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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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A B S T R A C T

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 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).

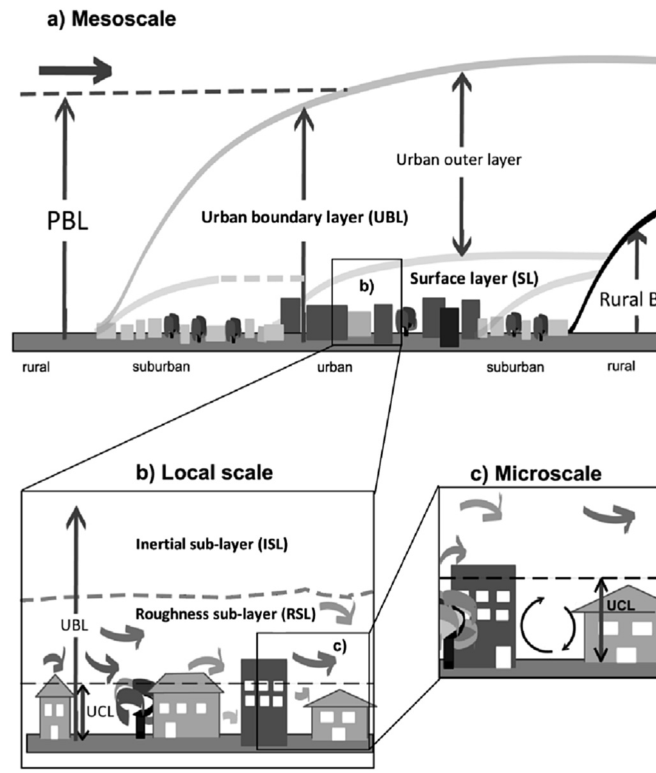

Fig. 1. Sketch of the urban boundary-layer structure indicating the various sub-layers and their names.
Adapted from Piringer et al. (2007).

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

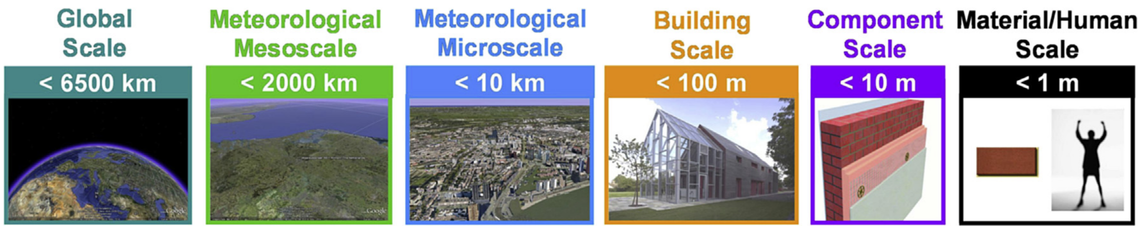

Fig. 2. Schematic representation of relevant spatial scales in pollutant dispersion. From Blocken et al. (2013).

micro-scale dispersion, two different dispersion regimes are distinguished in the literature since turbulent diffusion differs in the near and the far regions from a continuous point source (Efthimiou and Bartzis, 2011): (i) the near-field dispersion that concerns the near-vicinity of the pollutant source and for which the relevant turbulence time and length scales controlling dispersion are related to the mean building height and to the spacing between buildings (Huq and Franzese, 2013), and (ii) the far-field dispersion of interest in plumes with a flow-structure and a vertical dimension larger than the urban canopy height for which the dispersion is governed by the ABL scales (Hajra et al., 2011). In the near-field dispersion case, the pollutant particles released from various sources inside the urban canopy, are mixed and dispersed over and around buildings because of the interactions between many physical processes that contribute to its evolution (White and Senff, 1999) including the dynamics of flow over urban topography and the building configurations.

2.2. Homogeneity of the ABL

In recent decades, the efforts of boundary-layer researchers have been directed towards problems of surface–atmosphere interaction over complex surfaces including the homogeneous surface-layer relationships used to describe the mean and turbulence properties (Roth, 2000). Homogeneity is defined by Panofsky and Dutton (1984) as one of special characteristics of turbulence, but vertical homogeneity is almost never valid near the ground. Kaimal and Finnigan (1994) noted that the assumption of horizontal homogeneity is more easily realised in the surface layer (SL) than elsewhere in the ABL. Moreover, Rotach (1999) argued that the flow can be considered horizontally homogeneous if the density, height and distribution of roughness elements do not vary over the upwind area of influence. Under the hypothesis of horizontal homogeneity, the average values of temperature, flow field and heat flux turn out to depend only on the height over the ground (Antonacci, 2005), and there are streamwise gradients in neither the mean wind speeds nor the turbulent quantities (O'Sullivan et al., 2011). In this regard, for the case of numerical studies, the scientific community advises to assess the effects of horizontal inhomogeneity by performing a simulation in an empty computational domain (Franke et al., 2007; Blocken et al., 2007b; Yang et al., 2008). For instance, Fig. 3, adapted from works of Blocken et al. (2007a), illustrates the development of the horizontal inhomogeneity within an empty computational domain.

2.3. Wind velocity profile of the ABL

For modelling wind engineering problems within the atmospheric surface layer, several authors (e.g. Richards and Hoxey, 1993; Blocken et al., 2007b; Hargreaves and Wright, 2007; Yang et al., 2009; Cai et al., 2014) pointed out the need of modelling the flow as a homogeneous flow essentially by well reproducing the turbulence profiles including the wind velocity profile. Therefore, the velocity profile which varies with the nature of the surface and the magnitude of the wind is one of the most important parameters (Kossmann et al., 1998) when modelling the surface boundary layer. According to Varshney and Poddar (2011), the simulation of the wind velocity profile within the atmospheric boundary layer (ABL) is relatively simple, but an accurate prediction of wind induced loads and contaminant transport needs an accurate simulation of the level of turbulence and the integral length scales. In order to make generalised conclusion, most researchers impose homogeneity and invariable velocity profile. For instance, Kaimal and Finnigan (1994) noticed that the wind profile can frequently be logarithmic for applications very close to the ground.[2] While for ABL that are of interest in building studies, Straw (2000) emphasized that the logarithmic law is able to predict wind velocities more accurately within the lower regions than the power law. On the other hand, the power law proves adequate for modelling wind velocities in the upper regions (Iyengar and Farell, 2001). Furthermore, Barlow and Coceal (2009) concluded that the mean velocity profile is logarithmic in the inertial sub-layer and deviates appreciably from log behaviour within the roughness sub-layer. Although, Cheng and Castro (2002) noted that spatially averaged profiles still have a logarithmic form in the above-roof region of the roughness sub-layer (RSL) over regular urban-type roughness, while the few extant studies (MacDonald, 2000) have indicated that the mean velocity obeys an exponential decay law for vegetative canopies. In addition, Rotach (1993a) characterised the ABL as an almost always turbulent layer having a logarithmic profile. White (2000) concluded that many authors observed that the ABL also obeys the logarithmic law during a neutral stratification which occurs when thermal effects are negligible. Kaimal and Finnigan (1994) underlined that the logarithmic wind profile is strictly valid only for the neutral atmosphere. In addition, for cases where the convection is negligible and the mechanical turbulence prevails, the stratification is nearly neutral. Panofsky and Dutton (1984) noted that the velocity profile follows more the logarithmic law than the power law. Holmes (2001) has detailed the two approaches (i.e. logarithmic and power laws) and concluded that: (i) in strong wind conditions the logarithmic law is the most accurate mathematical expression, but has some characteristics which may cause problems since the logarithms of negative numbers do not exist, thus it is less easy to integrate; (ii) the power law is often preferred by wind engineers to avoid some of these problems, and it is quite adequate for engineering purposes. Finally,

[2] Although simulation of a logarithmic approach flow is most common during physical or numerical modelling, it is not always the most accurate or realistic profile shape. Profiles can be irregular due to surface non-homogeneities in roughness or temperature, distances from changes in structures, diurnal effects. Also profiles are not logarithmic at interfaces between flows governed by different upwind fetches of roughness or temperature (Avissar et al., 1990; Wu and Meroney, 1995).

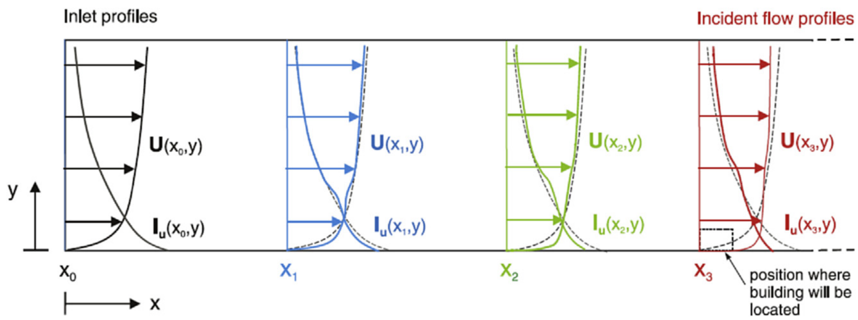

Fig. 3. Schematic illustration of the development of an internal boundary layer (horizontal inhomogeneity) in a CFD simulation in an empty domain.
Adapted from Blocken et al. (2007a).

according to all the previous statements, one can say that the mean velocity profile can be best represented by a logarithmic law in the inertial sub-layer (ISL), while the power law is more appropriate within the urban canopy (Barlow and Coceal, 2009). However, when modelling a neutral atmospheric boundary layer for outdoor environmental applications (e.g. pedestrian wind environment around buildings, wind-driven rain on building facades and air pollutant dispersion around buildings), the mean velocity profile is expressed either by a logarithmic law or a power law (Blocken et al., 2011; Xia et al., 2014).

3. Wind-flow field around buildings

The prediction of effects of wind flow around buildings is of primary importance to a wide variety of engineering applications such as designing durable building envelopes, dispersion of air pollutants, natural ventilation, wind loading, etc. (Tutar and Ogguz, 2004). The wind flows in the atmospheric boundary layer over buildings are inherently complex and exhibits a wide range of physical phenomena including large low-speed areas, strong pressure gradients, unsteady flow regions, three-dimensional effects, and confluence of boundary layers and wakes (Deck, 2005). In the case of the present study, the prediction of the nature of a turbulent flow through the urban environment is in principle prerequisite to the solution of the problem of contaminant dispersion in the urban complex (Lien et al., 2008). The complexity of the flow around an obstacle or group of obstacles has been recognised (Cheng et al., 2003) – as shown by Murakami et al. (1991) in Fig. 4 – and turbulent flow remains one of the unresolved problems of classical physics (Qu, 2011). Consequently, a complete understanding of the wind-flow processes and structures over buildings in urban areas has not yet been attained, despite the many years of intensive research (Davidson, 2004). For studies which involve wind loading, structures and dispersion of contaminants around buildings, the flows with high Reynolds numbers are more closely matching the atmospheric flows characterising flows in an urban environment (Haupt et al., 2011). These flow patterns around buildings within urban canopy layer are influenced by a large number of parameters (e.g. the thickness of the boundary layer, the layout of the buildings, characteristics of the approach flow) that are identified and investigated in details (Cheng et al., 2003). In these cases, the flow patterns are characterised by complex flow phenomena due to the interactions produced between the various buildings already existing within the site, however some of the results cannot be generalised since they probably include local effects such as secondary structures (Mavroidis et al., 2003).

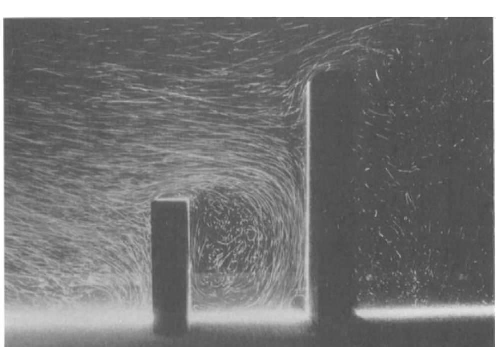

Fig. 4. Airflow around a low building arranged in the front of a tall building.
From Murakami et al. (1991).

In order to simplify the structure of the flow field, many researchers have studied the well documented case of flow around the three dimensional surface of a cube using field experiments (e.g. Meroney and Yang, 1970; Castro and Robins, 1977; Hosker, 1985; Meroney et al., 1985; Lim et al., 2007; Richards and Hoxey, 2008; Bitsuamlak et al., 2010; Richards and Hoxey, 2012), physical modelling[3] (e.g. Meroney and Yang, 1970; Martinuzzi and Tropea, 1993; Hoxey et al., 2005) and numerical simulations (e.g. Murakami and Mochida, 1989; Paterson and Apelt, 1990; Lakehal and Rodi, 1997; Straw et al., 2000; Krajnović and Davidson, 2002; Wright and Easom, 2003; Gao and Chow, 2005; Yakhot et al., 2006; Paik et al., 2009; Kose and Dick, 2010; Vardoulakis et al., 2011). For this case, the features of the wind-flow pattern – as shown in Fig. 5 – are well established in the wind engineering community as detailed by several authors (e.g. Oke, 1988; Meinders and Hanjalić, 1999; Blocken and Stathopoulos, 2008; ASHRAE, 2009; Blocken et al., 2011; Moonen et al., 2012a) including stratified effects (e.g. Meroney et al., 1986; Kot, 1989; Yang and Shao, 2008). Among the cited references and the nature of their investigation, only the physical measurements are considered appropriate for validation. The surface-mounted cube case is defined as the geometrically simplest 3D case commonly called "generic case" and has proven quite suitable for validation, verification and sensitivity analyses (Blocken et al., 2011). Other studies, commonly called "applied studies", investigated much more complex configurations that consist of real sites or building blocks (e.g. Meroney et al., 1975; Meroney and Hatcher, 1977; Meroney et al., 1981; Meroney, 1982; Häggkvist et al., 1989; Rotach, 1993b; Johnson and Hunter, 1998; Roth, 2000; Cheng et al., 2003; Lien et al., 2004; Calhoun et al., 2005; Ricciardelli and Polimeno, 2006; Van-

[3] The term "physical modelling" refers to the reduced-scale measurements that are commonly conducted for studying airflow and pollutant dispersion around buildings (i.e. wind-tunnel and/or water-channel experiments) as specified by Xia et al. (2014). Therefore, this note will remain valid for the rest of this work.

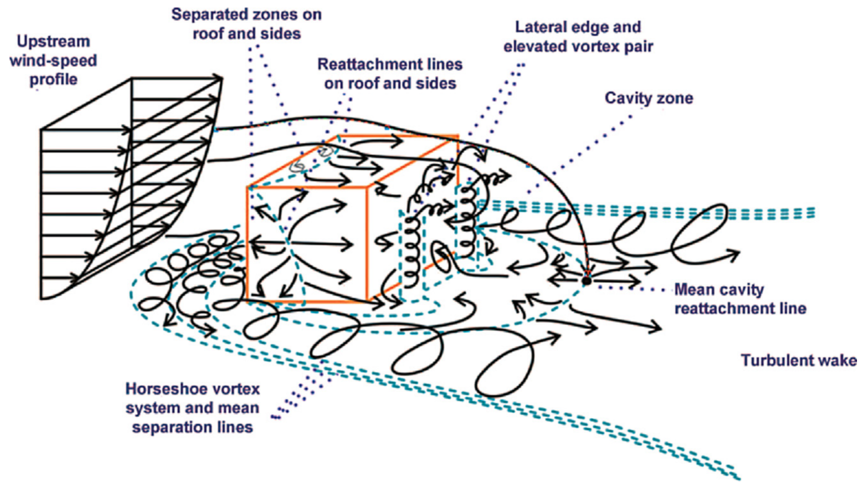

Fig. 5. Schematic representation of the mean atmospheric boundary layer flow around an isolated sharp-edged low-rise building. From Hosker (1985) and modified by Blocken et al. (2011).

Hooff and Blocken, 2010; Fernando et al., 2010; Huang et al., 2011; Hang and Li, 2012; Moonen et al., 2012b; Razak et al., 2013; Lateb et al., 2013a,b). Such studies were primarily directed towards the influences of neighbourhood buildings, wind directions, wind velocities, Reynolds stress components, etc. on a specific obstacle or building under study.

Through this brief section, the urban flows are mainly dominated by a complex interplay between meteorological conditions and urban morphology (Moonen et al., 2012a), thus their "correct" prediction is currently an unresolved issue (Hsieh et al., 2007). In addition, owing to the strong relation existing between the flow-field pattern and the transportation of pollutant contaminants in the urban environment (Huang et al., 2009), it is clear that accurately predicting the pollutant dispersion around buildings – that is the topic of the following section – seems to be far from straightforward.

4. Dispersion field around buildings

It is clear that correctly modelling the pollutant dispersion within a group of buildings remains a very complex challenge, since the wind flow in an urban area may strongly affect the dispersion of pollutants around buildings (Zhang et al., 2005) as illustrated by Petersen et al. (2002) wind-tunnel simulations shown in Fig. 6. Indeed, the disturbance of atmospheric flows by various building configurations can change the local concentrations by an order of magnitude (Lien et al., 2006). Therefore, to understand well the processes governing the dispersion of pollutants, an accurate concentration prediction of contaminants released into the urban environment is needed (Tseng et al., 2006). Table 1 summarises the various existing methods devoted to pollutant dispersion phenomena around buildings including their advantages and limitations.

A number of different approaches have been widely used for studying pollutant dispersion around buildings in urban environments: full-scale field measurements (Drivas and Shair, 1974; Ogawa and Oikawa, 1982; Jones and Griffiths, 1984; Wilson and Lamb, 1994; Higson et al., 1996; Mavroidis et al., 1999, 2003; Stathopoulos et al., 2004, 2008; Yassin et al., 2005; Santos et al., 2009; Finn et al., 2010; Baldauf et al., 2013), physical modelling (Li and Meroney, 1983; Poreh and Cermak, 1990; Higson et al., 1994; Wu and Meroney, 1995; Sini et al., 1996; Delaunay et al., 1997; Stathopoulos et al., 1999; White, 2003; Chang and Meroney, 2003; Aubrun and Leitl, 2004; Gomes et al., 2007; Nakiboglu et al., 2009; Liu et al., 2010; Pournazeri et al., 2012; Carpentieri et al., 2012; Yassin, 2013; Meroney et al., 2015), semi-empirical methods (Saathoff and Stathopoulos, 1997; Ratcliff and Sandru, 1999; Stathopoulos et al., 2002; ASHRAE, 2007; Hajra et al., 2010, 2013; ASHRAE, 2011; Chavez et al., 2011; Hajra and Stathopoulos, 2012; Gupta et al., 2012; Musalaiah et al., 2013), and computational fluid dynamics (CFD) simulations (Adair, 1990; Li and Stathopoulos, 1997; Riddle et al., 2004; Cai et al., 2008; Hefny and Ooka, 2009; Lateb et al., 2010, 2011; Yoshie et al., 2011; Weil et al., 2012; Rodriguez et al., 2013; Blocken, 2014, 2015; Gousseau et al., 2015). Such approaches have improved the understanding of many environmental problems (Gavrilov et al., 2013) that have a

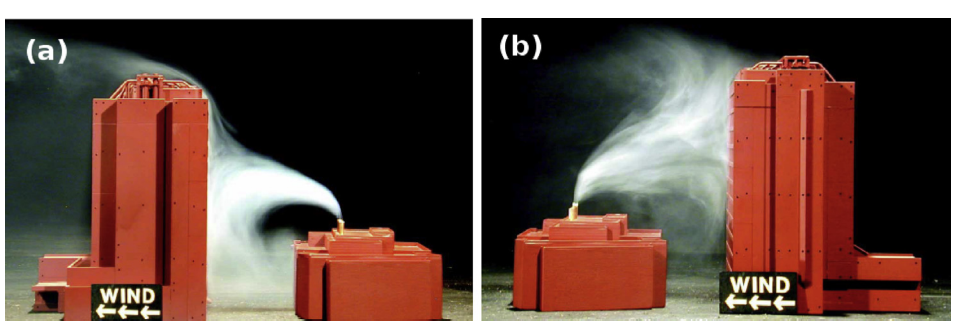

Fig. 6. Plume impact on taller (a) downwind building and (b) upwind building. Adapted from Petersen et al. (2002).

Table 1
Summary of the various existing methods for pollutant dispersion investigation including their advantages and limitations.

Methods	Advantages	Limitations	Sources
Full-scale experiments	Performed under real conditions; take in consideration all phenomena (e.g. thermal stratification, chemical reactions, buoyancy forces, pollutant transport, etc.); provide information on the full complexity of the dispersion problem.	Boundary conditions are uncontrollable; conditions can vary at any time; number of measured point are limited; repeat an identical experiment is not possible; assessment of new urban development is inherently not possible; expensive and time-consuming.	Barlow and Coceal (2009); Schatzmann and Leitl (2011); Moonen et al. (2012a); Blocken et al. (2012); Montazeri and Blocken (2013); Xia et al. (2014).
Physical modelling	Performed under controlled conditions; stationary flow condition can be maintained throughout measurements; appropriate boundary condition can be chosen according to the problem being solved; utilised to enhance field data.	Can suffer from the limited set of points in space due to the nature intrusive of some of the measuring techniques; costly and time-consuming in set-up; limitation in similarities; unable to simulate low and unsteady wind conditions.	Schatzmann et al. (2000); Stathopoulos (1997); Blocken and Stathopoulos (2008); Barlow and Coceal (2009); Cochran and Derickson (2011); Moonen et al. (2012a); Pournazeri et al. (2012); Cochran et al. (2015).
Semi-empirical methods	Based on a Gaussian distribution in vertical and horizontal direction under steady conditions; relatively simple and easy to use; successfully employed in simplified flow configurations; useful for flat and unobstructed landscape.	Need some empirical or semi-empirical parameters from observation; inadequate for complex surfaces as cities and/or group of buildings; unable to model the effects of upstream and adjacent buildings; provide less accurate estimations.	Petersen et al. (2002); Lien et al. (2006); Holmes and Morawska (2006); Tominaga and Stathopoulos (2009); Rossi and Iaccarino (2009); Schatzmann and Leitl (2011); ASHRAE (2011); Chavez et al. (2012).
CFD modelling	Simulations can be conducted both in full scale and reduced scale; preformed under well-controlled conditions without similarity constraints; less expensive; provide whole-flow field data; volume-averaged flow and scalar quantities are easily obtained; suitable for parametric studies.	Solution verification and validation against experimental tests are imperative; assessment of the simulation quality is required; results are very sensitive to the wide range of computational parameters; setting-up may require an expert user; numerical results do not compare themselves.	Robin (2003); Meroney (2004); Di-Sabatino et al. (2007); Huang et al. (2009); Wang and Mu (2010); Moonen et al. (2012a); Montazeri and Blocken (2013); Blocken et al. (2013); Abohela et al. (2013); Blocken (2014).

direct impact on human health, such as the outdoor pollution sources (e.g. emissions from rooftop stacks, motor vehicle exhausts, industrial applications, etc.). Each approach has its specific advantages and disadvantages as detailed below.

4.1. Full-scale measurements

Field measurements mean that the flow and concentration tests are conducted under real atmospheric conditions (Xia et al., 2014). However, full-scale measurements are usually performed on a limited number of points in space (Montazeri and Blocken, 2013). In addition, there is no control over the variation of the wind and weather conditions, therefore repeating an experiment under identical conditions is not possible (Schatzmann and Leitl, 2011). Consequently, this leads to a wide scatter in measured data (Moonen et al., 2012a).

4.2. Physical modelling

Reduced-scale experiments have an important advantage, in comparison to the field tests, such that the boundary conditions can be chosen to be appropriate to the problem being solved (Schatzmann et al., 1997), and the stationary flow conditions can be maintained throughout measurements (Barlow and Coceal, 2009). However, laboratory physical modelling also suffer from the limited set of points in space (Stathopoulos, 1997) despite new techniques – such as particle image velocimetry (PIV), laser Doppler velocimetry (LDV) and laser-induced fluorescence (LIF). In certain applications, these techniques which in principle allow planar or even full 3D data to be obtained can induce laser-light shielding due to obstructions from the complicated geometries of the urban model (Blocken and Stathopoulos, 2008). In addition to the high costs associated with running a reduced-scale experiment (i.e. personnel, instrumentation, the building and other indirect costs) (Cochran and Derickson, 2011), the set-up can be time-consuming and requires adherence to similarity criteria that can be a problem for many applications such as multi-phase and buoyant flows (Pournazeri et al., 2012).

4.3. Semi-empirical methods

The semi-empirical methods, such as the Gaussian models and the ASHRAE models (ASHRAE, 2007, 2011) are based on a Gaussian distribution of the plume in the vertical and horizontal directions under steady conditions (Holmes and Morawska, 2006; Meroney and Derickson, 2014). Their prediction is based on concentration measurements obtained in reduced-scale simulations (Tominaga and Stathopoulos, 2009). These models usually need some empirical or semi-empirical parameters from observation and make crude simplifications (Li et al., 2006). While Gaussian models are successfully employed in simplified flow configurations and useful for landscape that is approximately flat and unobstructed, they are wholly inadequate for surface–atmosphere interactions over "complex" surfaces such as cities and other built-up areas (Lien et al., 2006). The prediction of scalar dispersion over complex and realistic geometries remains challenging because of additional flow features arising such as separated regions, secondary flows or three-dimensional effects which cannot be properly accounted for (Rossi and Iaccarino, 2009). For instance, Gaussian models are unable to model the effect of upstream and adjacent buildings (Hajra et al., 2011), and are not designed to model the dispersion under low wind conditions or at sites close to the source for which the distance is less than 100 m (Holmes and Morawska, 2006). It is accepted that these models are not suited for predicting concentration in complex structured urban or industrial areas, which is, unfortunately, where pollutants that are of major concern at present are emitted (Schatzmann and Leitl, 2011).

4.4. Numerical modelling

Numerical simulations with CFD offer some advantages compared to other methods; they are relatively less expensive, they provide results of flow features at every point in space simultaneously (Moonen et al., 2012a) and they do not suffer from potentially incompatible similarity because simulations can be conducted at full scale (Montazeri and Blocken, 2013). In addition, at the micro-scale, the CFD technique is the preferred way of investigation (Britter and Schatzmann, 2007) and very suitable for parametric studies for various physical flow and dispersion processes (Gousseau et al., 2011). Due to the rapid development in computer hardware and numerical modelling, CFD has been increasingly used and adopted to simulate the flow development and pollutant dispersion (Wang and Mu, 2010). Many studies have shown that the approach is capable of reproducing the qualitative features of airflow and pollutant distributions (Huang et al., 2009). However, the accuracy and reliability of CFD are of concern, thus solution verification and validation studies are imperative (Blocken et al., 2013). Since experience has already shown that numerical results do not compare among themselves (Stathopoulos, 1997), experimental tests (i.e. field and reduced-scale measurements) appear unquestionably necessary for fulfilling the requirements of assessing the quality of CFD simulation (Abohela et al., 2013). In addition, one of the objectives of laboratory studies has frequently been to aid the development of dispersion algorithms that can be used in dispersion modelling packages to predict behaviour near and around buildings (Robin, 2003).

According to Stathopoulos (1997), the principal and most significant areas for improvement in computational wind engineering (CWE) are: (i) the numerical accuracy which requires high-order approximations, (ii) boundary conditions that depend on the specific problem under consideration and (iii) refined turbulence models capable to perform well beyond the specified flow conditions for which they have been developed. All these parameters are the main subjects of the following section which deals with the significant errors that can compromise the accuracy and reliability of numerical simulations.

5. Errors and quality in computational wind engineering (CWE)

The use of CFD to predict pollutant dispersion properties has been successful in many ways, but also leads to many problems since an accurate prediction of these properties is challenging due to the complex nature of turbulence modelling, the assumptions that are made and the resulting uncertainties (Rohdin and Moshfegh, 2011). For instance, the assumptions commonly used when modelling pollutant dispersion to understand the wind flow and dispersion field behaviours around individual and/or groups of buildings are: (i) the contaminants are mostly treated as a chemically and dynamically passive gases (Sini et al., 1996) – i.e. inert and having a constant density – therefore the effect of contaminant particles on the flow field may be neglected (Wang and James, 1999) and their diffusion process is quite weaker than the turbulent diffusion process due to the neglecting buoyancy forces (Ma et al., 2012), and (ii) the atmosphere is taken to be adiabatic and horizontally homogeneous (Cermak and Cochran, 1992).

5.1. Numerical modelling errors

Two types of errors are classified and recognised as critical (Franke et al., 2011). One is the physical modelling arising from the employed turbulence models and the applied boundary conditions, and the other one stems from numerical simulation such as computational domain size, grid design, truncation of discretisation scheme, numerical iteration algorithm, etc. (Roy, 2005; Yang et al., 2008). In addition, these two types of errors are directly related to the large number of computational parameters that have to be set by the user (Ramponi and Blocken, 2012b). Indeed, in a typical CFD simulation, the user has to choose the approximate equations describing the flow (steady RANS, unsteady RANS (URANS), LES or hybrid URANS/LES), the level detail of the geometrical representation of the buildings, the size and the mesh of the computational grid, the boundary conditions, the discretisation schemes, the initialisation data and iterative convergence criteria (Blocken et al., 2012). Therefore, detailed and generic sensitivity analyses are important to provide guidance for the execution and evaluation of the CFD studies (Ramponi and Blocken, 2012a).

Regarding the complex and random character of the flow field – mainly due to the complex nature of the turbulence within urban environments – and the close relation that existing between the dispersion field and the overall behaviour of the wind flow (Tominaga and Stathopoulos, 2009), eliminating and/or reducing the turbulence modelling errors is revealed (i) crucial to reproduce an accurate dispersion process and (ii) essential to understand the pollutant transport mechanisms (Lateb et al., 2014). Consequently, it seems more than necessary to advise the reader on the importance of this particular error when using CFD approach.

Among the various existing turbulence models[4] reported in the literature and well known to the computational wind engineering (CWE) community, the RANS (k–ε) models are the most widely used for many applications (Assimakopoulos et al., 2003; Xie et al., 2005) including pollutant transport (Xie and Castro, 2006). However, according to numerous references, their short comings resulting from: (i) the isotropic turbulent viscosity concept (Nallasamy, 1987; Pope, 2000; Wright and Easom, 2003) and (ii) the steady-state methodology (Rodi, 1997; Cheng et al., 2003; Canepa, 2004; Shirasawa et al., 2008) do not allow to these models to correctly reproduce many wind-flow characteristics such as transient vortices, periodic fluctuations, etc. Therefore, their use is restricted and suited to statistically steady mean flows that are, in turn, a difficult requirement to satisfy when it is question of flows in urban environments. Additionally, the use of URANS model fails to capture the transient mixing process (Salim, 2011), then induces limitations in the performance accuracy. This is a result of the basic concept itself of URANS models, which consists of computing the unsteady flow properties from the ensemble averaging of the statistical mean flow (Franke et al., 2007). On the other hand, LES turbulence model is recognised as a research tool rather than as an instrument to solve practical cases of interest (Tominaga and Stathopoulos, 2009). The LES strategy, of resolving the dominant unsteady structures at large scales and modelling the dissipation at small scales, seems to be the most promising method. Furthermore, the expected future advances in computational tools will certainly make this model more accessible in terms of calculation time-consuming. Consequently, the LES methodology appears as the most suitable numerical method for the purpose of numerical dispersion studies in urban areas.

5.2. Verification, validation and sensitivity analysis

As stated by Britter and Schatzmann (2007), the verification, validation and sensitivity analysis are important parts when numerically modelling the pollutant dispersion. According to Meroney (2004),[5] continued verification and validation is required at almost every level of CFD modelling. For instance, the verification of the models and their results is used, respectively, to find and reduce programming errors in the models, and to estimate the numerical errors present in the solution (Schatzmann et al., 2010). While the sensitivity analysis provides additional information relevant to uncertainty estimation (Britter and Schatzmann, 2007).

In view of their importance, many sensitivity tests and detailed

[4] RANS, URANS, hybrid URANS/LES and LES turbulence models.

[5] Meroney (2004) has defined: (i) the verification as "the procedure to ensure that the program solves the equations correctly" and (ii) the validation as "the procedure to test the extent to which the model accurately represents reality".

Table 2
Summary of some review and overview articles as well as practice guidelines related to pollutant dispersion topic published during the past few decades.

Classification	Authors/organisation (year)
Review/ overview	Fan et al. (1972); Turner (1979); Builtjes (1980); Vardoulakis et al. (2003); Britter and Hanna (2003); Meroney (2004); Canepa (2004); Ahmad et al. (2005); Li et al. (2006); Holmes and Morawska (2006); Moreira et al. (2009); Fernando et al. (2010); Blocken and Stathopoulos (2010); Kawamoto et al. (2011); Moonen et al. (2012a); Capelli et al. (2013); Tominaga and Stathopoulos (2013); Di-Sabatino et al. (2013); Blocken et al. (2013); Musalaiah et al. (2013); Meroney and Derickson (2014); Blocken (2014); Xia et al. (2014); Janhall (2015); Chen et al. (2015)
Practice guidelines	EPA (1978, 1981); Snyder (1981); Meroney (1987); Roache (1994); EPA (1995); EEA (1996); Roache (1997); Coleman and Stern (1997); AIAA (1998); Casey and Wintergerste (2000); Stern et al. (2001); Roy (2005); Bluett et al. (2004); Oberkampf et al. (2004); Franke et al. (2004); Hadjisophocleous and McCartney (2005); Franke et al. (2007); Tominaga et al. (2008); Celik et al. (2008); EPA (2009); ASME (2009); AIAA (2010); Roy (2010); Franke et al. (2011)

verification and validation exercises have been conducted (Blocken et al., 2012) and many important best practice guidelines have been developed and/or published (EPA, 1978; Meroney, 1987; Roache, 1994; Coleman and Stern, 1997; Oberkampf et al., 2004; Tominaga et al., 2008; ASME, 2009; AIAA, 2010; Franke et al., 2011). This can be considered as a milestone in the acceptance process of CFD as a tool for the evaluation of wind flow and pollutant dispersion around buildings in urban areas (Blocken et al., 2012). Among these studies, some of them (Casey and Wintergerste, 2000; Schatzmann and Leitl, 2002; Franke et al., 2007; Tominaga et al., 2008; Franke et al., 2011; Blocken et al., 2012) have detailed the main steps that must be addressed when it is question of conducting numerical simulations. Other studies are devoted to how to avoid and/or to reduce the errors and uncertainties that can be induced by a specific factor such as turbulence modelling (Nallasamy, 1987; Cheng et al., 2003; Xie and Castro, 2006; Tominaga and Stathopoulos, 2010; Salim et al., 2011; Rohdin and Moshfegh, 2011; Tominaga and Stathopoulos, 2012; Lateb et al., 2013a, 2014), cell geometry (Murakami, 1998; Hefny and Ooka, 2009), boundary conditions (Richards and Hoxey, 1993; Hargreaves and Wright, 2007; Gorlé et al., 2009; Richards and Norris, 2011; An et al., 2013), near-wall treatment (Blocken et al., 2007b; Eça and Hoekstra, 2011; Parente et al., 2011; Utyuzhnikov, 2012), discretisation scheme (Stern et al., 2001; Celik et al., 2008; Galvàn et al., 2011), etc. Table 2 summarises the most relevant studies published as review and overview articles, and those classified as practice guidelines commonly referred to when one investigates the pollutant dispersion in urban environments.

According to the workshop[6] proceedings report edited by Schatzmann and Britter (2005), models used to predict micro-scale dispersion lack quality assurance due to the lack of: (i) a generally accepted quality assurance procedure and (ii) data sets that are not quality checked and generally accepted as a standard for model validation purposes. However, the workshop has reviewed the present practices for model validation and data that are available and can be made accessible for micro-scale evaluation. Finally, recommendations have been made to develop coherent and structured procedures which give clear guidance to developers and users as to how properly assure their quality and their proper application. Notwithstanding, it should be noted that CFD solution verification and validation and complete reporting of the followed procedure are essential components of quality assurance (Blocken et al., 2011). Consequently, each study has to respect the different steps of the procedure – for instance, the detailed and recommended procedure by Tominaga et al. (2008) and Franke et al. (2011) – and to report the grid-sensitivity analysis and validation by comparison with high-quality reduced-scale data and/or on-site measurements (Janssen et al., 2013) to make the study reliable and credible from a quality assurance perspective.

[6] International workshop on quality assurance of micro-scale meteorological models, COST 732 and European Science Foundation, July 28–29, 2005, Hamburg, Germany.

6. Concluding remarks

The topic of micro-scale dispersion still requires further investigations (Ramponi and Blocken, 2012a) to understand the effect of all the parameters on wind flow and pollutant dispersion in urban areas (Huang et al., 2009). Indeed, the increase in knowledge of the flow structure within the urban canopy and of the transport by advection and turbulent diffusion, as well as the development of operational pollutant dispersion models, require more systematic studies of their dependence on factors such as geometry and external flow dynamics (Sini et al., 1996). In addition to the importance of the topic and advances in computational resources (Blocken et al., 2013), since the validation of such models has not always been satisfactory (Meroney et al., 1999) and such systematic studies are too difficult to realise in real sites and still relatively costly in physical modelling, computational modelling offers an appealing alternative (Sini et al., 1996) and thus becomes a practical method for predicting the flow and dispersion around buildings (Wang and Mu, 2010). In other words, there is a clear need for the development of computational methods for wind engineering applications utilising three-dimensional (3D) numerical modelling of flow and dispersion fields around buildings (Tutar and Ogguz, 2004) as well as for more validation studies (Blocken et al., 2007b).

The numerical applied studies are highly valued by the research communities (Blocken et al., 2013) since they attempt to reproduce real cases of existing sites. After the solution verification and validation of such cases, the very important reliable and credible results contribute significantly: (i) to understand and to emphasize the effects of various parameters on wind flow and dispersion behaviours, and (ii) to shed light on the short comings of the computational methods and models as well as their development for future improvements to produce reasonable predictions and acceptable results (Stathopoulos, 1997).

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