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Review

On the use of numerical modelling for near-field pollutant dispersion in urban environments – A review

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ABSTRACT

This article deals with the state-of-the-art of experimental and numerical studies carried out regarding air pollutant dispersion in urban environments. Since the simulation of the dispersion field around buildings depends strongly on the correct simulation of the wind-flow structure, the studies performed during the past years on the wind-flow field around buildings are reviewed. This work also identifies errors that can produce poor results when numerically modelling wind flow and dispersion fields around buildings in urban environments. Finally, particular attention is paid to the practical guidelines developed by researchers to establish a common methodology for verification and validation of numerical simulations and/or to assist and support the users for a better implementation of the computational fluid dynamics (CFD) approach.

1. Introduction

The field of wind engineering is defined by the International Association for Wind Engineering (IAWE)[1] as a multi-disciplinary subject concerned with multifold topics including the atmospheric dispersion of pollutants which is the main subject of the present work. This topic especially in the urban environment is concerned with the transportation of pollutants in the lower atmospheric boundary layer by the wind flows. Dispersion of pollution represents an important environmental problem with respect to human health. In urban areas, several sources of pollution (e.g. wind-blown dust, vehicle exhaust, toxic and odorous emissions) may be unpleasant and dangerous (ASHRAE, 2007). Among them, pollutant emissions from rooftop stacks is a factor that can seriously affect the quality of fresh-air at intakes of the emitting and/or surrounding buildings, and potentially compromising the well-being of these buildings' occupants. Additionally, inside cities – where the building density increases – the stack emissions can be accumulated between buildings, thus inducing an increase of the contaminant concentration because reduced airflow passes through the zone's boundaries as compared to free-stream flow (Rock and Moylan, 1999). Current standards for building ventilation systems recommend that rooftop stacks be designed such that their emissions do not contaminate the fresh-air intakes of the emitting building or the nearby buildings (Stathopoulos et al., 2004). The scientific community has responded by providing solutions for controlling and maintaining air quality, in buildings and offices, above the acceptable norms typically established either by governments or within the respective professional organisations (Sterling, 1988).

Acronyms: ABL, atmospheric boundary layer; AIAA, American Institute of Aeronautics and Astronautics; ASHRAE, American Society of Heating, Refrigerating and Air-conditioning Engineers; ASME, American Society of Mechanical Engineers; CFD, computational fluid dynamics; CWE, computational wind engineering; EEA, European Environment Agency; EPA, United States Environmental Protection Agency; IAWE, International Association for Wind Engineering; IRS, inertial sub-layer; LDV, laser Doppler velocimetry; LES, large-eddy simulation; LIF, laser-induced fluorescence; PIV, particle image velocimetry; PLB, planetary boundary layer; RANS, Reynolds averaged Navier–Stokes; RSL, roughness sub-layer; SL, surface layer; UBL, urban boundary layer; UCL, urban canopy layer; URANS, unsteady Reynolds averaged Navier–Stokes.

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[1] Definition from the International Association for Wind Engineering (IAWE) website.

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Urban air quality is directly related to the atmospheric boundary layer (ABL) flows and their interactions with obstacles which are themselves strongly dependent on many aspects of meteorology, wind engineering and environmental science (Salim, 2011). In the lower part of the atmospheric boundary layer, specifically in cities around individual and/or groups of buildings, the local wind fields consist of many complex flow features that may contain recirculation zones and stagnation points (Easom, 2000). The superposition and interaction of the flow patterns induced by the buildings and structures strongly affect the dispersion and govern the movement of pollutants (Chang and Meroney, 2001). Consequently, the control of the dispersion phenomena and the air pollutant transport, including the stack emissions, becomes difficult. In addition, the state-of-the-art, as noted by Stathopoulos et al. (2004), is not sufficiently advanced to allow building engineers to find appropriate design criteria to avoid the re-ingestion of stack emissions problem at fresh air intakes. Therefore, finding a way to resolve this harmful phenomenon still remain a challenge for scientific researchers in wind engineering.

In this respect, the aim of this review article is to enlighten the reader on the use of numerical modelling methods for pollutant dispersion in urban areas. In addition, this work highlights the relevant phenomena that should be taken into account when numerically modelling the pollutant dispersion around buildings, and provides the critical parameters that can compromise significantly the accuracy and reliability. For this purpose, the article is organised as follows. Section 2 summarises the literature survey which specifically introduces readers to the atmospheric boundary layer (ABL) and its characteristics. Section 3 concentrates on the important behaviour of the wind-flow field around buildings. The dispersion field around buildings is addressed in Section 4. The next section, Section 5, details the errors and quality in computational wind engineering (CWE). Finally, concluding remarks are presented in Section 6.

2. Literature survey

2.1. Atmospheric boundary layer (ABL)

The atmospheric boundary layer is defined as the lowest region of the atmosphere directly influenced by the proximity of the earth's surface (Bonner et al., 2010) where physical quantities such as flow velocity, temperature, moisture, etc. display rapid fluctuations and the vertical mixing is strong (Georgoulias and Papanastasiou, 2009). The height of the atmospheric boundary layer is an important parameter in the dispersion of air pollution (Gryning et al., 1987; Van-Pul et al., 1994). It can change both in space and time, and may vary from less than one hundred to several thousand metres depending on the orography, surface cover, season, daytime and weather (Hennemuth and Lammert, 2006).

The ABL is almost continuously turbulent over its entire depth (Stull, 2009), particularly in urban environment where the main disturbing features are the buildings of different height and shapes. These buildings introduce a large amount of vertical surfaces and high roughness elements, and generate complex local flows between buildings (Piringer et al., 2007). In this particular area (i.e. urban environment), the vertical structure of the atmospheric boundary layer – also called urban boundary layer (UBL) – is composed of a roughness sub-layer (RSL) near the ground and an inertial sub-layer (ISL) above (Fisher et al., 2006) as can be seen in Fig. 1. Both the roughness sub-layer and the inertial sub-layer are encompassed within the surface layer (SL), and above which the urban outer layer extends to a height where the wind is unaffected by the earth's surface. In the surface layer, strong vertical gradients produce a differential longitudinal transport of products that reach

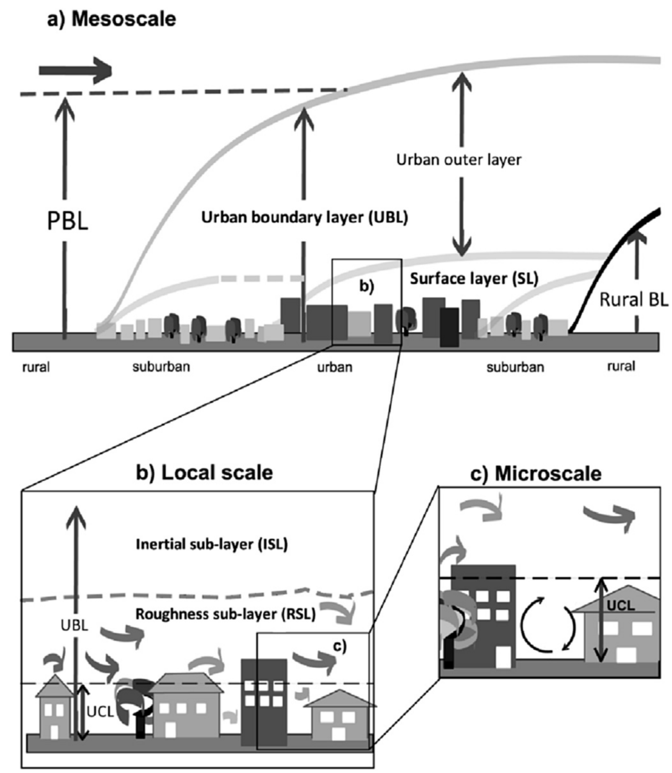

Fig. 1. Sketch of the urban boundary-layer structure indicating the various sub-layers and their names.
Adapted from Piringer et al. (2007).

various vertical layers. The turbulence, in turn, transports heat, momentum, gaseous constituents and aerosols from and to the earth's surface (Georgoulias and Papanastasiou, 2009). The turbulence phenomenon is mainly driven by wind shear and is not enhanced or suppressed by stability effects in neutral stratification (Van-Pul et al., 1994). In the urban outer layer and free atmosphere, the Coriolis force, friction and pressure gradients are responsible for the wind flow. In the surface layer and for stratified stable or unstable flows, the roughness of the surface can be fairly insignificant in determining the velocity profile. In case of unstable flows, the profiles can disappear and gradients are near zero, whereas in strong stable flows the gradients can become quite large (Crasto, 2007).

The roughness sub-layer is the region at the bottom of the boundary layer and can be defined as the layer where flow is dynamically influenced by the characteristic length scales of the roughness elements (Barlow and Coceal, 2009). This region is of great importance due to its vertical extension over large roughness elements (Fisher et al., 2006). Near the ground surface, the buildings form an urban canopy layer (UCL) and the dispersion is determined by a number of factors including the configuration of the building and the location of the pollutant emitting source (Huq and Franzese, 2013). Urban dispersion is governed by the characteristic length scales of atmospheric boundary-layer turbulence, rather than urban canopy length scales that are more likely to affect dispersion only in the vicinity of the source (Franzese and Huq, 2011). It is worth mentioning that this urban outdoor pollutant dispersion is classified as micro-scale dispersion and refers to small scale meteorological phenomena that affect very small areas (micro-scales are likely to be of the order of metres) compared to large scale meteorological phenomena (macro-scale and meso-scale) as detailed by Blocken (2014) and clearly shown in Fig. 2. Within this

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