Interaction of traffic pollutant dispersion with trees in urban street canyons

Citation for published version (APA):
Gromke, C. B., & Ruck, B. (2010). Interaction of traffic pollutant dispersion with trees in urban street canyons. In *Proceedings of the CLIMAQS Workshop 'Local Air Quality and its Interactions with Vegetation', January 21-22, 2010, Antwerp, Belgium* (pp. 93-97).

Document status and date:
Published: 01/01/2010

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 17. Nov. 2023

Interaction of traffic pollutant dispersion with trees in urban street canyons

Christof GROMKE[1,2,*], Bodo RUCK[2]

[1] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

[2] Institute for Hydromechanics, Karlsruhe Institute of Technology KIT, Germany

* Corresponding author: gromke@slf.ch

Introduction

In the present study, wind tunnel measurements of traffic-originated pollutant concentrations and dispersion processes in urban street canyons with trees are investigated. 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, 2009a,b), Gromke et al. (2008), Gromke (2009), 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.

Material and methods

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 (sulfur 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

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

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

A typical urban atmospheric boundary layer flow with power law exponents of α=0.30 for the mean velocity profile and α_I=-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.

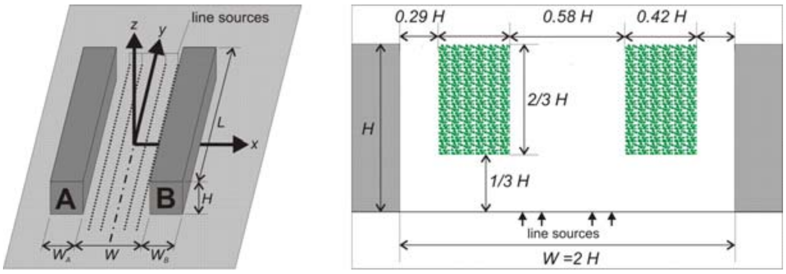

Fig. 1. Street canyon geometry and tree planting arrangement (W_A=W_B=H).

Small scale modeling of trees and similarity criterion

Tree crowns are porous objects and permeable to air flow. The flow past porous objects differs crucially from the flow 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}=96.0% (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 (ρ=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 ρ=0.5, ρ=0.33, etc.) However, in the present paper, tree planting of high stand density (ρ=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

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

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 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.

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 $\lambda_{\text{full scale}}$ ranging from 0.4 m^{-1} to 13.4 m^{-1} with the majority lying in the range of $1.0\ m^{-1} < \lambda_{\text{full scale}} < 3.0\ m^{-1}$.

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.

$$[\Delta p / p_{dyn}]_{\text{full scale}} = [\Delta p / p_{dyn}]_{\text{small scale}} \tag{3}$$

which, with Eq. (2), yields to

$$\frac{\lambda_{\text{full scale}}}{\lambda_{\text{small scale}}} = \frac{d_{\text{small scale}}}{d_{\text{full scale}}} = M\,. \tag{4}$$

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 $\lambda_{\text{small scale}}$ is now straightforward and using the values found by Grunert et al. (1984), one obtains $120\ m^{-1} < \lambda_{\text{small scale}} < 4000\ m^{-1}$ whereas the great majority lies in the range of $300\ m^{-1} < \lambda_{\text{small scale}} < 900\ m^{-1}$.

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. 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.

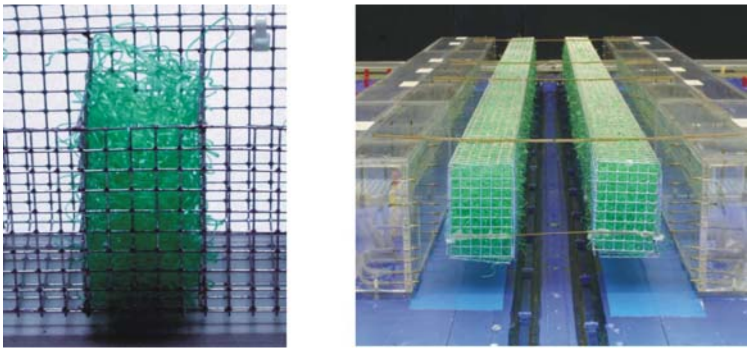

Fig. 2. Wadding material incorporated in single cage cell; street canyon with two-rowed avenue-like tree planting (W/H=2).

Results and discussion

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, top, 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.

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. 3, middle) are found in comparison to the tree-free reference case (Fig. 3, top). The relative increases in the canyon central part of wall A are 58 %, whereas the relative decreases in the central part of wall B are 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.

Street canyon W/H=2 with tree planting of low crown porosity (P_{Vol}=96.0%)

In the case of lower crown porosity (P_{Vol}=96.0%), the overall pollutant concentration pattern (Fig. 3, bottom) is similar to that found for the high crown porosity tree planting shown in Fig. 3, top. 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 61% 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%.

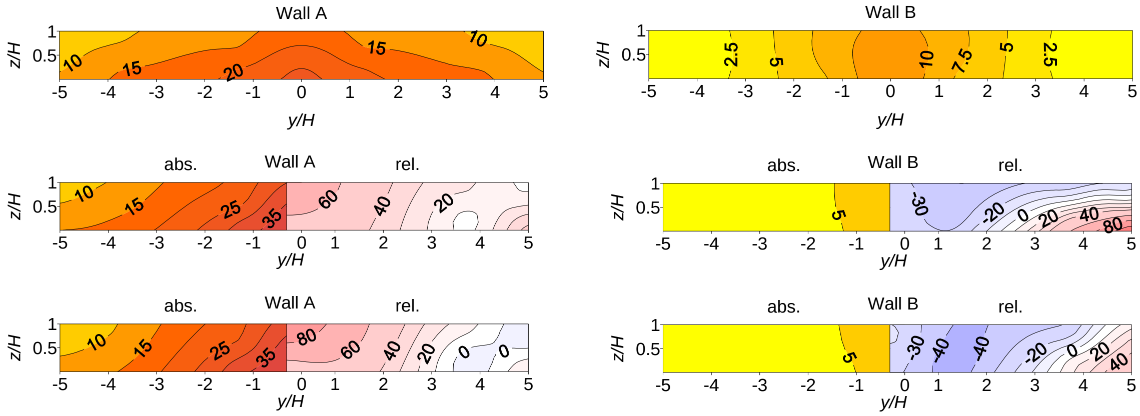

Fig. 3. Normalized pollutant concentrations [-] and relative deviations in concentrations [%] for the tree-free street canyon (top), the street canyon with tree planting of high (P_{Vol}=97.5%) and low (P_{Vol}=96.0%) crown porosity (middle and bottom). Relative deviations in concentrations refer to the tree-free street canyon.

Conclusion

Avenue-like tree planting in street canyons lead all in all to 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 (Table 1). Since the concentrations at leeward wall A are usually much higher than at windward wall b, the net effect is an increase of concentrations in the canyon. This effect is stronger pronounced for lower tree crown porosities.

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

Street canyon	Concentration [-] and rel. change to reference case [%] in ()		
	wall average		wall maximum
	A	B	A
without trees	14.8 (-)	5.2 (-)	24.2 (-)
with high c.p. (PVol=97.5%)	20.7 (+40)	3.9 (-25)	38.2 (+58)
with low c.p. (PVol=96.0%)	20.8 (+41)	3.6 (-32)	38.9 (+61)

The 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 a critical exceedance of pollutant concentration limits and may cause hazardous conditions for the residents. Generally, it can be recommended for intra-urban arterial roads 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-released pollutant concentration levels.

Finally, based on wind tunnel experiments comprising more than 40 street canyon/tree planting configurations with varying (i) ratios (W/H=1, 2) of street width to building height, (ii) one- or two-rowed tree planting, (iii) stand density (ρ=0.5, 1.0), (iiii) crown porosity (P_{Vol}=0.0%, 96.0%, 97.5%, 100.0%), (iiiii) approaching wind direction (α=0°, 45°, 90°)**,** a relationship for the maximum pollutant concentration c^+_{max} at the canyon wall has been derived

$$c^+_{max} = a_1 - a_2 \exp\{- a_3 [\rho(100 - P_{Vol})]\} \tag{5}$$

with

$$a_i = c_{i1} + c_{i2} a_r + c_{i3} \alpha + c_{i4} \alpha^2 + c_{i5} a_r \alpha + c_{i6} a_r \alpha^2 \tag{6}$$

and a_r=W/H (aspect ratio) and the coefficients c_{ij} according to Table 2. A detailed derivation of Eq. (5) and Eq. (6) is given in Gromke (2009).

Table 2. Coefficients c_{ij}.

i	c_{i1}	c_{i2}	c_{i3}	c_{i4}	c_{i5}	c_{i6}
1	55.3	-23.8	94.2	-48.7	-15.5	10.7
2	14.1	-5.3	41.0	-17.6	6.4	-6.0
3	0.0	0.9	0.3	-0.2	-0.8	0.4

References

Balczó, M., Gromke, C., Ruck, B., 2009. Numerical modeling of flow and pollutant dispersion in street canyons with tree planting. Meteorologische Zeitschrift 18, 197-206.

CODASC 2008 Concentration Data of Street Canyons. Internet data base, www.codasc.de.

Gromke, C., Ruck, B., 2005. Die Simulation atmosphärischer Grenzschichten in Windkanälen. Proc. 13. GALA Fachtagung "Lasermethoden in der Strömungsmesstechnik". 13, 51/1-51/8.

Gromke, C., Ruck, B., 2007. Influence of trees on the dispersion of pollutants in an urban street canyon - Experimental investigation of the flow and concentration field. Atmospheric Environment 41, 3287-3302.

Gromke, C., Ruck, B., 2008. Aerodynamic modeling of trees for small scale wind tunnel studies. Forestry 81, 243-258.

Gromke, C., Buccolieri, R., Di Sabatino, S., Ruck, B., 2008. Dispersion modeling study in a street canyon with tree planting by means of wind tunnel and numerical investigations - Evaluation of CFD data with experimental data. Atmospheric Environment. 42, 8640-8650.

Gromke, C., Ruck, B., 2009a. Effects of trees on the dilution of vehicle exhaust emissions in urban street canyons. International Journal of Environment and Waste Management 4, 225-242.

Gromke, C., Ruck, B., 2009b. On the Impact of Trees on Dispersion Processes of Traffic Emissions in Street Canyons. Boundary-Layer Meteorology 131, 19-34.

Gromke, C., 2009. Einfluss von Bäumen auf die Durchlüftung von innerstädtischen Straßenschluchten. Dissertationsreihe am Institut für Hydromechanik IfH der Universität Karlsruhe (TH), Heft 2008/2, Karlsruhe 2009.

Gross, G., 1987. A numerical study of the air flow within and around a single tree. Boundary Layer Meteorology 40, 311-327.

Grunert, F., Benndorf, D., Klingbeil, K., 1984. Neuere Ergebnisse zum Aufbau von Schutzpflanzungen. Beiträge für die Forstwissenschaft 18, 108-115.

Ruck, B., Schmidt, F., 1986. Das Strömungsfeld der Einzelbaumumströmung. Forstwissenschaftliches Centralblatt 105, 178-196.