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A coupled level set and volume of fluid method on unstructured grids for the direct numerical simulations of two-phase flows including phase change

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ABSTRACT

In the present study, a coupled level set and volume of fluid (CLSVOF) method is developed for two-dimensional unstructured grids to perform direct numerical simulations of two-phase flows including phase change. The volume fraction is advected using a multi-directional advection algorithm, where the flux polygons are constructed using vertex velocities and a scaling factor based on cell face velocities is used to correct the advected volume fraction. The level set field is advected using a total variational diminishing (TVD) scheme and geometrically reinitialized at the end of each time step. The performance of the proposed CLSVOF method is evaluated in detail on unstructured grids, both qualitatively and quantitatively, prior to simulation of phase change problems. A number of advection test cases and two-phase flow problems are considered for this purpose. Results obtained for film boiling over a horizontal flat plate using an unstructured grid show excellent agreement with results available in the literature. The numerical study of natural convection film boiling over a horizontal cylinder at different wall superheats shows a better agreement with semi-empirical correlations compared to other available numerical results.

1. Introduction

Phase change phenomena like boiling are characterized by high heat transfer rates and thus find applications in a plethora of fields such as power generation, refrigeration, nuclear reactors, and electronics cooling. Sustained efforts towards understanding the flow physics and heat transfer associated with different regimes of boiling is thus of fundamental importance. In the second half of the twentieth century, boiling was the subject of many experimental and analytical studies. Experiments have provided numerous correlations to predict boiling characteristics under different regimes for specific geometries. On the other hand, theoretical studies involve several assumptions pertaining to aspects such as vapor and fluid properties, and surface tension. Nevertheless these studies have immensely improved our understanding of boiling, and would continue as we look for further insights. With the rapid and massive advancements in the field of computational fluid dynamics over the last few decades, it was imperative that numerical techniques would be developed to model two-phase flows including phase change phenomena such as boiling. Moreover, as noted by pioneers in this field [1–3], the small spatial and temporal scales associated with the physics of boiling make experimental measurements very difficult, and computations of boiling flows would help to uncover aspects that may still not be well understood.

Two-phase flows can be modelled using Euler-Euler model, which requires a priori information to a certain extent about the interfacial transport processes [4]. Direct numerical simulations of two-phase flows avoid any empiricism by identifying the sharp interface and solving the transport mechanisms directly across the interface. Surface tension between the two phases thus becomes an important factor that affects the interface shape. Keeping track of the interface position with time, an abrupt change in properties across the sharp interface, and non-linear surface tension force render these numerical simulations quite challenging.

The methods predominantly used presently for direct numerical simulation of two- phase flows are the volume-of-fluid (VOF) method, the level set (LS) method, the coupled level set and volume-of-fluid (CLSVOF) method, and the front tracking method. The front tracking method involves solution of transport equations on a fixed grid while utilizing a moving grid for tracking the interface. The front tracking approach for incompressible multi-fluid flows developed by Unverdi and Tryggvason [5], was extended

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Nomenclature

c_p	specific heat at constant pressure (J/kg K)
F	volume fraction or colour function
F_{st}	volumetric surface tension force (N/m^3)
g	acceleration due to gravity (m/s^2)
H	smoothed Heaviside function
h_{lv}	latent heat of vaporization (J/kg)
k	thermal conductivity (W/m K)
$\dot{m}$	mass flux across interface (kg/m^2 s)
$\mathbf{n}$	interfacial unit normal vector
Nu	Nusselt number
P	pressure (Pa)
$\boldsymbol{q}''$	heat flux vector (W/m^2)
S	surface area (m^2)
t	time (s)
T	temperature (K)
u, v	velocity components in x and y coordinates (m/s)
$\mathbf{V}$	cell velocity vector (m/s)

Greek symbols

κ	interfacial curvature (m^{-1})
μ	dynamic viscosity (N s/m^2)
ρ	density (kg/m^3)
σ	surface tension coefficient (N/m)
ϕ	level set function
λ_o	characteristic capillary length scale (m)

Subscripts

int	interface
l	liquid phase
v	vapor phase
sat	saturation

for boiling flows by Juric and Tryggvason [2]. The other methods mentioned above capture the interface on an Eulerian grid, and are thus classified as interface capturing methods. This can arguably be the reason for a lower computational complexity leading to their wider use.

The VOF method uses a colour function with a value of 0 or 1 in either of the two phases, while having an intermediate value at the interface cells, representing the volume fraction of one of the phases in each cell. VOF methods either use high resolution schemes to advect the interface or involve geometrical interface advection and reconstruction. The former method usually leads to a diffused interface. Hence, the geometrical approach is more popular. Welch and Wilson [3] used the VOF method with Young's piecewise linear interface calculation (PLIC) scheme [6] to simulate horizontal film boiling. The mass conservation implicit within the VOF method has kept it relevant and widely in use till date. However, a major drawback is the generation of spurious currents due to inaccurate calculation of interface curvature, since it is based on the discrete colour function distribution. Several improvements have subsequently been proposed for two-phase flows on structured uniform grids, which focus on improved interface reconstruction techniques and accurate surface tension calculation [7–10]. However, the applicability, performance, computational cost and complexity of many of these methods on non-orthogonal or unstructured grids is not well-established or reported.

The VOF-PLIC schemes still remain the most popular choice for interface reconstruction. Height function (HF) method for estimating curvature from volume fractions has been reported [11,12] to provide second-order accurate results on structured grids, and its implementation is also easier than parabolic or spline interface reconstruction [13]. However, studies have also revealed that HF method which uses a fixed stencil of cells may lead to poor results in regions where the curvature is not adequately resolved by grid size [11,12] and the spurious currents are sensitive to errors in the VOF transport scheme [14]. HF method has been implemented on unstructured grids in a few studies [15,16]. However, detailed investigations of these methods for different practical problems is yet to emerge. To reduce spurious currents, some of the studies have also highlighted the need for an algorithm to balance the pressure and surface tension forces in the vicinity of the interface [12,17,18].

Another aspect of VOF methods covered in several studies [9,17,19,20] is the unsplit or multi-dimensional advection of the colour function, which as opposed to operator split advection does not require advection in each coordinate direction separately for every time step. This not only reduces computational time but also makes the use of VOF methods feasible for irregular or complex geometries with unstructured grids.

After Welch and Wilson [3], several researchers have used VOF framework for simulation of film boiling, for which the reader may refer to the review by Kharangate and Mudawar [21]. Recently, Tsui and Lin proposed a modified VOF method [22] applicable to unstructured grids requiring successive corrections of colour function value at a given time step. The performance of the method on unstructured grids is shown only qualitatively for two advection test cases, while other two-phase flow results are presented only for structured grids. Tsui et al. [23] used the above method to simulate two-dimensional film boiling over a flat plate and a horizontal cylinder. Recently, Tsui and Lin [24] extended their method for three-dimensional simulation of film boiling over a flat plate using a structured grid. Ding et al. [25] presented a VOF based method for phase change problems using an energy source donor-acceptor scheme to suppress the numerical oscillations resulting from different factors in such simulations.

Level set (LS) methods form another important class of interface capturing methods originating from the work of Osher and Sethian [26] and further developed by Sussman et al. [27]. The LS methods use a signed distance function that takes positive values of distance from the interface in one of the phases, negative in the other, while the zero contour represents the interface. The LS advection equation is solved directly with appropriate discretization schemes without any complex geometric tasks as employed in VOF methods. Hence, an extension of the LS method to three dimensions or unstructured grids is relatively easier. The curvature and surface tension can be calculated accurately from the smooth distribution of the LS function. However, the LS function does not remain a smooth signed distance function as it advects over time and also inherently suffers from mass conservation errors. To maintain it to be a smooth signed distance function, reinitialization of the LS function at each time step proposed by Sussman et al. [27] is widely used. Still, the reinitialization procedure leads to mass errors further compounded during interface evolution. Subsequent improvements to the LS method deal with the mass errors and are highlighted in the work of Gada and Sharma [28]. Another development is the use of ghost fluid method [29] in conjunction with the LS method for sharp interface simulations. Son and Dhir [1,30] first used the LS method to simulate film boiling on horizontal surfaces,