Progress in the Application of Lattice Boltzmann Method for Turbulent Flows

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ABSTRACT

We present a review of applications of the Lattice Boltzmann Method in turbulent flows. Canonical flows of interest to off-shore (coastal) engineering are highlighted. Such flows include turbulence with thermal gradients, turbulence with frame rotation, turbulence subject to periodic shear, two-fluid turbulent jets and flows past bluff bodies. LBM turbulence calculations at all levels—direct numerical simulations (DNS), large eddy simulations (LES) and Reynolds averaged Navier-Stokes simulations (RANS)—are investigated. The theoretical challenges and computational advantages of LBM turbulence calculations are detailed.

KEY WORDS: Lattice Boltzmann Method, turbulence, frame rotation, periodic shear, turbulent jets, bluff-bodies, temperature fluctuations, decaying turbulence, homogeneous shear, oscillating shear, two-fluid models, binary mixtures.

INTRODUCTION

Kinetic Boltzmann equation describes the evolution of a single particle velocity probability distribution function subject to collisions with other particles in the flow. The kinetic Boltzmann equation provides flow description at the mesoscale level, which is between microscale and macroscale in degree of detail. The mesoscale Boltzmann equation is valid over the entire range of Knudsen numbers and a broader range of physics than the macroscale Navier-Stokes equations. For gases, this equation enjoys a wide range of applicability—rarefied gas dynamics, hypersonic non-equilibrium flow, astrophysical gas dynamics and flow in nano-scale devices. This equation is also valid in many instances wherein constitutive relations are not available, as fluxes can be directly computed from the particle distribution function. Despite a wider range of applicability than the Navier-Stokes equations, Boltzmann equations, until recently, had not been used for computational fluid dynamics (CFD) computations due to the fact that appropriate numerical strategies were not yet developed. The last two decades have witnessed important progress in many areas that has led to widespread use of kinetic based methods for a variety of CFD applications. The single important development is the lattice-based solution of the Boltzmann equation—the so-called lattice Boltzmann method (LBM). In this method, the nearly infinite degree of freedom Boltzmann equation is approximated to a much smaller system with an order of ten degrees of freedom. These restricted degrees of freedom form a lattice in velocity space and hence the name lattice Boltzmann method. The next major advancement of this method came with the proof that the lattice Boltzmann equation is in fact equivalent to non-traditional discretized Navier-Stokes equation. This discretization allows for many computational advantages not possible in conventional discretized methods. Particularly, the advective operator is represented nearly exactly in this approach. This represents a major advantage for LBM over conventional CFD for the simulation of turbulent flows, wherein much of the numerical difficulties arise due to the advective term. Further, the close connection with Navier-Stokes methods enables LBM to be applied without any change to all flows including those of fluids. Therefore, LBM has the potential for becoming a frontline CFD tool for the ocean engineering community.

In this paper, we will focus on the various turbulence calculations performed using LBM and other kinetic theory-based methods. The procedure for filtering Boltzmann equation for filtered turbulence description is provided in Girimaji (2007). The focus here will be mostly on direct numerical simulations (DNS) and large eddy simulations (LES) of various turbulent flows. This review of kinetic-theory based turbulence calculations is divided into three classes based on flow complexity: (i) decaying isotropic turbulence (DIT) with rotation and temperature fluctuation effects; (ii) homogeneous shear turbulence with constant and periodic shear; and (iii) complex inhomogeneous flows.

A REVIEW OF LBM APPLICATIONS

Decaying isotropic turbulence

Over the last decade, application of kinetic theory based methods in turbulence calculations has taken great strides. Kinetic theory based LBM have been applied to a wide range of fluid dynamic simulations. McNamara and Zanetti (1988) and Higuera and Jimenez (1989) were amongst the first to point out the lattice Boltzmann equation (LBE) as a possible efficient tool to simulate two and three-dimensional fluid flows. Benzi and Succi (J. Phys., 1990) investigate in detail, the ability