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A Coupled Level Set and Volume of Fluid method with multi-directional advection algorithms for two-phase flows with and without phase change

B.M. Ningegowda, B. Premachandran *

Department of Mechanical Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India

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ABSTRACT

A Coupled Level Set and Volume of Fluid (CLSVOF) interface capturing method using a multi-dimensional advection algorithm for non-uniform grids has been developed for two phase flows with and without phase change for two-dimensional problems. A finite volume method with a collocated grid arrangement is used for solving the governing equations. The SIMPLE algorithm is used for velocity and pressure coupling. The piecewise linear interface calculation (PLIC) based geometrical reconstruction procedure and an Edge Matched Flux Polygon Advection (EMFPA) multi-dimensional algorithm have been implemented for the Volume of Fluid (VOF) method. For the Level Set (LS) advection equation, the convective terms are discretized using the second order accurate essentially non-oscillating (ENO) scheme. The proposed multi-dimensional advection of CLSVOF method requires interface reconstruction for the advection of VOF function and the Level Set function re-initialization only once compared to the requirement of twice interface reconstruction and Level Set re-initialization in the operator-splitting method for 2D problems. The performance of proposed CLSVOF method is evaluated for accurate mass conservation, surface tension force and interface mass transfer through various standard benchmark problems. The numerical study of two-dimensional saturated film boiling flow over a horizontal plane surface was carried out for different constant wall superheats in order to validate the implementation of boiling flow model. The present numerical results of boiling flows show better agreement with the experimental correlations.

1. Introduction

For modeling two-phase flows with sharp interfaces, the following methods are widely used: (a) interface fitting method (b) interface tracking method and (c) interface capturing method [1]. In the interface fitting (Lagrangian) method, the interface is treated as a sharp boundary and a moving mesh is used to follow the phase interface. However, this method cannot handle bubble breakup and coalescence [2]. Also, this method is computationally expensive due to the requirement of grid modification to follow the transient moving interface. In the interface tracking method, a fixed grid is used to obtain the velocity field and a moving surface mesh is used for interface tracking. In this method surface remeshing is required as the interface deforms [3]. Hence this method is computationally intensive and difficult to implement. In the interface capturing methods, the position of moving interface is captured in a fixed (Eulerian) grid based on an indication function. These methods can capture strong topological changes such as break up and merger of bubbles. These methods are computationally inexpensive and robust compared to the interface fitting and interface tracking methods. Hence, these methods are widely used in the numerical study of two-phase problems, with or without phase change. However, these methods may lead to poor mass conservation or inaccurate prediction of surface tension force. Many researchers have proposed various modifications in the interface capturing methods to overcome these problems.

Most commonly used interface capturing methods are the Level Set (LS), Volume of Fluid (VOF) and Coupled Level Set and Volume of Fluid (CLSVOF) methods. The LS method was first developed by Osher and Sethian [4] for the simulations of two-phase flows and further modified by Sussman et al. [5] for the simulations of two-phase flows. In this method, the moving interface is described through a smooth continuous LS function, ϕ. This function indicates a shortest signed distance from the interface, whose value is zero at the interface. Its value is negative in one fluid

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* Corresponding author.
E-mail address: prem@mech.iitd.ac.in (B. Premachandran).

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Nomenclatures

A_{F_T}	net advection flux of the cell, m^2
C_P	fluid specific heat at constant pressure, J/kg K
F	Volume of Fluid (VOF) or void fraction function
F_{st}	interfacial volumetric surface tension force, N/m^3
F_{sa}	interfacial surface tension stress, N/m^2
Gr	Grashof number
g	acceleration due to gravity, m/s^2
h_{lg}	latent heat of vaporisation, J/kg K
$H(\phi)$	smoothed Heaviside function
Ja	Jacob number
k	thermal conductivity of fluid, W/m K
m_I''	interfacial rate of mass flux, kg/m^2 s
Nu_{λ_d}	local Nusselt number
$\overline{Nu}_L$	space averaged Nusselt number
$\overline{Nu}_T$	time averaged Nusselt number
$\vec{n}$	unit normal vector of the phase interface
P	pressure, Pa
Pr	Prandtl number
q_I''	interface heat flux, W/m^2
S_I	surface area (S_{cf}) of the interface line segment, m^2
S_C	surface of line segment bounded by the control volume cell, m^3
T	temperature, K
u, v	velocity components in x and y directions respectively, m/s
$\boldsymbol{V}$	velocity vector (u, v), m/s
V_I	interfacial velocity due to mass transfer, m/s

Greek symbols

α	thermal diffusivity, m^2/s
δ_s	Dirac surface delta function
ε	width of smoothed transition region, m
κ	interfacial local mean curvature, 1/m
λ	characteristic length scale for phase change, m
μ	dynamic viscosity of fluid, N s/m^2
ρ	density of fluid, kg/m^3
σ	surface tension coefficient, N/m
ϕ	continuous level set function

Subscripts

f	fluid phase
g	vapour or gas phase
I	liquid–vapour phase interface
l	liquid phase
Sat	saturation

Superscripts

n	previous time level
$n+1$	current time level

and positive in the other fluid. This method provides accurate unit normal vector, mean curvature and surface tension force of the interface. Implementation of this method is easy even for three-dimensional two-phase flows. The main drawback of this method is poor mass conservation which may lead to inaccurate capturing of dynamic interfaces.

In the VOF method, the moving interface is captured implicitly by a discontinuous VOF indicator function, F. In this method, the indicator function is zero in one fluid and one in the other fluid. At the interface cell, it vary between zero and one. Two approaches are used to solve the VOF Eq. (1) discretization of the volume fraction equation using anyone of high resolution schemes and (2) approximation of the interface geometrically in a two-phase cell using the void fraction, F. The first approach is easy to implement even for unstructured grids. However, this approach produces a highly diffusive interface and affects the accuracy of the solution. Hence, this approach is not preferred for the phase change problems and not discussed further. The second approach is the advection of volume fraction based on geometric interface reconstruction. This approach provides a sharp interface between two phases. The widely used interface reconstruction methods are SLIC (Simple Line Interface Calculation) [6] and PLIC (Piecewise Linear Interface Calculation) [7]. The VOF method has good mass conservative property, but computes the interfacial unit normal vector, mean curvature and surface tension force inaccurately. The inaccurate evaluation of the surface tension force across the interface may lead to the generation of spurious currents. In order to improve the solution, ELVIRA (Efficient Least squares Volume-of-fluid Interface Reconstruction Algorithm) [8] and PROST (Parabolic Reconstruction Of Surface Tension) [9] methods were introduced. Other methods which are limited to 2D flows are SIR (Spline-based Interface Reconstruction) [10] and QUASI (QUAdratic Spline based Interface) [11]. These methods are either difficult to implement or computationally expensive for both non-uniform structured grids and unstructured grids.

Various time integration schemes are used to solve the VOF function equation. The multidirectional un-split time integration scheme, as shown in Fig. 1(a), causes inaccuracy due to double fluxing problem [12]. The twice fluxing problem may lead to overshoot ($F > 1$) or undershoot ($F < 0$) of the VOF function, F in the computational domain. In order to avoid double fluxing problem, an operational split method [13] is used. In this method, at each time step, the advection equation of the VOF function is solved in each spatial coordinate direction as shown in Fig. 1(b) and (c) for the case of 2D problem. The geometric reconstruction of the interface has to be carried out before solving the advection equation in each spatial direction based on the VOF functions obtained from the solutions of the previous spatial direction advection. As the directional advection method required reconstruction of the interface twice and thrice for the 2D and 3D problems respectively this approach is computationally expensive and time consuming. Hence, Rider and Kothe [14] introduced a multi-dimensional (or un-split) advection algorithm for the VOF method to avoid the double fluxing as shown in Fig. 1(a). However, the twice (or double) fluxing problem could not be eliminated completely mainly due to an inaccurate geometrical construction of mass flux advection polygon at each control volume faces as shown in Fig. 1(d). To avoid this problem in the solutions, Lopez et al. [10] developed the Edge Matched Flux Polygon Advection (EMFPA) algorithm for two-dimensional problems (Fig. 1(e)) and Hernandez et al. [15] and Lopez et al. [16] developed the Face Matched Flux Polyhedron Advection (FMFPA) algorithm for three-dimensional problems. Very recently, Tsui and Lin [17] introduced a multidirectional advection algorithm for the VOF method for non-orthogonal grids.

Taking positive aspects of both the VOF and the LS methods, the Combined Level Set and Volume of Fluid (CLSVOF) method was first proposed by Bourlioux [18]. Implementation of CLSVOF method by Sussman and Puckett [19] has popularised this method. The CLSVOF method is more accurate for the simulation of two-phase flows because of its better mass conservation, accurate