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An auxiliary grid method for computations of multiphase flows in complex geometries

Metin Muradoglu *, Arif Doruk Kayaalp

Department of Mechanical Engineering, Koc University, Rumelifeneri Yolu, Sariyer 34450, Istanbul, Turkey

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Abstract

A method is developed for computations of interfacial flows in complex geometries. The method combines a front-tracking method with a newly developed finite volume (FV) scheme and utilizes an auxiliary grid for computationally efficient tracking of interfaces in body-fitted curvilinear grids. The tracking algorithm reduces particle tracking in a curvilinear grid to tracking on a uniform Cartesian grid with a look up table. The algorithm is general and can be used for other applications where Lagrangian particles have to be tracked in curvilinear or unstructured grids. The spatial and temporal errors are examined and it is shown that the method is globally second order accurate both in time and space. The method is implemented to solve two-dimensional (planar or axisymmetric) interfacial flows and is validated for a buoyancy-driven drops in a straight tube and the motion of buoyancy-driven drops in a periodically constricted channel.

Keywords: An auxiliary grid method; Particle tracking; A finite-volume/front-tracking method; Interfacial flows; Complex geometries

1. Introduction

Simulation of multiphase flows is notoriously difficult mainly due to the presence of deforming phase boundaries. A variety of numerical methods have been developed and successfully applied to a wide range of multifluid and multiphase flow problems [16,20,21,23,26]. In spite of this success, significant progress is still needed especially for accurate computations of multiphase flows involving strong interactions with complex solid boundaries. It is of great importance to be able to accurately model strong interactions between bubbles/drops and curved solid boundaries in many engineering and scientific applications such as microfluidic systems [22], pore-scale multi-phase flow processes [13,14] and biological systems [7,19]. It has been recently shown that adaptive grid methods combined with a level-set approach can be successfully used to solve interfacial flow problems in complex geometries [1,6,28]. Here a front-tracking approach is taken to account for the effects of the interfacial tension and change in material properties in different phases.

* Corresponding author. Tel.: +90 607 254 5402; fax: +90 607 255 1222/212 338 1548.
E-mail address: mmuradoglu@ku.edu.tr (M. Muradoglu).

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The front-tracking method developed by Unverdi and Tryggvason [25] has proved to be an effective tool for computations of interfacial flows and it has been successfully applied to a wide range of multiphase flow problems but almost all in relatively simple geometries [23] except for the cut-cell Cartesian method developed by Udaykumar et al. [24]. The front-tracking method has many advantages such as its conceptual simplicity and small numerical diffusion. However, its main disadvantage is probably the difficulty to maintain the communication between the Lagrangian marker points and Eulerian body-fitted curvilinear or unstructured grids. In the cut-cell method [24,27], the interface is tracked explicitly on a regular Cartesian grid and the grid cells cut by the interface are modified according to their intersections with the interface. The interface cells are then treated specifically in order to accurately discritize the governing equations. Although the method has been successfully applied to a variety of two-dimensional problems [24,27], the main difficulty with this method arises from the large number of possible intersections between the fixed grid and the interface resulting in various types of interface cells each requiring a special treatment. In addition, in the cases of highly deformed interfaces, the interface cells may have unavoidable irregular shapes with very small volumes and very large aspect ratios, which adversely impacts the accuracy and stability of the flow solver. Furthermore, it is not straightforward to incorporate the method in existing flow solvers as it requires to modify the basic solution algorithm. The present method overcomes these difficulties while maintaining the main advantages of the front-tracking method. In this approach, the front-tracking methodology is extended to body-fitted curvilinear grids and is combined with a newly developed finite-volume method to facilitate accurate and efficient modeling of strong interactions between the phases and complex solid boundaries. The method incorporates an efficient and robust tracking algorithm developed for tracking the front marker points in body-fitted curvilinear grids. The tracking algorithm utilizes an auxiliary uniform Cartesian grid and it can be easily adapted to unstructured grids as well. The algorithm reduces particle tracking in a curvilinear grid to tracking on a uniform Cartesian grid with a look up table. Furthermore, it can be used in other applications where Lagrangian particles have to be tracked on curvilinear or unstructured grids such as the particle-based Monte Carlo method widely used for solving the PDF equations of turbulent reacting flows [10,18]. The finite-volume method is based on the concept of dual (or pseudo) time-stepping method. The dual time-stepping method uses sub-iterations in pseudo time and has a number of advantages including direct coupling of the continuity and momentum equations for incompressible flows, the elimination of factorization error in factored implicit schemes, the elimination of errors due to approximations made in the implicit operator to improve numerical efficiency, the elimination of errors due to lagged boundary conditions at the solid and internal fluid boundaries, and ability to use non-physical, preconditioned iterative methods for more efficient convergence of the sub-iterations [5].

The main advantages of the present method that make it attractive compared to alternative approaches can be summarized as follows:

1. It retains all the advantages of the front-tracking method [23] while treating complex geometries in a natural way using a body-fitted curvilinear grid without substantial increase in computational cost.
2. It does not require any major modification to the basic flow solver so that it can be easily incorporated into virtually all existing flow solvers including commercial CFD packages through user defined functions (UDFs).
3. It is straightforward to extend the present approach to unstructured grids and to three-dimensional geometries.
4. The tracking algorithm is very robust and computational efficient. It reduces particle tracking in a curvilinear grid to tracking on a uniform Cartesian grid with a look up table and can be used in other applications where Lagrangian particles have to be tracked on a curvilinear or unstructured grid as mentioned above.

The method is implemented to compute two-dimensional (planar or axisymmetric) interfacial flows in complex geometries and has been successfully applied to compute the motion and breakup of viscous drops in complex geometries [11,15] and mixing in a plug moving through a serpentine channel [12]. In the present study, the performance of the tracking algorithm is tested and its temporal and spatial accuracies are quantified in a simple setting of a rigid body rotation of fluid in a two-dimensional circular channel. The method is