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Investigation of multi-level wind flow characteristics and pedestrian comfort in a tropical city

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ABSTRACT

An accurate CFD modelling of wind flow around a city is important for a large variety of application. CFD simulations are heavily influenced by the large number of computational parameters defined in the model. This article presents a thorough and broad sensitivity study of the impact of computational parameters on the numerical outcome for wind flow pattern of a tropical city. In this current study, a series of 3D steady state RANS simulations are conducted in full scale for a region in the city with CFD software OpenFOAM. As CFD simulations are influenced by the computational parameters including turbulence models, for accurate wind flow modelling different turbulent models are tested. The numerical outcomes are compared with on-site measured data which are obtained from anemometers placed at different locations and heights within the downtown of the tropical city for a 2-year period. The impact of a variety of computational parameters is considered which include the mesh resolution and different turbulence models. The test for turbulence models shows that SST k-ω returns the most accurate result among other examined models compared to experimental data. A pedestrian comfort map is then derived based on extended land beaufort scale table and velocity field data from CFD. The result is consistent with long-term observations. In addition, vertical profile of the wind speed near every corner of some interested buildings is investigated for the potential installation of micro wind turbines.

1. Introduction

The analysis of urban wind flow has become a topic of great concern from the point of view of wind energy assessment, pollutant dispersion control, natural ventilation, pedestrians wind comfort and safety (Blocken and Hooff, 2010; Blocken et al., 2012; Toja-Silva et al., 2015a). For example it is important to perform accurate analysis of wind flow around an urban area in order to gain more insights about possible locations of building-integrated wind turbines to take advantage of the accelerating effects of the wind flow above buildings and in canyons (Tominaga et al., 2008; Li et al., 2006; Abohela et al., 2013). The dissipation of air pollution in cities can also be enhanced by appropriate placement or shape of the buildings. Moreover, the outdoor comfort of pedestrian can be improved by installing wind breakers at strategic locations within a city (Chen, 2009).

The latest addition to the world of Computational Wind Engineering (CWE) is the study of wind flow patterns around buildings and urban areas. In the past, the Computational Fluid Dynamics (CFD) study of the wind flow around buildings was limited to single isolated buildings (Hanson et al., 1986; Stathopoulos and Baskaran, 1996). For instance, the first 2D flow simulation of air around an obstacle was performed by Yamada and Meroney (1971) and results were compared with wind tunnel experiments. Good agreements

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were obtained. Hirt and Cook (1972) analysed flow over 3D structures and complex terrains and Paterson and Aplet (1986) employed the k-ε model for turbulence to solve the 3D flow of wind over a rectangular shape. Similar studies have been performed by Baskaran and Stathopoulos (1989) whereby the flow around block shaped buildings were modelled; a similar type of work has been reported by Summers et al. (1986). Comparison of their modelling results with wind tunnel experiments revealed good correlations. In around the same period, multiple studies have been performed to analyse the flow of wind around 3D buildings. Some examples are: Hanson et al. (1986), Matthews (1987), Mochida et al. (1993), Murakami and Mochida (1987), Murakami et al. (1987). Paterson and Holmes (1992) analysed the wind flow around arched-roof buildings. The results were validated with the benchmark experiments performed on the Texas Tech building which provided a good understanding of the complex nature of wind flow around different shapes.

Recently, due to the emergence of more powerful computers, urban areas with increasingly complex building arrangements have been considered (Blocken and Carmeliet, 2002, 2004a,b; Blocken et al., 2007). This subject has thoroughly been reviewed by Vardoulakis et al. (2003) and Li et al. (2006); summarizing recent advancements in the CFD modelling of wind field in street canyons. Further studies have analysed the influence of parameters on the flow, for example building geometry (Toja-Silva et al., 2015b), street dimensions and wind direction (Sabatino et al., 2008; McNabola et al., 2007), the closeness and packing density of the buildings (Sabatino et al., 2007), thermal stratification (Baik et al., 2007; Kang et al., 2008), vehicular movement (Solazzo et al., 2007; Kumar et al., 2008), flow between canyons (Blocken et al., 2008) and so on. For this endeavor, the use of Geographical Information Systems (GIS) is favoured, for both rural and urban planning. Gagliano et al. (2013) provide a good overview on how to exploit wind flow in urban areas while using CFD codes with GIS software. It involves the merging of digital maps and geo-referenced data which explains clearly the position and shape including elevation and roughness factor of the area under consideration. Several vegetation canopy models proposed for the study of aerodynamic effects of trees to improve our understanding of the role of vegetation on wind flow patterns are also found in the literature. Amorim et al. (2013) employed CFD to study the effects of roadside trees on air quality for a couple of urban regions at pedestrian level. They concluded that the effects of the urban canopy on air pollutants dispersion are extremely spatially dependent, which is further confirmed by the more recent analysis of Valente et al. (2014). These studies emphasise the importance of urban planning to optimize the effects of green areas on human comfort and overall health. More details on the past works performed in CWE can be read by the work compilation published by Baker (2007), Solari (2007) as well as Blocken (2014).

The use of CFD in CWE offers great advantages compared with *in-situ* measurements. Vital information of the flow of wind over the required area are provided. However, validation studies are very important while using a CFD model as these will determine the accuracy of the chosen models. This requires full-scale or wind tunnel measurements which have to abide by the quality criteria assessment (Blocken, 2014). It is also well known that CFD simulations can be very sensitive to the wide range of computational parameters which are defined in the model. This will be further discussed in further sections of this article.

The main concerns of CFD simulations are accuracy and reliability which necessitate validation analyses and sensitivity studies, including solution authentication (Chen, 2009). Authentication of a CFD model can be performed with either wind tunnel experimentations or with investigational measured data taken on-site. The dependability and precision of the CFD simulation results are very responsive to the wide computational parameters which have to be laid down by the users. Hence generic sensitivity analyses are vital for the implementation and assessment of any CFD study. In this work, the effect of various computational parameters on the CFD results is explored such as the resolution of the computational grid, the turbulence model employed and the order of the discretization schemes. The simulation is performed with OpenFOAM solver (simpleFoam) which is an Open source CFD package. For the present steady state simulations, RANS turbulence models are chosen and compared to each other. The most compatible numerical result with experimental data is chosen to further investigate pedestrian comfort and good locations for installation of micro wind turbines.

2. Description of the study area

The tropical city considered is Port Louis, which is the capital of the Republic of Mauritius found in the Indian Ocean at latitude 20.16° South and longitude 57.5° East. It lies at the feet of a mountain range (the Moka mountain range), which almost surrounds its South East part. Fig. 1 displays a top view of Port Louis which shows the buildings, location of the harbour, industrial zone and Moka mountain range. The height of the buildings are also shown and the business zone is encircled. Small in area (42.7 km^2), the topography of Port Louis is regular, with a gentle slope towards the sea (North West) side. It has a dry climate for most of the year except from December till April where it is wetter. The typical temperature in summer (October to March) ranges from 30 to 36 °C and in winter (April to September) it is around 24 °C. The humidity value is on average 80% and mean yearly precipitation is around 75 mm (Forecast, 2016). Port Louis is a city which is still undergoing development, especially in the business zone (which is the focus of this study), with high-rise buildings being built to encompass offices, pent houses, apartments among others. It holds a population size of around 150 000 during business hours. The business zone (Fig. 2) houses the island's tallest buildings with heights of up to 110 m above ground level.

2.1. The experimental wind measurement campaign

On-site wind data measurements have been performed over a period of 2 years (January 2014 to January 2016) at five sites in the business zone using cup anemometers. It should be mentioned that the anemometers were verified and calibrated by the supplier (Barani Design) before being utilized for this study. Their accuracy is smaller than 2 RMS for wind incidence of up to 40° from the horizontal. Fig. 3 shows the measurement locations (points 1 to 5). Point 1 is on top of the State Bank of Mauritius (SBM) at a height