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Numerical Simulation of Phase Change Modeling Including Conjugate Heat Transfer

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Abstract
In the present study, volume of fluid method in OpenFOAM CFD package is extended to consider phase change phenomena due to heat transfer from solid region. Both fluid phases are considered immiscible and incompressible and mass transfer is accounted for Lee model. Newtonian flows are solved using a finite volume scheme based on PISO algorithm. This code is validated with three simple test cases.

Keywords: Film Boiling, OpenFOAM, VOF, Heat Transfer

Introduction

In last two decades, various computational schemes for modeling of interfacial and two phase flow have been extended. Interface resolving method combined with single fluid formulism has been applied extensively for modeling of isothermal interfacial flow [1, 2]. Single-fluid formulism is based on solving a single set of transport equations for the whole computational domain and treating the two phases as a single fluid with variable material properties. Changes in these properties are accounted for by advection a phase indicator or color function. Single-fluid model is called as a direct numerical simulation of interface motion (not of turbulence) [3]. The key to these methods is the use of a single-phase set of conservation equations. Surface tension, mass transfer and etc are added as source term in equations. Interface resolving method can be divided in two main groups: sharp interface method and diffuse interface method [1]. Three most popular interface resolving methods are volume of fluid (VOF) [4], level set (LS) [5] and front tracking (FT) [6]. Each method has its own advantages and disadvantages. VOF method keep the mass conserve better than LS or FT, however it represents interface curvature or normal vector less accurate than LS or FT [1]. VOF methods can be classified based on interface reconstruction to: 1) VOF with interface reconstruction (IR-VOF) such as SLIC-VOF [7], PLIC-VOF [8], PROST [9] 2) VOF without interface reconstruction which called color function VOF (CF-VOF) such as CICSAM [10]. (CF-VOF) for ease of implantation and omit of geometrical reconstruction of interface are getting popular. In past decade interface resolving method is extended to include mass transfer in evaporation process. Extension of phase change in interface tracking methods is reported for VOF [11], level-set [12], front-tracking [13], CLSVOF [14].

Analysis of conjugate heat transfer generally requires the solution of the Navier-Stokes and energy equations for the fluid side coupled with the energy equation for the solid side. Numerical methods for the solution of the conjugate problem with single-phase Fluids are well established. However, analysis of conjugate heat transfer involving boiling fluids represents a much more challenging problem. The problem is a moving-boundary problem mathematically. Two fluid phases are separated by a moving and deformable interface with both phases possibly impinging on a solid wall. The location of the phase interface is not known a priori and must be found as part of the solution procedure

In present article, OpenFOAM code is developed to simulate conjugate heat transfer in boiling. The solver is validated with two simple test cases, and then it will apply on much more complex phenomena of film boiling.

Numerical Method

The equations that need to be solved in the boiling model are the conservations for mass, momentum, energy and volume fraction:

$$\frac{\partial}{\partial t}(\rho)+\nabla.(\rho U)=0 \tag{1}$$

$$\frac{\partial(\rho U)}{\partial t}+\nabla.(\rho UU)=-\nabla p+\nabla.(\mu(\nabla U^{T}+\nabla U))+\sigma\kappa\nabla a_{L} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho C_{p}T)+\nabla.(\rho C_{p}UT)=\nabla.(k\nabla T)-\dot{m}^{'''}h_{LG} \tag{3}$$

$$\frac{\partial\alpha_{L}}{\partial t}+U.\nabla\alpha_{L}+\alpha_{L}\nabla U=-\frac{\rho_{G}\nabla U}{(\rho_{L}-\rho_{G})} \tag{4}$$

The volume fraction filed (α_L) determines the liquid volume fraction in each cell.

$$\alpha_{L}(\vec{x},t)=\frac{V_{Liquid}}{V}=\begin{cases}1 & \vec{x}\in \text{Liquid}\\ 0<\alpha_{L}<1 & \vec{x}\in \text{interface}\\ 0 & \vec{x}\in \text{gas}\end{cases} \tag{5}$$

The physical properties of vapor and liquid such as: viscosity (μ), density (ρ), thermal conductivity (k), specific capacity (C_p) are defined as:

$$y=a_{L}y_{L}+(1.0-a_{L})y_{G} \tag{6}$$

where $y=\{\mu,\ \rho,\ k,\ C_p\}$