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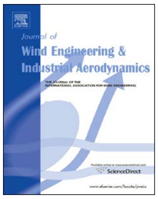

Optimization of urban building patterns for pollution removal efficiency by assuming periodic dispersion

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ABSTRACT

Air pollution is often a major problem in densely built cities, mainly due to the urban canopy consisting of high-rise buildings and other obstructions that hinders the transport of traffic-produced pollution. Ventilation characteristics principally depend on geometrical parameters such as the variations in building height and building density. The aim of this paper is to introduce an effective method for finding optimum building patterns via CFD modelling. In these models the urban canopy is approximated by an infinite 2D lattice of a given elementary building pattern, which also incorporates pollution sources. The surface mass transfer coefficients are computed for various wind directions and the non-dimensional form of the average value is used for characterizing ventilation intensity. The model does not require input data for boundary conditions, therefore the resulting ventilation intensity depends only on the geometrical configuration. Resultant velocity and turbulence profiles are found to be in close agreement with earlier models and wind tunnel measurements. The methodology of optimization is demonstrated on simple geometrical configurations and further results are shown for a more complex building arrangement characteristic of Central Europe. The model can be further developed to non-isothermal conditions, and supports the application of the Large Eddy Simulation.

1. Introduction

According to the statement by the United Nations Environmental Program (UNEP, 2015), urban air pollution is linked to approximately 1 million premature deaths each year worldwide, furthermore, it costs approximately 2% of GDP in developed countries and 5% in developing countries. 90% of air pollution is caused by vehicle emissions in large cities located in developing countries, which are the most critical from this point of view. This problem can be fought by cutting emissions and improving the ventilation characteristics of urban areas.

Urban ventilation has an extensive literature (see the recent survey by Blocken (2014)), yet very few guidelines are known for supporting low pollution urban design. Oke (1988) proposed keeping the ratio of H building height to W_s street width between 0.4 and 0.6. The onset of skimming flow occurs around H/W_s=0.65 at a building density of 0.25 (ratio of plan area and total surface area), and this causes a rapid decrease in ventilation efficiency. It is noted that the proposed maximum H/W_s ratio is exceeded in almost every large city, since the typical value in Europe is 0.75–1.7 and the typical value in North-America is 1.15–3.3. The lower limit is necessary for providing sufficient shelter in the cold North-American climate.

It is known that a solitary high-rise building pumps fresh air into the urban canopy because intense down-flow occurs along the up-stream front wall (Heist et al., 2009; Brixey et al., 2009). Moreover, pollution ascends in the wake of the building, decreasing the ground level concentration. If the urban canopy is densely populated with high-rise buildings, an adverse effect can be observed due to the increased canopy drag and higher H/W_s ratio. Investigation of transport phenomena around a single building is not conclusive for building policy, consequently, larger patterns of buildings, blocking objects and sources need to be taken into account. Theurer (1999) investigated various building arrangements characteristic for south-western Germany and categorized building patterns. From wind tunnel measurements, Theurer found ventilation efficiency to be in strong correlation with H/W_s and the characteristic street length L_s. Hang et al. investigated the relationship between urban morphology and large scale urban dispersion through numerical models of various idealized urban complex shapes and street topologies (Jian et al., 2009; Hang et al., 2009a, 2009b). Variations in building height effectively enhances purging efficiency as shown by Hang et al. (2012).

A simple approach for taking into account the interaction of buildings is to assume bidirectional horizontal periodicity. Nevertheless, the advantage of using bounded geometrical patterns is that the evolution of periodic flow in the flow direction can also be investigated. Full-scale urban models were extensively studied by Yee and Biltoft (2004), Narita et al. (2006), and the same approach can be adopted in wind tunnel experiments. Finite-sized models can be adopted in CFD models as well, nonetheless, developed periodic flow patterns can be more easily obtained from numerical models by the application of periodic boundary conditions on lateral sides. In this

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way, only one single instance of the elementary geometrical pattern needs to be resolved, which greatly reduces memory demand and computational cost. Unfortunately, these solutions are difficult to compare with measurements.

Periodic flow models can provide reference data for the development of the distributed canopy drag model originally proposed by Martilli et al. (2002). Another question is how well such porous models perform at the boundaries of a finite-sized porous region. This was analyzed by Hang and Li (2010) by comparing the results of a state-of-the-art macroscopic porous canopy model with those from a finite extent building resolved simulation, which found that the velocity profile agrees well with the fine scale model results, but turbulent kinetic energy was underestimated at the beginning of the zone.

Santiago et al. (2008) investigated average flow quantities around a periodic array of cubes by using FLUENT and compared their results with high accuracy DNS data. Coceal et al. (2014) also utilized DNS by incorporating the pollution source and re-initialization of the concentration field at lateral boundaries by using a sponge zone. The shortcomings of this approach are that the dispersion process can be investigated only in the vicinity of the source and the effect of a periodic source field cannot be taken into account.

Periodic numerical models are also used for determining hydraulic resistance and the surface heat transfer coefficient in channel flows, as well as for discovering favorable surface patterns (Lohász, 2009; Hernádi and Kristóf, 2014). In such models the temperature field must be made periodic in the axial direction as originally proposed by Patankar et al. (1977). This methodology was further developed in our study on the method for allowing pollution transport in arbitrary horizontal directions, which is essential for modelling urban ventilation.

CFD is a complex procedure with uncertainties due to geometrical simplifications, turbulence modelling and boundary conditions, moreover errors due to discretization, the finite number of iteration steps and the finite representation of real numbers. However, the magnitude of errors (from the latter three components) can be estimated (Roache, 1997; Casey and Wintergerste, 2000; Rákai et al., 2014) and also be reduced if more computational resources are available. These common error estimation methods were also used in our current study. The different magnitude of model inaccuracies can be observed in different field quantities. For instance, the uncertainties caused by turbulence modelling cause inaccuracies both in advection and in turbulent fluxes. This is why typically higher errors are observed in concentration fields than in mean velocity or pressure fields (see e.g. Schatzmann et al., 2010). It should also be noted that accuracy needs to be viewed differently regarding the aims of the present investigation: in the case of an optimization procedure, the important question is how accurate is the location of the optimum. In this sense, simple models can be very useful sometimes, e.g. it is often possible to select the best solution without actually predicting its performance (or cost).

The tradeoff between simplicity and modelling accuracy is necessary in almost every case when turbulent flows are analyzed. The role and performance of various turbulence models are detailed in the recent review of Tominaga and Stathopoulos (2013). Those Reynolds Averaged Navier-Stokes (RANS) models which also assume isotropic turbulence offer relatively inexpensive solutions. k-ε and k-ω models belong to this model family. A known shortcoming of these models is that simulations provide much lower lateral turbulent diffusion compared with wind tunnel experiments (see e.g. Eichhorn and Balczó, 2008). Nevertheless, the various versions of the k-ε model are the most common approach and several successful validations can be found in the literature. Among them, Donnelly et al. (2009) compared WinMISKAM dispersion simulations to field experiments (MUST) and found that the model performance was well within the bounds proposed by Chang and Hanna (2004). Santiago et al. (2008) found close agreement in average vertical profiles between model results from standard k-ε turbulence and FLUENT and high accuracy DNS data for a staggered arrangement of cubes. Large Eddy Simulation (LES) models provide deep details on turbulent flow and its temporal averages are often more accurate than the results of RANS models. LES, however, requires finer mesh and temporal resolution, therefore the simulation is usually more costly by almost two orders of magnitude. Other scale-resolving models such as Scale Adaptive Simulation (Menter, 2015) might offer higher accuracy for moderate computational overhead.

Our current study used the Realizable k-ε model (Shih et al., 1995). The presented methodology also supports the application of scale resolving turbulence models. The application of those is greatly simplified by the periodic lateral boundary conditions. That way, one can avoid the generation of synthetic turbulence in the form of time dependent velocity profiles at the inlet boundaries and the consequential modelling uncertainties. The proposed periodic approach therefore opens the door for the substantial reduction of modelling uncertainties in dispersion studies.

According to our approach, the urban canopy is approximated by an infinite 2D lattice of a given elementary pattern of buildings and pollution sources. The ventilation performance of individual arrangements is evaluated from dispersion simulations by the periodic model in which a constant bulk flow pressure gradient is assumed. The results of such virtual smoke experiments for a building arrangement characteristic of Central European inner-city areas can be seen in Fig. 1. Details of this simulation can be found in Section 3.4; in Fig. 1 45° wind direction was assumed.

We demonstrate the feasibility of optimization by repeating the calculations for a series of geometrical models in a way that the useful building volume over a unit surface area is constant. For the sake of quantitative comparison, the surface mass transfer coefficient is normalized with the help of the friction velocity (u*) characterizing the wind force above the canopy (see later Eq. 13), so that a special interpretation of the dilution coefficient k* is formulated. k* is believed to be the most characteristic quantity for the ventilation performance of a unique building configuration.

The proposed methodology gives rise to a number of difficult questions: 1) Does the dilution coefficient truly represent the impact of hydraulic resistance on ventilation efficiency? 2) What is the sufficient complexity of elementary patterns in order to simulate an urban canopy? 3) To what extent can the ventilation characteristics of a finite size city be improved by adopting the building patterns which were optimized in periodic models?

In our opinion, the above questions will remain unanswered for a long time, therefore the building patterns that are optimized in periodic models will have to be tested within a greater part of the investigated city. Potential testing methods could be: A) with wind tunnel experiments, B) building resolving CFD models, or C) full-scale experiments. In the framework of the present study such large scale tests were not possible, so practical applications have yet to be targeted. Nevertheless,

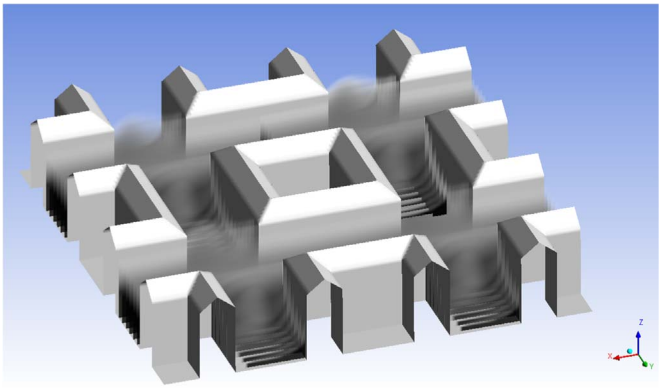

Fig. 1. Virtual smoke experiment in a periodic test-box.