Building and Environment 139 (2018) 110–124

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Wind comfort assessment by means of large eddy simulation with lattice Boltzmann method in full scale city area

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ARTICLE INFO

Keywords:
Large-Eddy Simulation
Lattice Boltzmann method
Urban flow
Pedestrian wind comfort

ABSTRACT

Large-eddy simulations based on the Lattice-Boltzmann method of the flow in a realistic, full scale urban area are performed to compare several wind comfort criteria. It is observed that popular criteria for pedestrian comfort lead to very different conclusions, due to the access to high spatio-temporal resolution data. Different mixed strategies based on the combination of several criteria are proposed and compared to enhance pedestrian wind comfort assessment in practical cases.

1. Introduction

Pedestrian comfort is a global field of urban physics dealing with wind comfort, pollutant dispersion and thermal comfort close to the ground of cities. It can be addressed using either wind tunnel or in situ measurements that provide data at specific locations or using Computational Fluid Dynamics (CFD) which gives access to data over wide areas with very high spatial resolution. All these approaches are complementary considering that in situ and wind tunnel measurements permit to generate complete database that will be used to validate numerical model and to define guidelines for CFD studies which permit to obtain plenty of data on full scale geometries to assess pedestrian comfort.

Pedestrian wind comfort is sensitive to several kind of parameters such as the local wind (mean velocity, turbulent intensity), the location of the city (atmospheric conditions, building density) or the peoples (age, weight) so it is necessary to find or define universal rules to study it. In the literature those studies are mainly based on a mixing of meteorological data, aerodynamic data and comfort criterion to address local wind comfort in cities. Different criteria have been proposed in the literature, which are observed to a significant dispersion of results in some cases. Ratcliff and Peterka [1], Ohba et al. [2], Bottema [3] and Koss [4] listed and compared several wind comfort criteria such as those discussed in Davenport [5], Gandemer [6,7], Isyumov and Davenport [8,9], Lawson and Penwarden [10], Melbourne [11] and Hunt et al. [12]. This variability of pedestrian comfort criteria is significantly impacted by the nature of their input data: time-averaged velocity, turbulent intensity and averaging period length, from a few seconds to a few hours. In order to reduce the uncertainty induced by this high sensitivity of wind comfort criteria, comparing them on the same case can be a good way to evaluate pedestrian comfort quality but many kind of aerodynamic data can be necessary to this end. CFD is then an interesting tool since it permits to assess different data at many locations with a moderate effort.

The use of CFD for urban flow simulation is more and more widespread. Many studies are available in the literature and best practice guidelines [13–15] on the use of CFD for that kind of application have been proposed. Most of existing CFD simulations have been performed using the Reynolds Average Navier Stokes (RANS) approach, which resolves only the mean, time-averaged flow while the turbulent motion is modelled, on simplified [16–19] or realistic [18,20–29] geometries. However time-resolved approaches such as Detached Eddy Simulation (DES, see Ref. [30]) have been used recently on both simplified isolated buildings geometries [31,32] and complex urban area like Shinjuku AIJ test case [32]. Steady RANS simulations are widely used because of their low computational cost, but they do not permit to assess unsteady data, and therefore do not allow to consider all existing wind comfort criteria. Another commonly reported weakness is that they over-predict the turbulent energy dissipation, leading to a bad prediction of recirculation bubbles observed at the top or in the wake of buildings. To cure that problem Large Eddy Simulation (LES, see Refs. [33,34]) which allows for the direct resolution of a wide range of turbulent frequencies, can be used. However, the computational cost increase associated to LES due to its high spatio-temporal resolution can become a problem when simulations of flow over complex realistic geometries is targeted. These methods were first applied to simplified geometries or reduced area of cities, e.g. Refs. [35–39], but also for simulations of pollutant dispersion over complex urban areas [40], wind loads on buildings [41]

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https://doi.org/10.1016/j.buildenv.2018.05.015
Received 7 March 2018; Received in revised form 7 May 2018; Accepted 8 May 2018

Table 1
Example of existing CFD simulations at pedestrian level.

	Turbulence model	Computational domain	Area of interest	Pedestrian level	Wind comfort criteria	Grid points
He [35]	LES	$700 \times 700m^2$		$1.7m$		
Blocken [20]	RANS	$900 \times 700m^2$		$1.75m$	Bottema [3]	2.9×10^6
Blocken [21]	RANS	$3000 \times 3000m^2$	Amsterdam Arena	$2m$	NEN8100 [45]	2.8×10^6
Letzel [42]	LES	$1.6km^2$	$\simeq 1km^2$	$2.5m$		7.2×10^8 & 1.6×10^9
Jansen [23]	RANS	$2077 \times 1838m^2$	$1918 \times 1430m^2$	$1.75m$	NEN8100 [45], Isyumov [8], Melbourne [11], Lawson [46]	7.5×10^6
Montazeri [26]	RANS	$2076 \times 1963m^2$	Antwerp tower balconies	$1.7m$	NEN8100 [45]	$\simeq 16 \times 10^6$
Blocken [22]	RANS	$\simeq 2700 \times 2300m^2$	$1600 \times 1100m^2$	$1.75m$	NEN8100 [45]	7.5×10^6
Shi [47]	RANS	$3000 \times 3000m^2$		$1.5m$		1.14×10^6
Zheng [29]	RANS	$7950 \times 7650m^2$	Outdoor platforms of megatall building	$2m$	NEN8100 [45], Lawson [46]	7.18×10^6
Kang [24]	RANS	$1000 \times 1000m^2$		$1.75m$	Isyumov [8]	$\simeq 14.2 \times 10^6$
Adamek [43]	LES	$4270 \times 2440m^2$	$\simeq 600 \times 600m^2$	$1.5m$	Soligo [48]	1.1×10^6
Present study	LES	$4600 \times 5000m^2$	Shinjuku area	$2m$		$22 \times 10^6 - 136 \times 10^6$

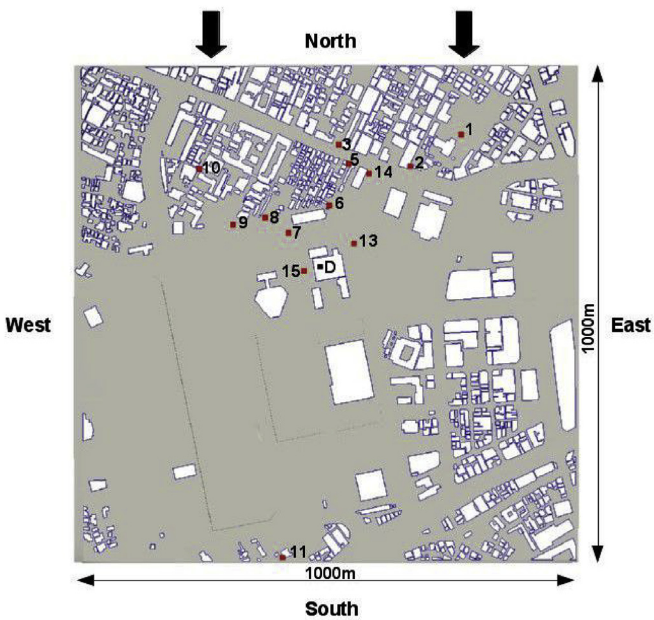

Fig. 1. Positions of measurements points.

and pedestrian wind comfort assessment [42,43]. A review of urban CFD simulations at pedestrian level is given in Table 1. In order to reduce computational cost of LES simulation it is possible to switch from the classical CFD approach base on the Navier-Stokes equations to Lattice Boltzmann method (LBM) solvers which are very efficient for parallel computations of separated low Mach number flows. This is illustrated in Ahmad et al. [44], who performed simulations to assess pedestrian level gust index in a $19.2km \times 4.8km \times 1.0km$ area of Tokyo with a $2m$ finest grid resolution taking advantage of high efficiency of lattice Boltzmann method for parallel simulation. The LBM method is very interesting for CFD because it is fully local which avoid the use of complex and time consuming numerical methods and the complete algorithm needs only to access the data of the first order neighbors which increase the performance for parallel simulations. Furthermore the computational grid is based on a hierarchy of embedded uniform meshes with a ratio of 2 for the grid step between two successive refinement levels. The use of immersed boundary conditions allows to handle complex geometries such as city in a very easy and automatic way. This is also interesting considering that the ratio dx/dt is kept identical at all grid refinement levels, which means that only the nodes at the finest refinement level are computed every time step reducing the number of floating point operations during the simulation.

The present study deals with the application of an LES-LBM solver to wind comfort assessment at pedestrian level in full scale urban geometry using different wind comfort criteria. The aim is to compare different existing criteria thanks to the high space-time resolution data provided by LES in a realistic configuration, and to check their coherency and robustness with respect to the accuracy of input data. In Section 2 key features of the Lattice Boltzmann method used in this paper are presented. Section 3 presents the validation of the present method on a realistic urban configuration, namely the case F of the Architectural Institute of Japan open database [14,27]. Section 4 is devoted to the results obtained dealing with pedestrian wind comfort assessment at a height of 2 m from the ground. Conclusions are given in Section 5.

2. Numerical method

All the CFD simulations presented here have been carried out using a research version of ProLB [49] that use the Lattice Boltzmann Method [50–54] to solve fluid dynamics equations. It is based on the resolution of Boltzmann equation (Eq. (1)) that describes the evolution of a particle distribution function $f = f(\vec{x}, \vec{c}, t)$ which is related to the probability density of particles with velocity $\vec{c}$ at time t and position $\vec{x}$. This equation is solved on a DdQq (d dimensions, q discrete velocities) lattice.

Table 2
Grid parameters and computational time for the Shinjuku area test case.

Grid	Δx_{min} (m)	Δt_{min} (s)	Grid refinement level	Grid points (10^6)	Number of processors	Computational time for 1 h
Coarse	2	0.03	5	22	120	9h
Basic	1	0.015	6	54	240	20h
Fine	0.5	0.0075	7	136	504	50h