

Recent advancement from flow and dispersion studies around bluff bodies for urban environment applications

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ABSTRACT: This paper reviews recent studies pertaining to flow and pollutant dispersion around buildings and complex geometries (real cities). Field/laboratory experiments and numerical simulations (mainly Computational Fluid Dynamics, with attention to Large Eddy Simulation approach) performed by us as well as by other researchers who have looked at flow, turbulence, dispersion and ventilation around bluff bodies are considered. We attempt to review state of the art results considering that the urban complexity is not only due to the packing density, but also spatial building-height variability, thermal properties, the presence of vegetation. These findings are discussed in light of recent advances of operational urban dispersion models.

KEYWORDS: flow and dispersion, modelling, experiments, city breathability, urban models

1 INTRODUCTION

Health risks associated with exposure to pollutant concentrations in cities have motivated research to improve numerical models for local air quality. One of the difficulties arises from the complexity of the urban form which continues to be a challenge for modellers. An urban canopy consists of a large collection of buildings, trees and other obstacles affecting transport and distribution of scalars (pollutants, temperature, humidity etc.). A large number of experiments and simulations of flow around bluff bodies has been performed to understand the wide range of complex flow phenomena. This has led to the development and improvement of obstacle resolving models, such as Computational Fluid Dynamics (CFD) models.

Most of the studies have been performed separately depending on the specific application and a comprehensive overview is still missing. In this context, the paper reviews and summarizes some of the most recent advances in numerical (with attention to the Large Eddy Simulation techniques) and experimental findings obtained by us as well as by other researchers who have looked at flow and turbulence around single and groups of bluff bodies to adequately predict pollutant dispersion at the micro-scale. These advances are examined in light of the development of recent operational dispersion models, which are commonly used to determine the exposure of the population to pollutants in urban areas and to develop strategies for its reduction.

2 BUILDING AND STREET SCALE

2.1 *Flow and dispersion around isolated buildings*

Several studies, both numerical and experimental, were carried out in the past analyzing flow and dispersion in flat terrain and around bluff bodies (buildings). Among the pioneering studies,

Riddle et al. (2004) considered the simulation of the dynamics of the basic atmospheric boundary layer using a CFD code and an integral, operational model for the prediction of gas dispersion for neutral stability and flat terrain situations. Overall, they proposed to artificially increase the plume dispersion by reducing the typical turbulent Schmidt number Sc_t value in order to increase the turbulent diffusion near the ground in the Reynolds-averaged Navier–Stokes (RANS) k - ϵ model. Similar analyses and results were performed by Di Sabatino et al. (2007, 2008a). The work by Tominaga & Stathopoulos (2009) is one of the more systematic attempt to examine prediction accuracy of flow and dispersion around a cubic building for several wind directions using various k - ϵ models, comparing numerical results with wind-tunnel data. As for the flat terrain cases, the standard k - ϵ model provided inadequate results for the concentration field, because it cannot reproduce the basic flow structure, such as the reverse flow on the roof.

Only very recently, there has been an increasing interest in using Large Eddy Simulation (LES) models which, although computationally expensive, have the advantage over RANS in that they explicitly resolve the majority of the energy carrying eddies and the internally or externally induced periodicity involved, whereas only the universal small scale eddies are modelled. Following Tominaga & Stathopoulos (2010), Gousseau et al. (2011a, 2012) compared the convective and turbulent mass fluxes predicted RANS and LES for isolated buildings and analyzed the turbulent mass transport mechanism by unsteady concentration and velocity statistics. They showed that RANS models predict erroneous convective fluxes and are largely outperformed by LES in terms of prediction accuracy of mean concentration. Calculated results by Yoshie et al. (2011) confirmed better agreement of LES results with experiments.

2.2 *Flow and dispersion within urban street canyons*

Several works have been performed to understand flow and dispersion in urban street canyons. Most of the researches focused on the idealized case of an infinitely long street, within which a recirculating flow develops, driven by an external wind blowing perpendicularly to the street axis. These studies have provided fundamental knowledge on flow dynamics and pollutant dispersion in presence of obstacles for several engineering applications and for the optimization of the urban comfort. Moving from this basic knowledge, recent studies have been focusing on more complex phenomena. Among these we focus here on the effects induced by varying wind directions on the flow within a street canyon and at the intersection of two or more canyons. The effect of vegetation and buoyancy is also taken into account.

Reviews of recent progress in CFD and operational modelling of wind field and pollutant transport can be found in Vardoulakis et al. (2003) and Li et al. (2006). More recently, Blocken et al. (2011) and Chavez et al. (2011) reviewed various aspects of outdoor air pollution modelling through CFD in the urban environment which included isolated buildings, airborne particles in dense urban areas etc. Recent studies pertaining to CFD modelling techniques to assess pollutant dispersion in different street canyons have been reviewed by Hajra (in press), who discussed modeling technique advantages and demerits. This study shows that the future of CFD is bright and in the coming years LES model is more likely to be used due to its computational preciseness despite increased computer simulation time (Tominaga & Stathopoulos, 2011).

2.2.1 *Wind direction and street intersections*

Most of the studies have been devoted to the case of a wind blowing perpendicularly to the street axis since it is widely believed to maximize the retention time of pollutants. However, field experiments and numerical simulations have demonstrated that if the street is sufficiently long, the wind blowing along the street causes an accumulation of pollutants and the resulting concentra-

tion at the downwind end of the street can exceed that produced when a similar wind blows perpendicular (e.g. Berkowicz et al., 1996; Soulhac & Salizzoni, 2010; Hang et al, 2012). The evaluation of the advective fluxes along the canyon is then essential to predict and model the wide range of dispersion conditions that can occur within a street canyon.

A review of experimental studies of the flow induced in a street by an external wind blowing at an arbitrary angle is given in Ahmad et al. (2005) and described as a complex 3D helicoid. Soulhac et al. (2008) have shown that certain aspects of the flow can be obtained from the linear superposition of two asymptotic cases - flow parallel to the street and flow perpendicular to the street - providing an analytical model wind velocity along the street axis spatially averaged over the transverse street section. This result is the basis for finer parametric modeling approach for the exchange phenomena of pollutant, heat or momentum between the urban canopy and the overlying atmosphere (Cantelli et al., 2011; Soulhac et al., 2011).

Advective transfer along the street axis within a street of finite length causes dynamical effects within a street intersection. A detailed review on the state of the art has been given by Tiwary et al. (2011). Numerical simulations, wind tunnel and field experiments have provided a detailed picture of some of the major flow mechanisms that occur (e.g. Soulhac et al, 2009, Carpenitieri et al, 2019) showing that, even for simple configurations, the flow structure is very complicated, with significant variation of local averages of pollutant concentrations and even larger instantaneous variations, due to both wind direction variations and local smaller scale turbulence.

2.2.2 Thermal effects

To date relatively few studies investigated the role of heat fluxes in urban canyons, which are generated by temperature difference between the canyon walls and the air within the canyon. The temperature difference is typically induced by the direct solar radiation and can reach over tens of degrees in summer (Offerle et al., 2007). Thermal fluxes generate buoyancy forces within the canyon which have a relevant influence on the flow within it, especially in low wind conditions.

First studies were performed numerically by Sini et. al. (1996) and Kim & Baik (2001) and experimentally by Kovar-Pankus et al. (2002). Full scale experiments were performed in central Nantes (France) by Idczac et al. (2007) and in central Gothenburg (Sweden) by Offerle et al. (2007). Recently, numerical studies of these phenomena have captured increasingly interest. Memon et al. (2010) developed a two-dimensional $k-\varepsilon$ turbulence model with a Renormalization Group (RNG) closure scheme to assess the impact of the street canyon aspect ratio and wind speed on the intensity of heat. The street canyon model was validated by comparing results with reported wind tunnel data and similar numerical models (e.g. Uehara et al., 2000; Kim & Baik, 2001; Xie et al., 2007). Results uncovered the importance of street canyon aspect ratio and wind speed on urban heating and that urban cool island (i.e., daytime lower temperatures in an urban area) may be associated with direct ground heating. Another recent contribution was given by Defraeye et al. (in press) who proposed an adjusted wall function for temperature intended for forced-convective heat transfer at surfaces of bluff bodies. Finally Cheng & Liu (2011) performed LES simulations to examine characteristics of flows and pollutant dispersion in two-dimensional urban street canyons of aspect ratio equal to one in neutral, unstable, and stable thermal stratifications. While pollutants tend to be well mixed in street canyons in neutral and unstable conditions, improved pollutant removal in unstable conditions was observed due to the enhanced roof-level buoyancy-driven turbulence. Similar results were found by Cai (2012).

2.2.3 *Effects of vegetation*

To complete the picture, one should also consider how urban vegetation affects urban canopy flows, the microclimate and air pollution levels. Although particle deposition on plant surfaces removes pollutants from the atmosphere, thus reducing their concentration, it also should be noted that trees themselves act as obstacles to airflow decreasing air exchange with the above roof level atmosphere. Many research studies are underway to determine the role of vegetation in urban microclimates (e.g. CODASC Database, 2008; Mochida et al., 2008; Buccolieri et al., 2009; 2011). In numerical simulations using CFD models, trees have been modelled as porous media to which is associated a pressure loss according to the specific tree porosity. Typically, a modification to the governing equation is done by adding a momentum sink term. The interpretation of concentration results is done by looking at modifications that the flow undergoes in presence of trees. Though numerical studies using LES type of models should be employed (Salim et al., 2011; Park et al., 2011), RANS CFD simulations suggest that the presence of trees in the canyon break the main vortex structure expected in the tree-free cases and modifies the corner vortices at the street ends thus reducing mass exchanges with the various openings, therefore in first approximation dilution is much reduced. Real-city applications have further complications and both buildings and trees have to be considered together (Buccolieri et al., 2011).

3 DISTRICT SCALE

3.1 *The influence of building geometry and arrangements on pollutant dispersion*

When the urban rough surface interacts with the atmospheric flow above it, the disturbed flow field can become extremely complex depending on the obstacles' geometry, spacing and the spatial arrangement. Nowadays, several high-quality experimental and numerical data sets are available in the literature. Street-level pollutant concentrations have been proven to be attributable to several factors such as wind direction and velocity, street canyon aspect ratios, the presence of street intersections and upstream buildings, building roof geometry (Yassin, 2011), building packing density etc. In this context, a recent contribution has recently been made by the COST Action 732 (2005-2009, <http://www.mi.uni-hamburg.de/Home.484.0.html>) numerical team which has highlighted current potential and pitfalls of CFD models using data from the Mock Urban Setting Test (MUST) wind tunnel experiments (Bezpalcova, 2007). In addition, the CEDVAL dataset (2006-2009) have been recently studied by several authors in the context of model validation (e.g. Di Sabatino et al., 2008a; Franke et al., in press).

Even though different attempts were made to improve the capability of RANS models by modifying model parameters to improve their capability to reproduce real wind flow fields, turbulence and concentration patterns (e.g. Solazzo et al., 2009), interest in LES is increasing. Spatial distribution of the turbulent scalar flux inside building arrays by comparing the numerical results obtained by LES and RANS computations have confirmed what found for simple street canyon model, that is RANS underestimates turbulence diffusion in the building canyon when compared with LES due to the difference in the representation of turbulent scalar flux (Tominaga & Stathopoulos, in press). Another recent comparison between LES and RANS (Gousseau et al., 2011b) has further shown by comparison with wind tunnel experiments in Montreal that the performance of the standard $k-\epsilon$ model strongly depends on the turbulent Schmidt number, whose optimum value is case-dependent and unknown a priori. In contrast, LES showed a better performance without requiring any parameter input to solve the dispersion equation. As an example

Figure 1 (left) shows that even in presence of symmetrical geometry, the instantaneous concentrations can be asymmetric, which can be captured only by using the LES approach.

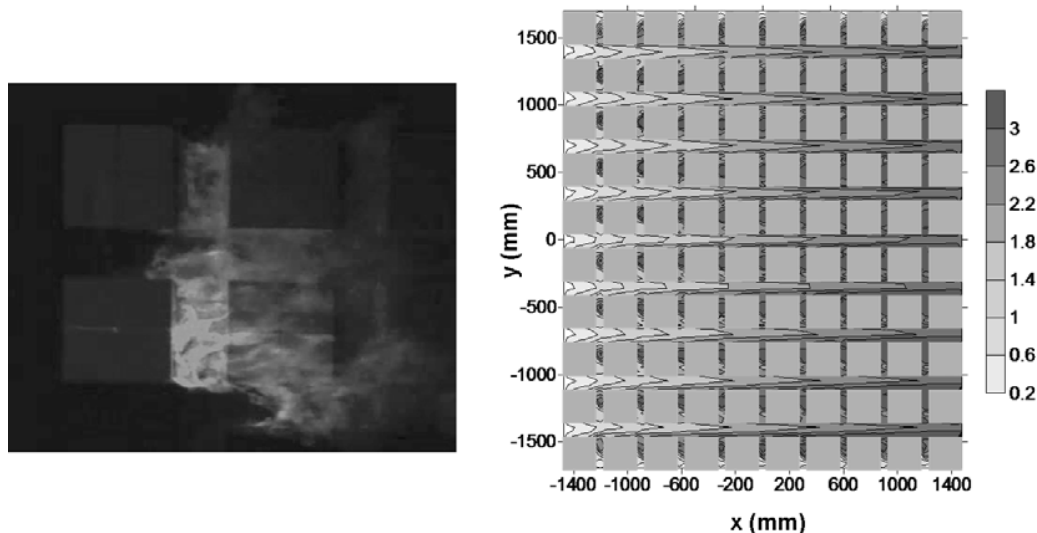


Figure 1. Visualization of a passive scalar injected by a line source at ground level within a regular obstacle array (left) and example of a map of normalized mean age of air (right). The wind blows from the left.

3.2 City breathability

An approach to determine street level pollutant dilution has recently been offered by the implementation of building ventilation concepts previously used to evaluate indoor exposure (Chen, 2009). Among the most recent studies, Hang et al. (2012) analyzed the nature of the flow being advected into the city from its surrounding rural areas using the concept of local mean age of air (Etheridge & Sandberg, 1996), which intuitively represents the time taken by an air parcel to reach a given place after it enters the city. A poorly ventilated region, as occurs at the end of the array (Figure 1, right) implies a large mean age, i.e. air mass takes a long time to reach a given region and therefore pollutant removal will be slower. Buccolieri et al. (2010) introduced the expression city breathability to describe this effect. Those authors set a conceptual frame to interpret pollution concentration levels in urban-like geometries using a bulk flow balance approach to calculate flow rates by means of RANS CFD simulations. Wind tunnel and numerical simulations analyses suggested a way to classify city's neighbourhoods into three groups: sparse, compact and very compact cities. Further, the presence of a low spatial building-height variability (a negative effect with respect to city breathability) and a low value of built-up area index (positive effect) together with the intracity variability of city morphometry is expected to be relevant for city breathability and still needs to be quantified (Di Sabatino et al., 2010).

4 URBAN DISPERSION MODELLING

As discussed above, CFD codes have been proven to be successful in predicting flow and dispersion at city scale by resolving the flow and dispersion down to the building scale. However, when a district of hundreds of streets and a large amount of the pollutant emissions have to be considered, CFD requires still unfeasible computational costs for operational purposes. Alterna-

tive approaches have then to be adopted and operational dispersion models are commonly used to determine the population's exposure to pollutants and to develop strategies for its reduction. We discuss here four different simulation strategies: Coupling dispersion models with diagnostic flow models, Street network models, Canopy models and Adapted Gaussian models. The models are hereafter presented for decreasing computational costs, which is strictly associated to the accuracy adopted in the description of details the urban geometry and of the velocity field within it.

4.1 *Coupling dispersion models with diagnostic flow models*

This method aims in reproducing the local urban geometry with high accuracy. The modeling chain can be directly fed with Geographic Information System (GIS) data of the buildings. Pollutant concentrations are obtained by coupling a Lagrangian dispersion model with velocity field predictions obtained by diagnostic models. These can be eventually modified using analytical corrections to better simulate the recirculation zones developing in the wakes of buildings and obstacles (Kaplan & Dinar, 1996). Examples of this approach are given by Moussafir et al. (2004) and Tinarelli et al. (2007), which present simulations of pollutant dispersion around isolated buildings or in groups of buildings in domains with lengths scales of few hundreds of meters. The computational cost are significantly lower than those needed to run simulations with prognostic CFD codes but not sufficiently low to use this model for simulations of multiple sources over a whole district or to run simulations over a whole year.

At larger scales, that span between the district and the city scale, when it is not possible to represent the details of recirculation zone developing within canyons and building wakes, the velocity field within the urban area can be reconstructed by correcting the output of a mass-consistent diagnostic model with analytical solution of the spatial averaged velocity within the urban canopy (Cionco, 1965; Macdonald et al., 1998). These velocity fields can then be used to run Gaussian puff dispersion models (e.g. Chang et al, 2005).

4.2 *Street network models*

Further reduction of the computational costs can be achieved adopting a street network approach. These are box models at heart but formulated with explicit modelling of the exchange of flow and pollutant fluxes at urban intersections and capable of providing a detailed concentration field at the street scale over a whole urban district. These models adopt a simplified description of the urban canopy. The streets in a district are modelled as a simplified network of connected street segments represented by boxes, whose mass exchanges are modelled by means of parametric laws. The flow within each street is driven by the external wind and the pollutant is assumed to be uniformly mixed over the street. In order to compute the mean concentration within each street, these models account for three transport mechanisms: the convective mass transfer along the streets (Soulhac et al., 2008) due to the mean wind along their axis, the turbulent transfer across the interface (Salizzoni et al., 2009) between the streets and the atmosphere, the convective transport at street intersections (Soulhac et al., 2009). An example of implementation of this approach is provided by Soulhac et al. (2011). Recent studies have evaluated the performances of this approach both against laboratory experiments (Carpentieri et al, in press) and field experiments (Soulhac et al, 2012). These approaches provide reliable results for high density canopy, and the width of the building blocks exceeds that of the streets separating them, as for most central part of European cities. Their performances decrease in case of sub-urban districts, when the spacing between the buildings increases, the physical limits of the street volume becomes unclear and the flow field within the street is strongly coupled with that of the atmosphere just above.

4.3 *Canopy models*

Much effort has been done in order to relate mass, heat and momentum exchanges between an urban canopy and the overlying atmosphere to spatially averaged characteristics of the urban geometry. As an example we cite here Di Sabatino et al. (2008b) who have recently proposed a modelling approach for the computation of the spatially-averaged flow field, where the average is defined at the neighbourhood scale, between 0.2 up to 10km. The novel idea is the description of the drag forces in terms of height dependent morphological parameters based on detailed knowledge of building geometry. This is nowadays available in digital format (Digital Elevation Models) which can be easily analyzed using image processing techniques (Di Sabatino et al., 2010). The goal is the development of a fast model for the prediction of the flow and pollutant concentration fields at the neighbourhood scale taking into account building arrangement in terms of porosity parameters and spatial building height variability. In terms of computational costs canopy models are similar to street network models. However, canopy models loose details in the spatial resolutions of the concentration fields, since they are not able to grasp the flow details in the streets at the local scale or the channelling effect occurring along the axes of the street canyons. Their application can be however particularly interesting in sub-urban areas or in general in district with low density of buildings, which have proven to be critical for street network approach.

4.4 *Adapted Gaussian models*

For short-range local problems (up to about 5km), simple Gaussian models are used. It is accepted that in urban areas these models can still be applied when pollutants disperse above the buildings or when the dimensions of the cloud are much bigger than the dimensions of the obstacles. Under such conditions classical Gaussian models may still play a role as screening tools but lack the potential for realistic predictions (COST Action 732).

The performances of these models can however be significantly improved by accurately correcting the plume spreading parameterizations implemented in it with specific semi-empirical relations. In particular, at the micro-scale the retention of pollutant within the recirculating flow structures in building wakes and street canyons, that inhibit street ventilation and enhances ground level concentrations, can be computed as the sum of two components: the background concentration due to street canyon trapping effect and the concentration related to the direct contribution of vehicles emissions within the street (e.g. Hertel & Berkowicz, 1989; Schulman et al., 2000). Further, at slightly large scales the enhanced lateral spreading of a pollutant plume due to increased plume meandering in the buildings wakes can be efficiently simulated with simple parametric relations linking the intensity of the turbulent fluctuations to the time averaged later spread of the plume (e.g. Venkatram et al., 2004). At the district scale, similar corrections for the parameterization of the plume can be taken into account to model the enhanced diffusivity within the roughness sub layer (Raupach et al., 1991; Rotach, 1993; Salizzoni et al., 2009), taking advantage of the fact that turbulent characteristics have proven to be almost uniform with height (Venkatram et al., 2005). It is worth mentioning however, that these approaches are reliable mainly in case of sparse obstacle arrays, and not in dense packed obstacle array, where the channelling of pollutant along the street axes is one of the main transfer process (Garbero, 2010).

5 CONCLUSIONS

This short review tried to show recent advancement from flow and dispersion studies around bluff bodies for urban environment applications. The focus was to select some very recent works in this area. Until now a large number of experiments and simulations of flow around bluff bod-

ies has been performed to improve fluid dynamics around obstacles and to understand the wide range of complex flow phenomena. Physical simulation studies in wind tunnels show a high potential since the influence of bluff body's geometry, presence of obstacles etc. can be investigated by controlling each parameter independently. This has also led to the development and improvement of obstacle resolving models, such as CFD, with LES more likely to be used in future owing to its accuracy.

Up to now computational dispersion models have been proven to be successful in predicting flow and dispersion at city scale by resolving the flow and dispersion down to the building scale. However, when a district of hundreds of streets is considered and a large amount of the urban pollutant emissions has to be taken into account, the application of CFD codes requires computational costs that are still unfeasible for operational purposes. In this context, operational dispersion models are commonly used to determine the exposure of the population to pollutants in urban areas and to help develop strategies for its reduction.

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