A FAST MODEL FOR FLOW AND POLLUTANT DISPERSION AT THE NEIGHBOURHOOD SCALE

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Abstract: This paper deals with the development of a simple urban model for flow and dispersion in the urban canopy layer (UCL). The flow module of the model calculates spatially-averaged wind profiles adopting a technique recently proposed in the literature, which is based on a balance equation between the obstacle drag force and the local shear stress. Spatially-averaged wind profiles are used as input for a newly proposed dispersion model which solves the advection-diffusion equation at neighbourhood scale. In the model, the effects of the buildings within the UCL are taken into account by means of morphological parameters λ_f and λ_p (the ratios of plan area and frontal area of buildings to the lot area).
Spatially-averaged mean concentrations output by the developed model are compared with numerical results obtained from the computational fluid dynamics (CFD) model FLUENT. In particular, two configurations of constant height UCL have been considered, which refer to as $\lambda_p = \lambda_f = 0.16$ and $\lambda_p = \lambda_f = 0.44$. The originality of the study is that the dispersion model itself integrates the equations without explicitly resolving the flow around individual buildings but still accounts for their effects. The computational costs are much reduced which makes it suitable for the predictions of concentrations over the neighbourhood scale in an operational context.

Key words: *pollutant dispersion, urban canopy, morphological parameters, spatially-averaged wind profiles, neighbourhood scale.*

1. INTRODUCTION

The growing attention worldwide towards urban air quality issues has inspired in the last decades the development of numerical flow and dispersion models of increasing complexity. Up to now computational dispersion models based on Computational Fluid Dynamics (CFD) have been proved to be successful in predicting flow and dispersion at city scale by resolving the flow and dispersion down to the building scale. However, their use in an operational context is still limited due to computational cost and lack of adequate evaluation. Simplified models such as Gaussian type ones are preferred to more complex models as they require fewer input parameters often routinely available and they are able to run fast. However, currently used operational flow and dispersion models are too simplistic as they are typically based on a single surface roughness approach concept.

Di Sabatino, S. et al. (2008) have recently proposed a new modelling approach for the computation of the spatially-averaged flow field, where the average is defined at the neighbourhood scale, i.e between 0.2 up to 10 km (Britter and Hanna, 2003). The flow field is described by a stationary equation for the momentum balance between the urban canopy and the layer above. The underlying 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, known as Digital Elevation Models, which can be easily analyzed using image processing techniques. The general 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 and spatial building height variability.

Within this framework, this paper deals with the extension of the morphologically based flow modelling approach to pollutant dispersion. The computed flow fields are used as input for a numerical model which solves the Eulerian advection-diffusion equation for the prediction of spatially-averaged concentration of pollutant released from a point source at the neighbourhood scale. Computed flow and concentration results are validated using results from building resolving CFD simulations. Results of the analyses are presented and discussed.

2. THE NEW MODEL

The starting point for the development of the new model proposed in this study is the model recently proposed by Di Sabatino et al. (2008), which allows the prediction of the spatially-averaged mean wind profiles for real cities at the neighbourhood scale. The model is based on the momentum balance equation in the urban canopy given by:

$$d\tau = \frac{1}{2}\rho C_D U^2(z)\frac{dA_f}{A_T} \tag{1}$$

where U is the spatially-averaged flow field, ρ the air density, $d\tau$ the change in shear stress and dA_f the portion of frontal area of the buildings between levels z and $z + dz$, and $C_D(z)$ the drag coefficient at height z. A_T is the lot area per building or total ground surface area divided by the number of buildings. In the equation (1) buildings are treated as cylinders or parallelepiped with a sectional drag coefficient $C_D(z)$ (Macdonald et al., 2002). It is assumed that at each horizontal cross-section there is a balance between the drag force due to the buildings and the local shear stress expressing the momentum loss. It is recognised that at the top of a homogeneous canopy, a shear layer forms. As a first approximation, we can make the assumption that the turbulent shear stresses within the urban canopy can be described by a Prandtl's mixing length approach. With this assumption, equation (1), describing the momentum transport in the canopy, can be written as an ordinary differential equation

$$\frac{d}{dz}\left[\left(l(z)\frac{dU}{dz}\right)^2\right]=\frac{1}{2}C_D U^2(z)\frac{\lambda_f(z)}{H} \tag{2}$$

where $l(z)$ is a mixing length scale in the canopy and $\lambda_f=A_f/A_t$ the frontal area index. The geometry of the canopy is replaced by using morphometric parameters such as the planar area index λ_p and λ_f, which represent the plan area and the frontal area of buildings relative to the total surface area, respectively (Grimmond and Oke, 1999). In general, the morphological parameters can be derived by based image analysis of digital elevation models (DEMs) (Ratti et al., 2006). In this paper, two configurations of constant height urban canopy have been considered, which are characterized by $\lambda_p = \lambda_f = 0.16$ (intermediate canopy) and $\lambda_p = \lambda_f = 0.44$ (dense canopy).

Equation (2) is numerically solved by setting as boundary conditions the velocity and its gradient at the top of the domain where the logarithmic law is valid. Figure 1 (left) shows the spatially-averaged wind profiles as function of the height for the canopies investigated.

The wind profiles resulting from equation (2) are then used as input in the steady state advection-diffusion equation , which, for a single inert gas reads (Seinfeld, J.H. and S.N. Pandis, 1998)

$$U_j\frac{\partial C}{\partial x_j}-\frac{\partial}{\partial x_j}\left(D(z)\frac{\partial C}{\partial x_j}\right)=S(\vec{r},t) \tag{3}$$

where C is the mean concentration of the inert gas and $D(z)$ the turbulent diffusivity, defined as follows

$$D(z)=l^2(z)\left|\frac{dU(z)}{dz}\right| \tag{4}$$

Figure 1 (right) shows the diffusivity profiles for the two cases considered.

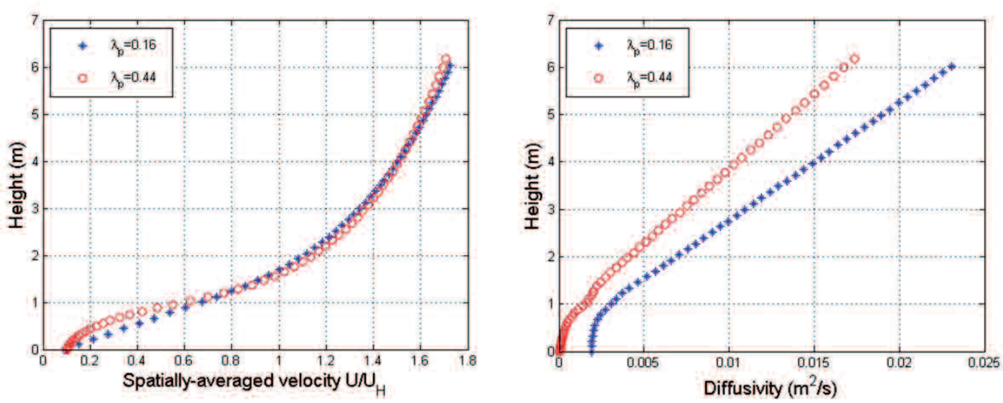

Figure 1. Profiles of spatially-averaged wind velocity (left) and turbulent diffusivities (right) for a canopy with H (average building height) equal to one.

Equation (3) has been solved numerically using the Finite Volume Method (Ferziger and Peric, 2000). The code was written in C++ programming language and allows to calculate solutions for both two-dimensional and three-dimensional cases. As boundary conditions, we set C = 0 at the inlet of the domain and zero diffusive flux at the remaining boundaries.

Several tests have been performed to verify the independence of the solution from the chosen computational domain and grid. The final number of grid nodes used for our solution is about one million.

3. CFD SETTINGS

Simulations have been carried out under the assumption of neutrally stratified boundary layer. The computational domain consists of hexahedral elements with increasing resolution in the vicinity of the ground and in the regions of the flow where large velocity gradients are likely to take place. Several tests have been performed to verify grid size independence with increasing mesh cells until further refinements gave no significant improvements. The final number of the computational cells is about one million. The geometry consists of cubes laid out in a staggered pattern as shown in Figure 2 (right). The standard k-ε turbulence model (Launder and Spalding, 1974) has been adopted for the CFD simulations. The inlet wind velocity is assumed to follow a power law profile with a profile exponent p = 0.26

$$\frac{U}{U_H} = \left(\frac{z}{H}\right)^p \tag{5}$$

where U_H = 0.0505 m/s is the undisturbed wind velocity at the building height H. Turbulent kinetic energy and dissipation rate profiles are specified as follows

$$k = \frac{u_*^2}{\sqrt{C_\mu}} \quad \text{and} \quad \varepsilon = \frac{u_*^3}{\kappa z}\left(1 - \frac{z}{\delta}\right) \tag{6}$$

where δ is the boundary layer depth, u_* is the friction velocity, κ the von Kàrmàn constant (0.40) and C_μ=0.09.

For simulating dispersion, the advection diffusion (AD) module was used. In turbulent flows, FLUENT computes the mass diffusion flux as follows

$$J = -\left(\rho D + \frac{\mu_t}{Sc_t}\right)\nabla Y \tag{7}$$

where D is the molecular diffusion coefficient for the pollutant in the mixture, μ_t the turbulent viscosity, Y the mass fraction of the pollutant, ρ the mixture density. $Sc_t = \mu_t/(\rho D_t)$ is the turbulent Schmidt number and D_t the turbulent diffusivity. The source emission rate Q was set at 1.0 g/s. The point source was positioned at about 6-7H from the first upstream building lines in the middle of the array

For medium to large packing densities, Di Sabatino, S. et al. (2007) have shown that it is necessary to increase diffusion in the CFD model to achieve better predictions as the ventilation through the street canyon top predicted by the CFD model is too low when employing the k-ε model. Therefore, in this study Sc_t = 0.4 has been used.

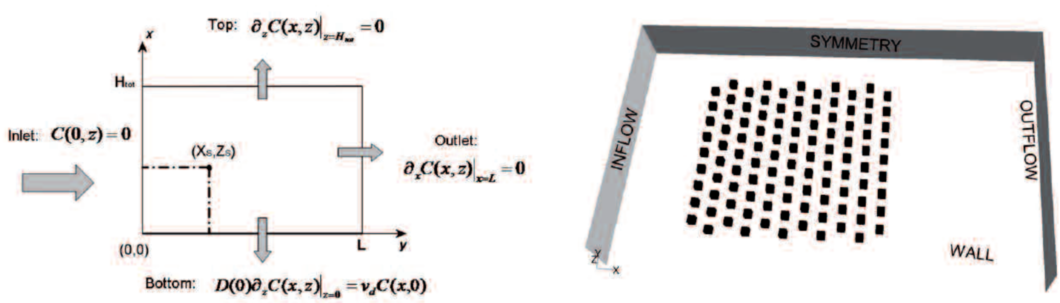

Figure 2. Boundary conditions of the computational domain used in our model (left) and CFD simulations (right). Xs and Zs are the coordinates of the point source.

4. RESULTS AND DISCUSSION

In this section we analyse the dispersion from a point source focusing on the effect of packing density by comparing results obtained from our model with those predicted by the CFD model.

Since FLUENT is a building-resolving model, it does not provide results where buildings are present. On the other hand, our fast urban model incorporates information on the building arrangements through synthetic parameters (λ_p and λ_f). They appear explicitly in the velocity equation and in diffusive terms so that computed velocity and concentration fields are available everywhere in the computational domain. Thus, in order to compare CFD results with our model, spatially-averaged mean concentrations have been extracted from CFD outputs. As shown in Figure 3, for each grid node P of our model, we have chosen a centred volume DV and averaged CFD concentrations enclosed in that volume. The above volume was large enough in the horizontal plane in order to remove details not captured by our model, but shallow enough to maintain the differences in the vertical direction.

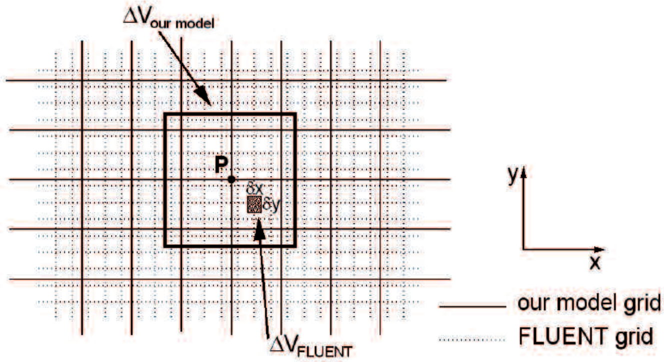

Figure 3. Sketch of the method used to overlaid grids used in our model and FLUENT.

Intermediate canopy
Figure 4 shows concentration (g/m^3) contour plots obtained from our model (left) and the CFD model (right) at z = 0.4H and z = H from a ground level point source (X_s = 4.5m, Y_s = 9m), for the intermediate canopy. From the figure, we note that the shape of the concentration curves predicted by the two models at both the height is similar. Overall, the plume width predicted by our model is comparable to the CFD one, even if our model predicts smaller concentrations in the middle of the investigated area. In particular, independently from the height of the source, horizontal profiles (not show here) along the plume centreline show that our model overestimates CFD results near the source while at larger distances slightly underestimations are found. Moreover, up to about a height of 2H, our model slightly underestimates CFD results, while it overestimates above.

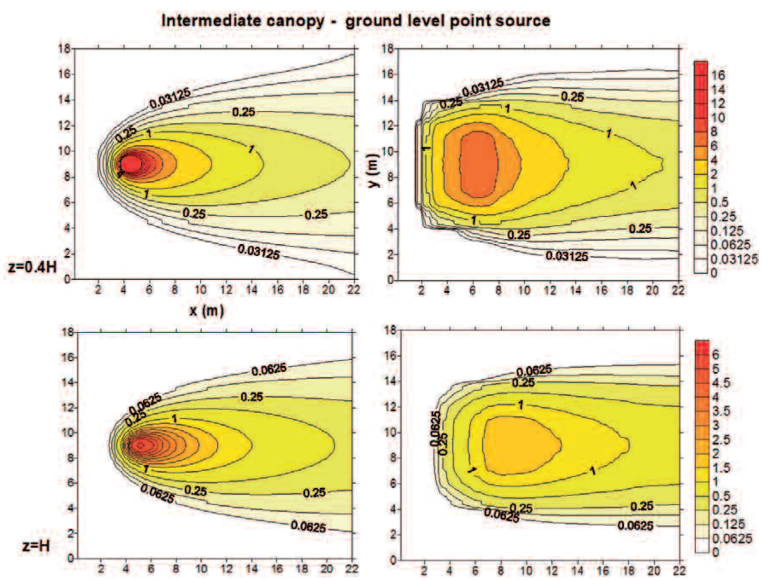

Figure 4. Intermediate canopy: concentration (g/m3) contours from our model (left) and FLUENT (right) at z=0.4H (top) and z=H (bottom).

Dense canopy
Figure 5 shows concentration contour plots obtained from our model (left) and the CFD model (right) for the dense canopy when the source is positioned at the height z = H (X_s=4 m, Y_s=9 m). As found in the previous case, the shape of the concentration curves predicted by the two models at both heights is similar. Overall, the plume width predicted by our model is comparable to CFD one. Quantitatively, this case show a better agreement with CFD predictions, except for a small zone near the source where our predicted concentrations are underestimated. In cases where the source is not at z=H (not show here), our model tend to overestimate concentrations predicted by the CFD model.

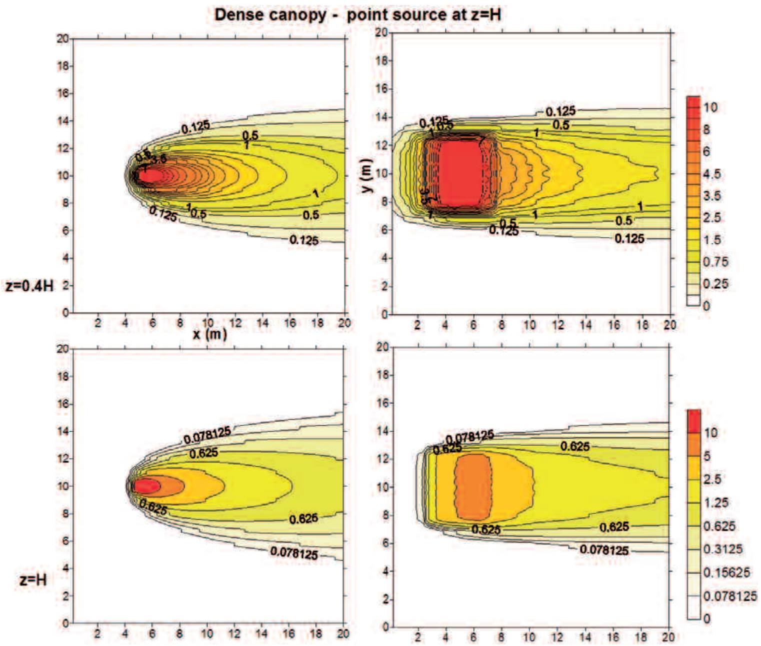

Figure 5. Dense canopy: concentration (g/m3) contours from our model (left) and FLUENT (right) at z=0.4H (top) and z=H (bottom).

5. CONCLUSIONS AND FUTURE WORK

This paper has dealt with the development of a simple urban model for flow and dispersion in the urban canopy layer (UCL). It solves the advection-diffusion equation in an urban canopy taking into account the effect of the buildings. The originality of the study is that the model itself integrates that equation without explicitly represent the buildings, which are indeed replaced by morphometric parameters such as λ_p and λ_f which synthesize the main geometric characteristics of the urban canopy.

We have compared results with predictions obtained from a CFD model which has been proved to give good results in this type of applications. From the analysis we have shown that our model is successful in predicting concentrations and the main aspects for the different cases investigated, even if there is a general overestimation near the source and underestimation at larger distances.

At practical level, since the proposed model requires few input data, requires small computational resources and give a fast response, it can be used in an operational context and screening purposes. However, further studies are still required to improve the model. In particular further analysis for a better formulation of the turbulent diffusivity still need to be investigated.

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