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REVIEW

A Review on the development of lattice Boltzmann computation of macro fluid flows and heat transfer

D. Arumuga Perumal [a,*], Anoop K. Dass [b]

[a] Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore 575025, India
[b] Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

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Abstract The Lattice Boltzmann Method (LBM) is introduced in the Computational Fluid Dynamics (CFD) field as a tool for research and development, but its ultimate importance lies in various industrial and academic applications. Owing to its excellent numerical stability and constitutive versatility it plays an essential role as a simulation tool for understanding micro and macro fluid flows. The LBM received a tremendous impetus with their spectacular use in incompressible and compressible fluid flow and heat transfer problems. The applications of LBM to incompressible flows with simple and complex geometries are much less spectacular. From a computational point of view, the present LBM is hyperbolic and can be solved locally, explicitly, and efficiently on parallel computers. The present paper reviews the philosophy and the formal concepts behind the lattice Boltzmann approach and gives progress in the area of incompressible fluid flows, compressible fluid flows and free surface flows.

Contents

* Corresponding author at: Department of Mechanical Engineering, NIT Karnataka, Surathkal, Karnataka 575025, India. Tel.: +91 91598 60535; fax: +91 361 2690762.
E-mail address: d.perumal@alumni.iitg.ernet.in (D. Arumuga Perumal).
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1. Introduction

1.1. General background

The continuous growth of computer power has motivated the scientific community to use CFD for numerical solution of the governing equations of fluid dynamics [1]. Generally the mathematical models used in CFD include convective and diffusive transport of some variables. These mathematical models consist of governing equations in the form of ordinary or partial differential equations (ODEs or PDEs). As a great number of such model equations like the Navier–Stokes equations do not possess analytical solutions, one has to resort to numerical methods [2]. The difficulty in solving the Navier–Stokes equations is due to their nonlinear terms. In conventional numerical methods, the macroscopic variables of interest such as velocity and pressure are usually obtained by solving the Navier–Stokes equations [3].

Over the years, the finite difference method (FDM) and finite volume method (FVM) are frequently being used in CFD [4]. FDM consists in essentially setting up a uniform rectangular grid in the problem domain, discretizing the governing equations with respect to the grid by replacing the derivatives with their finite-difference approximations and solving the resulting algebraic equations numerically [5]. For non-uniform grids FDM requires a transformation of the physical space onto a computational space with an uniform grid. FVM requires no such transformation as it solves the integral form of the governing equations that are integrated over (generally) irregularly-shaped finite volumes. The finite element method (FEM) has not gained as much popularity in fluid mechanics as it has in structural mechanics.

In the last two decades, a different kind of numerical method for applications in CFD, namely, the Lattice Boltzmann Method (LBM) has gained popularity [6]. The LBM has emerged as a new effective and alternative approach of CFD and it has achieved considerable success in simulating fluid flows and heat transfer problems [7]. In the LBM approach, one solves the kinetic equation for the particle distribution function. The macroscopic variables such as velocity and pressure are obtained by evaluating the hydrodynamic moments of the particle distribution function [8]. One of the most popular and simple approaches in the LBM is lattice Boltzmann equation with linearized collision operator based on the Bhatnagar–Gross–Krook (LBM-SRT) collision model. It is known that, through a Chapman–Enskog analysis, one can recover the governing continuity and momentum equations in the low Mach number limit [9].

1.2. Overview of LBM

In the past few years, researchers have been using lattice Boltzmann method for simulating and modelling in physical, chemical, social systems including flows in magnetohydrodynamics [10], immiscible fluids [11], multiphase flows [12], heat transfer problems [13–15], porous media [16] and isotropic turbulence [17]. Historically, LBM originated from the method of Lattice gas automata (LGA), which was first introduced in 1973 by Hardy, Pomeau and de Pazzis (HPP) [18]. In LGA, the term Lattice implies that one is working on a lattice which is d-dimensional and usually regular. Gas suggests that a gas is moving on the lattice. The gas is usually represented by Boolean particles (0 or 1). Automata indicate that the gas evolves according to a set of rules. In the LGA model, the space, time and particle velocities are all discrete. The iteration of an LGA consists of a collision and propagation step. But, the major drawbacks of the LGA were intrinsic noise, non-Galilean invariance, an unphysical velocity dependent pressure and large numerical viscosities. In 1986, Frisch, Hasslacher and Pomeau (FHP) obtained the correct Navier–Stokes equations using a hexagonal lattice. Lattice Boltzmann equations has been used at the cradle of Lattice Gas Automata (LGA) by Frisch et al. [19] to calculate viscosity. To eliminate statistical noise, in 1988 McNamara and Zanetti [20] did away with the Boolean operation of LGA involving the particle occupation variables by neglecting particle correlations and introducing averaged distribution functions giving rise to the LBM.

Higuera and Jimenez [21] brought about an important simplification in LBM by presenting a Lattice Boltzmann Equation (LBE) with a linearized collision operator that assumes that the distribution is close to the local equilibrium state. A particularly simple version of linearized collision operator based on the Bhatnagar–Gross–Krook (BGK) [22] collision model was independently introduced by several authors including Koelman [23] and Chen et al. [24]. The lattice BGK (LBGK) model [25,26] utilizes the local equilibrium distribution function to recover the macroscopic Navier–Stokes equations.

Boundary condition plays a crucial role in lattice Boltzmann simulations [27–34]. The bounce-back boundary condition is a popular boundary condition in LBM. It is derived from LGA and has been extensively applied in LBM simulations. In this scheme, the particle distribution function