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NUMERICAL MODELLING OF CONDENSATION PHENOMENA FOR SUBCOOLED FLOW BOILING APPLICATIONS

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1. ABSTRACT

A methodology is presented for the investigation of the hydrodynamic and heat transfer effects of subcooled flow boiling phenomena. We employ interface capturing simulation with mechanistic calculation of the local rate of phase change. The numerical accuracy of the methodology is demonstrated for the modelling of condensation, by considering the case of heat-controlled collapse of a spherical vapour bubble surrounded by subcooled water. Our results demonstrate excellent agreement with the analytical solution.

2. INTRODUCTION

Subcooled flow boiling is a highly efficient mechanism of heat transfer. This is of vital importance in the nuclear sector for its role in water-cooled reactors, but the physics of such boiling remains poorly understood. This is due to the multi-physics and multi-scale nature of the problem. Interface-resolving simulation of the boiling phenomenon on the micro scale has been made possible by advances in computing power and modelling techniques, enabling the investigation of the fundamental physics of boiling. Such analyses are limited to small populations of bubbles due to the fine meshes required to capture the phase interface and thermal boundary layer. Nonetheless, such simulations provide an opportunity for the development of accurate physics-based closure relationships for component-scale boiling simulations.

The present work offers a step toward a CFD model which can be applied to study the hydrodynamic and heat transfer behaviours of bubbles, applied to subcooled flow boiling in which evaporation and condensation effects are simultaneously present. Verification of the model is performed against the analytical solution for the collapse of a spherical bubble, demonstrating the model's accuracy in the modelling of condensation. Future validation will evaluate the model against experimental test cases, where no analytical solution exists.

3. METHDOLOGY

The incompressible Navier-Stokes equations can be expressed as

$$\frac{\partial(\rho\vec{u})}{\partial t} = -\nabla\cdot(\rho\vec{u}\vec{u}) + \nabla\cdot\left[\mu\left(\nabla\vec{u} + \nabla^{T}\vec{u}\right)\right] - \nabla p + \vec{f}\,, \tag{1}$$

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where ρ is density, $\vec{u}$ is velocity, p is pressure, μ is dynamic viscosity, t is time, and $\vec{f}$ is a body force. The body force comprises a force due to gravity and a force due to surface tension. The latter is calculated using the continuum surface force (CSF) method in the present study. For incompressible flows with phase change, the continuity constraint is given by Equation (2), where $\dot{m}$ is the mass source term.

$$\nabla \cdot \vec{u} = \dot{m}/\rho. \tag{2}$$

The volume of fluid (VOF) method [1] is used to capture the phase interface by the advection of an indicator function α, which takes on values between 0 and 1 to represent the volume fraction of the phases in each cell. The transport of the indicator function is governed by Equation (3), where $\vec{u}_r$ is an artificial compressive velocity, which acts at the phase boundary to sharpen it [2].

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \vec{u}) + \nabla \cdot (\alpha(1-\alpha)\vec{u}_r) = \alpha \frac{\dot{m}}{\rho}. \tag{3}$$

The temperature field is governed by

$$\frac{\partial \rho c T}{\partial t} + \nabla \cdot (\rho c \vec{u} T) - \nabla \cdot (\lambda \nabla T) + \dot{q} + c_{hlv} = 0, \tag{4}$$

where T is the temperature, c is the specific heat capacity, λ is the thermal conductivity, and $\dot{q}$ is the heat sink term. The c_{hlv} term corrects for the sharp change in fluid properties at the interface, and is obtained by considering the jump conditions across the interface [3]. It is defined by Equation (5),

$$c_{hlv} = (\dot{q}/h_{lv})(c_l - c_v)(T - T_{sat}), \tag{5}$$

where h_{lv} is the latent heat of vaporisation, and the subscript sat denotes saturation. The phase change model in the present work is that of Hardt and Wondra [4], derived from the kinetic theory of gases and based on the continuum representation of source terms. The heat sink term is calculated as

$$\dot{q} = \alpha h_i \Delta T |\alpha|, \tag{6}$$

where $\Delta T = T - T_{sat}$, and h_i is the evaporation heat transfer coefficient [4]. The "raw" mass source term is directly calculated from the heat sink term, giving the local rate of phase change within the phase interface as

$$\dot{m}_0 = \dot{q}/h_{lv}\,. \tag{7}$$

As this term is concentrated entirely in the interface region, its gradient is large. This causes numerical instability in the pressure equation. The method of Hardt & Wondra [4] is used to obtain a mass source term $\dot{m}$ from the raw one, $\dot{m}_0$, by smearing over the neighbouring cells to improve numerical stability.

4. RESULTS

The test case considered is that of the heat-controlled collapse of a spherical bubble. Florshuetz & Chao [5] provide an exact analytical solution in terms of nondimensional radius and time. The evolution of the collapsing vapour bubble over time can be seen in Fig. 1. The properties of water and saturated steam are used for the liquid and vapour phases respectively, and the temperature is initialised with a thin thermal boundary layer at the interface, as done by Can & Prosperetti [6]. The initial radius of the bubble is 0.3mm, and the vapour within it is initialised at saturation temperature. The surrounding liquid is subcooled by 5K. Taking advantage of the spherical symmetry, the domain is a 5° wedge of half of the bubble. We adopt a mesh resolution of $1\mu m$. It can be seen in Fig. 2 that excellent agreement is achieved between the model and the analytical solution for the prediction of bubble radius over time.

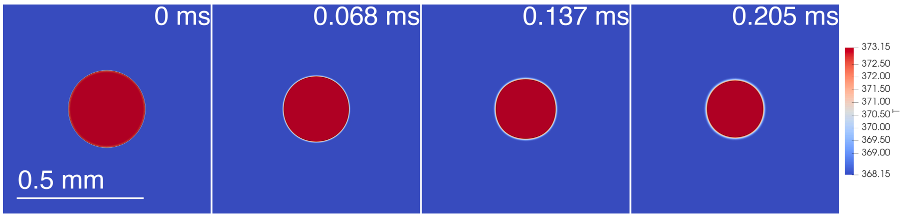

Fig. 1. Evolution of the temperature field in the spherical bubble collapse case.

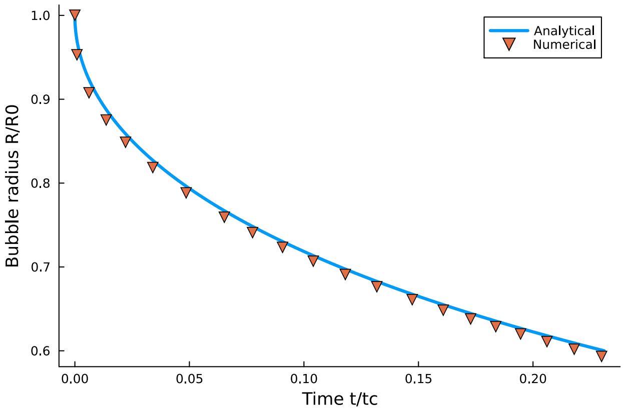

Fig. 2. Nondimensional bubble radius against nondimensional time for the case of a collapsing spherical bubble.

5. CONCLUSIONS

A mechanistic model for liquid-vapour phase change has been developed, implemented, and verified against an analytical solution for the heat-controlled collapse of a spherical bubble in a subcooled liquid. Excellent agreement was observed with the analytical results, demonstrating the methodology's capability in modelling condensation effects at a curved surface. This is despite the challenging conditions involving a high density ratio and high rate of mass transfer; conditions that frequently are encountered in water-cooled reactors.

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