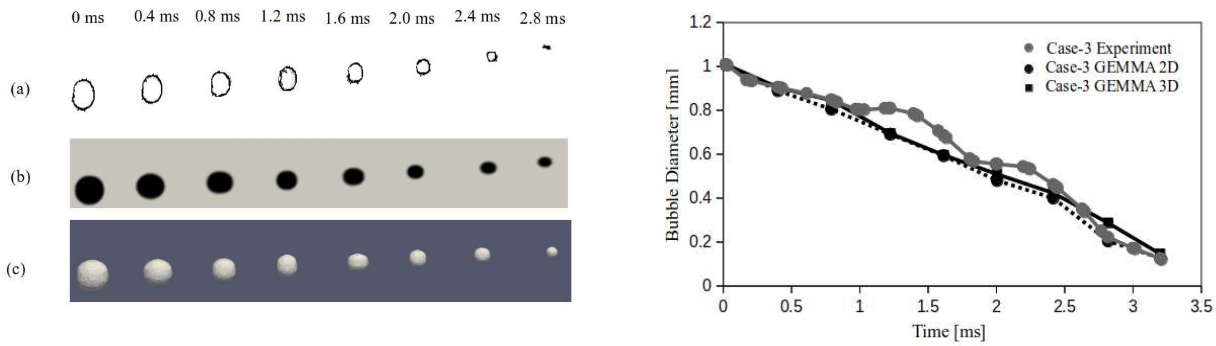


Figure 2: Bubble shape history comparison between (a) experiment, (b) two- and (c) three-dimensional simulations for case 3 (left) and bubble diameter history comparison between experiment, and two- and three-dimensional simulations for case 3 (right).

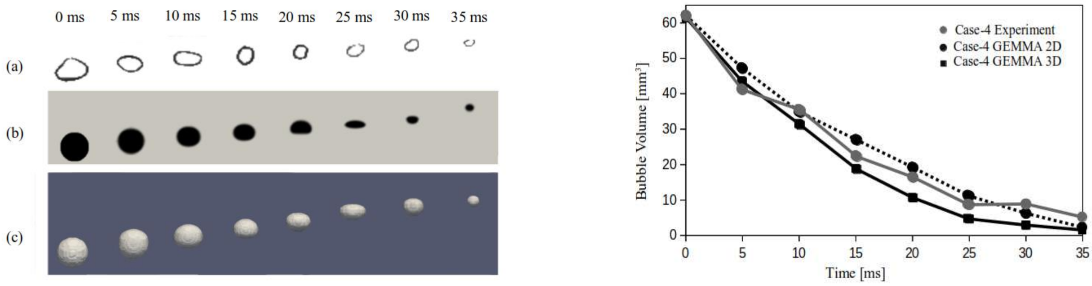


Figure 3: Bubble shape history comparison between (a) experiment, (b) two- and (c) three-dimensional simulations for case 4 (left) and bubble volume history comparison between experiment, and two- and three-dimensional simulations for case 4 (right).

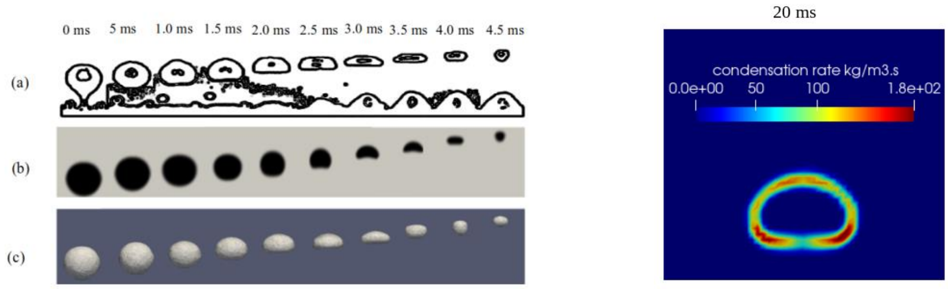


Figure 4: Bubble shape history comparison during condensation for case 5 (left) and interfacial condensation rate at 2ms for case 4 (right).

## 4. Conclusions

In this work, the ability of the GEMMA model extended using a thermal phase change model to predict the condensation process of a single steam bubble in a subcooled flow was evaluated. A validation study was performed with different initial bubble diameters and the change in bubble shape during the condensation process was compared with experimental images, with satisfactory agreement achieved. A further study of heat and mass transfer from steam to water through an interfacial area in a turbulent stratified flow, which gave similar levels of agreement with data, is not included due to space limitations, but this case is included in the full paper with a focus on the treatment of turbulence at the free surface.

## 5. References

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