Fachtagung "Experimentelle Strömungsmechanik"
4. – 6. September 2018, Rostock

On the Effects of street-flanking Hedge Rows on Traffic Pollutant Dispersion in Street Canyons

Über die Auswirkungen von straßenparallelen Heckenreihen auf die Ausbreitung von Verkehrsschadstoffen in Straßenschluchten

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Key words: air quality, vegetation, pollutant concentration, urban greening, porous barrier
Schlagworte: Luftqualität, Vegetation, Schadstoffkonzentrationen, Stadtgrün, poröse Barriere

Abstract

The dispersion of gaseous traffic pollutants in urban street canyons with centrally aligned roadside hedges was investigated. The study was performed in an atmospheric boundary layer wind tunnel using a reduced-scale (M = 1:150) canyon model. Various hedge row configurations of differing height, permeability were investigated. For a perpendicular approach wind, improvements in air quality in the street canyon were found in comparison to the hedge-free reference case. In the center of the street canyon, area-averaged reductions between 39% and 61% were observed below pedestrian head height level on the leeward side in front of the building. Improvements were also found in the areas at the lateral canyon ends next to the crossings for the central hedge arrangements. Apparently, hedge rows alter the ground-level flow field and, thus, the pollutant dispersion. It is concluded that continuous hedge rows can effectively be employed to control concentrations of traffic pollutants in urban street canyons. They can advantageously affect the air quality at street level and can be a significant remedy to the pedestrians' and residents' exposure in the most polluted street canyon center area (approximately one-third of the canyon length).

Introduction

The maximum air pollutant concentrations in cities usually occur in street canyons flanked by buildings where the natural ventilation is limited and traffic emissions accumulate at pedestrian level. In the context of passive pollutant control measures, solid and porous structures in urban street canyons, e.g. low boundary walls, noise protection walls, on-street parking cars, trees, shrubs, hedges, which affect flow and dispersion are increasingly discussed (Gallagher et al. 2015, Janhäll 2015). The effect of these structures in street canyons on air quality can be positive as well as negative. While low vegetation, e.g. hedges, can filter out particulate matter (PM) because of its proximity to the emission sources, high vegetation, e.g. trees, reduces the mixing and dilution with clean air from aloft and results in increased concentration levels.

Investigations of the effect of elongated solid and porous barriers (noise protection walls, vegetation strips) on the dispersion of traffic pollutants were mainly performed at roadsides outside central urban areas or along highways (e.g. Al-Dabbous and Kumar, 2014; Baldauf et al., 2008; Bowker et al., 2007; Hagler et al., 2012; Steffens et al., 2012; Tiwary et al., 2008). Regarding the impact of low vegetation such as shrubs or hedges inside urban street canyons on the dispersion of traffic pollutants, however, appropriate investigations are missing. Few studies examined the effect of rather wide shrub greenbelts on the dispersion of PM in urban roads flanked by low-rise buildings. Shan et al. 2007 studied the effect of 15 m wide shrub greenbelts on both sides of a road in Shanghai, China. For total suspended particulates, they measured removal efficiencies between 30% and 65%. Chen et al. 2015 investigated 2.5 m to 3.5 m wide shrub greenbelts along streets in Wuhan, China. PM_{10} removal efficiencies between 7% and 10% were found for shrubs with heights smaller than 1.60 m. In a recent study Li et al. 2016 measured carbon monoxide concentrations next to a road in Shanghai, China. In street sections which were flanked by hedge rows and trees, reductions in CO concentrations ranging from 24% to 53% were found on the footpath and bicycle way compared to vegetation free sections.

Since the knowledge regarding the impact of roadside hedges on air quality in urban street canyons is limited, the question arises whether or not roadside hedges in urban street canyons affect pollutant dispersion, and if so, whether and to what extent there exist any layouts or hedge attributes which are specifically beneficial in terms of mitigating pedestrians' and residents' exposure to traffic pollutants.

Experiment Setup and Measurement Technique

A reduced-scale street canyon model (scale M = 1:150) was used to study the dispersion of traffic pollutants in an atmospheric boundary layer wind tunnel. The street canyon was formed by two parallel aligned blocks representing full-scale dimensions for street length L = 180 m, building height H = 18 m, building breadth $B_A = B_B = 18$ m and street width W = 36 m, i.e. the aspect ratios were W/H = 2 and L/H = 10 (Fig. 1). Hedges were located at the center of the road between the traffic lanes. Hedge configurations of differing heights, porosities (permeabilities) were studied. In addition, low boundary walls, i.e. solid barriers, were investigated. As a reference case, a street canyon without hedge row / low boundary wall was investigated. The experiments were performed with wind approaching perpendicular to the street canyon length axis.

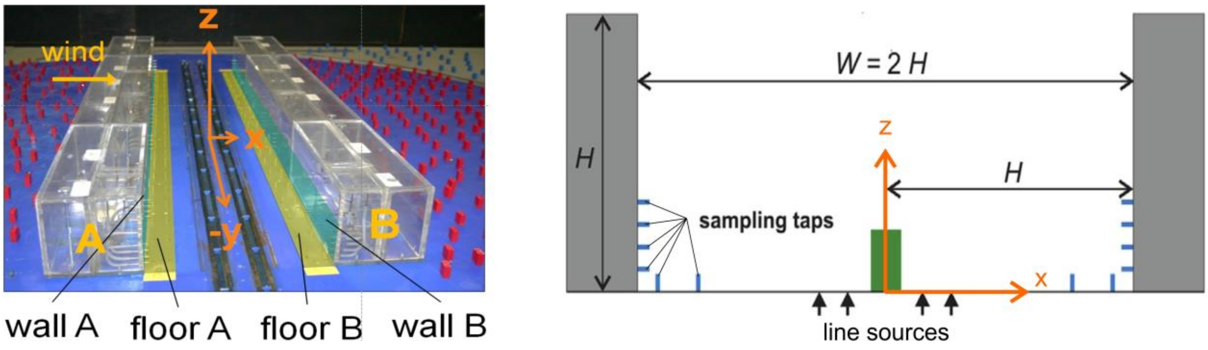

Fig. 1: Wind tunnel street canyon model and geometry.

For the pollutant dispersion experiments, an atmospheric boundary layer flow was simulated in the wind tunnel. The simulated vertical profiles of mean horizontal velocity U(z) and turbulence intensity I(z) can be described by power law formulations according to

$$\frac{U(z)}{U(z_{ref})} = \left(\frac{z}{z_{ref}}\right)^{0.30} \tag{1}$$

$$\frac{I(z)}{I(z_{ref})} = \left(\frac{z}{z_{ref}}\right)^{0.36} \tag{2}$$

where z_{ref} is the reference height which was taken here to be the building height H. According to various wind tunnel guidelines and recommendations, both profile exponents correspond to typical atmospheric boundary layer profiles over urban / suburban terrain. For a more detailed description of the simulated boundary layer flow the reader is referred to Gromke and Ruck 2005, Gromke 2009 or the Internet database CODASC 2008. For the present investigation, a flow velocity of $U(z_{ref} = H) = 4.65\ ms^{-1}$ was realized. The Reynolds number based on the building height H and the velocity u_H was $Re_H = 37.000$.

The release of traffic emissions was simulated by means of a mixture of a tracer gas (sulfur hexafluoride SF_6) and a carrier gas (air) that was emitted from four parallel line sources embedded at street level. For the concentration measurements, sampling taps were installed in the street canyon model at the bottom of the building walls, below H/3 = 6 m, and in the reduced-traffic zones at pedestrian level. In total, the street canyon model was provided with 136 sampling taps. The measured concentrations were normalized according to

$$c^{+} = \frac{c\, u_H H}{Q_l} \tag{3}$$

where c^{+} is the normalized concentration, c is the measured concentration, u_H is the free stream velocity at building height H, and Q_l is the source strength per unit length of the tracer gas emission.

In order to model hedges in the reduced-scale wind tunnel experiments, porous open-cell foam materials (reticulated foams) were employed. Two types of porous open-cell foams were employed, denoted by PPI-10 and PPI-20, where PPI stands for pores per inch. Both foams had a reasonable isotropic pore structure with pore volume fractions of 96.1% and 94.5%, respectively. The foam materials were processed to hedge models presenting full-scale hedge rows of height either $h_h = 1.50$ m or $h_h = 2.25$ m and width $w_h = 1.50$ m.

The aerodynamic performance of the porous foam materials was characterized by their pressure loss coefficients λ and by means of scaling laws aerodynamic similarity with full-scale hedges could be demonstrated, see Gromke et al. 2016, Gromke 2018, or Gromke and Ruck 2018 for more details.

Results

Fig. 2 and Fig. 3 show the normalized concentrations according to Eq. (3) measured at the street canyon without hedge (reference case - ref) and for a street canyon with a 1.50 m high hedge row made of foam PPI-20. A comparison of the contour plots in Fig 2 and Fig 3 reveals that the traffic pollutant concentrations in the street canyon with central hedge row are in general lower than in the reference street canyon without hedge except at the outer parts of the canyon close to y/H = ±5 where slightly higher concentrations appear. In particular in the center of the canyon, considerably lower concentrations are found. These reductions are highly valuable and beneficial in terms of people's exposure because the maximum and hence most critical traffic pollutant concentrations occur at the leeward side (floor A and wall A) in center area of the street canyon (Gromke et al. 2016).

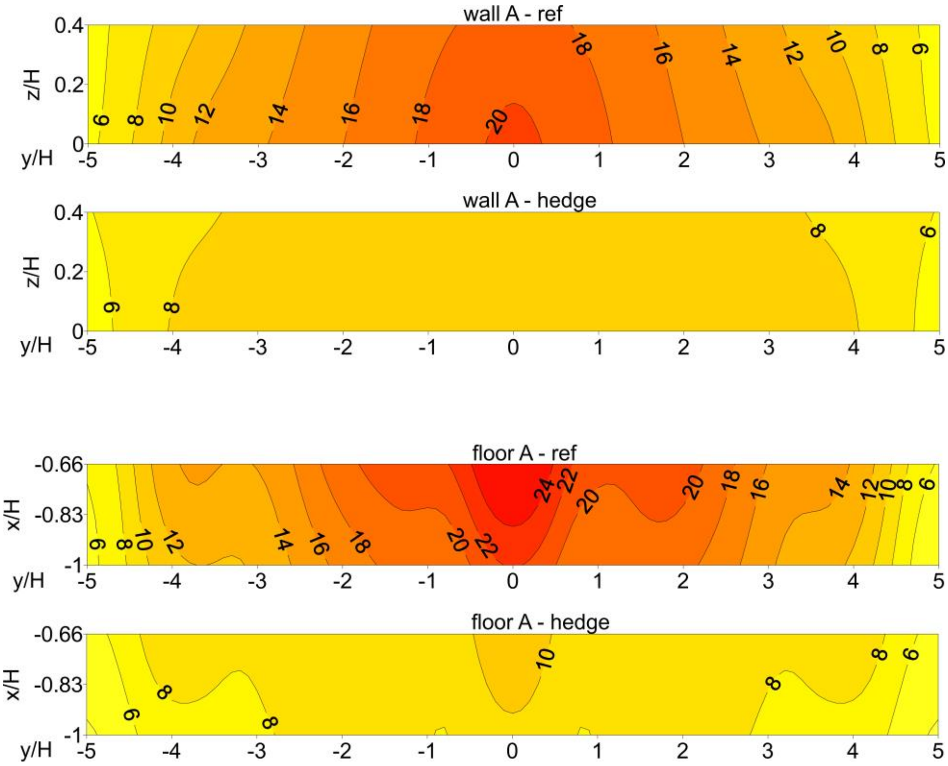

Fig. 2: Normalized pollutant concentrations c^+ on wall and floor at side A for reference case (no hedge) and street canyon with central hedge row of height h_h = 1.50 m made of foam PPI-20.

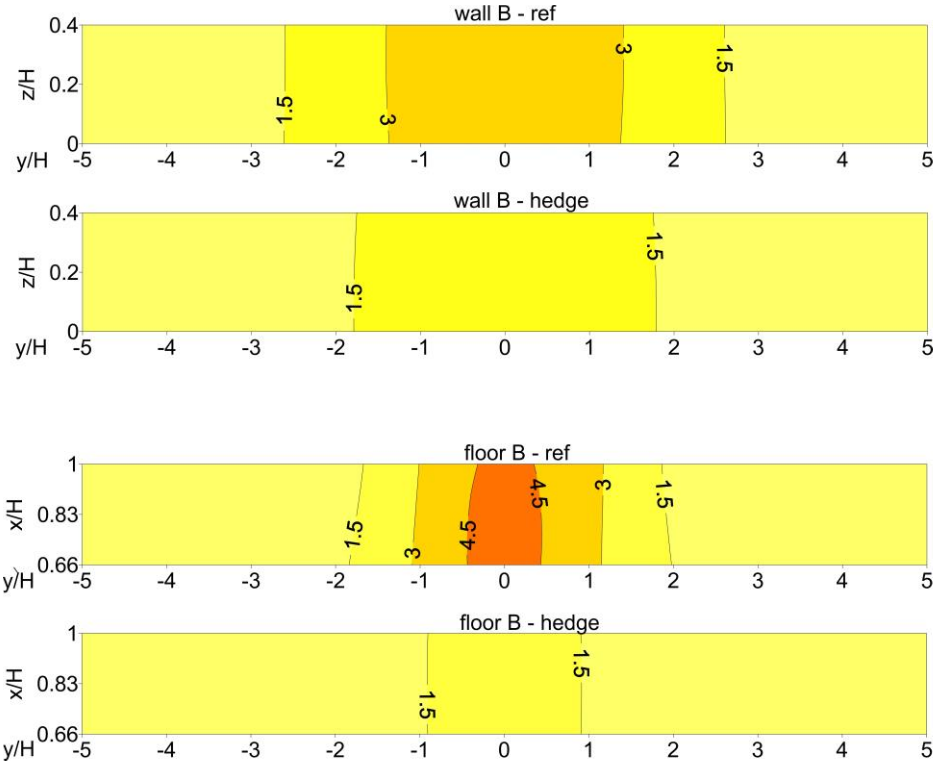

Fig. 3: Normalized pollutant concentrations c^+ on wall and floor at side B for reference case (no hedge) and street canyon with central hedge row of height h_h = 1.50 m made of foam PPI-20.

For the subsequent analysis and discussion of the concentration data, the street canyon was divided into areas which were sectioned along the length axis of the street canyon in regard to the dominating flow and vortex structures (see Gromke et al. 2016), i.e. the corner vortex, the corner eddy, and a superposition of both (Fig. 4):

- area I (-2.0 ≤ y/H ≤ +2.0), area of the street canyon where the canyon vortex is the only dominating larger flow structure
- area II (|±2.0| < y/H ≤ |±3.5|), area of the street canyon where the canyon vortex and the corner vortex are the dominating larger superimposing flow structures
- area III (|±3.5| < y/H ≤ |±5.0|), area of the street canyon where the corner vortex is the only dominating larger flow structure

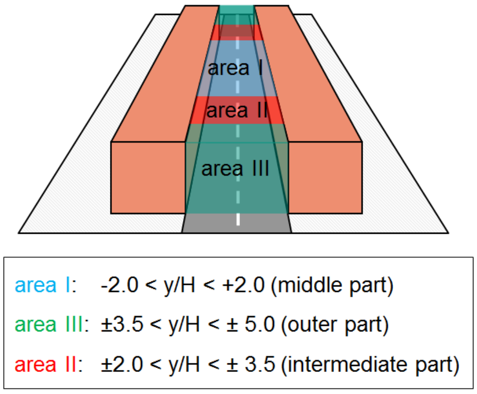

Fig. 4: Areas in the street canyon.

For these areas, relative area-averaged differences separated for the two canyon sides A or B and the wall or floor zones were calculated according to

$$\Delta c^{+}_{\text{rel,area}} = \frac{\sum_{i}^{N} c^{+}_{i(\text{hedge,lbw})} \qquad \sum_{i}^{N} c^{+}_{i(\text{ref})}}{\sum_{i}^{N} c^{+}_{i(\text{ref})}} \tag{4}$$

where i is the ith sampling tap and N is the total number of samplings taps in an area. Since the concentrations on the windward side (floor B and wall B) of the street canyon are comparatively low, in the remainder, the focus is laid on the leeward side (floor A and wall A).
The area-averaged differences in pollutant concentrations $\Delta c^{+}_{\text{rel,area}}$, see Eq. (4), at the canyon leeward side (floor A and wall A) for streets with hedge rows / low boundary walls are presented in Fig. 5. All investigated arrangements resulted in traffic pollutant decreases in all areas, with stronger reductions in the floor than in the wall zones, except for the 1.50 m high wall. In the area with the largest concentrations, area I, reductions between 38% and 65% were attained. This is particularly beneficial in terms of people's exposure to the maximum concentrations. The area-averaged differences decreased from the center area towards the end areas of the canyon.
Overall, the impact of a central hedgerow on the traffic pollutant concentration in the floor zone was larger than in the wall zone, where in vast parts of the street canyon, reductions of 50% and more were found for most hedge configurations. The contaminated air flowing in the near-ground level from the windward to the leeward side is partly blocked by the central hedgerow and deflected upwards. This shelters the floor A and wall A zones from direct exposure to the advected pollutants originating from the traffic lanes on the windward side of the street canyon. The pollutant concentrations measured in the floor A and wall A zones in the center area originate largely from the leeward side traffic lanes itself, and explains the approximately 50% reduction in the presence of hedgerows when compared to the hedge-free reference case.

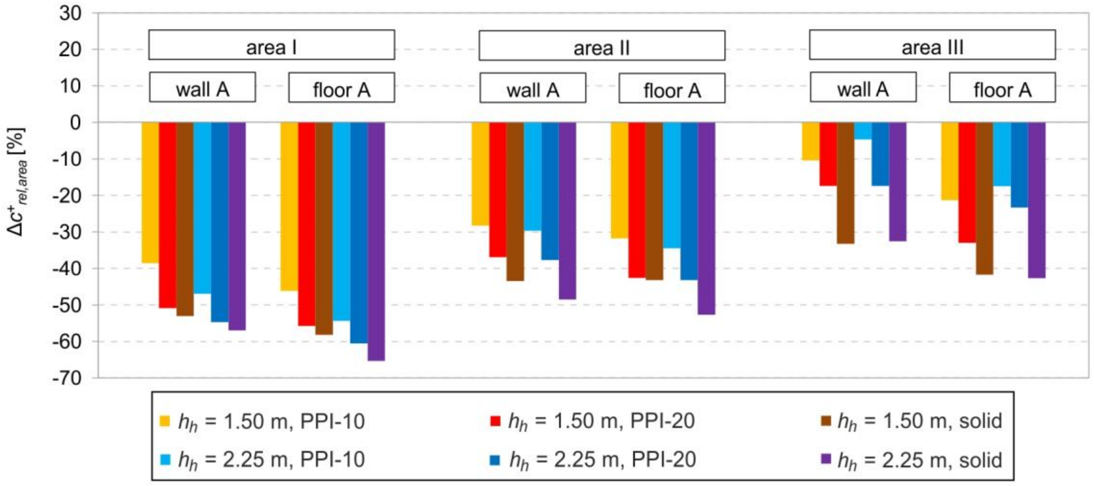

Fig. 5: Area-averaged differences in pollutant concentrations $\Delta c^{+}_{rel,area}$ for street canyons with hedge rows and low boundary walls referred to the reference street canyon without hedge.

An analysis of the hedge attributes and their impact on and relevance to the concentrations shows in general larger reductions with decreasing hedge permeability (larger PPI values), with the additional gains being more pronounced for the hedge / low boundary wall of lower height. However, in the wall zone, the differences between the hedges with the larger permeability and the walls were hardly identifiable. The effect of an increasing hedge height h_h, in the center area of the street canyon, was to further reduce the traffic pollutant concentrations. This effect was strongest for the low permeability hedges. However, an overall predominance of the permeability over the height as for the sidewise hedge row arrangements cannot be observed. Excluding the low boundary walls, the largest reductions were achieved for the highest hedge with the smallest permeability. For a more detailed analysis and discussion of the concentration data, the reader is referred to Gromke et al. 2016.

Conclusions

For perpendicular approach wind, the centrally aligned hedge rows and low boundary walls resulted in improved air quality in the street canyon. The improvements in air quality were larger in the floor zones in front of the buildings than in the wall zones at the bottom of building facades. The maximum reductions occurred in the center area of the street at the leeward canyon side where area-averaged reductions of up to 61% were measured. These reductions are of particular relevance to urban planning and street design since here the highest concentrations in traffic pollutants occur. Decreases in area-averaged concentrations, although less pronounced, were also observed at the lateral end areas of the street canyon. The reductions in gaseous traffic pollutant concentrations were larger for the higher and for the less permeable hedge configurations. Low boundary walls, also resulted in air quality improvements which outperformed those obtained with the hedge rows.

It is emphasized that in the present study, the dispersion of gaseous pollutants was investigated but the effect of hedges to filter out particulate matter (PM) was not addressed. The finding of increasing improvements in air quality with decreasing hedge permeability, including low boundary walls, is restricted to gaseous pollutants. However, the investigations indicate that continuous hedge rows can be employed as an effective passive control measure for air quality in urban street canyons. They can beneficially affect the dispersion of traffic pollutants at street level as well as at the bottom of the building facades and considerably remedy the exposure of pedestrians and residents in the strongest polluted areas in street canyons.

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