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Lattice Boltzmann Methods for Multiphase Flow Simulations across Scales

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Abstract. The simulation of multiphase flows is an outstanding challenge, due to the inherent complexity of the underlying physical phenomena and to the fact that multiphase flows are very diverse in nature, and so are the laws governing their dynamics. In the last two decades, a new class of mesoscopic methods, based on minimal lattice formulation of Boltzmann kinetic equation, has gained significant interest as an efficient alternative to continuum methods based on the discretisation of the NS equations for non ideal fluids. In this paper, three different multiphase models based on the lattice Boltzmann method (LBM) are discussed, in order to assess the capability of the method to deal with multiphase flows on a wide spectrum of operating conditions and multiphase phenomena. In particular, the range of application of each method is highlighted and its effectiveness is qualitatively assessed through comparison with numerical and experimental literature data.

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1 Introduction

The understanding of multiphase flows across space-time scales has always been of great interest both from a theoretical and a practical point of view. A number of industrial and technological processes are, in fact, associated with dispersed or separated multiphase flows, over a wide spectrum of different scales. Micro and nanometric multiphase flows play a crucial role in many emerging applications in material science, chemistry, engineering and biology. Similarly, the macroscopic phenomena related to multiphase fluid dynamics are also particularly important in many engineering areas, from cavitating pumps and turbines to water waves formation and propagation. A deeper understanding of the physics of fluids and the ability of predicting the fluid flow behaviour in such engineering processes is of paramount importance to these applications. However, the simulation of the above phenomena is a great challenge due to the inherent complexity of the involved phenomena (emergence of moving interfaces with complex topology, droplet collision and break-up), and represents one of the leading edges of computational physics [1]. A general computational approach encompassing the full spectrum of complexity exposed by multiphase flows is not available, yet. This is a consequence of the variety of phase combinations and interphase interactions and processes (i.e., viscosity, surface tension, heat conduction, phase transition, fragmentation and coagulation of drops and bubbles) which affect the physics of multiphase flows. The numerical methods based on the traditional continuum approach (i.e., Navier-Stokes with closure relationships) usually rely upon rather complex correlations and often require transient solution algorithms with very small time steps. In the last two decades, a new class of mesoscopic methods, based on minimal lattice formulation of Boltzmann kinetic equation, have gained significant interest as an efficient alternative to continuum methods based on the discretisation of the NS equations for non ideal fluids [2]. Since its early days, the Lattice Boltzmann shed promises of becoming a valuable tool for the modeling of multiphase flows. The continuum approach, in fact, may become inadequate to describe complex flow phenomena (i.e., droplet formation, break-up, cavitation and coalescence, water waves and free-surface flows) associated to the contemporary presence of different phases. Such difficulties are often signalled by a singular behaviour of the continuum equations (i.e., tip rupture) [3]. The kinetic approach is in principle better suited to handle the complex phenomena related to multiphase flows, since it can incorporate (minimal) aspects of microscopic physics (i.e., interphase interactions) without surrendering the computational efficiency of continuum methods.

With concern to the latter point, it is worth noting that a still widespread misbelief is that LBE should apply only to dilute gases, the reason being that it derives from an approximation of the continuum Boltzmann equation, which was originally derived under the assumption of dilutedness. This line of thinking fails to recognize that, although kinetic theory was originally meant to describe weakly-interacting (dilute) systems, it can also be applied whenever strong interactions between elementary degrees of freedom can be cast in the form of weak interactions between appropriate collective degrees of