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THE ROLE OF TREES IN TRAFFIC EMISSION DISPERSION AND AIR QUALITY IN URBAN STREET CANYONS

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Abstract: Traffic pollutant concentration and dispersion phenomena in urban street canyons with avenue-like tree planting have been investigated in an atmospheric boundary layer wind tunnel. The study comprises tree planting of different crown porosity, aligned in two rows in an isolated street canyon of width to height ratio W/H = 2 and length to height ratio L/H = 10. The tree planting has been realized according to a new modelling approach which accounts for aerodynamic similarity of the flow through the permeable crown by the pressure loss coefficient λ. In the presence of tree planting, considerable larger pollutant concentrations at the leeward canyon wall and slightly lower concentrations at the windward canyon wall in comparison to the tree-free reference street canyon were measured. Overall, an increase in pollutant level due to tree planting is found. Concluding, a relationship allowing to estimate the maximum traffic pollutant concentration at the canyon walls is presented.

Key words: *street canyon, avenue, trees, traffic emission, pollutant dispersion*

INTRODUCTION

Traffic emissions are the dominant source for air pollution in urban areas. They have significant influence on the quality of life and health of the city population. Critical situations arise in dense built-up inner city areas, which are usually formed by urban street canyons. Here, the air exchange between the street level and the wind above the building roofs is limited. As a consequence, near ground traffic-released emissions remain and accumulate at the street level, resulting in high pollutant concentrations.

Dense avenue-like tree planting inside urban street canyons even complicates the issue, since it affects the prevailing flow field and therefore pollutant dispersion and exchange processes. In particular, the lower and the upper street level parts are separated by the tree crown layer and the air exchange with the above roof wind is hindered.

In former studies Gromke, C. and B. Ruck (2007), Gromke, C. and B. Ruck (2009a) and Gromke, C. and B. Ruck (2009b) investigated flow and concentration fields in street canyons with avenue-like tree planting in a boundary layer wind tunnel. For a street canyon with aspect ratios of W/H = 1 and L/H = 10 (W street width, H building height and L street length) subjected to perpendicular approaching flow, overall concentration increases at the building walls of up to 50% and local peak increases of up to 90% due to tree planting were found. Furthermore, smaller wind velocities inside the street canyons and reduced ambient air exchange due to blocking effects of the trees were measured. These phenomena were also found in complementary numerical simulations (Buccolieri, R. *et al.*, 2009, Balczó, M. *et al.*, 2009, Gromke, C. *et al.*, 2008) as well as in the numerical study of Ries, K. and J. Eichhorn (2001).

In this paper, we focus on wind tunnel experiments performed in broad street canyons of aspect ratios W/H = 2 and L/H = 10 with avenue-like tree planting aligned in two rows on each side of the road (Figure 1). This kind of street canyon/tree planting configuration can be found often in city main streets with dense traffic and, hence, high pollutant emissions. Concentration measurement results obtained for avenues of high tree planting density, i.e. with interfering neighbouring tree crowns and varied crown porosity are presented.

APPROACH

The street canyon was formed by two rows of houses (scale M = 1:150) forming an isolated canyon of length L = 180 m, height H = 18 m and street width W = 36 m (Figure 1). A boundary layer flow approaching perpendicular to the street axis with profile exponents of $\alpha_u = 0.30$ and $\alpha_I = -0.36$ according to the power law formulations of mean horizontal and turbulence intensity profiles, $u(z)$ and $I_u(z)$ respectively, were reproduced

$$\frac{\Phi_i(z)}{\Phi_i(z_{ref})} = \left(\frac{z}{z_{ref}}\right)^{\alpha_i} \qquad (1)$$

with $\Phi_1 = u$, $\alpha_1 = \alpha_u$ and $\Phi_2 = I_u$, $\alpha_2 = \alpha_I$. A flow velocity of u_H = 4.70 m/s at building height H was realized, resulting in a Reynolds number of Re = 37000 based on u_H and the building height H, thus, ensuring a Reynolds number independent flow field. More information on the simulated atmospheric boundary layer flow, including data on the integral length scale profile $L_{ux}(z)$ and spectral distributions of turbulent kinetic energy $S_{uu}(z,f)$ are documented in Gromke, C. and B. Ruck (2005) and in the internet database CODASC (2008).

A tracer gas emitting line source embedded in the street ground was installed for the simulation of traffic exhaust releases (Meroney, R.N. *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-wall canyon air. The samples were analyzed by Electron Capture Detection (ECD) yielding mean concentrations which were normalized according to

$$c^{+} = \frac{c\, u_H\, H}{Q_T / l} \tag{2}$$

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

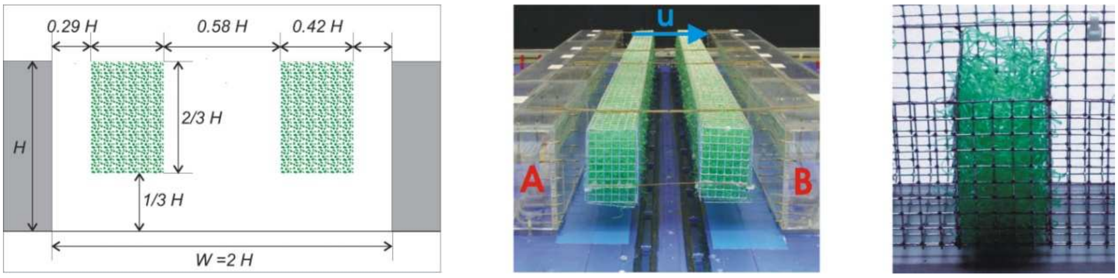

Figure 1: Street canyon with avenue-like tree planting and close-up of tree model.

The tree crown modelling was realized using custom-made lattice cages forming cubes with cross-sections of 0.42 *H* width and 0.67 *H* height (Figure 1). Spanning the entire street canyon of length *L*, the cages were divided into 31 cells, each of 0.32 *H* depth, which were filled with a filament/fibre-like synthetic wadding material. The cells' purpose was to ensure a uniform distribution of the wadding material. Crown porosities with pore volume fractions of P_{Vol} = 97.5% (large crown porosity) and P_{Vol} = 96% (small crown porosity) were modelled (Gromke, C. and B. Ruck, 2009b).

The fluid dynamical similarity of the crowns is based on the pressure loss coefficient λ [m^{-1}] which has been determined for wadding material samples of the given pore volume fractions in forced convection conditions, according to

$$\lambda = \frac{\Delta p_{stat}}{p_{dyn}\, d} = \frac{p_{ww} - p_{lw}}{0.5\ \rho\, u^2 d} \tag{3}$$

with Δp_{stat} the difference in static pressure windward (ww) and leeward (lw) of the porous sample, p_{dyn} the dynamic pressure, u the mean stream velocity and d the porous sample thickness in streamwise direction. Measurements resulted in pressure loss coefficients of λ = 80 m^{-1} and λ = 200 m^{-1} for the model tree crowns of high (P_{Vol} = 97.5%) and low (P_{Vol} = 96.0%) porosity, respectively.

Grunert, F. *et al.* (1984) have determined pressure loss coefficients λ of artificially arranged natural vegetation elements simulating wind shelter belts. Their measurements resulted in pressure loss coefficients λ ranging from 0.4 m^{-1} to 13.4 m^{-1} with the majority lying in the range of 1.0 $m^{-1} < \lambda <$ 3.0 m^{-1}.

The derivation of a similarity criterion is based on energy considerations and expressed by the postulation that the normalized pressure losses (normalized by the dynamic pressure p_{dyn}) have to be equal in full scale (fs) and model scale (ms), i.e.

$$[\Delta p / p_{dyn}]_{fs} = [\Delta p / p_{dyn}]_{ms} \tag{4}$$

which, with equation (3), yields

$$\frac{\lambda_{fs}}{\lambda_{ms}} = \frac{d_{ms}}{d_{fs}} = M\ . \tag{5}$$

That is, the ratio of the pressure loss coefficients has to be equal to the scale factor *M* (here *M* = 1:150). Calculating the required small scale pressure loss coefficients λ_{ms} is now straightforward and using the values determined by Grunert, F. *et al.* (1984), one obtains 60 $m^{-1} < \lambda_{ms} <$ 2000 m^{-1}. Thus, the realized pressure loss coefficients of the high (λ = 80 m^{-1}, P_{Vol} = 97.5%) and low (λ = 200 m^{-1}, P_{Vol} = 96.0%) porosity model tree crowns match the lower limit of Grunert’s down-scaled values.

RESULTS AND DISCUSSION

Street canyon without trees: reference case

Before discussing the influence of trees on pollutant dispersion, the traffic pollutant concentrations in a tree-free street canyon, so called reference case, is studied. Figure 2 shows the measured traffic pollutant concentrations at the canyon walls. Two characteristic features are evident, (i) the leeward wall A shows larger pollutant charges than the windward wall B and (ii) a steady decrease in concentrations towards the street ends at both walls. In the canyon centre parts, concentration levels are 3 to 4 times higher compared to the outer parts. The normalized wall-averaged pollutant concentrations (equation (2)) are c^+_A = 14.8 [-] and c^+_B = 5.2 [-] for wall A and B, respectively.

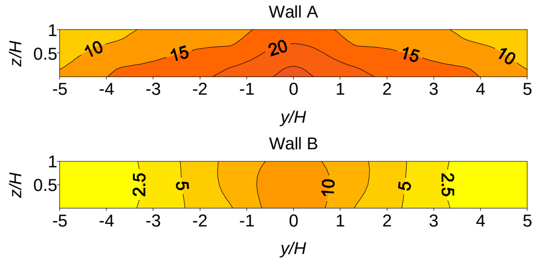

Figure 2: Normalized pollutant concentrations c^+ [-] in the tree-free street (reference case).

The observations can be explained by the dominating vortex structures inside the canyon. The higher concentrations at the leeward wall A are due to the canyon vortex. At roof level, air of the atmospheric flow is entrained into the canyon and moves downwards in front of the windward wall B. The flow at street level is directed reverse to the atmospheric flow and accumulates near-ground released traffic emissions. These are transported towards wall A 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 concentration decreases towards the street ends are due to the enhanced natural ventilation at the street canyon ends, where the corner eddies ensure additional air exchange. A more detailed discussion on the canyon flow fields and vortex structures is given in Gromke, C. and B. Ruck (2007) or in Gromke, C. and B. Ruck (2009b).

Tree planting of high stand density with large and small crown porosity

In comparison to the reference street canyon (Figure 2), increases in pollutant concentrations at wall A and decreases at wall B are present for both the tree planting with large and small crown porosity as can be seen in Figure 3. Maximum relative increases occur in the upper central part of wall A (60% resp. 80%). However, the peak concentrations are not strongly affected by the planting and the pattern of concentration distribution remains almost unchanged. The maximum relative concentration decreases at wall B also occur near the street central part (30% resp. 40%), but are smaller than the increases at wall A. Because of this and the inherent lower pollutant charges at wall B, an overall increase in concentration remains inside the street canyon, which is slightly stronger for the planting with small crown porosity (Figure 3, right). The wall-averaged pollutant concentrations are c^+_A = 20.7 [-] and c^+_B = 3.9 [-] (large crown porosity) and to c^+_A = 20.8 [-] and c^+_B = 3.6 [-] (small crown porosity) reflecting relative increases for wall A of 40% and 41% and decreases for wall B of 25% and 32%.

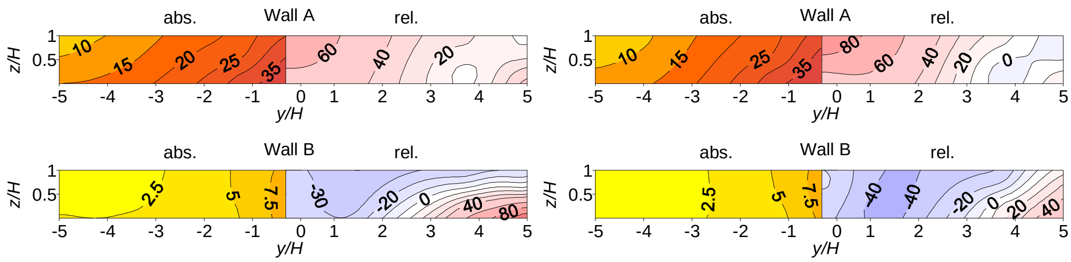

Figure 3: Normalized pollutant concentrations (abs.) c^+ [-] and relative changes (rel.) [%] in comparison to the reference case (Figure 2) for tree planting of high stand density with large crown porosity (left) and small crown porosity (right).

DIMENSIONAL ANALYSIS AND ESTIMATE OF MAXIMUM POLLUTANT CONCENTRATION

Based on wind tunnel experiments which comprise more than 40 street canyon/tree planting configurations (CODASC, 2008) with varying

- street width to building height ratio (W/H = 1 or 2)
- one- or two-rowed tree planting
- tree stand density (ρ = 0.5, 1.0)
- crown porosity (P_{Vol} = 0%, 96%, 97.5%, 100%)
- approaching wind direction (α = 0°, 45°, 90°),

a relationship for the maximum pollutant concentration c^+_{max} at the canyon wall was derived. By dimensional analysis and additional considerations (e.g. assuming Reynolds number independent flow), it was found that the maximum pollutant concentration can be expressed by a relationship of the type

$$c^{+}_{max} = \frac{c_{max}\, u_H H}{Q_T / l} = f\left(\frac{W}{H}, \rho, P_{Vol}, \alpha\right). \tag{6}$$

Using the dataset of wind tunnel measurements, an explicit equation for the estimation of the maximum concentration c^{+}_{max} according to

$$c^{+}_{max} = a_1 - a_2 \exp\left\{-a_3 \left[\rho (100 - P_{Vol})\right]\right\} \tag{7}$$

was derived. The parameters a_1, a_2 and a_3 are functions of the street width to building height ratio W/H and the wind direction α and can be determined by means of the diagrams given in Figure 4. A detailed derivation of equation (7) can be found in Gromke, C. (2008).

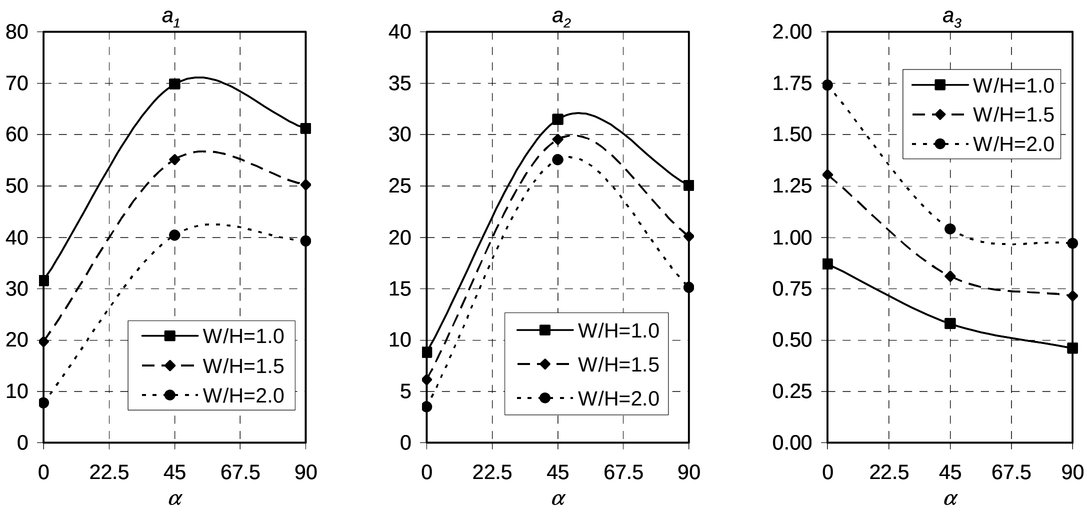

Figure 4: Parameter a_1, a_2 and a_3 of equation (7) as functions of W/H and α.

CONCLUSIONS

The results show that the street canyon air quality is significantly affected by avenue-like tree planting. Pronounced increases in traffic pollutant concentrations at the leeward canyon wall A and rather moderate decreases at the windward canyon wall B were measured in the wind tunnel experiments. Table 1 summarizes the main results.

Table 1. Overview on wall average and maximum pollutant concentrations (c.p: crown porosity).

street canyon	concentrations c^{+} [-] and rel. changes to reference case [%] in ()		
	wall average		wall maximum
	A	B	A
without trees	14.8 (-)	5.2 (-)	24.2 (-)
with high c.p. (P_{Vol} = 97.5%)	20.7 (+40)	3.9 (-25)	38.2 (+58)
with low c.p. (P_{Vol} = 96.0%)	20.8 (+41)	3.6 (-32)	38.9 (+61)

The results clearly show that the implications of avenue-like tree planting on pollutant dispersion and concentration inside urban street canyons have to be considered carefully. Reduced street canyon ventilation performance may result in critical exceedance of pollutant concentration limits and cause hazardous conditions for the residents.

The estimate given in equation (7) can be used by town planners and support local decision-makers by assessing the implications of trees on traffic pollutant concentrations in urban street canyons. In particular, the estimate allows to design avenue-like tree planting with respect to street canyon air quality and to control traffic pollutant concentrations.

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