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Lattice Boltzmann Simulation of 3D Gravity Currents around Obstacles

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The aim of this work is to carry out a preliminary assessment of the capacity of a two-layer Shallow Water-equivalent Lattice Boltzmann Method formulation (SWLBM) to simulate the interaction of a gravity current with an emerging cylinder. The Immersed Boundary technique is employed here as it facilitates the representation of complex emerging obstacles in the SWLBM framework. The assessment is achieved by means of a comparison with numerical results obtained from a fully 3D Navier-Stokes (NS) model. The latter is first validated against both experimental and theoretical benchmark data and then used to obtain a reference numerical solution for the considered flow. The benchmark cases are 2D and an axisymmetric gravity current. Numerical results show a satisfactory agreement with the benchmark data (theoretical for the 2D and experimental for the axisymmetric gravity current). Finally, the interaction of a gravity current with a cylindrical obstacle is considered. The 3D NS model is used as a numerical laboratory. The comparison between numerical results shows a fairly good agreement. Conclusions are drawn based on the comparisons.

INTRODUCTION

The Lattice Boltzmann Method (hereinafter LBM) is a powerful method which was introduced in the Computational Fluid Dynamics (hereinafter CFD) field a couple of decades ago. The development of the LBM has been tremendous and many interesting and excellent results have been obtained in several fields of CFD. The review of Aidun and Clausen (2010) gives a perspective of the cutting-edge applications of the LBM, while the books of Succi (2001) and Wolf-Gladrow (2000) are good introductions to the method with particular regard to its historical development. Zhou (2004) presents the extension of the method to Shallow-Water (hereinafter SW) flows. The reason for this rapid development is the intrinsic simplicity of the LBM compared to any classical CFD method, based on the mass, momentum and energy balance equations. This simplicity comes from the fact that the LBM is based on a mesoscopic representation of the fluid, instead of a macroscopic representation, from which the well known mass, momentum and energy balance equations are obtained. In other words, the fluid is seen as a set of particles, which can travel undisturbed for a while and then collide with each other. The distance covered by a fluid particle between two subsequent collisions is a sort of mean free path and has an order of magnitude much smaller than that of the characteristic length-scale of the fluid domain. The description of the state of the fluid is made by means of probability distribution functions (hereinafter PDF), which give the probability, at a given instant of time, of finding a particle in a given position and with a given velocity. The evolution of these PDF is governed by a system of semilinear kinetic equations, whose number is equal to the number of PDF. This is the first great advantage of the LBM with respect to methods based on the Navier-Stokes (hereinafter NS) or the SW equations. A second advantage of the method is represented by the "modularity" of the LBM. Indeed the latter consists of well distinct parts: the lattice, the kinetic equations, the collision operator and the equilibrium PDF. It is possible to change one or more parts to obtain results with different characteristics or even to simulate completely different flows.

The aim of this work is to carry out a preliminary assessment of the capacity of a two-layer SW-equivalent LBM formulation (hereinafter SWLBM) to simulate the interaction of a gravity current with an emerging cylinder. The Immersed Boundary (hereinafter IB) technique is employed here as it facilitates the representation of complex emerging obstacles in the SWLBM framework. The assessment is achieved by means of comparison with numerical results obtained from a fully 3D NS model. The latter is tested against experimental and theoretical data and then used to obtain a reference numerical solution for the considered flow.

The investigation of gravity currents is important because they model many environmental flows, such as those occurring in estuarine and coastal zones, where the density difference between the marine salty water and the river fresh water is responsible for the formation of salt wedges (the gravity current). These salt wedges can travel upstream for tens of kilometers (Fischer et al., 1979), affecting the environmental equilibrium and the quality of water and interacting with the structures immersed in the stream.

An acceptable representation of such flow is given by two shallow layers of immiscible liquids, with densities ρ_1, ρ_2 ($\rho_1 > \rho_2$), interacting with each other across their separation surface by means of pressure forces. No hypothesis is assumed on the magnitude of the density ratio r ($r = \rho_2/\rho_1$). The immiscibility hypothesis is usually assumed in investigating gravity currents, as it is well known that mixing has a negligible effect, at least during the initial stages of the gravity current's evolution (Ungarish, 2009).

The investigation of the dynamics of gravity currents by means of mathematical models based on NS or SW equations is a very difficult task (La Rocca and Bateman, 2010). The intrinsic simplicity of the LBM then could represent an attractive alternative for studying the dynamics of gravity currents in complicated domains and/or in presence of obstacles.

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KEY WORDS: Lattice Boltzmann method, gravity currents, immersed boundary, shallow water equations.