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Lattice-Boltzmann Large-Eddy Simulations of the flow field and dispersion around a bidimensional obstacle

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Abstract

Flow and dispersion dynamics in the urban atmosphere are characterized by the complex interaction between the atmosphere and the urban geometry, consisting of buildings, vegetation, and infrastructure. Furthermore, in cities, the concentration of human activities is responsible for pollution and heat emissions that are characterized by high spatial and temporal heterogeneity. The investigation and understanding of these dynamics is essential to address crucial aspects related to the urban microclimate (wind, humidity, temperature) and the air quality.

Today, the main investigation techniques are experiments and numerical simulations. Experiments allow to directly measure the turbulent flow field as well as to analyse the interaction of complex processes such as dispersion of pollutants and buoyancy effects due to solar heating. However, they provide limited spatial resolution and are used to analyse a small number of configurations (e.g., the number of geometries or external forcings). These two aspects are instead overcome by numerical approaches, and in particular by CFD (Computational Fluid Dynamics) simulations. In urban physics, most studies rely on RANS (Reynolds-averaged Navier–Stokes) simulations due to their low computational cost. For the analysis of dispersion processes and turbulent transfers, Large Eddy Simulations (LES) are more suitable as they resolve large scale turbulence. However, their great computational cost still makes them prohibitive for operational applications.

In this context, the Lattice Boltzmann Method LBM-LES approach is promising as it describes flow dynamics around complex geometries with a lower computational cost than traditional Navier Stokes approaches. Differently from Navier-Stokes equations, that macroscopically describe fluid motion, the LBM solves the Lattice Boltzmann (LB) equation which adopts a mesoscopic perspective (Kruger et al. 2015). The Boltzmann equation describes the behaviour of a collection of fluid particles by means of a distribution function, and their interactions by the BGK (Bhatnagar-Gross-Krook) collision operator. The discretized version of the Boltzmann equation is solved on a three-dimensional lattice. Once the distribution function is determined, the macroscopic density and velocity of the fluid can be easily derived. Moreover, the LES technique can be implemented in the LB equation: eddies smaller than the grid mesh are modelled by using the Smagorinsky subgrid viscosity model. To solve the conservation equations for species (passive scalar transport), an additional superimposed lattice is considered. Alternatively, a hybrid approach is adopted where the species conservation equation is solved using a standard finite volume method (Feng et al. 2019)

The LBM formulation makes the technique inherently parallel. Moreover, the use of the immersed boundary method allows to reduce the preprocessing time in the presence of complex geometry. For these reasons, in the last decade, the technique has found application in the field of urban climate and pollution. Recent applications concern the investigation of the link between urban morphology and pedestrian comfort (Ahmad et al. 2017, Jacob and Sagaut, 2018), the dispersion of pollutants in complex urban environments (Merlier et al. 2019), and in vegetated street canyons (Merlier et al. 2018).

To further examine the suitability of the method for urban applications, we evaluate in this work the performance of the LBM in predicting the velocity field and the turbulent dispersion in a boundary layer flow that develops over urban-like geometries. This is achieved by performing LBM-LES simulations using the software ProLB (CS, 2018). ProLB software is developed within an industrial and academic consortium including CS-GROUP, Airbus, Renault, Ecole Centrale Lyon, Aix-Marseille University and CNRS.

As a first step, we test the development of the turbulent boundary layer on a flat plate. We observe boundary layer indicators such as the boundary layer thickness, the logarithmic mean velocity profile, and the profiles of turbulent velocity fluctuations. The results are compared with classic experimental studies and DNS simulations.

The fully development of the turbulent boundary layer requires a long adaptation region and thus unfeasible computational cost for application to real urban geometries. This raises the necessity to inject synthetic turbulence at the entrance of the computational domain. To this aim, a tailor-made condition for synthetic inlet turbulence is implemented in the simulations. The condition is based on the method proposed by Shur et al. (2014). Velocity fluctuations are generated as a superimposition of weighted spatiotemporal Fourier modes with amplitudes designed to reproduce the actual Reynolds stress tensor. We compare the results provided by the inlet turbulent condition with those obtained from the simulated development of the boundary layer.

We then move to an idealized building geometry, and we simulate the flow around a two-dimensional obstacle. This configuration is used to assess the performance of the LBM simulation in reproducing flow recirculation around an obstacle. These circulating structures are common in the urban environment and are generated by the interaction of the wind with buildings. Furthermore, they play a fundamental role in dispersion dynamics as they can trap pollutants released at street level and delimit regions with high concentration.

The numerical results are compared with measurements from a detailed experimental characterization performed in the wind tunnel of the Ecole Centrale de Lyon. In the experiment, the flow field is measured by means of a Hot Wire Anemometer. The results show that the simulations are able to reproduce the mean velocity field (Figure 1). Furthermore, the turbulent flow field is tested with and without the application of the synthetic inlet turbulence condition.

In the last part of this work, we simulate the dispersion of a passive scalar behind the obstacle. In the wind tunnel experiment, ethane (acting as a passive tracer) is released by a line source at ground level. The concentration field is measured by means of a Flame Ionisation Detector. In ProLB, pollutant dispersion is simulated using temperature as a passive scalar. The source is reproduced as a surface (with extension equal to that of the linear source used in the experiment) at fixed temperature $T_S = T_{ref} + \Delta T$, where T_{ref} is the reference temperature and ΔT is the temperature rise at the source. A suitable non-dimensionalization of the concentration in the experiment and of the temperature in the simulation is implemented to compare the results obtained with the two techniques. Results show a good agreement between simulations and measurements for the mean concentration field. Moreover, the concentration variance and turbulent mass fluxes are assessed.

This study confirms that the LBM technique is suitable for reproducing dispersion around building-like geometries, while allowing the use of fine spatial and temporal resolution thanks to the computational efficiency. Future studies aim to simulate the effects of buoyancy due to heating of building surfaces and reproduce the flow and dispersion field in more realistic urban geometries in order to create a large dataset of numerical results for research purposes.

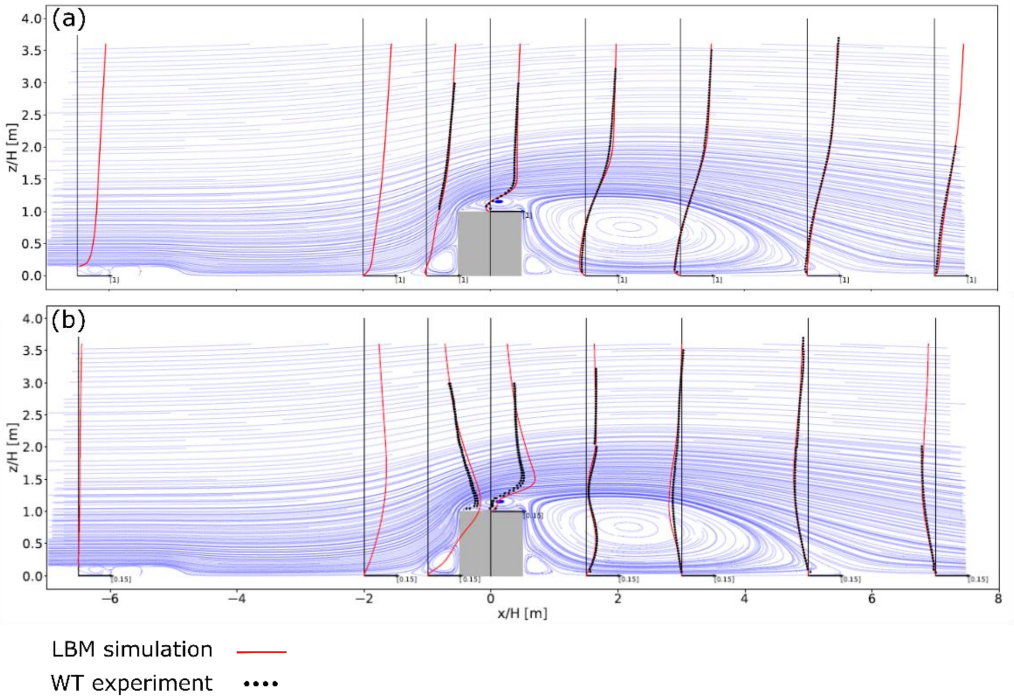

Figure 1: Comparison between the results from LBM simulations (red line) and measurements from the wind tunnel experiment (black dots). (a) Mean horizontal velocity. (b) Mean vertical velocity.

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