EVALUATION OF NUMERICAL FLOW AND DISPERSION SIMULATIONS FOR STREET CANYONS WITH AVENUE-LIKE TREE PLANTING BY COMPARISON WITH WIND TUNNEL DATA

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Abstract: Flow and traffic-originated pollutant dispersion in an urban street canyon with avenue-like tree planting have been studied by means of wind tunnel and CFD investigations. The study comprises tree planting of different crown porosity, planted in two rows within a canyon of street width to building height ratio $W/H = 2$ and street length to building height ratio $L/H = 10$ exposed to a perpendicular approaching boundary layer flow. Numerical simulations have been performed with the commercial CFD code FLUENT™ by employing the RSM turbulence model. In the presence of tree planting, both measurements and simulations show considerable larger pollutant concentrations in proximity of the leeward wall and slightly lower concentrations in proximity of the windward wall in comparison to the tree-less street canyon. In particular, FLUENT slightly underestimated pollutant concentrations in proximity of the leeward wall in all cases studied, while near the windward wall there is no general tendency towards underestimation or overestimation. Overall, numerical computations compare qualitatively well with experimental data. Results from commonly used statistical tests also suggest the CFD predictions to be satisfactory. Results obtained in this work by combining wind tunnel experiments and CFD based simulations in a novel aspect of research suggest ways to obtain quantitative information for planning and implementation of exposure mitigation using trees in urban street canyons.

Key words: *street canyon, tree planting, pollutant dispersion, wind tunnel, CFD.*

1. INTRODUCTION

Traffic emissions commonly constitute the major source for air pollution in cities and have large impact on the health of city population. In dense built-up areas, air exchange between the street level and the atmospheric wind above the roof level is limited. Near ground traffic-released emissions remain at street level, resulting in large pollutant concentrations. Especially in urban street canyons, critical situation can arise. In addition, avenue-like tree planting in urban street canyons evidently affect pollutant dispersion and exchange processes as they occupy considerable canyon fractions. So far, a large number of air quality studies in street canyons and urban areas has been performed. However, the impact of trees in street canyons on pollutant dispersion has not been widely considered. Urban street canyons with tree plantings have been addressed only in a few studies (Gross, 1987; Ries and Eichhorn, 2001). Recently, Gromke and Ruck (2007) and Gromke and Ruck (in press) investigated experimentally the impact of tree planting in wind tunnel studies. They reported moderate to strong increases in pollutant concentrations at the leeward wall and slight decreases at the windward wall in comparison to the tree-free configuration due to modification of air exchange and entrainment conditions inside the canyon.

In this paper, the influence of trees on pollutant dispersion from a ground level line source within an isolated street canyon is analyzed by means of wind tunnel and numerical investigations. A new set of experimental data were obtained from boundary layer wind tunnel experiments at an isolated street canyon model of aspect ratio $W/H = 2$ in presence of model trees with permeable crowns. The focus is that of analysing the effect on concentration due to different tree configuration and crown porosity. Numerical simulations were performed by using the commercial CFD code FLUENT™ V6.2 (FLUENT, 2005) by employing the RSM turbulence model and the advection-diffusion method. Results were also compared with experimental data.

The overall goal of the paper is that of identifying a strategy for supporting wind tunnel measurements by using a commercial CFD code such as FLUENT that could be applied to study dispersion in street canyon with tree planting to obtain useful suggestions for exposure mitigation in urban areas.

2. METHODOLOGY

Description of wind tunnel setup and measurements

The wind tunnel model (scale 1:150) consists of two parallel aligned rows of houses forming an isolated urban street canyon of full scale length $L = 180$ m, height $H = 18$ m and street width $W = 36$ m (Fig. 1). Tree models of different crown porosities have been placed in two rows along the street length axis. A boundary layer flow with mean velocity profile exponent $\alpha = 0.30$ according to the power law was reproduced, approaching perpendicular to the street axis (Gromke, C. and B. Ruck, 2005). The Reynolds number Re, calculated by using the building height H and the velocity u_H of the undisturbed flow at building height H, is equal to 37,000 and ensures a Reynolds number independent flow field.

A tracer gas emitting line source is embedded at street level for simulating the release of traffic exhausts (Meroney et al., 1996). Sulfur hexafluoride (SF_6) was used as tracer gas to model the traffic emissions. Measurement taps were applied along the leeward and windward canyon wall (wall A and wall B, respectively) to sample the near-façade canyon air. The samples were analyzed by Electron Capture Detection (ECD) yielding mean concentrations and normalized according to

$$c^{+} = \frac{c\, u_H\, H}{Q_T / l} \tag{1}$$

with c the measured concentration and Q_T/l tracer gas source strength per unit length of the line source.

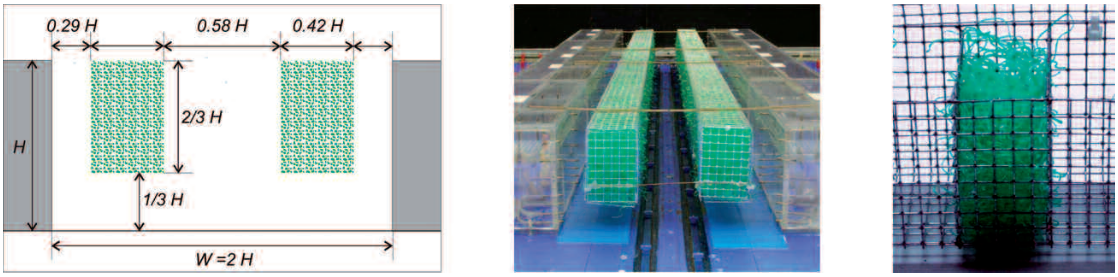

Figure 1. Street canyon configuration and close-up of tree model.

The modelling of porous tree crowns was realized using custom-made lattice cages (Fig. 1) forming cubes with cross-sections of 0.42 H width and 0.67 H height. These lattice cages were aligned symmetrically along the street axis with the top edge facing the roof level. Spanning the street canyon of length L, the cage was divided into 31 cells, each of 0.32 H depth. A filament/fibre-like synthetic wadding material was used to fill the cells, whose purpose was to facilitate a uniform distribution of the wadding material throughout the entire length of the lattice cage. Different crown porosities were realised by filling all the cells homogeneously with defined masses of wadding material. Pore volume fractions of P_{Vol} = 97.5% (loosely filled) and P_{Vol} = 96% (densely filled), typical for crown porosities of deciduous trees were modelled (Gross, 1987; Zhou et al. 2002). In this way, avenue-like planting of high stand densities with interfering neighbouring tree crowns were modelled.

In order to describe the aerodynamic characteristics of the realized tree model which is determined by crown porosity, internal crown structure and surface properties of the wadding material, the pressure loss coefficient λ [m^{-1}] was determined in forced convection conditions, 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 length. Measurements resulted in pressure loss coefficients of λ = 80 m^{-1} and λ = 200 m^{-1} for the loosely (P_{Vol} = 97.5%) and densely (P_{Vol} = 96%) filled model crown, respectively.

Description and setup of FLUENT flow and dispersion model

Simulations were carried out by considering a neutral boundary layer. The computational domain was built using hexahedral elements with a finer resolution close to the ground and in those regions with large gradients. Several tests were performed to verify grid size independence with increasing mesh cells until further refinements gave no significant improvements. The final number of the computational cells used for all simulations is about 400,000. The Reynolds Stress Model (RSM) was used (Launder, 1989). Based on wind tunnel experiments, the inlet wind speed was assumed to follow a power law profile with a profile exponent α = 0.30. Turbulent kinetic energy and dissipation rate profiles were specified as follows

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

where δ is the boundary layer depth, u_* = 0.52 m/s is the friction velocity, κ the von Kàrmàn constant (0.4) and C_μ= 0.09. The remaining boundary conditions are those used in Di Sabatino et al. (2007).

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

$$J = -\left(\rho D + \frac{\mu_t}{Sc_t}\right)\nabla Y \tag{4}$$

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. $Sc_t = \mu_t/(D_t)$ is the turbulent Schmidt number and D_t the turbulent diffusivity. The FLUENT default setting Sc_t = 0.7 was used for dispersion simulations.

Tree crowns were modelled employing the FLUENT porous media conditions by assigning the pressure loss coefficient λ to those cells occupied by the crown. Porous media are modelled by adding a momentum source term to the standard fluid flow equations. The source term is composed of two parts: a viscous loss term and an inertial loss term. FLUENT solves the standard conservation equations for turbulence quantities in the porous medium, by treating turbulence in the medium as though the solid medium has no effect on the turbulence generation or dissipation rates.

3. RESULTS

Reference case: Tree-free street canyon

In a first step, concentration patterns in a tree-free street canyon are investigated. In Figure 2 (left), two characteristic features can be seen in the concentration at the canyon walls. The first feature is that in proximity of the leeward wall A larger pollutant charges than at the windward wall B are evident and the second one is that a steadily concentration decrease towards the street ends at both walls is also clearly observed.

As wind velocity measurements are not available, data are interpreted using flow fields obtained from numerical simulations. In particular, the first feature can be understood by the dominating vortex-like structure around the street canyon centre. At the roof level, air of the atmospheric flow is entrained into the canyon and moves downwards in front of the windward wall. The flow at street level is directed reverse to the atmospheric flow and accumulates near-ground released traffic emissions. These are transported towards the leeward wall before the flow moves up and is mixed into the above roof flow. Here, an exchange between polluted street canyon air and the atmospheric flow takes place, before the flow is again entrained into the street canyon in front of wall B. The second feature, also evident from numerical simulations, can be explained by the enhanced natural ventilation at the street canyon ends, where air exchange is not only provided by vertical exchange with the above roof flow but also with entering flow laterally.

From Figure 2 (right), we note that the overall FLUENT concentration pattern is qualitatively similar to that obtained in the wind tunnel, even if there is a slight underestimation of the measured concentrations in proximity of wall A.

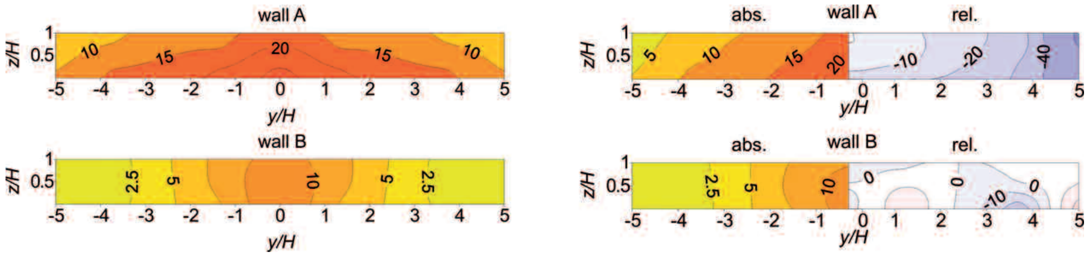

Figure 2. Tree-less street canyon. Measured concentrations c^+ [-] (left) and calculated concentrations c^+ [-] with relative deviations [%] in respect of measurements (right).

Street canyon with tree planting of large crown porosity (P_{Vol} = 97.5%, λ = 80 m^{-1})

As in the tree-free reference case, FLUENT simulations show downward and upward directed flows in front of the windward and leeward wall, respectively. Slightly smaller flow velocities in the upward but significantly lower velocities in the downward moving part are found when compared to the tree-free street canyon (not shown).

In comparison to the reference street canyon (Fig. 2, left), increases in concentrations in proximity of wall A and decreases near wall B are found in the wind tunnel measurements, but the pattern of pollutant concentration distribution remains overall unchanged (Fig. 3, left). Maximum concentrations are present at pedestrian level in proximity of wall A. The gas released at ground level is in fact advected towards the leeward wall A, but, since the circulating fluid mass is reduce in the presence of tree planting, the concentration in the uprising part of the canyon vortex in front of wall A is larger. Differently to the tree-free street canyon case, no direct transport of pollutants from wall A to wall B occurs, but all of the uprising canyon vortex is intruded into the flow above the roof level. Here, it is diluted before partially re-entrained into the canyon. As a consequence, lower traffic exhaust concentrations are present in proximity of wall B.

FLUENT simulations were successful in predicting an increase in concentrations in proximity of wall A and a decrease near wall B (Fig. 3, right) and the relative deviations in respect of tree-less street canyon, even if, as in the reference case, they slightly underestimated experimental data. This confirms that the RSM turbulence model is adequate for this type of applications.

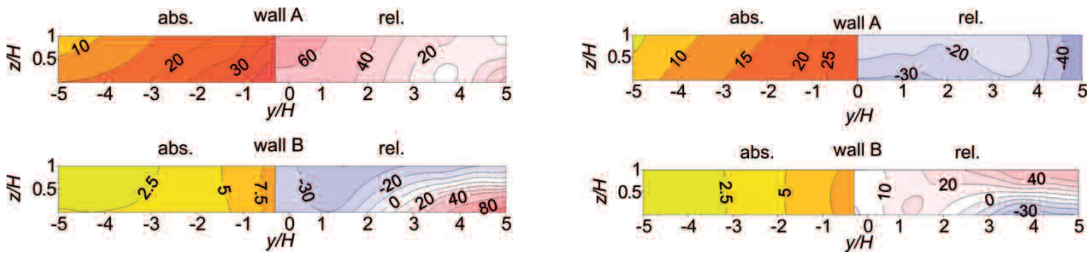

Figure 3. Street canyon with tree planting of large crown porosity (P_{Vol} = 97.5%). Measured concentrations c^+ [-] with relative deviations [%] in respect of tree-less street canyon (left) and calculated concentrations c^+ [-] with relative deviations [%] in respect of measurements (right).

Street canyon with tree planting of small crown porosity (P_{Vol} = 96%, λ = 200 m^{-1})

FLUENT velocity patterns (not shown here) of downward and upward directed flow in front of the windward and leeward walls generally remains unaltered and only marginal changes can be noticed in comparison to the previous case. This is due to the fact that the degree of crown porosity is of minor relevance for flow and dispersion processes inside the street canyon as the tree planting is arranged in a sheltered position with wind speeds being very small. This result is in agreement with previous investigations by Gromke and Ruck (in press), who showed a similar impact of a small porosity tree crown with P_{Vol} = 96 % and an impermeable model tree crown (P_{Vol} = 0 %) on the concentration field inside the street canyon.

The small impact of crown porosity is also reflected in the concentration plots of Figure 4. When compared to the concentrations found in the street canyon with the tree planting of large crown porosity (Fig. 3), no considerable changes can be found, neither in the experimental results (left) nor in the numerical simulations (right).

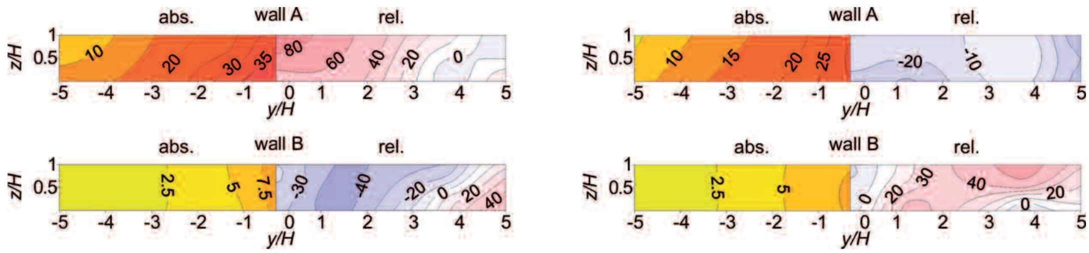

Figure 4. Street canyon with tree planting of small crown porosity (P_{Vol} = 96%). Measured concentrations c^+ [-] with relative deviations [%] in respect of tree-less street canyon (left) and calculated concentrations c^+ [-] with relative deviations [%] in respect of measurements (right).

4. DISCUSSION

In order to asses quantitatively the model performance, several statistical methods were used, such as the normalized mean square error (NMSE), the correlation coefficient (R), the fraction of predictions within a factor of two of observations (FAC2) and the fractional bias (FB) (Chang and Hanna, 2004). Recommendations for model acceptance criteria have been summarized and are given by: NMSE ≤ 4; FAC2 ≥ 0.5; −0.3 ≤ FB ≤ 0.3. All statistical measures are within the accepted values for satisfactory model performance (Table 1).

Table 1. Results of statistical analysis with BOOT

	NMSE	R	FAC2	FB
tree-less street canyon	0.06	0.96	0.97	0.15
large crown porosity (P_{Vol} = 97.5 %)	0.13	0.98	1.00	0.21
small crown porosity (P_{Vol} = 96 %)	0.09	0.99	1.00	0.14

The contour plots of relative deviations in concentrations (Figs. 2, 3, 4, right) show maximum differences of -40 to +60% between experimental and numerical results. Pollutant concentrations in proximity of the leeward wall were slightly underestimated in the numerical simulations, while near the windward wall both slightly over- and underestimations were present.

The results of this study are in general agreement with previous experimental and numerical investigations. Gross (1987) investigated the influence of a tree planting consisting of two rows arranged sidewise of the street next to the building walls. Using a k-ε turbulence closure scheme and modelling the tree crowns by porous bodies, he found decelerated flow velocities near the building walls and increased pollutant concentrations inside the street canyon when compared to the setup without trees. In another numerical simulation of comparable tree arrangement, Ries and Eichhorn (2001) found local increases of the pollution concentration at the leeward wall accompanied by reduced flow velocities due to trees. However, in both investigations, two-dimensional models were applied, which do not account for the highly three-dimensional flow fields present in real urban street canyons of finite length. Extensive wind tunnel investigations of flow and concentration fields in urban street canyons of aspect ratios $W/H = 1$ and $L/H = 10$ with various avenue-like tree planting setups are documented in Gromke and Ruck (2007) and Gromke and Ruck (in press). Tree planting characteristics like crown shape, diameter, height, porosity and planting density were systematically varied and flow and concentration fields were measured for perpendicular approaching wind. When compared to the tree-free street canyon, increases in pollutant concentrations at the leeward wall and decreases in concentrations at the windward wall were found. Air exchange and entrainment conditions were considerably modified, resulting in lower flow velocities and in overall larger pollutant charges inside the canyon.

5. CONCLUSIONS

Flow and dispersion of traffic exhausts in urban street canyons with tree planting were investigated by means of wind tunnel experiments and CFD investigations. In the wind tunnel measurements and numerical simulations, reduced flow velocities and larger overall traffic exhaust concentrations were found in street canyons with tree planting when compared to the tree-less case. Large concentration increases in proximity of the leeward wall and moderate concentration decreases near the windward wall were found. Based on the statistical tests performed, the performance of the RSM in predicting pollutant concentrations in urban street canyons with tree planting under the present boundary conditions is satisfactory.

Overall, this study suggests that the in-canyon air quality can be significantly altered by avenue-like tree planting. The combination of experimental and numerical investigations in a novel aspect of research, as done in this study, can provide a strategy to investigate pollutant dispersion in street canyons with tree planting. It is helpful to obtain useful suggestions for assessment, planning and implementation of exposure mitigation in urban areas.

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