Journal of Computational Physics 316 (2016) 789–813

Contents lists available at ScienceDirect

Journal of Computational Physics

www.elsevier.com/locate/jcp

A Ghost Fluid/Level Set Method for boiling flows and liquid evaporation: Application to the Leidenfrost effect

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ARTICLE INFO

Article history:
Received 26 June 2015
Received in revised form 2 March 2016
Accepted 16 April 2016
Available online 19 April 2016

Keywords:
Evaporation
Boiling
Level Set
Ghost Fluid
Leidenfrost

ABSTRACT

The development of numerical methods for the direct numerical simulation of two-phase flows with phase change, in the framework of interface capturing or interface tracking methods, is the main topic of this study. We propose a novel numerical method, which allows dealing with both evaporation and boiling at the interface between a liquid and a gas. Indeed, in some specific situations involving very heterogeneous thermodynamic conditions at the interface, the distinction between boiling and evaporation is not always possible. For instance, it can occur for a Leidenfrost droplet; a water drop levitating above a hot plate whose temperature is much higher than the boiling temperature. In this case, boiling occurs in the film of saturated vapor which is entrapped between the bottom of the drop and the plate, whereas the top of the water droplet evaporates in contact of ambient air. The situation can also be ambiguous for a superheated droplet or at the contact line between a liquid and a hot wall whose temperature is higher than the saturation temperature of the liquid. In these situations, the interface temperature can locally reach the saturation temperature (boiling point), for instance near a contact line, and be cooler in other places. Thus, boiling and evaporation can occur simultaneously on different regions of the same liquid interface or occur successively at different times of the history of an evaporating droplet. Standard numerical methods are not able to perform computations in these transient regimes, therefore, we propose in this paper a novel numerical method to achieve this challenging task. Finally, we present several accuracy validations against theoretical solutions and experimental results to strengthen the relevance of this new method.

1. Introduction

Boiling is the phase change of a pure liquid into a saturated vapor. It arises when the liquid is heated (or depressurized in the case of cavitation) beyond its boiling point. To start, it requires the activation of a nucleus, either in the bulk (homogeneous nucleation) or on a heated wall (heterogeneous nucleation). Many previous works on the direct numerical simulation of two-phase flows propose numerical methods which allow dealing with boiling flows [7,13,21,23,37,40,41,46,47].

Unlike boiling, evaporation does not require any nuclei activation to start. Indeed, it occurs spontaneously, whatever the pressure and the temperature conditions, at the interface between a liquid and a gas whose chemical compositions

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http://dx.doi.org/10.1016/j.jcp.2016.04.031
0021-9991/

are different, such as the evaporation of liquid water in air, or the evaporation of fuel droplets in an ignitable mixture. A few previous works [6,15,18,26,28,39,45] propose numerical methods able to compute the evaporation of a liquid in the framework of the direct numerical simulation of two-phase flows with moving and deformable interfaces.

The direct numerical simulation of liquid–vapor phase change is a powerful and promising tool to perform accurate predictions and to improve the understanding of various physical phenomena which are involved in many industrial applications. For example, nucleate boiling is a topic of interest for the optimization of heat exchangers, since it is well-known that the heat transfer can be strongly favored by the nucleation of vapor bubbles on the wall of a heat pipe. On the other hand, if the wall heat flux reaches a critical value, the formation of a film of saturated vapor occurs and leads to a drastic decrease in the heat transfer coefficient. This phenomenon, known as the boiling crisis, is feared particularly in nuclear power plant. Other existing industrial applications, e.g. the fluid management of cryogenic liquids in microgravity conditions inside the tanks of space launchers, further motivate accurate studies of nucleate boiling.

The evaporation of droplets is also a topic of interest which is involved in many practical situations. For instance, it is an important step in the description of the combustion in automotive and aircraft engines. The prediction of this complex phenomenon requires an accurate description of the interaction between a cloud of moving and vaporizing droplets and flame fronts. As the dynamics of droplets can be strongly affected by thermal, chemical and collective effects, performing direct numerical simulations of such flows with a well-resolved description of the droplets would be a step forward in the description and the understanding of these flames. The evaporation of a droplet spray is also a significant phenomenon in the steel industry for cooling systems using liquid jet impingements. This latter involves the description of the interactions of vaporizing droplets with a very hot steel plate. This situation seems even more difficult than spray combustion. Indeed, many complex phenomena arise during the impact of a droplet on a hot wall. For example, in the so-called “Leidenfrost regime”, which occurs when the wall superheat is high, the formation of a thin layer of saturated vapor between the impinging droplet and the hot plate leads to the droplet levitation during its spreading; no contact line is formed during the impact. This regime is quite similar to the film boiling regime.

The main motivation of this paper is to present a novel numerical strategy to perform direct numerical simulations of the Leidenfrost droplets. Some previous works propose various strategies to achieve this difficult task. In [16,17,33], Volume-Of-Fluid simulations are carried out with a microscopic model for phase change. This microscopic model, which is based on the Schrage’s law from the kinetic theory [2], allows deducing the local mass flow rate of phase changes from the discontinuities of local thermodynamics properties (temperature and pressure). Whereas it can provide acceptable results in some situations, many criticisms can be addressed to that kind of approaches. First, this microscopic model has been designed to describe the phase change in non-equilibrium thermodynamic conditions, thus the local mass flow rate of phase change will be different from zero if the interface temperature is different in the liquid and in the vapor. However, assuming the local thermodynamic equilibrium, the jump condition on the entropy points out that the temperature must be continuous at the interface [19]. Let us note that this last assertion is not strictly exact if the pressure is discontinuous at the interface, but the corrections resulting from the influence of the pressure jump condition on the temperature continuity are weak, see [21] for more details on this other topic.

Moreover, it appears that using the Schrage’s law does not allow for accounting on the dependence of the local mass flow rate of phase change with the local temperature gradient at the interface. Instead, it depends on the temperature discontinuity and on an accommodation coefficient, whose value is not always perfectly known. To summarize, we think that using this law in numerical simulations, based on a local thermodynamic equilibrium assumption, leads to a disagreement with the first law of thermodynamic (mass flow rate of phase changes does not depend directly on the heat flux jump condition), and/or with the second law of the thermodynamic (the temperature is not considered continuous at the interface in contradiction with the jump condition on the entropy). Moreover, since the local mass flow rate of phase changes can be deduced from the jump condition on the thermal flux if the temperature is continuous at the interface, considering an additional law which involves an accommodation coefficient leads to an over-determined problem. Nevertheless, the Schrage’s law is still frequently used in various contexts, since it allows determining much more easily a mass flow rate of phase change than by the classical approach based on the assumption of local thermodynamic equilibrium. Indeed, in the latter case the thermal gradient at the interface must be accurately computed which is a much more demanding task.

In [9,10], another approach has been developed to perform numerical simulations of Leidenfrost droplets. In these papers, a Level Set Method, used to describe the droplet motion in an isothermal domain, is coupled to a lubrication model to account to thermal transfer in the vicinity of the hot wall through an ALE auxiliary grid. Although many interesting results are provided in this study, this technique does not address the overall problem, since the thermal effects and the phase change are only solved in the vicinity of the hot wall. Moreover, a lubrication model in the thin vapor layer is not able to fully describe the complex and unsteady fluid dynamic in this microscopic region, which is strongly coupled to the interface motion.

Therefore, we present in this paper some new developments in order to perform simulations of Leidenfrost droplets with fully-resolved computations of the vapor layer dynamic, of the heat transfer and of the phase changes. The key-points to achieve these difficult simulations are the development of a phase change model which can deal both with evaporation and with boiling, as well as the use of very refined grids close to the hot wall. Such refined grids must be used with implicit algorithms for the temporal discretization of all the diffusion terms. Moreover, we will see that a semi-implicit temporal solution of the extrapolation techniques based on a PDE approach [1,12] can also be required to alleviate the number of temporal iterations of these extrapolations when the interface crosses grid cells with very different resolutions.