Simplified CFD Modeling of Air Pollution Reduction by Means of Greenery in Urban Canyons

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Abstract: A simple numerical model, implemented through COMSOL Multiphysics 5.2 (© COMSOL AB), that can be usefully adopted to evaluate the effect of greenery in the pollution reduction in urban canyons, is presented. The model can be easily tailored to account for different plant species and greenery shapes. Some preliminary results obtained with reference to green façades and green hedges show that a good reduction in the pollutant dispersion in the canyon is achievable.

Keywords: Air pollution, greenery, urban canyons, CFD modelling.

1. Introduction

In the recent literature, increasing attention has been paid to the role of urban design and vegetation choice in order to improve air quality. As is well known, in fact, air pollution is among the major environmental issues in urban areas, and epidemiological studies demonstrate their adverse health effects and a strong correlation between increased air pollution and adverse health effects (Brook et al., 2010; Dominici et al., 2006). Indeed, urban planning and urban design strategies should be aimed at reducing this major environmental issue. In this framework, the integration of vegetation can play a key role.

For this reason many studies have been done in order to investigate the effect of greenery, and an interesting review on this topic id presented in Janhäll (2015) showing, for example, that leaves closed to pollution source can increase air quality with deposition, with a plant's porosity which allows pollutants to find enough deposition surface (penetration), and affects also pollutants dispersion. Moreover, in Janhäll is shown that also choosing tall or short plants determines the effectiveness of vegetation.

The air quality improvement due to vegetation is mainly related to the absorption of fine dust particles and the uptake of gaseous pollutants, with effects related to pollutant deposition and dispersion (Janhäll, 2015).

Focusing on (greening) street canyons instead of, for example, urban parks can potentially be more effective, due to the difficulty in finding empty spaces for large green areas in dense cities. Paying attention to this focus, there is an increasing interest in the study of air dynamics – typically with Computational Fluid Dynamic (CFD) simulations – within urban street canyons (Kastner-Klein et al., 2001).

In the literature, some authors have paid attention also to the shape (Vos et al. 2013) or the vegetation characteristics (leaf area index, porosity, etc.) (Köhler, 1993), showing that both features play a key role and have to be taken into account in order to properly design the greenery.

In the present paper, a simplified model to evaluate the effect of greenery on the possible reduction of pollution in a straight urban canyon is presented. Two aspects are taken into account: the inlet wind velocity and the greenery shape. In the numerical simulations, in fact, different wind velocities and greenery shapes are considered.

2. Numerical model

Let us consider the geometry shown in Fig.1, that represents a straight road between two continuous lines of buildings (depicted in light grey). The road has width W, length L and all the buildings have the same height H. Let us assume W = 20 m, L = 100 m and H = 20 m. Let us suppose that air flows along the main axis of the road coming in through the inlet section denoted by 1 with an inlet velocity U_{wind}, and exiting from the outlet section, denoted by 2.

For modeling simplicity, the presence of cars is not considered as an obstacle to the fluid flow; however, since cars and vehicles are the main source of pollution within the road, their effect is taken into account by means of the volume denoted Vc and colored in red in Fig. 1, having width W_S, length L and height H_S, which is placed in the middle of the road. Let us assume

W_s = 5 m and H_s = 0.5 m. Due to the symmetry of the considered geometry shown by the cutting plane in dot-point line, only half geometry is adopted in the following.

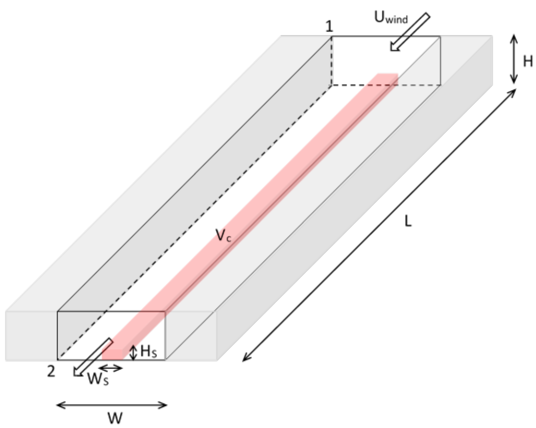

Figure 1. Sketch of the geometry of the considered urban canyon.

A greenery displaying two different shapes is considered in the following: first, a continuous green façade, having thickness T_f = 0.3 m (see Fig. 2, where a representative cross-section of the geometry is shown, regardless the relative dimensions of the parts); then, a continuous hedge, having height H_h =1.5 m, width W_h = 1 m placed at a distance D_h = 8 m from the symmetry plane of the domain (see Fig. 3).

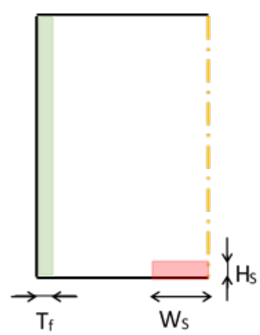

Figure 2. Qualitative cross section of the geometry: green façade.

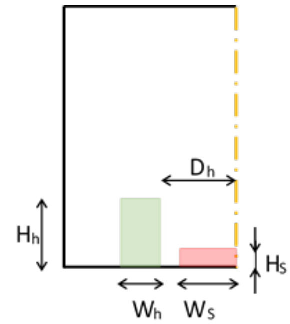

Figure 3. Qualitative cross section of the geometry: green hedge.

The presence of the greenery is evaluated by comparison with the “clear” canyon, where the pollutant source is present, but there are no plants.

In order to best focus on pollution reduction made by greenery, let us suppose that incoming air is pollutant free, i.e., the pollutant concentration c [mol/m^3] in incoming air is vanishing. Moreover, let us suppose that pollutant particles are uniformly generated inside the volume V_c and, thus, transported by the air mainstream for both convection and diffusion. In the following, we make reference to CO_2 as main pollutant emission by cars. If one denotes by U_c the average car speed in the road, by E_c the average CO_2 car emission [g/km], by M the molar mass of CO_2 [kg/mol], and by n_c the number of cars in the street, the pollutant emission rate per unit volume S can be expressed as

$$S = \frac{n_c}{V_c}\frac{E_c U_c}{M} \quad \left[\frac{mol}{m^3\, s}\right] \tag{1}$$

Thus, with reference for instance to E_c = 150 g/km, M = 0.044 kg/mol, U_c = 30 km/h, n_c = 250, one has S = 28409 mol/(m^3 s).

In order to account for pollutant absorption and retention made by greenery, let us model the presence of plants as a Darcian porous medium saturated by air, where the values of the porosity ε and the permeability κ have to be estimated accordingly to the specific plant species considered. In detail, let us assume that the pollutant particles transported by air undergo a reduction rate R in their concentration per unit volume that can be described by a function of both the module |u| of local air velocity and the local concentration c itself, namely

$$R = -a\,|\mathbf{u}|^{\alpha_1}\,c^{\alpha_2} \quad \left[\frac{mol}{m^3 s}\right] \qquad (2)$$

where the values of the constants a, α_1 , α_2 have to be chosen accordingly to the specific green species considered. In the following, let us assume for instance a = 0.5 m^{-1}, $\alpha_1 = 1$, $\alpha_2 = 1$.

Since the air flow domain is both that of a clear fluid and that of a fluid-saturated porous medium, let us adopt the Navier-Stokes equation to describe the flow in the clear region, and the Brinkman equation to describe the flow in the porous region. Since the resulting Reynolds number of the flow is high also for small values of the wind velocity due to the size of the domain, a RANS turbulent model (present in the CFD module of COMSOL Multiphysics) is adopted, where turbulence effects are included using an enhanced viscosity model based on the scaled wall distance.

3. Preliminary results

The numerical model has been implemented in COMSOL Multiphysics 5.2 and refers to a 3D domain and a stationary study. First, a mesh independence analysis has been performed for the three geometries considered. The chosen criterion is to have a reasonable compromise between accuracy and computational effort. Accordingly, we adopted for the final simulations the mesh that granted the obtained results for the average concentration on the outlet surface remaining in a confidence range lower than 4%. As an example, Table 1 shows the results of the grid independence analysis, with reference to the average pollutant concentration on the outlet section of the urban canyon with green hedge and a wind inlet velocity of 0.5 m/s.

Table 1. Mesh independence

mesh independence: green hedge, U_{wind} = 0.5 m/s	
number of 3D elements (hexahedrons)	outlet section
164288	6.594
205920	6.868
263102	6.915

In detail, a structured mesh made of 102960 hexahedral elements has been adopted in the final computations for the clear urban canyon, a mesh of 314400 hexahedral elements has been adopted for the geometry depicted in Fig.2, while a mesh of 205920 hexahedral elements has been adopted for the geometry depicted in Fig.3. An enlargement of the latter is shown in Fig. 4.

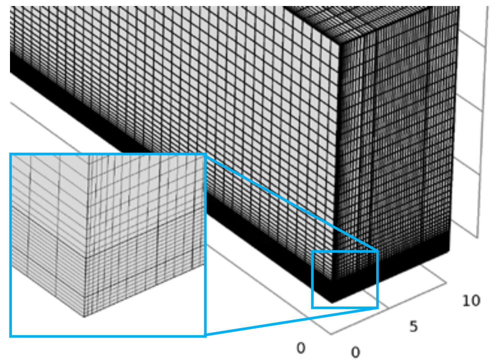

Figure 4. Detail of the structured mesh adopted for the presence of green hedges.

Figure 5 shows the air velocity distribution in the domain, with reference to the case of green hedges and an inlet wind velocity of 3 m/s.

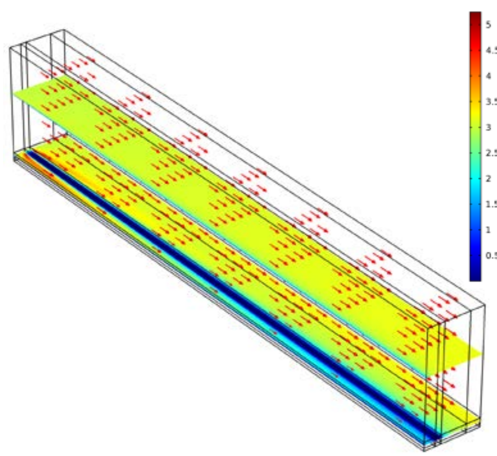

Figure 5. Detail of the structured mesh adopted for the presence of green hedges.

The main results are reported in Tables 2 and 3, with reference to U_{wind} = 0.5 m/s and U_{wind} = 3 m/s respectively.

Table 2. Results for U_{wind} = 0.5 m/s

	pollutant concentration [mol/m^3]		
U_{wind} = 0.5 m/s	clear canyon	green facade	green hedge
plane at 0.3 m from the ground	207.65	184.86	189.87
plane at 1 m from the ground	5.379	0.256	0.272
outlet section of the canyon	14.568	14.472	15.765
overall volume of the canyon	7.107	6.435	6.868

Table 3. Results for U_{wind} = 3 m/s

	pollutant concentration [mol/m³]		
U_{wind} = 3 m/s	clear canyon	green facade	green hedge
plane at 0.3 m from the ground	34.127	27.471	26.862
plane at 1 m from the ground	0.791	0.00489	0.00448
outlet section of the canyon	2.537	1.666	1.860
overall volume of the canyon	1.244	0.832	0.931

The tables show that the greenery has a positive effect in reducing the overall pollution within the urban canyon, which is greater as the wind speed is slower. This depends on the big influence of the convective transport of the pollutant rather than the transport due to diffusion. Moreover, the green façade seems to behave better than the green hedge, allowing a bigger reduction of the pollution.

4. Conclusions

A simplified numerical model that allows to evaluate the effect of greenery on the pollution reduction in urban canyons has been presented. The model takes advantages of the CFD capabilities of COMSOL Multiphysics 5.2 to account for the convection and diffusion processes of dispersion of the considered pollutant. The presence of greenery has been modelled by a porous medium where a given reaction of reduction of the pollutant takes place. The model has been designed to be a flexible tool to predict greenery effect. Indeed, by changing the values of the porosity ε and permeability κ of the porous medium and by tailoring the reduction reaction R, it allows different plant species to be modelled. To this aim, further investigations are foreseen, from both the numerical and the experimental standpoint.

5. References

1. Brook, R.D., Rajagopalan, S., Pope, C.A., Brook, J.R., Bhatnagar, A., Diez-Roux, A.V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M.A., Peters, A., Siscovick, D., Smith, S.C., Whitsel, L., Kaufman, J.D., American Heart Association Council on Epidemiology and Prevention, Council on the Kidney in Cardiovascular Disease, and Council on Nutrition, Physical Activity and Metabolism, 2010. Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circulation*, **121**, 2331–2378. doi:10.1161/CIR.0b013e3181dbece1

2. Dominici, F., Peng, R.D., Bell, M.L., Pham, L., McDermott, A., Zeger, S.L., Samet, J.M., Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. *JAMA*, **295**, 1127–1134 (2006)

3. Janhäll, S., Review on urban vegetation and particle air pollution – Deposition and dispersion. *Atmos. Environ.*, **105**, 130–137 (2015)

4. Kastner-Klein, P., Fedorovich, E., Rotach, M.W., A wind tunnel study of organised and turbulent air motions in urban street canyons. *J. Wind Eng. Ind. Aerodyn.*, **89**, 849–861 (2001)

5. Köhler, M., *Fassaden- und Dachbergrunung. Ulmer Fachbuch Landschafts- und Grunplanung*, Stuttgart.

6. Vos, P.E.J., Maiheu, B., Vankerkom, J., Janssen, S., Improving local air quality in cities: To tree or not to tree?, *Environ. Pollut.*, **183**, 113–122 (2013)