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Benchmarks and numerical methods for the simulation of boiling flows

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ABSTRACT

Comparisons of different numerical methods suited to the simulations of phase changes are presented in the framework of interface capturing computations on structured fixed computational grids. Due to analytical solutions, we define some reference test-cases that every numerical technique devoted to phase change should succeed. Realistic physical properties imply some drastic interface jump conditions on the normal velocity or on the thermal flux. The efficiencies of Ghost Fluid and Delta Function Methods are compared to compute the normal velocity jump condition. Next, we demonstrate that high order extrapolation methods on the thermal field allow performing accurate and robust simulations for a thermally controlled bubble growth. Finally, some simulations of the growth of a rising bubble are presented, both for a spherical bubble and a deformed bubble.

1. Introduction

Boiling flow is a topic of interest for various industrial applications as spray cooling, heat exchanger, cryogenic applications or fluid storage in micro-gravity for spatial applications. The development of numerical techniques dedicated to the direct numerical simulation of boiling flow is still challenging. A preliminary step, to compare these simulations with large scale experiments, is to succeed some benchmarks for simplified configurations. Accurate benchmarks, involving analytical theories, allow studying the performances of different numerical methods. This is relevant in the difficult context of direct numerical simulation of two-phase flows when phase changes occur. One of the main objectives of this paper is to propose a methodology in order to validate and to assess the global accuracy of numerical methods relevant for the simulations of boiling flows.

In [29] and [15], the authors present pioneering works where new numerical methods are designed to compute boiling flows respectively with a Level Set Method and with a Front Tracking algorithm for the interface description. In [17,37], the authors developed numerical methods to compute boiling flows with the Volume Of Fluid method. Some attempts of boiling flows simulations with Second Gradient Method have been proposed in [13]. In [38], computations with high density ratio are presented with a sharp-interface marker points method. A general methodology is presented in [3–5] for 3D computations in complex geometries. The coupled Level Set – Volume Of Fluid method is applied to boiling flows in [35]. A new approach, with a subgrid scale treatment of boundary layers, is proposed in [7,8] to deal with impacting boiling droplets on hot walls. In [30,31], 3D computations of the nucleate boiling on a horizontal surface and saturated

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film boiling on a horizontal cylinder are presented. In [11,34], the authors use the Ghost Fluid Method to design a sharp interface method devoted respectively to boiling flows and to droplets vaporization. More recently, sharp interface numerical methods for boiling flows have also been designed in the context of the Front Tracking method [26]. Few of the works cited above propose accurate comparisons of multidimensional computations with analytical theories, as it has been done with a boundary-fitted method in [19]. The accuracy and the performances of these various numerical methods are therefore difficult to evaluate. It will be demonstrated in this article, that the way to compute the boiling mass flow rate has a strong influence on the global accuracy. Another sensitive issue concerns the computation of the expansion flow due to the phase change of the liquid into a vapor (or collapsing flow for condensation). It will be shown in this paper that the Continuous Surface Force approach, where the interfacial source terms are smoothed across interface, can fail to determine accurately the bubble expansion rate due to the smearing out of the velocity field at the interface. At the opposite, we provide numerical evidences that a sharp interface method, as the Ghost Fluid Method, succeeds to compute the bubble expansion rate.

Our main focus is the numerical simulation of the bubble growth in a superheated liquid. In that specific situation, when the bubble is static, an analytical bubble growth prediction can be determined according to Scriven [28]. Bubble growth rate depends on thermal boundary layer thickness in the liquid around the bubble. It can be shown from theoretical analysis that the dimensionless bubble growth rate depends on the Jakob number Ja and a dimensionless parameter ε function of the density ratio between the vapor and the liquid. This analytical theory is very attractive to design benchmarks for boiling flows. A particular attention shall be paid to high Jakob number simulations (about 10) when the thermal boundary layer around the bubble is very thin in comparison to the bubble diameter. Performing simulations on this configuration involves very drastic resolution conditions which are particularly suitable to assess the global accuracy of the method. Another important requirement of this work is to design a numerical method whose accuracy and stability properties are preserved whatever the density ratio between the vapor and the liquid. Indeed, it is well known that strong density ratio and strong capillary effects can damage stability and accuracy properties of numerical methods, and that problem is even more acute if a phase change occurs. So the simulations presented in this paper imply strong discontinuities at the interface, as for liquid/vapor water which involves a density ratio above 1600 at ambient pressure conditions.

2. Equations and jump conditions

The model used to deal with a phase change is identical to those from [11], where the liquid and the gas are supposed incompressible and monocomponent. We assume the boiling temperature is uniform and only depends on the external pressure. Thus, the Marangoni convection, resulting from boiling temperature variation, cannot occur in that situation. Moreover, considering low Mach number flows with low temperature variations in the vapor phase as well as in the liquid phase, we can expect that the velocity field will respect divergence-free condition (except at the interface when phase changes occur).

A simplified energy conservation equation, based on enthalpy formulation, is used to predict temperature variations in the two phases. In this equation, the viscous heating and pressure effects are neglected.

The governing equations can be formulated in a "Whole-Domain Formulation" [2,18,32,36] or in a "Jump Condition Form" [16,24]. These two formulations, theoretically equivalent, imply different numerical methods when dealing with discontinuous fields. We define $\vec{N}$ as the normal vector at an interface Γ pointing in the direction of vapor phase, and the jump conditions at the interface Γ are expressed with the following operator:

$$[f]_\Gamma = f_{vap} - f_{liq}$$

2.1. Mass conservation equation

Both the liquid and the vapor phases are considered incompressible. So the divergence-free property is imposed in the bulk of the two phases:

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

where $\vec{V}$ is the velocity vector of the fluid flow. At the interface, if phase changes occur, the following velocity jump condition must be respected to preserve the mass conservation:

$$[\vec{V}]_\Gamma = \dot{m}\left[\frac{1}{\rho}\right]_\Gamma \vec{N} \tag{2}$$

where $\dot{m}$ is the phase change local mass flow rate and ρ is the density of the considered phase. The field equations are written in each phase separately and additional jump conditions have to be imposed at the interface to respect the conservation of mass, momentum and energy. This is known as the Jump Condition Formulation [27].

An equivalent formulation can be favored to express the mass conservation by using a Dirac distribution at the interface. The jump conditions are expressed in the field equations by introducing singular source terms:

$$\nabla \cdot \vec{V} = \dot{m}\left[\frac{1}{\rho}\right]_\Gamma \delta_\Gamma \tag{3}$$