TREES IN URBAN STREET CANYONS AND THEIR IMPACT ON THE DISPERSION OF AUTOMOBILE EXHAUSTS

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ABSTRACT

The aim of the present study is to clarify the influence of trees on the dispersion of automobile exhausts in urban street canyons. For this purpose, measurements have been performed with a small scale wind tunnel model of an idealized, isolated street canyon with model trees placed along the canyon center axis. Sulfur hexafluoride (SF_6) was released from a line source embedded in the street surface, simulating vehicle exhaust emissions. The influence of various tree planting arrangements on the concentrations at the canyon walls was investigated with an approaching boundary layer flow perpendicular to the canyon axis. Increasing pollutant concentrations at the leeward wall and decreasing pollutant concentrations at the windward wall were found for increasing plant density. At the ends of the street canyon, i.e. towards the intersections, a remarkable relative increase of concentrations at both canyon walls was observed. The results indicate that due to tree planting, typical vortex structures observed in empty street canyons were either significantly weakened or no longer present.

1. INTRODUCTION

Due to increasing traffic, air pollution in urban street canyons induced by cars is becoming a more and more serious problem in regard to the healthiness of people living or working in city centers. Beside gaseous exhaust emissions, particulate matter released by vehicles, such as motor combustion residues, abrasion of tires and brake disks, or entrained by vehicles such as roadside deposited dust, have to be diluted and removed efficiently from the street canyon. In the last three decades, a large number of investigations concerning flow and concentration fields inside empty urban street canyons have been performed and the pollutant dispersion processes are well understood (Chang and Meroney 2003, Gerdes and Olivari 1999, Baik and Kim 1999, Ahmad et al. 2005, Vardoulakis et al. 2003, Li et al. 2006). However, pollutant dispersion processes in the presence of obstacles, such as trees inside the street canyon have not been investigated systematically, except in Gromke and Ruck 2007.

2. METHODOLOGY

An isolated street canyon model at scale 1:150 (Figure 1) with aspect ratio H/W = 1 and length to width ratio L/W = 10 was exposed to a perpendicular approaching boundary layer flow. The wind profile was characterized by a profile exponent α = 0.30 according to the exponential wind law, see also Gromke and Ruck 2005. The flow field inside the empty street canyon and its dominating vortex structures like canyon vortex and corner eddies are sketched in Figure 1 (right). Model trees with either impermeable or permeable spherical crowns of diameter 15 m and a brunch free trunk of 4.5 m height were aligned equidistantly along the canyon center axis. The spacing between the trees was varied with 15, 20, 25 and 30 m. Sulfur hexafluoride was emitted from a line source at street level and tracer gas concentrations were measured by means of an electron capture detector (ECD) at both canyon walls A and B. The measured concentrations have been normalized according to the formula

$$c^+ = \frac{c_{meas} \, L_{ref} \, u_{ref}}{Q_T / l}$$

with c_{meas}: measured concentration, L_{ref}: reference length characterizing a building dimension (L_{ref} = H), u_{ref}: reference velocity characterizing the atmospheric flow ($u_{ref} = u_H$) and Q_T/l: tracer gas source strength per unit length of the line source. Additionally, all lengths in the subsequent concentration plots have been normalized by the reference length L_{ref} = H. These normalizations allow a transfer of measured concentration data to situations with different boundary conditions, e.g. differing reference velocity or building height.

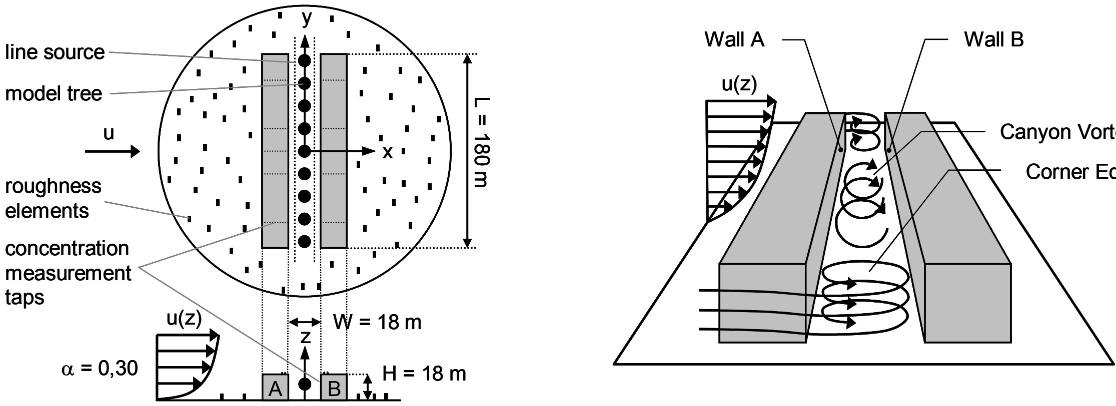


Figure 1. Model setup and flow field inside empty street canyon of aspect ratio H/W = 1.

3. RESULTS AND DISCUSSION

3.1 Empty street canyon without tree planting (reference case)

Figure 2 shows normalized concentrations at the canyon walls for the reference case without trees. The average pollutant concentration at wall A is 3.6 times higher than at wall B, which can be easily explained by means of the prevailing flow field in the canyon middle part. At roof level, an exchange of polluted canyon air with unpolluted air of the atmospheric flow takes place. Air of the atmospheric flow is entrained into the canyon vortex and transported downward into the street canyon in front of wall B. When recirculating from wall B towards wall A, traffic exhaust emissions are accumulated at the street level. Thus, the upward streaming part of the canyon vortex in front of wall A contains higher exhaust concentrations. The lower concentrations at the street ends are due to the superposition of the canyon vortex and sidewise entering corner eddies, leading to an enhanced exchange of air.

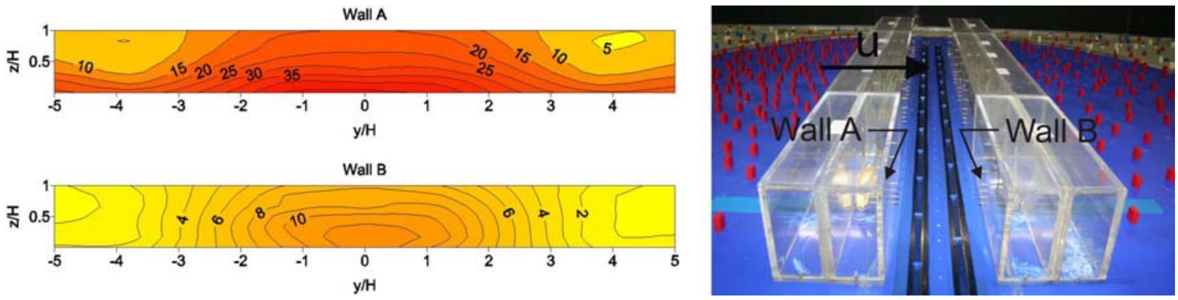


Figure 2. Normalized wall concentrations for empty street canyon without trees (reference case).

3.2 Tree planting with impermeable crowns and spacing 30 m

In the case of an equidistant tree planting spaced by 30 m, the gap between neighbouring trees amounts to 15 m at the crown waists and 20 % of the total canyon volume is occupied by crowns. In Figure 3 (left), the relative changes in concentration are shown for wall A and wall B when compared to the reference case of the empty street canyon (Figure 2).

At wall A, moderate concentration increases in the range of 0 to 20 % were measured in the canyon middle part ($-1.5 < y/H < +1.5$). In contrast, concentration decreases up to 40 % were measured in the middle part of wall B. These observations indicate modifications of the flow field inside the canyon due to the tree planting, which was supported by laser Doppler velocimetry (LDV) measurements showing changed entrainment conditions at the roof top level. Since the interspaces between crown waists and canyon walls amounts to only 1.5 m, it is obvious that the development of a canyon vortex is significantly restrained or even totally inhibited. In order to understand the decrease in concentration at wall B, one has to remember that exhaust concentrations found at this wall in the empty street canyon originate from traffic emissions released at street level, which have been transported by the canyon vortex itself towards wall B. Consequently, a weakened or missing canyon vortex leads to lower concentrations at wall B. At the canyon's outer parts, pronounced relative increases in concentration at both walls were observed. The outermost tree crowns represent obstacles, which hinder corner eddies to enter the street canyon and, thus, limit the natural ventilation. Flow field investigations with laser Doppler velocimetry revealed a considerable reduction of the lateral inflow volume rate caused by the blocking effect of the outermost tree crowns. In comparison to the reference case, an increase of wall average concentration at wall A of 14 % and a decrease at wall B of 26 % was measured.

3.3 Tree planting with impermeable crowns and spacing 15 m

Within this configuration, the closest possible tree spacing is realized. Neighbouring trees touching each other at the crown waists and 39 % of the canyon volume is occupied by tree crowns. The relative change in concentration at the canyon walls is shown in Figure 3 (right).
Again, two distinct regions of concentration changes can be found at both walls. An enhanced concentration level was observed when compared to the planting with tree spacing of 30 m (Figure 3, left). Since there is no free gap remaining between the waists of the crowns, the canyon vortex strength is additionally weakened. The wall average concentrations increase to 45 % at wall A and decrease to 44 % at wall B in comparison to the reference case without trees.

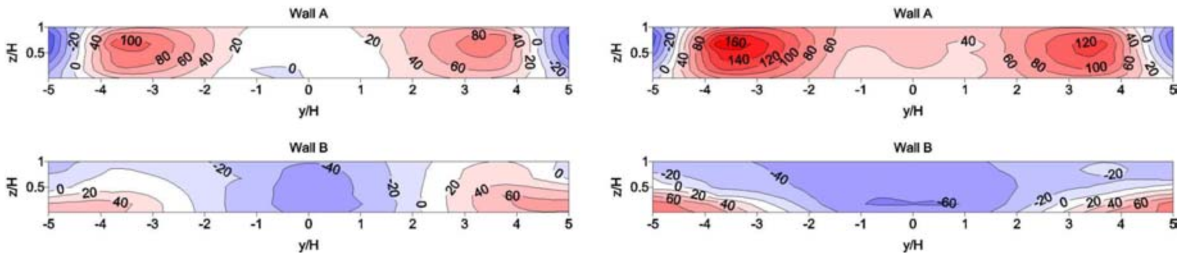


Figure 3. Relative changes in concentration for tree planting with spacing 30 m (left) and spacing 15 m (right) when compared to the reference case (Figure 2).

3.4 Tree plantings with impermeable crowns and spacings of 20 and 25 m

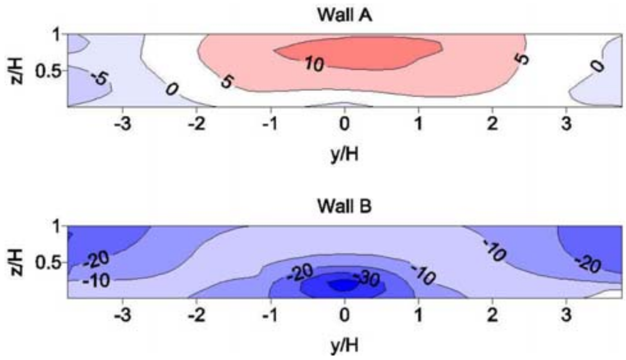
Further measurements of planting configurations with tree spacings of 20 and 25 m have been performed. The results fit well into the trend set by the planting configurations with spacings of 15 and 30 m (Figure 3). The wall average concentrations and relative changes when compared to the empty reference canyon are summarized in Table 1.

Table 1. Wall average concentrations and relative changes when compared to the reference case

Tree spacing [m]	empty		30		25		20		15	
Wall	A	B	A	B	A	B	A	B	A	B
norm. concentration [-]	19,5	5,4	22,3	4,0	23,6	3,9	24,7	3,6	28,3	3,0
rel. change [%]	0	0	+14	-26	+21	-28	+27	-33	+45	-44

3.5 Tree planting with permeable crowns and spacing 15 m

In order to take the influence of real crown permeability into account, spherical crowns have been made out of an open-pored foam material 10 ppi (10 pores per inch). This material is characterized by a relative pore volume of 97 % and a pressure loss coefficient λ = 210 - 275 Pa/(Pa/m) for flow velocities in the range of 0 to 7 m/s.
In Figure 4, the relative change in concentration for a tree planting with spacing 15 m and permeable crowns of 15 m diameter when compared to the configuration with impermeable crowns (chapter 3.3) is shown. At wall A, marked changes in concentration are not registered. At wall B, the relative change in concentration is more distinct. The mean relative change in comparison to impermeable crowns amounts to +4 % for wall A and to -15 % for wall B. The decrease in concentration at the outer parts of wall B can be ascribed to the crown permeability, which is blocking the corner eddies less effectively. It was found, that with the typical low wind conditions in street canyons, the crown permeability does not strongly influence the measured wall concentrations.



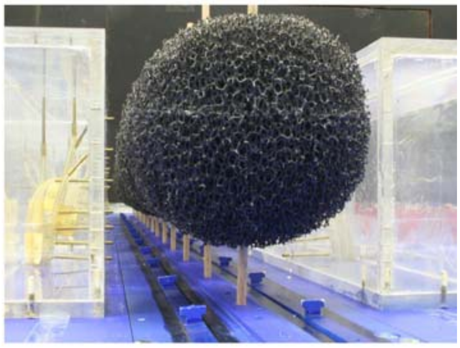


Figure 4. Relative changes in concentration for tree planting with spacing 15 m and permeable crowns when compared to tree planting with impermeable crowns.

4. CONCLUSION

In the present study, the influence of tree planting in street canyons have been investigated with respect to dispersion and removal of traffic-induced pollutants. The investigations have been performed in an atmospheric boundary layer wind tunnel with a simulated urban street canyon in perpendicular cross flow. Inside the street canyon, an avenue-like tree planting was realized and the exhaust emissions were simulated by a line source positioned at the center line of the street canyon. The tree spacing was varied systematically and wall concentration measurements have been performed. In comparison to the empty, tree-free street canyon, concentration increases at the leeward wall (wall A) and decreases at the windward wall (wall B) were found in the canyon middle part. With tree planting, high relative increases in concentration at both walls were measured towards the street ends at the canyon's outer parts. In general, the concentration level rises with higher tree density, i.e. with smaller tree spacings. Tree crowns represent flow obstacles which damp the natural ventilation and, thus, the dispersion and removal of pollutants. The entrainment conditions at the roof top level and at the lateral inlet cross sections of the canyon are altered significantly with trees leading to weakened or even suppressed canyon vortex and corner eddies. The influence of crown permeability on the concentration level was found to be not of primary significance. The investigations have shown that by providing sufficient tree spacing, the atmospheric wind is able to intrude into the street canyon avoiding relevant concentration increases. Thus, for a planting configuration with tree crowns of 15 m diameter and a tree spacing of 30 m, the average concentration at the leeward wall A was only moderately increased by 14 % when compared to the reference case without trees. In contrast, when doubling the tree plant density to a spacing of 15 m, a large increase in concentration of 45 % was observed.

5. ACKNOWLEDGEMENTS

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