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STUDY OF TREE-ATMOSPHERE INTERACTION AND ASSESSMENT OF AIR QUALITY IN REAL CITY NEIGHBOURHOODS

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Abstract: This paper is devoted to the study of the aerodynamic effects of trees on airflow and pollutant dispersion in urban street canyons. The dispersion of traffic-released pollutants in street canyons lined with trees is analysed by means of both wind tunnel experiments and Computational Fluid Dynamics simulations. Different tree planting and street canyon configurations are considered with a focus on the variation in the tree stand density and their implications on pollutant concentrations for several wind directions and aspect ratios. The concepts discussed in the paper can also be applied in practice. For example, we employ a similar methodology to investigate a complex urban site in Bari (Italy) where situations with and without trees are examined and numerical results are compared to field monitored data. The analysis of the results shows the crucial role of trees in dispersion modelling of urban areas.

Key words: *street canyon, urban road junction, tree planting effects, measurements and CFD simulations.*

INTRODUCTION

Air quality is a major concern for people living in urban areas. Vegetation has a significant influence on the urban environmental quality and outdoor thermal comfort owing to its evapo-transpiration and shading effects, and its role in pollutants' filtration in towns. Although particle deposition on plant surfaces removes particles from the air and therefore reduces the pollutant concentration, it must also be noted that plants (e.g. trees) themselves represent obstacles to airflow which can reduce airflow compared with tree-free areas and therefore increase pollutant concentration (Litschke, T. and W. Kuttler, 2008). One of the most extensive studies on the aerodynamic effects of trees in street canyons is the wind tunnel experiment carried out at the University of Karlsruhe/Karlsruhe Institute of Technology (CODASC Database, 2008). The database contains concentration measurement data of street canyons of different aspect ratios with avenue-like tree planting. Recently, a number of Computational Fluid Dynamics (CFD) studies, simulating parts of the CODASC wind tunnel studies, have been carried out to investigate aerodynamic effects of tree planting on pollutant concentration in urban street canyons (see e.g. Gromke, C. *et al.*, 2008; Balczó, M. *et al.*, 2009; Buccolieri, R. *et al.*, 2009). The influence of tree planting on the airflow and concentration fields when compared to the tree-free street canyon - i.e. the relative changes - were similar in the wind tunnel investigations and numerical simulations.

In this paper we focus on two main objectives. First we extend our previous findings following the procedure set up in Gromke, C. *et al.* (2008) and Buccolieri, R. *et al.* (2009) where street canyons of aspect ratios W/H = 1 and 2 have been investigated for perpendicular approaching flow. FLUENT (2006) simulations are performed to investigate the aerodynamic effects of trees of different stand densities in a street canyon of aspect ratio W/H = 2 for an approaching wind inclined by 45° to the street axis. Numerical results are compared with wind tunnel data available from the CODASC Database. The aim is to evaluate the combined effects of wind directions, aspect ratios and tree planting configurations on pollutant concentration in street canyons. Furthermore, we investigate the effects of trees within a complex urban streets junction in Bari (Italy). Numerical results are then compared to monitored data available from the "Sistema Integrato per il Monitoraggio del Particolato Atmosferico" (SIMPA), a project funded by Apulia Region (Italy).

DESCRIPTION OF WIND TUNNEL AND MONITORING FIELD EXPERIMENTS

Idealized scenario: isolated street canyon

Wind tunnel experiments used in this study refer to the isolated street canyon cases investigated at the University of Karlsruhe/Karlsruhe Institute of Technology (CODASC Database, 2008). A boundary layer flow with mean velocity profile exponent $\alpha = 0.30$ according to the power law formulation was reproduced as follows:

$$\frac{u(z)}{u_H} = \left(\frac{z}{H}\right)^{\alpha} \tag{1}$$

where $u_H = 4.7\text{ms}^{-1}$ is the wind velocity at building height H. For more information on the simulated atmospheric boundary layer flow the readers are referred to Gromke, C. and B. Ruck (2005). The street canyon model (scale 1:150) consists of two parallel aligned rows of buildings forming an isolated urban street canyon of length L = 180m, height H = 18m and street width W = 36m. The approaching flow is inclined by 45° to the street axis in this study.

Tree models with a pore volume fraction P_{Vol} = 96% were placed along the street canyon as shown in Figure 1a,b,c. Avenue-like plantings were characterized by high and low stand densities, i.e. with interfering neighbouring tree crowns and with trees separated by 0.32H in between (Figure 1c), respectively. The height of the branch free trunk is 1/3H (6m) in all cases. In order to describe the aerodynamic characteristics of the tree models, the pressure loss coefficient λ (m^{-1}) was determined according to:

$$\lambda = \frac{\Delta p_{stat}}{p_{dyn}\ d} = \frac{p_{windward} - p_{leeward}}{(1/2)\ \rho u^2 d} \tag{2}$$

with Δp_{stat} the difference in static pressure windward and leeward of the porous obstacle in forced convection conditions, p_{dyn} the dynamic pressure, u the mean stream velocity and d the porous obstacle thickness in streamwise direction. Measurements resulted in pressure loss coefficients of λ = 200m^{-1}. For further details see Gromke, C. and B. Ruck (2009). Sulfur hexafluoride (SF_6) was used as tracer gas to model ground level traffic emissions (Figure 1b). Measurements were carried out along the leeward and windward oriented canyon walls (wall A and wall B, respectively).

Real scenario: streets junction in a complex urban geometry

To complement the numerical and wind tunnel investigations of the flow and pollutant dispersion within an 'idealized' street canyon, the present work is extended to cover a real complex urban street junction in Bari (southern Italy) (Figure 1d). The geometric configuration consists of two asymmetric streets as shown in Figure 1d. The first one is located along the North-South direction (called NS henceforth) and is characterized by an average aspect ratio W/H ~ 1.8. The other one is along the West-East direction (called WE henceforth) and is characterized by an average aspect ratio W/H ~ 0.5. The two canyons intersect orthogonally, forming four major blocks of buildings and a junction. This geometry may be regarded as a kind of "repetition unit", i.e. representative of the urban texture of a larger portion of the city. Main geometry details were taken from digital files available from the website http://territorio.comune.bari.it:8008/Download.html (Comune di Bari - Assessorato all' Urbanistica). The area is characterised by evergreen avenue-like trees (*Quercus ilex* L.) with interfering neighbouring tree crowns. The height of the branch free trunk layer is 3m and the crown extends to 6m. As in the previous case, tree crowns are assumed to have the same pore volume fractions of P_{Vol} = 96%.

PM_{10} concentration data were collected from the monitoring devices placed close to the junction at the height of about 3m (red point in Figure 1d). Daily samplings of PM_{10} were performed during several months in the period 2006-2008 and analysed by Amodio, M. *et al.* (2009). For the purpose of the present study, we avoided investigating pollutant concentrations during summer months as increased concentrations were found not to be dependent on the local sources attributable to human activities. Therefore, we performed an analysis of meteorological data retrieved from the nearest station placed at the Bari airport (www.wunderground.com). The analysis showed a strong fluctuation of wind directions and temperature for most of the days. These meteorological data were then used in CFD simulations as boundary conditions in order to explain monitored PM_{10} concentrations.

As an example, we have chosen to analyse two wind directions, i.e. from the West and South (which will be called West case and South case, respectively). We investigated the 23th of March 2006, which was characterized by a wind direction from the West over most of the day (with an average wind speed U_{west} equal to 4.2ms^{-1} at 10m with an average temperature equal to 10°C) and the 10th of March 2006 characterized by a main wind direction from the South with an average wind speed U_{south} equal to 3.1ms^{-1} at 10m with an average temperature of 12°C. These sample dates were preferred as they are characterized by relatively similar strong winds and low temperatures, so we expect the buoyancy effects not to adversely affect the mean daily concentrations for both the West and the South cases.

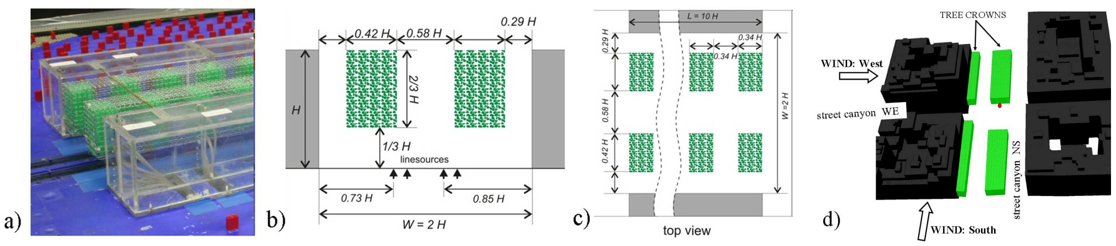

Figure 1. a) Street canyon with trees of low stand density. b) Street canyon cross-section and line sources position. c) Top view of street canyon with trees of low stand density (CODASC, 2008). d) Junction in Bari and monitoring station position (red point).

DESCRIPTION OF CFD SIMULATIONS

Idealized scenario: isolated street canyon

3D steady-state simulations were performed by means of the CFD code FLUENT. Generally we implemented main recommendations as provided in the COST Action 732 (2005-2009). The computational domain was built using about one million hexahedral elements. The smallest dimensions of the elements were δxmin = 0.04H, δymin = 0.2H, δzmin = 0.04H within the street canyon volume (as employed in Buccolieri, R. *et al.*, 2009), with an expansion ratio lower than 1.3 outside the canyon. The Reynolds Stress Model (Launder, B. E *et al.*, 1975) was used. The inlet wind speed was generated to follow a power law profile as in the wind tunnel experiments. Turbulent kinetic energy and dissipation rate profiles were specified as follows:

$$k = \frac{u_*^{\,2}}{\sqrt{C_\mu}}(1 - \frac{z}{\delta}),\ \varepsilon = \frac{u_*^{\,3}}{\kappa z}(1 - \frac{z}{\delta}) \tag{3}$$

where δ is the boundary layer depth, $u_* = 0.52\text{ms}^{-1}$ the friction velocity, κ the von Kàrmàn constant (0.40) and $C_\mu = 0.09$. Symmetry boundary conditions were specified on the top and lateral sides of the computational domain. At the boundary downwind of the street canyon, an outflow boundary condition was used to enable a fully developed flow. For dispersion, the advection diffusion module was used with a turbulent Schmidt number $Sc_t = 0.7$.

Tree crowns were modelled employing the FLUENT porous media model by assigning the pressure loss coefficient λ of the wind tunnel trees to those cells occupied by the crown. In essence, the porous media model is nothing more than an added momentum sink in the governing momentum equations. For details see Buccolieri, R. *et al.* (2009).

Real scenario: streets junction in a complex urban geometry

Principally, the fluctuation of the wind, the buoyancy effects, the presence of background concentrations and other variables limit the comparison between monitored and simulated data to a rather qualitative analysis of the concentrations at the monitoring positions since in the CFD simulations the wind speed is assumed constant, and neither the background concentrations nor the buoyancy effects are considered. The number of the computational cells was about three and a half million with cell dimensions δxmin = δymin = 1m, δzmin = 0.3m till a height of 4m (with an expansion ratio lower than 1.3 outside). Simulations were performed using a computational domain whose dimension are similar to those used in the wind tunnel street canyon case. The inlet wind speed was assumed to follow a logarithmic law profile as follows:

$$U = \frac{u_*}{\kappa} ln\left(\frac{z + z_0}{z_0}\right) \tag{4}$$

where $z_0 = 0.1\text{m}$ is the aerodynamic roughness length and the friction velocity u_* is 0.36ms^{-1} for the West case and 0.27ms^{-1} for the South case (derived from log-law curve fitting). Turbulent kinetic energy and dissipation rate profiles were specified as in equation 3, with δ = 368m. Six ground level sources (which correspond to six roadways) were modelled. SF_6 was used to model traffic emissions, even though PM_{10} had been monitored. There is no reason to expect PM_{10} to be different from gases, so we do not expect influence due to this choice. Based on a preliminary investigation of traffic data, we assumed the same emission rate at each source, which as an example was taken equal to 10gs^{-1}. Evergreen trees were modelled by using $\lambda = 200\text{m}^{-1}$. Scenarios with and without trees were considered.

RESULTS

Idealized scenario: isolated street canyon

Tree-free street canyon. Figure 2a shows contours of normalized concentrations at both walls. Mean concentrations are normalized as in Buccolieri, R. *et al.* (2009). Pollutant concentration increases from the centre to the street end (0 < y/H < 5) at both walls are found. Moreover, larger values are found close to downstream end of the street canyon (y/H = 5). In the wind tunnel experiments, at the beginning of wall A (-5 < y/H < -4) larger pollutant concentrations are observed. This phenomenon is very slightly reflected in the CFD simulations. Overall CFD concentrations are qualitatively similar to those obtained in the wind tunnel, even though there is some underestimation of the measured concentrations at wall A (the relative difference is about 30% on average).

A different concentration pattern is present in comparison to the perpendicular approaching flow case discussed in Gromke, C. *et al.* (2008) and Buccolieri, R. *et al.* (2009). In the present case, concentration contours suggest that the flow regime dominated by a canyon vortex and corner eddies does not occur anymore. Figure 2b shows vectors of normalized velocity magnitude U/U_H at two horizontal planes z/H = 0.5 and 0.9. The lower concentrations at both walls at the upstream entry between -4 < y/H < -3 of the street canyon are due to enhanced ventilation caused by the helical vortex as a consequence of the superposition of the canyon vortex and the corner eddy. The increasing pollutant concentrations towards the downstream end of the street clearly indicate that the flow along the street axis becomes a dominant pollutant transport mechanism.

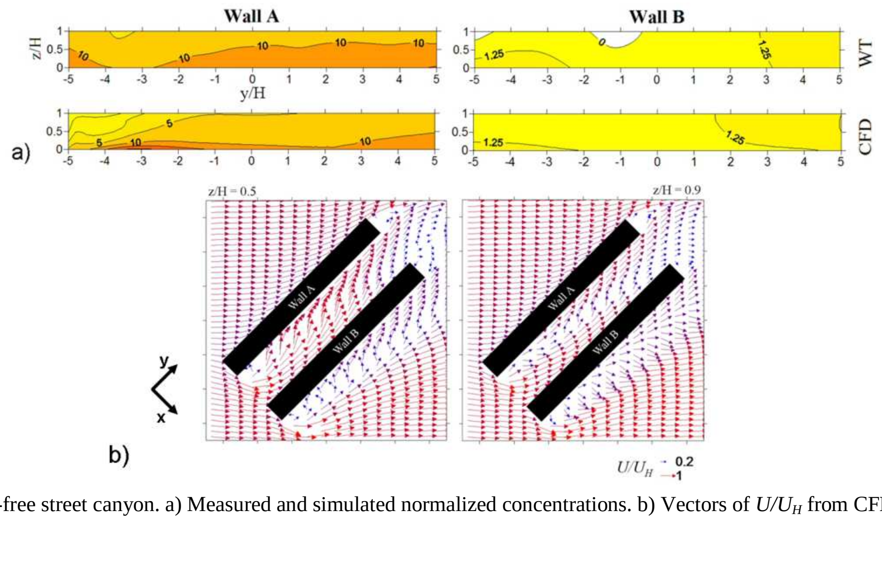

Figure 2. Tree-free street canyon. a) Measured and simulated normalized concentrations. b) Vectors of U/U_H from CFD simulations.

Street canyon with tree planting of high stand density. Both measurements and simulations show increases in concentrations at wall A as shown in Figure 3. Considerable concentration increases are also observed at the windward oriented canyon wall B. Overall FLUENT concentrations are similar to those obtained in the wind tunnel, even if there is an underestimation of the measured concentrations at wall A, especially close to the upstream entry. In this case, concentration patterns are due to the predominant parallel flow component. At the upstream entry of wall A the corner eddy found in the tree-free case does not occur anymore, due to the presence of trees. The helical flow vortex is also broken and, as a consequence, a wind flowing parallel to the walls is prevailing. Wind velocities are slower than those found in the previous case. As a result, the pollutant concentrations entrapped within the canyon are larger.

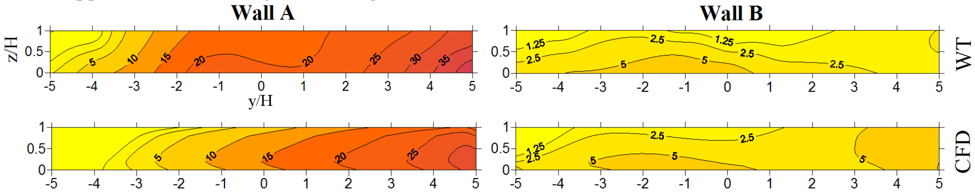

Figure 3. Street canyon with tree planting of high stand density. Measured and simulated normalized concentrations.

Street canyon with tree planting of low stand density. Qualitatively both wind tunnel experiments and numerical simulations predict a similar increase at the walls in respect to the tree-free case. The pattern of pollutant concentration distribution generally remains unchanged with respect to the high stand density case.

Sensitivity to the wind direction and aspect ratio. In all the cases considered, both experiment and numerical results show that tree planting lead to a large increase in pollutant concentrations at both the leeward and windward walls of the street canyon when compared to the tree-free case.

For the tree-free W/H = 2 street canyon, the overall level of pollutant concentrations is approximately 2 times larger in the perpendicular approaching wind case (Buccolieri, R. *et al.*, 2009) than in the 45° inclined flow due to less ventilation, reduced dispersion and dilution. Furthermore, the relative increase in concentration due to tree planting is larger in the 45° inclined case. This is a result of the accumulation of traffic exhaust along the street axis by the predominant parallel flow component and is directly related to the street canyon length. This result shows that that concentration fields depend crucially on the approaching wind direction rather than on tree planting arrangement. Finally, Table 1 shows that for the perpendicular approaching wind (Gromke, C. *et al.*, 2008; Gromke, C. and B. Ruck, 2009a; Buccolieri, R. *et al.*, 2009) the relative increase in concentration due to tree planting is larger for W/H = 1 case, while for the 45° inclined flow the increase due to tree planting is larger for W/H = 2 case.

Table 2. Effects of aspect ratio and wind direction on overall (at both walls) concentration relative increases due to tree planting.

		Perpendicular		45° inclined	
		W/H = 1	W/H = 2	W/H = 1	W/H = 2
Tree (high stand density) vs tree-free	WT	+48%	+23%	+65%	+99%
	CFD		+24%		+101%

Real scenario: streets junction in a complex urban geometry

In this section we discuss the influence of trees on flow and pollutant dispersion within the complex urban streets junction in Bari for two approaching wind directions (i.e. West and South). In order to compare CFD results with monitored data, we calculated the concentration ratio as follows:

$$\frac{C_{west}\times U_{west}}{C_{south}\times U_{south}} \tag{5}$$

where C_{west} and C_{south} are the concentrations in the West case and South case, respectively. Overall, the monitoring station gives a mean daily concentration ratio ranging from ~ 1.5 to ~ 2.2 during winter/spring time in 2005/2006. In particular, the monitoring station measured a mean daily concentration of 27μgm^{-3} for the West case and 25μgm^{-3} for the South case, giving a concentration ratio of ~ 1.5. CFD was successful in predicting a larger concentration (*CxU*) at the monitoring position for the West case similar to the field measurements, providing a ratio of ~ 1.1. The quantitative difference could be obviously due to the fact that only the aerodynamic effects of trees has been considered in CFD simulations.

We also performed a new set of CFD simulations without trees. We found an overall concentration decrease in both the tree-free cases. Furthermore simulations without trees resulted in an opposite trend with respect to the case with trees, where the West/South ratio at the monitoring position reduced to ~ 0.3. This clearly shows that it was crucial to model the effect of trees on pollutant dispersion to obtain numerical results in agreement with field observations.

CONCLUSIONS

Overall, this study confirms previous findings that the in-canyon air quality is significantly altered by avenue-like tree planting, with an increase at both the leeward and windward walls when the approaching wind is inclined by 45° to the street axis. The street canyon aspect ratio and the approaching wind direction were found to be the most essential parameters influencing the pollutant accumulation at pedestrian level. Specifically, for W/H = 1 the effect of trees on pedestrian level concentration was larger when the wind direction is perpendicular to the street axis, while for W/H = 2 the effect was larger for a 45° inclined wind. The methodology used in the present work was then applied to evaluate the traffic-released pollutant concentrations within a complex urban streets junction in Bari (Italy) characterised by several rows of trees. Comparison of the numerical simulations of a case without trees gave evidence that trees did indeed lead to an overall increase of concentration levels. The analysis also suggests that neglecting the effect of trees in CFD simulations can lead to a poor agreement between field and numerical results.

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