Accurate curved Dirichlet boundaries for fluid flow simulations on the lattice Boltzmann uniform Cartesian grid

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With the lattice Boltzmann Method (LBM), one can use a uniform Cartesian grid to accurately describe the interaction of a fluid flow with a complex solid surface. For that, one should employ a consistent *kinetic* boundary method. A "kinetic" type closure at the boundary operates a simplified *microscopic* population dynamics in agreement with the LBM algorithm in the bulk of the simulation. In LBM, the "populations" are the fundamental variables that are the discrete counterpart of the particle probability density function. The populations are synchronized on the regular grid such that their two first moments obey an incompressible-type Navier-Stokes equation for density and momentum, respectively. Therefore, the *macroscopic* Dirichlet velocity condition shall provide a grid-incoming population solution containing a Chapman-Enskog series of the macroscopic gradients in its non-equilibrium component. This problem has become the subject of intense research in the last three decades, yielding a zoo of possible schemes whose names and characteristics are cumbersome to remember even for insiders.

Our presentation shows that a straightforward extension of the bounce-back no-slip rule, where the outcoming population trivially inverts its direction, leads to a vast group of directional methods originating from the same principles but exhibiting different characteristics; the crucial point is that those link-wise schemes operate each incoming link independently of others. We analyze uniformly the link-wise family containing an infinite number of schemes and demonstrate how to optimize their five fundamental qualities: (i) exactness with respect to channel profile, (ii) accuracy order, (iii) linear stability, (iv) consistent physical parametrization, and (v) locality. The concept of locality determines the efficiency and versatility of the whole LBM algorithm because a *single-node* boundary scheme reduces memory access and allows for the coarsest representation of the narrow porous gaps. The two representative examples modeled inside an arbitrarily rotated channel are (i) an exact local description of the Poiseuille Stokes flow and (ii) an exact two-node solving of the Couette Navier-Stokes problem. We identify respectively two main groups of directional schemes. The first comprises compact schemes with linear exactness (LI) and, in the form of its extended linear (ELI) family, combines the local single-node implementation with the second-order accuracy, linear exactness, and physical consistency. The second is the Multi-reflection (MR) family, which gains parabolic exactness in the finite Reynolds number flow but abandons the locality. These developments are interesting as the popular and most recent directional rules cannot exhibit the same combination of features even in a grid-aligned channel. In addition, it is shown that the accuracy of the momentum solution does not deteriorate with the Reynolds number (Re) thanks to specific Re-dependencies of the ghost relaxation collision rates. The two benchmarks will confront the regular-grid LBM against the grid-aligned linear Finite Elements Method (FEM) in (i) porous flow through an array of the cylindrical obstacles and (ii) cylindrical Couette flow both in creeping and inertial regimes. Finally, the flow simulation through a porous medium using a modern *graphics processing unit* accelerator demonstrates the numerical performance of the ELI locality.

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