

Implications of tree planting on pollutant dispersion in street canyons

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Abstract

Traffic pollutant dispersion processes inside urban street canyons with avenue-like tree planting have been studied in wind tunnel experiments. Tree planting of different crown porosities and their effects on the pollutant concentrations at the canyon walls have been investigated for wind approaching perpendicular to the street axis. The results show that avenue-like tree planting in street canyons lead to overall increases in traffic originated pollutant concentrations in comparison to the tree-free reference case. Maximum increases in concentrations of 80 % have been measured at the building walls in the street canyon central part where the dispersion processes are affected strongest by tree planting.

1. Introduction

Traffic emissions generally dominate air quality issues in urban areas. Critical situations arise in dense built-up inner city areas which are formed by urban street canyons suffering from limited ambient air exchange and high pollutant concentrations. Vegetation inside urban street canyons even complicates the situation, since it affects the prevailing flow field and, therefore, pollutant dispersion and exchange processes. In particular, in the case of avenue-like tree planting where the lower and the upper street level parts are separated by a tree crown layer, the air exchange with the above roof wind is hindered.

In the present study, wind tunnel measurements of traffic-originated pollutant concentrations and dispersion processes in urban street canyons with trees are presented. Implications of two-rowed avenue-like tree planting with different crown porosities on pollutant concentrations inside an urban street canyon are discussed, complementing the investigations with single-rowed planting documented in Gromke and Ruck (2007), Gromke et al. (2008), Gromke (2009), Gromke and Ruck (2009a), Gromke and Ruck (2009b) and Balczó et al. (2009). Moreover, a new and promising method has been established for the small scale modeling of trees for the purpose of wind tunnel studies. Special emphasis is laid on the description of this method and its justification/verification by fluid dynamical similarity considerations.

2. Street canyon setup, measurement techniques and boundary layer simulation

The wind tunnel experiments have been performed in a model street canyon of scale $M=1:300$. A canyon of length L to building height H ratio $L/H=10$ and street width W to building height H ratio $W/H=2$ with typical two-rowed avenue-like tree planting has been investigated (Fig. 1). The release of traffic exhausts was realized by four tracer gas (sulphur hexafluoride SF_6) emitting line sources embedded in the street ground.

Electron Capture Detection (ECD) has been used to analyze the air/tracer gas mixtures which have been sampled inside the street canyon at positions $y/H=0.04$ in front of the canyon walls. The resulting concentrations have been normalized according to

$$c^+ = \frac{c u_H H}{Q_T/l} \quad (1)$$

with c the measured concentration, u_H the velocity of the undisturbed flow at building height H and Q_T/l the tracer gas source strength per unit length.

A typical urban atmospheric boundary layer flow with power law exponents of $\alpha=0.30$ for the mean velocity profile and $\alpha_t=-0.36$ for the turbulence intensity profile, approaching perpendicular to the canyon length axis, has been generated in the wind tunnel (Gromke and Ruck, 2005). Experimental studies with parallel and inclined approaching flow directions can be found in CODASC (2008) and in Gromke (2009). The Reynolds number Re , based on the building height H and the velocity u_H , is equal to 37.000 and ensures a Reynolds number independent flow field.

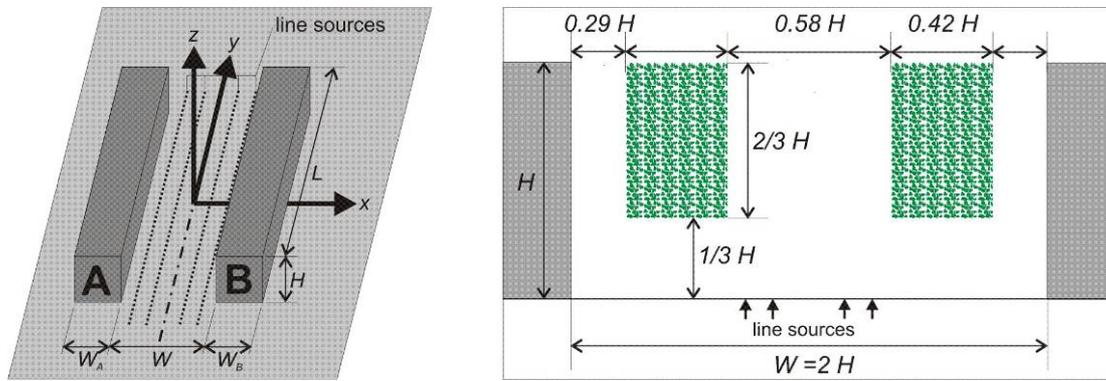


Fig. 1: Street canyon geometry and tree planting arrangement ($W_A=W_B=H$)

3. Small scale modeling of trees and similarity criterion

Trees, more precisely tree crowns, are porous objects and permeable to air flow. Flows past porous objects differ crucially from flows past non-porous counterpart objects. Characteristic differences can be found in the drag and in the wakes. Due to large volume specific surfaces of porous objects, skin friction becomes important. It can no longer be neglected as with non-porous objects, where the pressure difference on the windward and leeward side dominates the drag. Furthermore, wakes of porous objects extend further downstream and the leeward recirculation zone is often detached (Gromke and Ruck, 2008). In summary: due to their porosity, tree crowns show unique aerodynamic properties in comparison to non-porous bodies which have to be accounted for in wind tunnel.

As stated above, a new method has been developed for the small scale modeling of trees. The modeling of porous tree crowns has been realized using custom-made lattice cages constituting cubes with cross-sections of $0.42 H$ width and $0.67 H$ height (Fig. 2). These lattice cages have been aligned symmetrically along the street axis with the top facing the roof level. Spanning the street canyon of length L , the cages have been divided into 31 cells of $0.32 H$ depth each. A filament/fiber-like synthetic wadding material has been used to fill the cells, whose purpose was simply to facilitate a uniform distribution of the wadding material throughout the entire length of the lattice cage, see

also Gromke and Ruck (2009b). Different crown porosities/permeabilities have been realized by filling all the cells homogeneously with defined masses of wadding material. Pore volume fractions of $P_{Vol}=97.5\%$ (herein referred to as high crown porosity) and $P_{Vol}=96\%$ (herein referred to as low crown porosity), typical for crown porosities of deciduous trees have been modeled (Ruck and Schmidt, 1986; Gross, 1987). By filling each cell with the wadding material, avenue-like tree planting of high stand densities with interfering neighboring tree crowns have been modeled ($\rho=1$). In the same way, tree planting of lower stand densities with free space in-between can be realized by filling only every second, every third, and so forth, cage cell (corresponding to $\rho=0.5$, $\rho=0.33$, etc.) However, in the present paper, tree planting of high stand density ($\rho=1$) with interfering crowns are treated exclusively. Measurement results obtained with tree planting of lower stand density can be found in CODASC (2008) and in Gromke (2009).

The aerodynamic characteristics of the model trees are not sufficiently and definitely determined by their crown porosities. In fact, the internal crown structure, i.e. the pore size distribution, the arrangement and form of the crown constituting material and its surface properties are also important. In order to account for all these factors, the pressure loss coefficient λ [m^{-1}] has been determined for wadding material samples with pore volume fractions of $P_{Vol}=97.5\%$ (high crown porosity) and $P_{Vol}=96\%$ (low crown porosity) in forced convection conditions, according to

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

with Δp_{stat} the difference in static pressure windward and leeward of the porous sample in forced convection conditions, 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 $\lambda=80 m^{-1}$ and $\lambda=200 m^{-1}$ for the model tree crowns of high ($P_{Vol}=97.5\%$) and low ($P_{Vol}=96\%$) porosity, respectively.

In order to justify the chosen modeling approach and to base it on a scientific sound foundation, a fluid dynamical similarity consideration is needed. Pressure loss coefficients λ of artificially arranged natural vegetation elements simulating wind shelter belts have been determined by Grunert et al. (1984). Their measurements resulted in pressure loss coefficients $\lambda_{full\ scale}$ ranging from $0.4 m^{-1}$ to $13.4 m^{-1}$ with the majority lying in the range of $1.0 m^{-1} < \lambda_{full\ scale} < 3.0 m^{-1}$.

The derivation of 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 (nature) and small scale, i.e.

$$[\Delta p/p_{dyn}]_{full\ scale} = [\Delta p/p_{dyn}]_{small\ scale} \quad (3)$$

which, with Eq. (2), yields to

$$\frac{\lambda_{full\ scale}}{\lambda_{small\ scale}} = \frac{d_{small\ scale}}{d_{full\ scale}} = M. \quad (4)$$

In words: The ratio of the pressure loss coefficients has to be equal to the model scaling factor M (here $M=1:300$). Calculating the required small scale pressure loss coefficients $\lambda_{small\ scale}$ is now straightforward and using the values found by Grunert et al. (1984), one

obtains $120 \text{ m}^{-1} < \lambda_{\text{small scale}} < 4000 \text{ m}^{-1}$ whereas the great majority lies in the range of $300 \text{ m}^{-1} < \lambda_{\text{small scale}} < 900 \text{ m}^{-1}$.

Thus, the realized pressure loss coefficients of the high ($\lambda=80 \text{ m}^{-1}$, $P_{\text{Vol}}=97.5 \%$) and low ($\lambda=200 \text{ m}^{-1}$, $P_{\text{Vol}}=96 \%$) porosity model tree crowns match the lower limit of Grunert's down-scaled values. However, it has to be noted that the vegetation structures investigated by Grunert et al. (1984) appear, from visual impression, to be quite dense compared to usual tree crowns. Based on preceding wind tunnel experiments and on the concentration measurements (Gromke and Ruck, 2009b), it was concluded that the model trees realistically simulate the aerodynamic characteristics of full scale trees and their implications on the flow field.

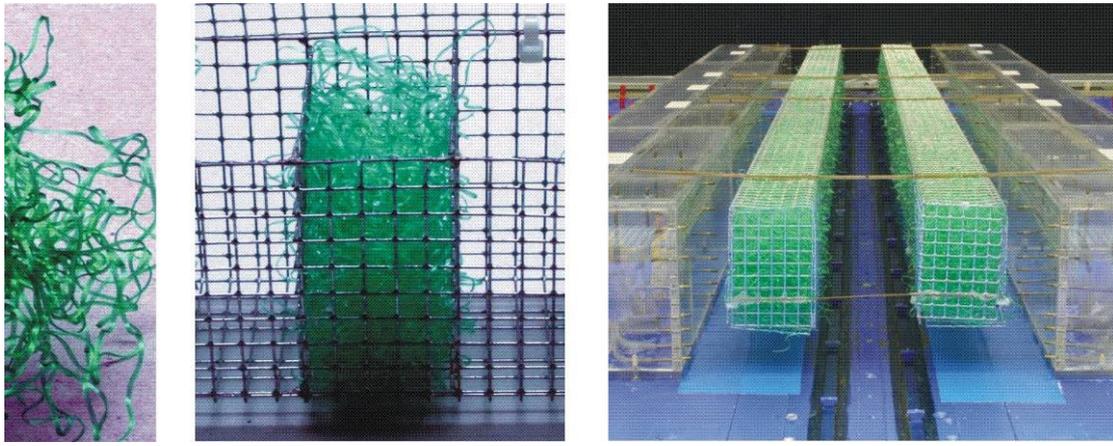


Fig. 2: Filament/fiber-like wadding material; wadding material incorporated in single cage cell; street canyon with two-rows avenue-like tree planting ($W/H=2$)

4. Results and discussion

4.1 Street canyon $W/H=2$ without tree planting

As a reference, traffic pollutant dispersion in a tree-free street canyon is discussed initially. Fig. 3 shows that the pollutant charge close at the leeward wall A is considerable higher than at the windward wall B. This phenomenon is due to the prevailing canyon vortex which transports the near street level released traffic pollutants to wall A before they are diluted by vertical air exchange at the roof level. Towards the street canyon ends, the influence of the corner eddies becomes visible. These large scale vortex structures serve for additional lateral air exchange and thus to the steady concentration decrease when approaching the street canyon ends.

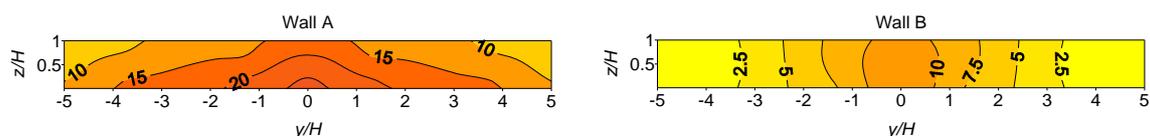


Fig. 3: Normalized pollutant concentrations [-] close to the walls A and B of the tree-free street canyon (reference case)

4.2 Street canyon $W/H=2$ with tree planting of high crown porosity ($P_{Vol}=97.5\%$)

For the street canyon with tree planting of high crown porosity, increases in concentrations at the leeward wall A and decreases at the windward wall B (Fig. 4) are found in comparison to the tree-free reference case (Fig. 3). The relative increases in the canyon central part of wall A are about 60 %, whereas the relative decreases in the central part of wall B are about 30 %. Calculating the wall average concentration changes yields a relative increase of 40 % at wall A and a decrease of 25 % at wall B. In summary, it remains an average relative increase in concentrations at the canyon walls of 23 % for the street canyon with tree planting. This is attributed to the blocking of the laterally entering corner eddies by the tree crowns at the canyon outer parts and to reduced ventilation of the gap between the upstream oriented planting and the leeward wall A.

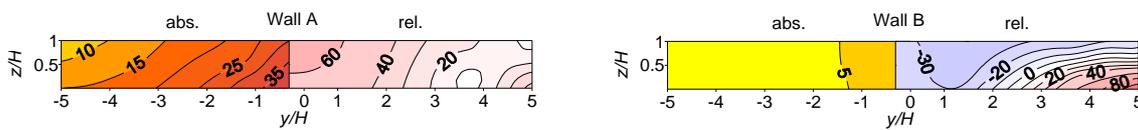


Fig. 4: Normalized pollutant concentrations [-] in the street canyon with tree planting of high crown porosity ($P_{Vol}=97.5\%$) and relative deviations in concentrations [%] related to the reference case of the tree-free street canyon (Fig. 3)

4.3 Street canyon $W/H=2$ with tree planting of low crown porosity ($P_{Vol}=96\%$)

In the case of lower crown porosity ($P_{Vol}=96\%$), the overall pollutant concentration pattern (Fig. 5) is similar to that found for the high crown porosity tree planting shown in Fig. 4. The major difference is that the changes relative to the tree-free reference case are slightly stronger pronounced with increased maximum pollutant concentrations at the pedestrian level near the central part of wall A. Concentration increases at wall A of maximum 80 % in the canyon central part and in average of 41 % and decreases at wall B of maximum 40 % and in average of 32 % are found, resulting in an overall increase in wall near pollutant concentrations of 22 %.

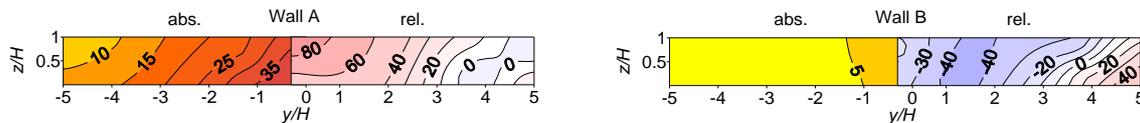


Fig. 5: Normalized pollutant concentrations [-] in the street canyon with tree planting of low crown porosity ($P_{Vol}=96\%$) and relative deviations in concentrations [%] related to the reference case of the tree-free street canyon (Fig. 3)

5. Conclusions

Avenue-like tree planting in street canyons leads to overall higher traffic-originated pollutant concentrations in comparison to the tree-free reference case. In particular, higher pollutant concentrations at the leeward wall A and lower concentrations at the windward wall B were found for flow approaching perpendicular to the street canyon axis. These effects are stronger pronounced the lower the tree crown porosity is. Maxi-

imum relative increases in pollutant concentration of 41 % for the wall average and of 80 % for localized spots in the canyon central part have been found in the presence of the tree planting with low crown porosity ($P_{\text{vol}}=96$ %). These results clearly show that the impact of avenue-like tree planting on pollutant dispersion and concentration inside urban street canyons have to be considered carefully. The reduced street canyon ventilation performance may result in critical exceedances of pollutant concentration limits and cause hazardous conditions for the residents. It is recommended to design avenue-like tree planting of low planting density and to employ tree species of high crown porosity (correlating with high permeability), in order to avoid high traffic-originated pollutant concentrations and hazardous conditions.

Acknowledgments

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