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Some Advances in Applications of Lattice Boltzmann Method for Complex Thermal Flows

Ridha Djebali[1,*], Habib Sammouda[1] and Mohammed El Ganaoui[2]

[1] *University of Tunis El-Manar, FS of Tunis, Department of Physics, LETTM, 1060 Tunis, Tunisia*
[2] *CNRS/SPCTS, UMR 6638, FST of Limoges, Department of Physics, 87060 Limoges, France*

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Abstract. Over the past two decades, there have been enormous advances in lattice Boltzmann (LB) numerical simulation and modelling. The lattice Boltzmann method has become a practical and promising tool for many fluid problems. A majority of recent studies have relied on numerical computations of isothermal flows. However, much less efforts have been devoted to complex thermal flows, such as flows in porous media subjected to external magnetic force, flows with temperature-dependent properties. In this paper, an overview is made based on some accomplishments in these numerical endeavours. Along with the paper's sections, the state-of-the-art trend and the LBM advances in modelling and in computational aspects for specific classes of problems of major interest will be fully touched on. Concluding remarks are given and the axis of our future studies will be traced.

AMS subject classifications: 76M28, 70K50, 76S05, 82D10

Key words: LB method, Bifurcations and instability, porous media flows, plasma jets.

1 Introduction

Over the past two decades, the lattice Boltzmann method (LBM) has been widely adopted to solve linear and nonlinear partial differential equations (such as Burger's equation, wave equation, Poisson equation etc.) and progressively the method shows its efficiency, to offer today a powerful tool for simulating fluid flows [1–4]. Unlike the conventional Computational Fluid Dynamics (CFD) ones based on continuum mechanics, the method starts from mesoscopic kinetic equation and statistical physics

*Corresponding author.
URL: `http://www.unilim.fr/spcts/-Doctorants-.html`
Email: ridha.djebali@etu.unilim.fr (R. Djebali), habib.sammouda@fsm.rnu.tn (H. Sammouda), ganaoui@unilim.fr (M. El Ganaoui)

(the Boltzmann equation) and determines the macroscopic quantities (density, velocity, pressure etc.). In the framework of the LBM, the lattice Boltzmann equation is time and space-discretized and a set of density distribution functions (corresponding to fictitious particles that colloid and stream) are stored at each lattice node. The updating mechanism consists of two steps: a streaming along a set of discrete velocities and a relaxation equivalent to the collision frequency of particles. In the LBM, the macroscopic quantities are locally computed by using each time step's density distribution functions. The pressure derives from the density via an equation of state. The solution procedure of the method provides many advantages resulting in simpler set of equations (resulting in algebraic operations unlike algebraic equations for classical CFD methods), parallel computations, easy handling of complex geometries, easy handling of coupling equations by simply adding force/sink term in discretized equation.

For instance, the LBM presents the features of simulating classical flows [5–9], flow with complex geometries [10], multiphase flows [11, 12], multicomponent flows [13], it overcomes some shortcomings of classical CFD methods (discretization, CFL stability condition, $\cdots$,) and enables us to investigate time-dependent flow transition more conveniently since its remarkable capability in recording transients of flow development. Moreover, previous LB based works almost used Cartesian coordinates system and focused the interest on steady state flows. Some recent works have attempted the fully unsteady flow regimes [14, 15] and other coordinate systems [16–19]. However, a fully LB-understanding of transition thresholds is less considered in the literatures although the occurring phenomena are of practical interest in industry [20], such as for crystal growth in low Prandtl number flows. Furthermore, very high temperature flows such as plasma jets (where all diffusion parameters are temperature dependent), free jet flows (where special attention is made for boundary condition treatment) and porous media flows under magnetic force (where the forcing term needs special treatment), are of practical and scientific interest and were not yet (or few) approached by the LBM at our knowledge. Since these topics are of vital importance in numerous applications, the present work is devoted to review our knowledge for recent improvement and progress in its modelling and simulation using the LBM.

The present works is organized as follows: the introduction section presents the basic concept of the LBM and its implementation for thermal flows; the validation section provides several investigations of steady and unsteady natural convection flows with qualitative and quantitative comparisons with previous numerical results. The last section is devoted to review some recent progress in LB simulation and modelling of some complex thermal flows, namely low Prandtl number fluid melts flows subject to symmetry breaking and transition to unsteady regimes, plasma jets flows for pure gas and gases mixture and flows in porous media subject to external magnetic force. For the three examples, the focus is put on the advances in LB modelling and the predictability level in the results rather than to describe the models in detail. Comparisons with previous results using classical CFD methods are given in all cases for model validation.