Journal of Computational Physics 303 (2015) 125–145

Contents lists available at ScienceDirect

Journal of Computational Physics

www.elsevier.com/locate/jcp

Modeling of liquid–vapor phase change using smoothed particle hydrodynamics

A.K. Das [a,*], P.K. Das [b]

[a] Department of Mech. and Ind. Engg., IIT Roorkee, Roorkee 247667, India
[b] Department of Mech. Engg., IIT Kharagpur, Kharagpur 721302, India

ARTICLE INFO

Article history:
Received 9 August 2014
Received in revised form 30 April 2015
Accepted 7 September 2015
Available online 25 September 2015

Keywords:
Smoothed particle hydrodynamics
Phase change
Diffused interface
Pseudo particle
Boiling

ABSTRACT

A model has been proposed based on smoothed particle hydrodynamics to describe gas liquid phase change. Pseudo particles of zero mass are initially placed to locate the interface. Mass generated due to phase change is assigned to the pseudo particles and their positions are updated at intervals to track the mobility of the interface. The developed algorithm has been used to simulate vapor formation around solid spheres both in the absence of gravity and in the normal gravitational field. Finally, bubble growth over a hot horizontal surface due to boiling has been simulated. Simulated results showed good matching with the reported literature.

1. Introduction

In two phase flow the continuum is intercepted by the presence of deformable interfaces across which there is a sharp variation of pressure, velocity and/or temperature. The change of phase introduces additional intricacy in two phase hydrodynamics. Firstly, the mass of an individual phase is not conserved due to change of phase. Secondly, the evolution of the interface depends on the conjugate effect of local hydrodynamics and the process of phase change. Thus the computational simulation of the two phase flow with phase change poses a significant challenge. One can trace back few fundamental investigations, mostly analytical in nature, which contributed towards the understanding of phase change process due to evaporation. The growth of a bubble in superheated liquid was first analyzed by Bosnjakovic [2]. The early theoretical works of Plesset and Zwick [20], Forster and Zuber [6], Scriven [24] establish the governing laws for bubble growth in superheated liquids over a wide range of Jacob number. Mikic et al. [15] proposed an equation for bubble growth which is independent of Jacob number. Lee and Nydahl [10] calculated the bubble growth rate by solving the flow and temperature field considering a wedge shaped microlayer below the hemispherical bubble. Zeng et al. [34] estimated the bubble departure diameter during single bubble growth under nucleate boiling situation. Later, several analytical efforts were made to predict the film growth [22] its collapse [19] and subsequent generation of vapor bubble nucleation [11]. An extensive review of the previous works is given in Shiotsu and Hama [25]. Despite decades of research still there are many aspects of boiling heat transfer that are not well understood.

With the advancement of numerical techniques, options opened towards the implementation of numerical methodologies for the prediction of phase change heat transfer. Welch used finite volume method for the numerical simulation of bubble growth under saturated condition considering the conduction in the solid wall. Son and Dhir [26] used moving grid method

* Corresponding author.
E-mail address: arupdas80@gmail.com (A.K. Das).

http://dx.doi.org/10.1016/j.jcp.2015.09.026
0021-9991/

for the prediction of interface of film boiling on horizontal flat plate. Juric and Tryggvason [9] used front tracking method for numerical analysis of film boiling heat transfer. Conventional interface tracking methods like volume of fluid [32] and level set [27] is also used for numerical simulation of film boiling heat transfer. Son et al. [28] considered spatial temporal distribution of wall heat flux and microlayer heat transfer for numerical simulation of isolated bubble on heated surface. They have used level set method for interface capturing. Esmaeeli and Tryggvason [5] combined front tracking method along with immersed boundary technique to account for the velocity boundary conditions on irregular solid surfaces. Tomar et al. [29] investigated bubble formation, growth and departure in film boiling situation using combined level set-volume of fluid method. They correlated the frequency of bubble formation with degree of superheat by considering film rupture phenomena due to Rayleigh–Taylor instability. Tomar et al. [30] performed a linear stability analysis for multimode bubble analysis and showed that increase of heat flux stabilizes the film until Rayleigh–Taylor instability sets in.

Recently, a number of meshfree methods have been proposed for analyzing fluid–fluid interfacial structures. These methods can be efficiently used for situation related to deformable boundaries, complex geometry and multiple scales. Among all the meshfree methods smoothed particle hydrodynamics [14,8] is one of the promising methods and widely used for versatile multiphase flow problems. But as phase change problem involve a large change in density, the implementation of the basic SPH scheme pose a difficulty in managing the particle near the interface. Monaghan et al. [18] used the concept of virtual solid particle to model freezing of one or two component system employing smoothed particle hydrodynamics. Particle redistribution was needed at regular intervals for capturing the dynamic interface. However, as the problem considered did not involve any fluid motion the interface location was dependant only on the energy equation. Though there is apparent similarity between the solid–liquid and liquid–vapor phase change, there are also some differences. For solidification and melting it is usually permissible to neglect change in density. But boiling or condensation is associated with an abrupt change in volume which complicates the phenomena compared to a problem of solid–liquid phase change. Moreover, this change of volume pose a great problem to the particle based models. Special algorithm is needed to tackle the change of volume during liquid vapor phase change. A robust algorithm which can take care of the evolution of complex interfaces in phase change problems with a large density difference is yet due.

In this paper, a novel numerical method is described for the modeling of phase change processes using smoothed particle hydrodynamics [4]. In the next section a brief description of the developed methodology is presented. Developed model can track the transformation of high density liquid particles into lighter vapor particles without violating the conservation of mass. Efforts have been made to model the phenomena film boiling around a spherical solid and on a horizontal plane surface. Results of numerical simulation are described for both the cases in the paper. The evolving interfaces are considered to start from the order of 10^{-6} m in dimension.

2. Model development

2.1. Governing equations

For the phase change, the conservation of mass, momentum and energy of each of the phases can be expressed using a Lagrangian description.

Continuity equation for the kth phase can be written as:

$$\frac{D\rho_k}{Dt} + \rho_k \nabla . v_k = \sum_k \frac{dm_g}{dt}. \tag{1}$$

In equation (1), the right hand side denotes the mass transfer from one phase to another.

The conservation of momentum can be mathematically expressed as follows:

$$\frac{Dv_k^\alpha}{Dt} = \frac{1}{\rho}\frac{\partial \sigma_k^{\alpha\beta}}{\partial x^\beta} + g_\alpha \beta_{Tk}(T - T_0), \tag{2}$$

where,

$$\sigma^{\alpha\beta} = -P\delta^{\alpha\beta} + \mu_k\left(\frac{\partial v^\beta}{\partial x^\alpha} + \frac{\partial v^\alpha}{\partial x^\beta} - \frac{2}{3}(\nabla v)\delta^{\alpha\beta}\right). \tag{3}$$

The last term in the right hand side of equation (2) denotes the body force term due to change of density in a temperature field. As a usual practice the change of density is considered only in the body force term based on Boussinesq approximation. Surface tension force is not added in the momentum equation as it is separately applied to the interfacial particles following the CSF methodology [16]. Instead of a sharp interface if a diffused interface [4] is considered equation (2) needs to be modified as follows to accommodate the conservation of surface energy:

$$\frac{Dv_k^\alpha}{Dt} = \frac{1}{\rho}\frac{\partial \sigma_k^{\alpha\beta}}{\partial x^\beta} + g_\alpha \beta_{Tk}(T - T_0) - \frac{C_k}{Cap_k Cn}\frac{\partial \phi}{\partial x^\beta}. \tag{4}$$

Chemical potential of the fluid (Φ) is calculated based on the color code near the interface around which a smooth transition of C is considered. Chemical potential is calculated for the particle based system in the following manner: