Flow and Dispersion Phenomena in Urban Street Canyons in the Presence of Trees

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ABSTRACT: In order to clarify the impact of trees on flow and concentration fields inside street canyons, measurements have been performed with a small scale wind tunnel model of an idealized urban street canyon. The model setup consists of two parallel aligned rows of houses forming the canyon and a tracer gas emitting line source for simulating traffic exhaust releases. Model trees with spherical crowns have been arranged along the canyon center axis. The setup was exposed to an approach flow perpendicular to the street axis and tracer gas concentrations at both canyon walls were measured. In the presence of trees, increasing values of exhaust concentrations at the leeward wall and decreasing concentrations at the windward wall were found. Velocity measurements reveal an extensive impact of trees on the flow field. Typical vortex structures observed in obstacle free street canyons were either significantly weakened or no longer present.

KEYWORDS: street canyon, pollutant dispersion, trees, canyon vortex, corner eddies

1 INTRODUCTION

The dilution and removal of traffic exhausts in urban street canyons is of great importance for the health and quality of life of people living or working in city centers. A large number of investigations addressing flow and concentration fields inside urban street canyons have been performed in the past and pollutant dispersion phenomena are well understood, see studies [1], [2], [3], [4] and [5] or the reviews [6], [7] and [8]. However, the presence of trees or other obstacles inside street canyons and their impact on pollutant dispersion has not been addressed systematically, except in [9]. The present study focuses on the dilution and the removal of traffic exhausts in urban street canyons with avenue-like tree planting.

2 MODEL SETUP AND MEASUREMENT INSTRUMENTATION

An idealized, isolated urban street canyon at model scale 1:150 with aspect ratio $H/W = 1$ and $L/W = 10$, equipped with a line source at street level for tracer gas emissions [10] was subjected to a simulated atmospheric boundary layer flow [11]. According to [12] and [13], the prevailing flow field in the urban street canyon under consideration is that of a skimming flow regime, with well established canyon vortices in the center part and corner eddies at the street ends. A sketch of the model setup and dominating vortex structures is shown in Figure 1. One row of model trees with spherical crowns was set up along the canyon center axis and tree plantings with different crown diameters and permeabilities were investigated.

Concentrations at both, the leeward and windward canyon walls A and B have been measured using an electron capture detector (ECD). Flow velocities were measured at the roof top level and street ends by means of 2-D Laser Doppler velocimetry (LDV).

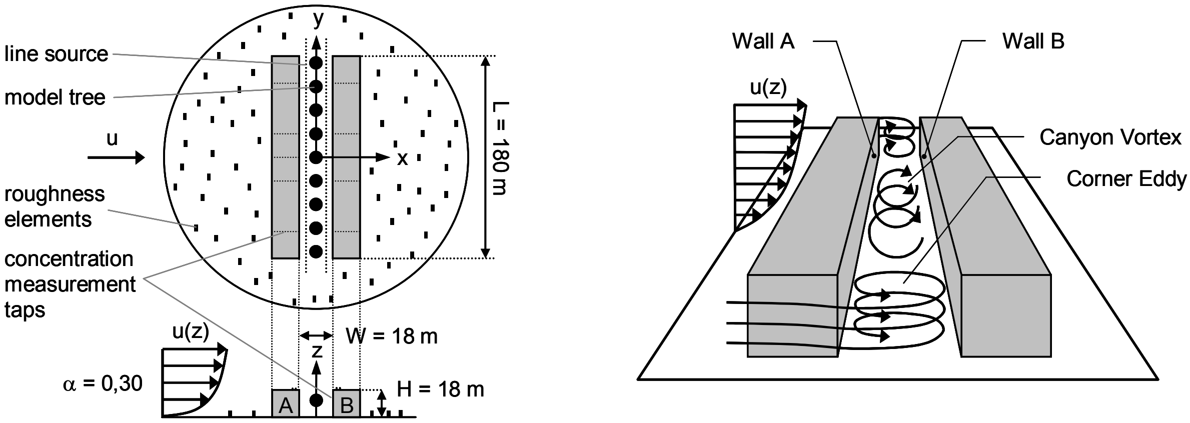

Figure 1. Model setup and flow field inside street canyon.

3 CONCENTARTION AND FLOW FIELD MEASUREMENTS

3.1 *Street canyon without trees (reference case)*

Before discussing the impact of trees on the pollutant dispersion, results of flow and concentration measurements carried out at the empty street canyon without trees, the so called "reference case", are presented in Figure 2. The concentrations have been normalized according to formula

$$c^+ = \frac{c_{meas}\, u_{ref}\, L_{ref}}{Q_T / l} \tag{1}$$

where c_{meas} = measured concentration; u_{ref} = reference velocity characterizing the atmospheric flow; L_{ref} = reference length characterizing the height of buildings; Q_T/l = tracer gas source strength of the line source. Additionally, the geometrical dimensions in Figure 2 have been normalized by the reference length $L_{ref} = H$. These normalizations allow a transfer of experimental data to full scale situations with different boundary conditions, e.g. differing reference velocity u_{ref} or building height H.

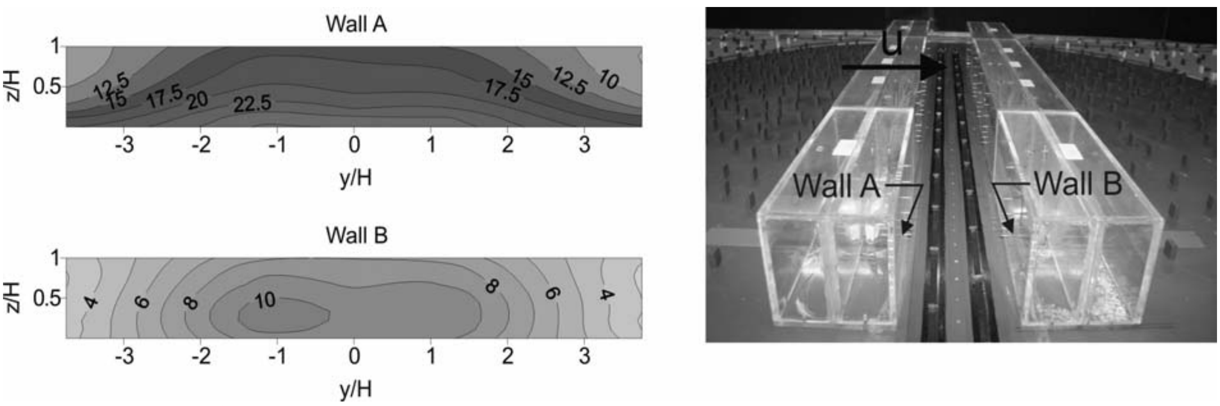

Figure 2. Dimensionless wall concentrations for reference case without trees.

The wall average concentration at wall A is approximately 2.5 times higher than at wall B. Driven by the skimming flow over the roof top, a canyon vortex rotating in clockwise direction is present between walls A and B. At roof level, clean air of the canopy flow gets partially entrained into the street canyon and diverts in front of wall B towards the ground. On the reverse flow from wall B towards wall A, the canyon vortex accumulates exhaust emissions released by the traffic. Thus, the ascending air in front of wall A shows higher concentrations. Towards the street corners, a decrease of concentrations for both walls can be observed, which is due to an additional ventilation caused by corner eddies.

Figure 3 shows the vertical flow component *w* and the corresponding velocity vectors in a vertical cross section located at the roof top level in the canyon center at *y/h* = 0. The contour plot of the vertical velocity component *w* shows zones of positive and negative flow velocities, i.e. air is streaming out or entering the canyon, respectively. This is in accordance with the before mentioned canyon vortex, having a positive velocity component *w* in the first half of the canyon's cross section ($-0.5 \leq x/H \leq 0$) and a negative velocity component *w* in the second half ($0 \leq x/H \leq 0.5$). In the vector plot below, the structure of the upper part of the canyon vortex and its gradual transition into the atmospheric shear flow are indicated.

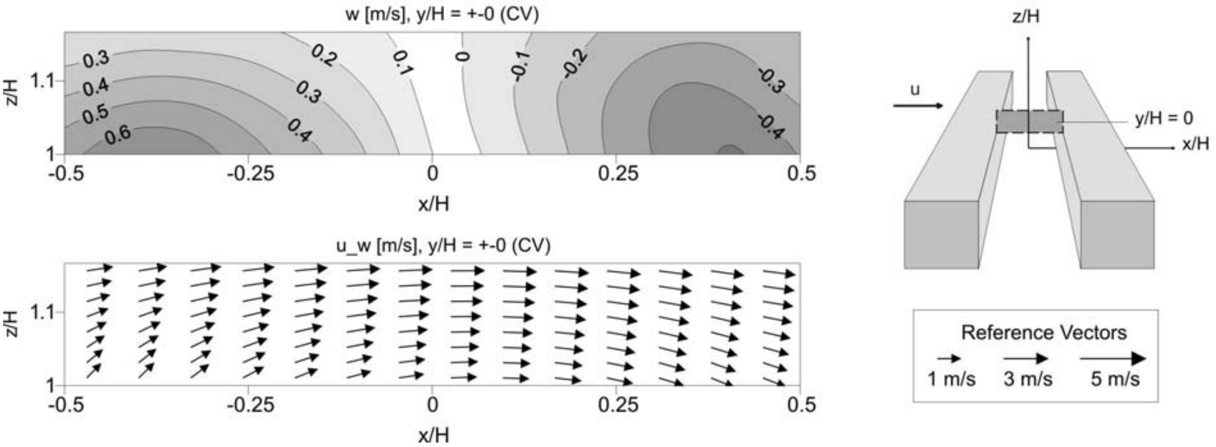

Figure 3. Velocity field at canyon center (*y/H* = 0) in roof top level for reference case without trees.

In Figure 4, the mean horizontal velocity component *v* of the lateral inflow induced by corner eddies at the end cross sections at *y/*H = ±5 is presented, with positive values indicating flow entering and negative values indicating flow coming out of the canyon.

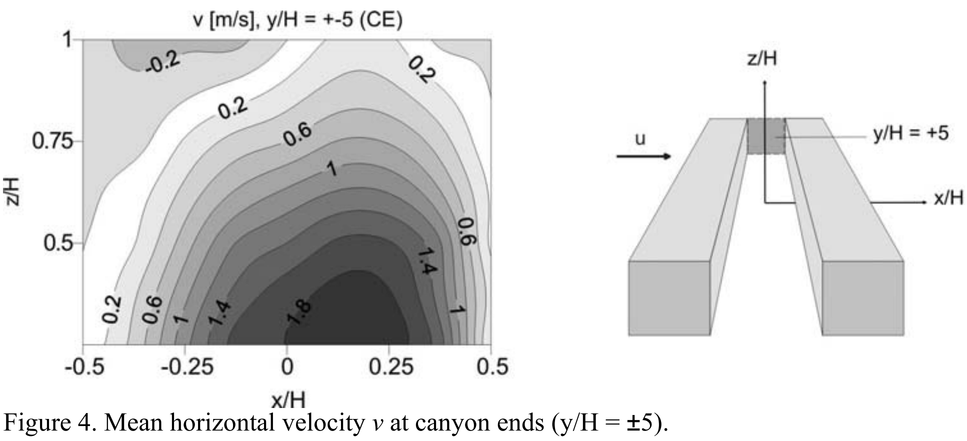

Figure 4. Mean horizontal velocity *v* at canyon ends (y/H = ±5).

The corner eddies, which separate at windward building A, enter the street canyon showing a somewhat eccentric center shifted to building B. Comparing the velocity values of the canyon vortex and corner eddies allows to quantify the contribution of the corner eddies to the pollutant removal and dilution in the canyon.

3.2 *Street canyon with trees of impermeable crowns of diameter 15 m and spacing 15 m*

The relative change in concentrations at walls A and B for a street canyon with one row of trees with spherical, impermeable crowns compared to the reference case without trees is depicted in Figure 5. With this arrangement, trees with spherical crowns of 15 m diameter were arranged along the canyon center axis at a distance of 15 m and a branch free trunk height of 4.5 m. 39 % of the street canyon volume was occupied by tree crowns.

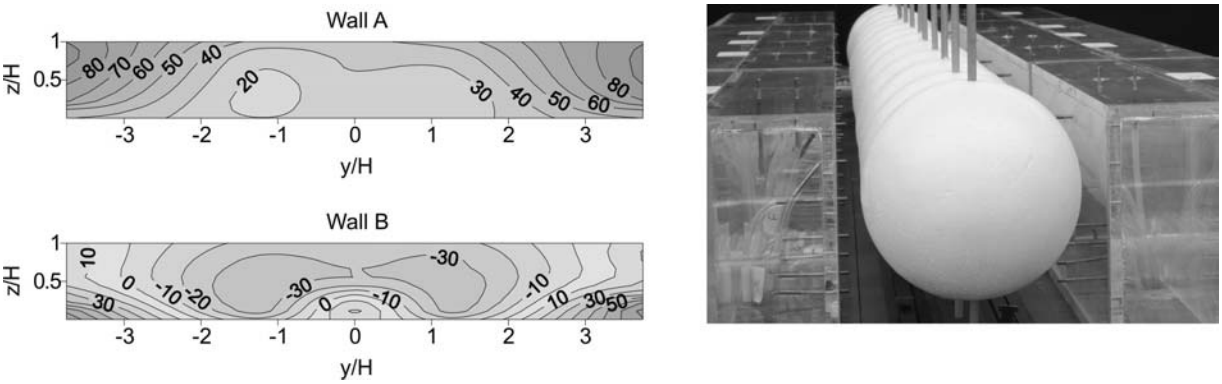

Figure 5. Relative change (%) in concentrations for street canyon with impermeable tree crowns of 15 m crown diameter and 15 m spacing when compared to reference case without trees (Figure 2).

Towards the canyon edges, strong relative concentration increases are found for both walls A and B. These increases can be attributed to the blockage of the laterally entering corner eddies by tree crowns. A significant increase of tracer gas concentration in the middle section of wall A (-2 < *y/H* < 2) is visible, indicating that the canyon vortex strength has been reduced. In the middle section of wall B a remarkable concentration decline is found. Apparently, the tree arrangement alters the flow field inside the canyon and the entrainment conditions at roof level, which lead to higher concentrations at wall A and smaller concentrations at wall B. When compared to the reference case without trees, the wall average concentration for wall A increases by 36 %, those of wall B decreases by 20 %.

In Figure 6, velocity plots of flow fields at roof level (*y/H* = 0) and at the sidewise street canyon ends (*y*/H = ± 5) are depicted. Regarding the canyon vortex, zones of airflow coming out as well as entering the street canyon are still to observe. However, whereas the values of up- and downwind for the configuration without trees showed values of almost the same size (Fig. 3), a considerable difference can be found in this case. The velocity of the downwind along wall B in the lee of the treetop is remarkably greater than the velocity of the upwind along wall A in front of the tree top. In comparison to the flow field at roof level of the reference case (Fig. 3), the entrainment situation is changed, suggesting considerable impacts on the flow field inside the street canyon.

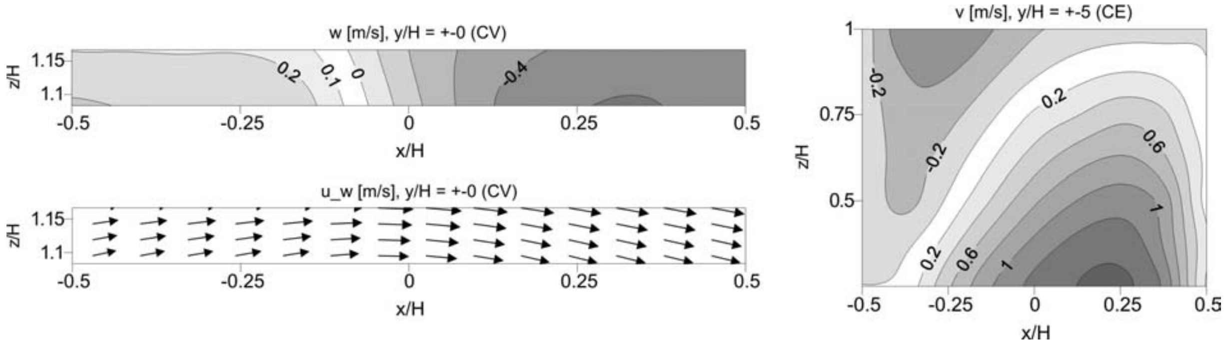

Figure 6. Velocity plots of central canyon vortex ($y/H = 0$) and sidewise corner eddies ($y/H = \pm 5$).

Moreover, since the free space between crown waists and canyon walls amounts to only 1.5 m, the formation of the canyon vortex is hindered or significantly damped. This explains the increase of concentration at wall A in the canyon middle part. In order to understand the decrease of concentration at wall B, one has to remember that the exhaust concentrations found in the reference case originate from traffic emissions released at the street level which have been transported by the canyon vortex itself towards wall B. Thus, the decrease of concentration at wall B, due to a reduced canyon vortex strength, becomes evident.

Concerning the flow fields at the sidewise canyon ends (Fig. 6), a remarkable decline of the horizontal velocity component v is found. The outermost tree crowns represent obstacles which hinder the corner eddies to enter the street canyon. As a consequence, the inflow volume rate is reduced by 39 % when compared to the reference case of Figure 4.

3.3 *Street canyon with trees of permeable crowns of diameter 15 m and spacing 15 m*

The change in relative concentration due to tree planting discussed in the foregoing chapter was based on investigations with impermeable tree crowns. However, real tree crowns consist of stems, leaves and stalks and form a permeable structure. In order to investigate the influence of crown permeability, spherical crowns with diameter 15 m have been manufactured, using porous foam characterized by 10 ppi (10 ppi stands for "10 pores per inch", see Fig. 7). Porosity measurements result in a relative pore volume of 97 %. The permeability expressed in terms of the pressure loss coefficient λ, i.e. static pressure loss Δp_{stat} per unit material thickness d normalized by the dynamic pressure Δp_{dyn}, was determined to λ = 210 - 275 Pa/(Pa*m) for flow velocities in the range of 0 to 7 m/s.

Figure 7 shows the relative change in concentration at the street canyon walls for trees with permeable crowns of 15 m diameter and 15 m tree spacing when compared to the configuration with impermeable crowns of chapter 3.2. At wall A, no pronounced deviations of the concentration distribution are detectible, the mean relative change in comparison to impermeable crowns amounts to + 4 %. At wall B, the relative change in concentration is somewhat stronger and amounts on an average to -15 %. Distinct concentration decreases are noticeable at the outer parts of wall B. Due to the permeability of the porous crown material, the corner eddies are blocked less effectively in comparison to the impermeable crown material. The enhanced lateral volume flow rate leads to a better dilution and reduced concentrations. However, all in all, no significant differences in absolute concentrations can be found when substituting impermeable by permeable tree crowns. This suggests that the influence of crown porosity on the pollutant dispersion is not of primary importance.

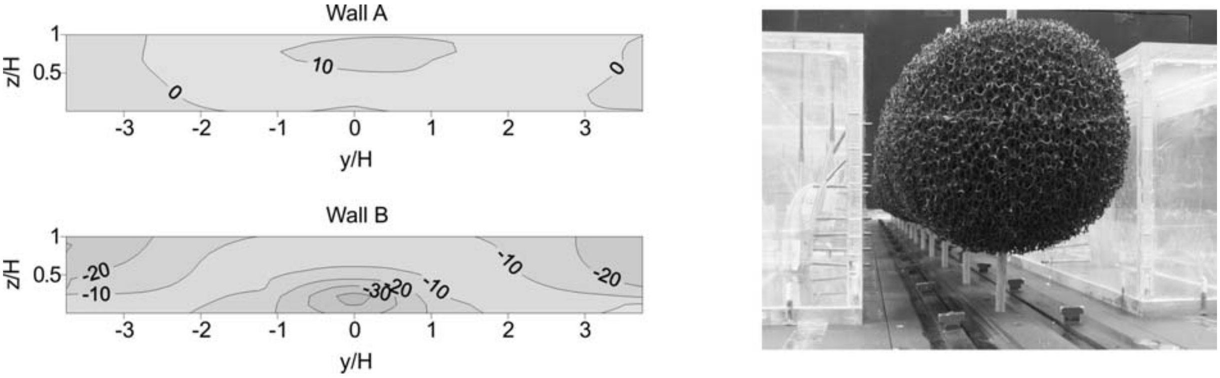

Figure 7. Relative change (%) in concentrations for street canyon with permeable tree crowns of 15 m crown diameter and 15 m spacing when compared to street canyon with impermeable tree crowns (Figure 5).

4 DISCUSSION

In the present article, the influence of an avenue-like tree plating on the dispersion of traffic exhausts and on the flow field within an urban street canyon have been discussed. Measurement results of wind tunnel studies with one row of trees positioned along the canyon center axis and a tracer gas emitting line source embedded in the street have been presented. Model trees with impermeable as well as permeable (97 % volume porosity) spherical crowns of diameter 15 m, arranged at a distance of 15 m, have been employed.

In regard to the concentrations at the canyon walls, high local relative increases (up to 90 %) have been found at the leeward canyon wall (wall A) when compared to the reference case without trees. At the windward canyon wall (wall B) moderate increases (50 %) as well as decreases (30 %) have been measured. The highest concentration increases occurred at the canyon ends where corner eddies are hindered in entering the street canyon by the tree crowns. All in all, the variation in wall average concentration for the configuration with impermeable crowns amounts to + 36 % for the leeward wall and to - 20 % for the windward wall (Fig. 5).

Concerning the flow field above the roof top, altered entrainment conditions with considerable consequences for the dispersion of traffic exhausts and the canyon vortex strength have been observed in the presence of trees. Moreover, it was found that the laterally entering of sidewise corner eddies is considerably hindered by the outermost tree crowns. LDV measurements showed a diminished lateral inflow volume rate of 39 % due to blocking effect of trees (Fig. 6).

The influence of crown porosity on the concentration field inside the street canyon turned out to be of less importance. No remarkable differences were found by a comparison between permeable and impermeable tree crowns (Fig. 7).

Beyond the investigations presented in this article, further concentration and velocity measurements in a street canyon with spherical, impermeable tree crowns of diameter 9 and 12 m have been performed. As before, the trees have been aligned in one row along the canyon center axis with spacing 15 m. For all these investigations, including the reference case without trees, an overview of wall averaged dimensionless concentrations is given in Figure 8. In the diagrams, the dimensionless (normalized) concentrations and the relative change in concentration when compared to the reference case (Fig. 2) for wall A and wall B are plotted against the percentage street canyon volume occupied by tree crowns. The dots (abscissa values of 8, 20 and 39 %) correspond to crown diameters of 9, 12 and 15 m, respectively. At the crown waists, the corresponding gaps between neighboring trees amount to 6, 3 and 0 m and to 4.5, 3, and 1.5 m towards the canyon walls.

For wall A, a steady increase in wall average concentration with increasing crown diameter is visible. In contrast, wall B shows a small decrease in pollution concentration for increasing crown diameter. In summary, tree plantings lead to an increase of the overall pollutant concentration due to traffic exhaust emissions inside an urban street canyon.

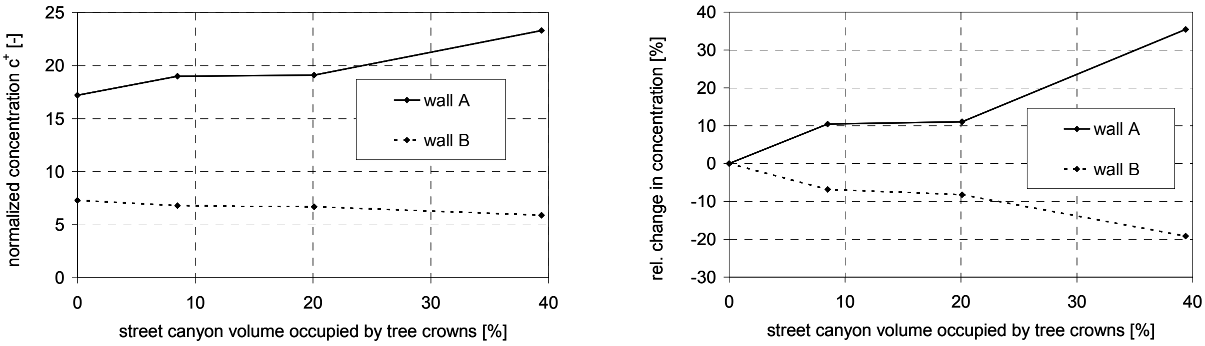

Figure 8. Wall averaged concentrations in dependency on street canyon volume occupied by tree crowns.

In Figure 9, the gross and net volume rates of flow entering the street canyon horizontally in direction of the street axis through the outermost cross sections at $y/H = \pm 5$ are shown. The gross flow rate denotes the total amount of flow rate entering the canyon through these cross sections. Subtracting the flow rate which leaves the canyon through these cross section delivers the net flow rate. As expected, a continuous decrease of gross and net flow rate is registered with increasing blockage of larger tree crowns.

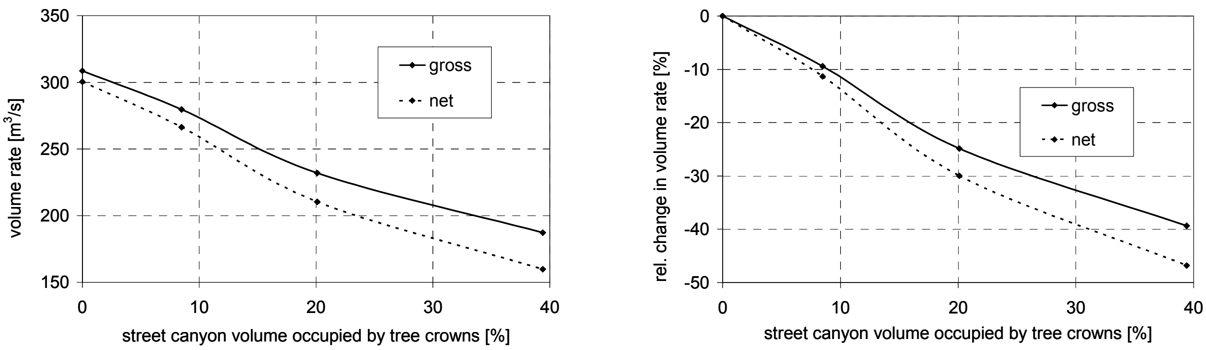

Figure 9. Volume rates of flow entering the street canyon horizontally through cross sections at y/H = ±5 in dependency on street canyon volume occupied by tree crowns.

A more detailed analysis of the wall concentrations in the presence of small-sized tree crows (9 m, i.e. 8 % of street canyon volume is occupied) reveals significant relative increases only at the street ends. No pronounced changes are observed in the canyon middle part, indicating the existence of a canyon vortex or canyon vortex-like structure. In the case of medium-sized tree crowns (12 m, i.e. 20 % of street canyon volume is occupied) enhanced concentrations were also found in the middle part of the canyon. As a rule of thumb and as a first approximation, the relative increase in wall average concentration at wall A can be set equal to the ratio of street canyon volume occupied by tree crowns to whole canyon volume.

5 CONCLUSION

Maximum concentrations were always found in the middle part of the canyon at the leeward wall A. When considering the dispersion of near-ground released traffic exhausts, a single row of trees planted at the street center axis leads to higher averaged wall concentrations at the leeward wall A and to somewhat lower concentrations at the windward wall B. The influence of tree planting is particularly noticeable towards the ends of the street canyon where the highest relative rises in concentration occur.

The results presented in this paper allow to formulate recommendations for city planners. Tree crowns should not occupy large canyon volumes. Otherwise, the natural ventilation is restrained leading to high rises of pollutant concentrations in the pedestrian level and at the leeward canyon wall. Sufficient free space between crowns and adjacent walls is of great importance in order to allow the canyon vortex or canyon vortex-like structures to develop. Moreover, a broad spacing between the trees ensures a better ventilation of the canyon. Leaving sufficient free space enables the atmospheric overflow to better intrude into the canyon and remove the polluted air.

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