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CFD MODELLING OF THE IMPACT OF URBAN HEDGEROWS ON AIR QUALITY IN AN IDEALIZED STREET CANYON

Riccardo Buccolieri[1]*, Elisa Gatto*[1]*, Paolo Maria Congedo*[2]*, Cristina Baglivo*[2] *and Christof Gromke*[3]

[1]Dipartimento di Scienze e Tecnologie Biologiche ed Ambientali, University of Salento, Lecce, Italy
[2]Department of Engineering for Innovation, University of Salento, Lecce, Italy
[3]Institute for Hydromechanics, Karlsruhe Institute of Technology KIT, Karlsruhe, Germany

Abstract: This paper studies the effects of hedges on pollutant dispersion in an idealized street canyon of width-to-building height aspect ratio equal to 2. The dispersion of traffic pollutants is analysed by Computational Fluid Dynamics simulations and wind tunnel experiments. Various hedge configurations with a focus on height and permeability under several wind directions are investigated. Results show that (i) the higher the hedge the lower the turbulent Schmidt number Sc_t has to be to achieve agreement with wind tunnel data and (ii) higher hedges with large leaf area density are preferable to enhance positive and diminish negative effects.

Key words: *hedges; traffic pollutants, aerodynamic effects; CFD; wind tunnel.*

INTRODUCTION

The spatial distribution of pollutants in urban areas is determined by several factors, such as building geometry and city morphology, wind speed and direction, atmospheric stability, and the presence of obstacles such as low barriers, trees and parked cars (Abhijith et al., 2017; Blocken, 2013; Gallagher et al., 2015; Lateb, 2016, Gromke et al., 2008, Buccolieri et al., 2009). Here we study the effects of hedgerows on the traffic pollutant dispersion in an idealized street canyon by means of Computational Fluid Dynamics (CFD) simulations. CFD results are first validated with wind tunnel experiments (Gromke et al., 2016) where, under perpendicular and parallel winds, continuous hedgerows were found to effectively control concentrations of traffic pollutants in urban street canyons by leading to air quality improvements, especially in the most polluted central area. Then, CFD is employed to extend wind tunnel analysis to study the impact of different hedgerow heights under an oblique wind direction.

METHODOLOGY

Both wind tunnel experiments and 3D CFD simulations were carried out to analyse the role of various hedge configurations in affecting pollutant dispersion in an isolated street canyon. Wind tunnel experiments were performed by Gromke et al. (2016). The focus is on the height and porosity of a continuous hedgerow placed in the middle of the canyon under perpendicular (90°) and oblique (45°) wind directions.

Description of wind tunnel setup and measurements

The wind tunnel model (scale 1:150) consists of an isolated urban street canyon of length L = 180m, height H = 18m and street width W = 36m, i.e. the aspect ratios were W/H = 2 and L/H = 10 (Figure 1). Two sidewise hedgerows (not analysed here) and one central hedgerow (investigated here) of different permeabilities were placed on the street. A boundary layer flow was reproduced, with mean velocity profile exponent equal to 0.30 and turbulence intensity profile exponent equal to -0.36 according to power law formulations, with u_H = 4.65m/s the reference velocity at building height H. Four tracer gas emitting line sources (Figure 1a) were embedded at street level for simulating the release of traffic exhausts. Concentration measurement sampling taps were installed in the street canyon model at the bottom of the building walls and in the reduced traffic zones at pedestrian level (floor). The number of measurement points was 16 at each wall and 20 at each floor in the two halves of the street (Figure 1b). The samples were analysed by Electron Capture Detection (ECD) yielding mean concentrations and normalized according to:

$$c^{+} = \frac{c u_H H}{Q_l} \qquad (1)$$

with c the measured concentration and Q_l the source strength per unit length of the tracer gas emission.

To model hedges, porous open-cell foam materials were employed. Two types of porous open-cell foams were employed, with pore volume fractions of 96.1% and 94.5%. The foam materials were processed to hedge models presenting full-scale hedgerows of height either h_h = 1.50m or 2.25m and width w_h = 1.50m. The pressure loss coefficients λ were measured in a forced flow setup leading to 250m^{-1} (1.67m^{-1} at full scale) and 500m^{-1} (3.34m^{-1} at full scale) for the 96.1% and 94.5% pore volume fractions, respectively. For more comprehensive information on the wind tunnel experiments see Gromke et al. (2016).

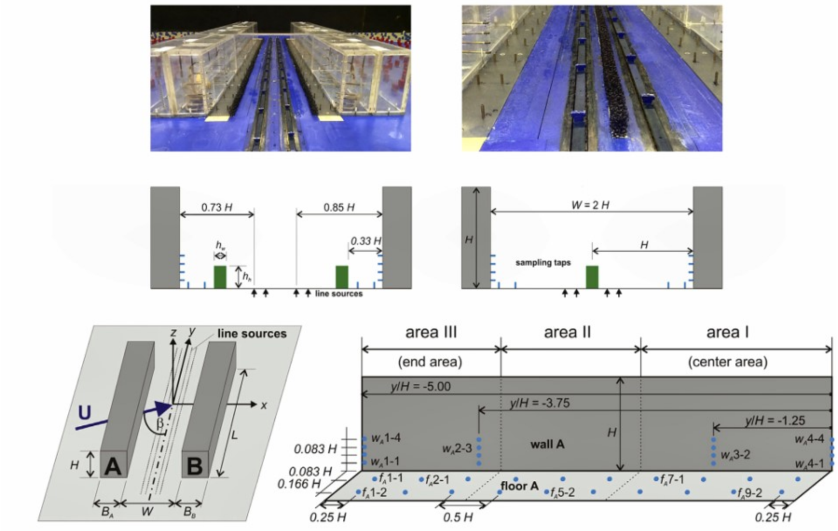

Figure 1. (a) Street canyon model: two sidewise hedgerows (left); one central hedgerow (right). (b) Positions of sampling taps at leeward Wall A and ground Floor A (analogous for Wall B and Floor B) (from Gromke et al, 2016©Elsevier, reprinted with permission of Elsevier)

Table 1 summarizes the cases investigated in the preset work.

Table 1. Summary of cases investigated (dimensions in full scale) by wind tunnel experiments and CFD simulations

	Hedge height h_h (m)			**Pressure loss coefficient λ (m^{-1})**			**Wind direction (°)**	
	1	**1.5**	**2.25**	**0 (ref.)**	**1.67**	**3.34**	**90 (perp.)**	**45 (oblique)**
WT	n	y	y	y	y	y	y	n
CFD	y							y

Note: n=no; y=yes; ref.=reference case (no hedges). Cases refer to the single continuous hedgerow of width w_h=1.50m placed in the middle of the street canyon (see Figure 1a, right).

CFD flow, dispersion and vegetation setup

3D simulations were performed by the CFD code FLUENT. The computational domain was built using hexahedral elements with a finer resolution close to the ground and in those regions with large flow field gradients. Several tests were performed to verify the grid size independence. The final number of the cells used was about 1,500,000, with dimensions $\delta_{x,min} = \delta_{y,min} = 0.05H$ and $\delta_{z,min} = 0.03H$ in the street canyon and an expansion ratio lower than 1.3 outside the canyon. The distance of the inlet plane to the first building and of the top of the domain to the building roof was 8H, the distance of the outflow plane to the downstream building was 20H, which fulfil the COST Action 732 recommendations.

The standard k-ε model was used. The inlet wind speed followed a power law profile with a profile exponent α = 0.30 as in the wind tunnel experiments. Turbulent kinetic energy (TKE) and dissipation rate (ε) profiles were specified as in Gromke et al. (2008) and Buccolieri et al. (2009). Symmetry boundary conditions were specified at the top (to enforce a parallel flow) and lateral sides of the computational domain. At the boundary downwind of the buildings, a pressure-outlet boundary condition was used. Second order upwind discretization schemes were used for pressure, momentum, k and ε to increase the accuracy and reduce the numerical diffusion. The SIMPLE scheme was used for the pressure-velocity coupling. For dispersion calculations, the advection diffusion module was used. The emission rate Q was set at 1gs^{-1}. Values of the turbulent Schmidt number Sc_t equal to 0.3, 0.5 and 0.7 were applied and its influence studied. The residual for the continuity equation reached approximately 1e-05, residuals for velocity components, k, ε and scalar were always below 1e-06.

The vegetation was modelled by adding a momentum sink term to the standard fluid flow equations in terms of leaf area density (LAD, m^2m^{-3}) as follows:

$$S_i = -LADc_d U u_i \tag{2}$$

where u_i is the wind velocity component, U is the wind speed and $c_d = 0.2$ is the drag coefficient for vegetation (dimensionless). This is the same approach of the porous media using $\lambda = LADc_d$.

RESULTS

Perpendicular wind direction (90°)

Model performance was first assessed using several standard metrics: mean, maximum, standard deviation (sigma), NMSE, FAC2 and FB (Table 2).

Table 2. Statistical analysis CFD *vs* wind tunnel (WT/CFD), perpendicular wind direction (90°)

λ (m^{-1})	h_h (m)		Mean	Max	Sigma	NMSE	FAC2	FB
0 (ref.)		W-A	12.43/12.03	24.03/22.59	6.26/5.96	0.06	0.93	0.03
		W-B	1.67/5.99	5.42/13.72	1.72/5.24	3.31	0	-1.13
		F-A	16.09/16.57	29.83/37.09	5.73/7.18	0.12	0.97	-0.03
		F-B	1.52/5.51	4.94/14.80	1.65/5.05	3.36	0	-1.14
1.67	1	W-A	-/10.15	-/20.21	-/5.89	-	-	-
		W-B	-/5.03	-/11.65	-/3.95	-	-	-
		F-A	-/12.76	-/24.65	-/4.86	-	-	-
		F-B	-/4.25	-/12.02	-/3.77	-	-	-
	1.5	W-A	9.06/7.99	13.88/16.23	3.10/4.83	0.2	0.75	0.13
		W-B	1.29/3.40	3.35/6.47	1.06/1.94	1.33	0.21	-0.90
		F-A	9.95/9.72	16.13/17.72	2.76/3.93	0.23	0.87	0.02
		F-B	1.03/3.17	2.70/6.69	0.85/1.79	2.39	0.25	-1.02
	2.25	W-A	8.70/8.60	11.81/17.22	2.53/5.01	0.29	0.71	0.01
		W-B	1.03/3.23	2.69/5.76	0.80/1.62	1.74	0	-1.03
		F-A	9.30/ 10.29	12.99/18.52	2.12/4.02	0.23	0.85	-0.10
		F-B	0.50/3.07	2.19/5.95	0.71/1.47	5.67	0.1	-1.44
3.34	1	W-A	-/10.20	-/20.34	-/5.88	-	-	-
		W-B	-/4.94	-/11.40	-/3.83	-	-	-
		F-A	-/12.71	-/23.74	-/4.71	-	-	-
		F-B	-/4.18	-/11.70	-/3.64	-	-	-
	1.5	W-A	7.77/8.04	10.95/16.27	2.56/4.82	0.29	0.64	-0.03
		W-B	1.01/3.37	2.84/6.33	0.84/1.87	2.08	0	-1.08
		F-A	8.33/9.74	12.50/17.47	2.24/3.88	0.27	0.82	-0.15
		F-B	0.76/3.15	2.04/6.54	0.63/1.73	3.61	0.15	-1.22
	2.25	W-A	7.44/ 8.66	11.07/17.22	2.56/4.97	0.36	0.64	-0.15
		W-B	0.80/3.21	1.90/5.67	0.60/1.54	2.71	0	-1.2
		F-A	8.25/10.30	13.06/18.29	2.07/3.93	0.28	0.82	-0.22
		F-B	0.70/3.08	1.76/5.78	0.53/1.39	3.46	0.15	-1.25

Note: Sc_t=0.7 for reference case, Sc_t=0.5 for h_h=1m and Sc_t=0.3 for the other cases; - stands for no wind tunnel data. W-A, W-B, F-A and F-B stands for Wall A, Wall B, Floor A and Floor B, respectively

According to COST Action 732, recommended criteria are: NMSE≤1.5; FAC2≥0.5; -0.3≤FB≤0.3. Please note that results refer to Sc_t=0.7 for reference case, Sc_t=0.5 for h_h=1m and Sc_t=0.3 for the other cases, since they provided better results when compared against wind tunnel data. A satisfactory model performance in terms of mean and maximum concentrations at the leeward side (Wall A and Floor A) was obtained, while at the windward side (Wall B and Floor B) the model over-predicted concentrations.

Figure 2 shows the percentage differences $\Delta C^{+}_{rel,mean} = {C_{hedge} - C_{ref}} / {C_{ref}} \times 100$ for all the cases investigated, where C_{hedge} is the mean concentration for a hedge case and C_{ref} the mean concentration for the reference case, i.e. the street canyon without hedge. Results show that:

- the percentage differences were quantitatively well predicted by the model at both walls and floors;
- higher hedges require lower values of Sc_t, because the higher the hedge, the more the flow field is disturbed compared to the reference case;
- the positive impact of hedges increases with increasing (i) hedge height from h_h=1m to h_h=1.50m, with no substantial difference with h_h=2.25m; and (ii) λ (or LAD), i.e. decreasing hedge porosity / permeability.

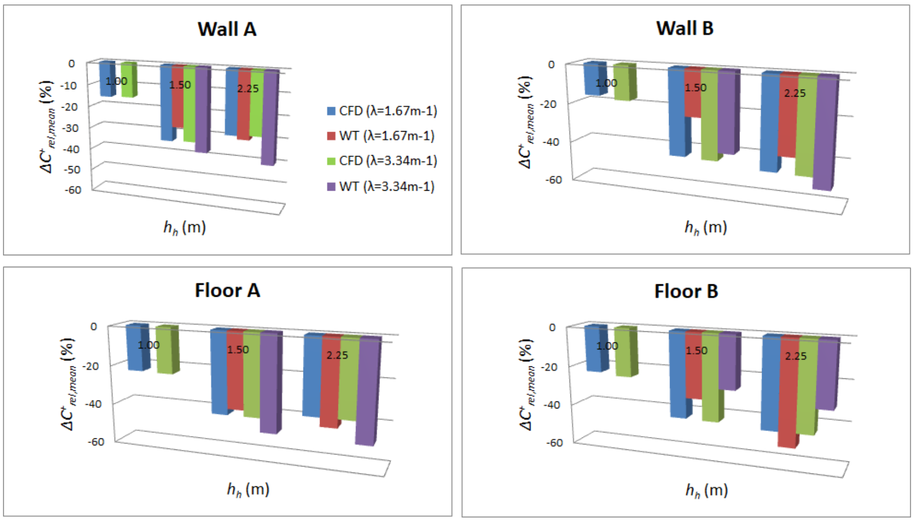

Figure 2. Percentage differences in mean concentrations for street canyons with hedges referred to the reference case, perpendicular wind direction (90°)

Oblique wind direction (45°)

Based on the validation performed for the perpendicular case, we employed the same Sc_t values (0.7 for the reference case, 0.5 for the h_h=1m and 0.3 for the other hedge cases) for oblique approach wind directions. Compared to perpendicular wind, mean concentrations are lower in the oblique wind direction wind case. In particular, both in the reference and hedge cases, they are 30-40% lower at the leeward side and 70-80% lower at the windward side, suggesting that the percentage reduction under oblique wind, with respect to the perpendicular wind, is independent of the presence of hedges and their height.

Figure 3 shows the percentage differences $\Delta C^{+}_{rel,mean}$. Results suggest that:

- similar to the perpendicular wind direction case, at the leeward side the positive impact of hedges increases with increasing height and porosity / permeability of the hedges;
- at the windward side, the impact of hedges turns to be adverse, with percentage increases up to about 20%. This negative impact (i) increases with increasing hedges height from h_h=1m to h_h=1.50m and 2.25m, due to the increased disturbance compared to the reference case; and (ii) decreases with increasing λ (or LAD), i.e. decreasing hedge porosity/permeability. Overall, concentrations at the windward side are much lower than those at the leeward side, and thus an overall decrease in concentrations occurs in the street canyon.

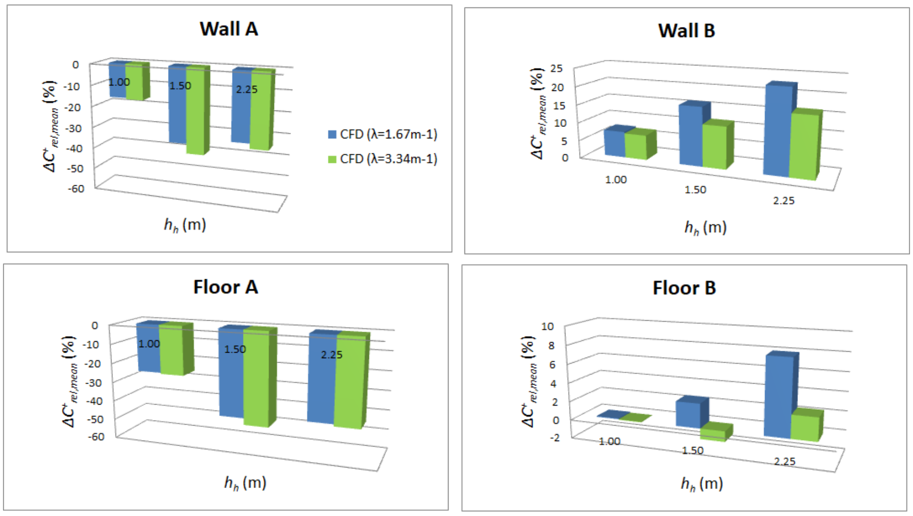

Figure 3. Percentage differences in mean concentrations for street canyons with hedges referred to the reference case, oblique wind direction (45°)

CONCLUSIONS

The investigation carried out in this work allowed to:

- set-up a CFD modelling methodology, based on the *k-ε* turbulence closure, for the study of the aerodynamic effects of hedgerows in street canyons. Results showed that higher hedges require lower values of the turbulent Schmidt number Sc_t;
- show the effects under perpendicular and oblique wind directions and different hedge heights. Results show that it is desirable to plant hedges up to a pedestrian height (about 2m) with a large leaf area density, which enhance positive effects and diminish the negative impact at the windward side under the oblique wind direction. Overall, the negative impact under oblique wind is less strong than the positive effect, suggesting that hedgerows can be used for overall improving air quality in street canyons.

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