

Modeling vegetation in Wind Engineering wind tunnel studies

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ABSTRACT: A vegetation modeling approach for Wind Engineering wind tunnel studies is presented. The approach is based on fluid dynamical similitude. It enables the small-scale modeling of different vegetation types, e.g. trees, shrubs, hedges, forests and field crops. Its suitability and applicability is demonstrated by wind tunnel pollutant dispersion investigations. To this end, tree-avenues in an urban street canyon were modeled and their effect on pollutant concentration was investigated. The experiments substantiate the modeling approach to be practicable for wind tunnel studies and suggest to provide small-scale results which can be reliably transferred to full-scale.

KEYWORDS: vegetation, wind tunnel, similarity, trees, street canyon, tree-avenue

1 INTRODUCTION

The transfer of small-scale wind tunnel findings to full-scale requires the adherence to similitude which is expressed by similarity criteria. Whereas for investigations of buildings and civil engineering structures classical bluff body aerodynamic similarity criteria are well-defined and proved in practice, rather few knowledge and experience is available for the appropriate modeling of vegetation. In contrast to classical bluff body structures, vegetation is permeable to wind and from a general fluid mechanical point of view, a highly complex porous medium consisting of stems, branches, stalks and leafs or needles, all giving rise to the development of boundary layers. Flow past porous bodies differs essentially from flow past non-porous bodies. Wakes extend further downstream, recirculation zones are, in case they exist, detached from the leeward body side and skin friction contributes considerably to the overall drag due to large volume specific surface areas. Skin friction can no longer be neglected as with bluff bodies, where the pressure difference on the windward and leeward sides dominates the drag. Moreover, vegetation is relatively flexible and susceptible for oscillating motions giving rise to fluid-structure interactions. Trees adjust their shape when subjected to wind and show varying aerodynamic properties when exposed to moderate and strong winds [1], [2], [3]. Consequently, principles and similarity criteria of classical bluff body aerodynamics cannot be carried forward directly to the modeling of vegetation.

In the following, after a short review of existing wind tunnel vegetation modeling approaches, a new approach is introduced. The modeling approach is validated using the results from wind tunnel experiments of pollutant dispersion in urban street canyons with tree-avenues.

2 REVIEW OF WIND TUNNEL VEGETATION MODELING APPROACHES

So far, only a few wind tunnel studies have been performed which explicitly include the small-scale aerodynamic modeling of vegetation. In these studies, vegetation has often been represented by model railway scenery accessories, e.g. [4], [5]. Moreover, brushes, metal screens, boughs, cotton balls, wooden pegs, matches and plastic stripes have been utilized [6]. Most of these materials have been used to model wind shelterbelts rather than single trees or forest stands. [6] investigated wind and turbulence characteristics in and above a model forest. The forest was assembled by tree models made up of plastic bough imitations and validated by arguing that drag coefficients and general wake characteristics agree well with those of real trees. In another study, [7] used pipe cleaners to simulate wind shelterbelts consisting of conifers. Attention was paid to comply with the Jensen number (ratio of shelterbelt height H to aerodynamic roughness length z_0) which was considered to be the dominating similarity criterion. Flow and stem ground-level bending moment measurements were performed by [8] at an aeroelastic forest model. The tree models were developed by Gardiner in Edinburgh (UK) according to aerodynamic and structure dynamical similarity criteria. The trees were made of injection-molded Nylon-66 stems with low density Polyethylene branch elements. Special attention was given to the branch element design in order to realize appropriate drag coefficients. Furthermore, tree model mass and stiffness were adjusted to match the natural sway frequency. [9] investigated flow fields in forest clearings in a wind tunnel study. Their forest was made of flexible tree models with eigenfrequency of 2.2 Hz. The foliage was modeled by plastic stripes which were attached to two interwounded steel wires forming the tree trunk. This approach allowed to simulate distinct leaf area densities or indices. More recently, [10] and [11] employed metallic mesh rings to model a forest. Their aim was to simulate the mean flow and turbulence characteristics in the above canopy region in order to study the exchange of biogenic emission with the atmosphere. By comparison with full-scale measurements, they concluded that their forest model satisfactorily simulates the mean flow and turbulence structure in the above canopy region. A further example for the modeling of forest stands can be found in [12]. In this study an open-porous foam material (foam 10 ppi - pores per inch) was used and the storm stability of the near forest edge region was investigated. Their results showed that the design of the near forest edge region is crucial for its storm stability. [13] found that the drag coefficient of model railway scenery conifer trees lies in the range for natural conifer trees and employed a wind tunnel forest set up of those tree models to validate numerical simulations of flow over forest clearings. [14] built wind tunnel tree models using filamentous materials which were enlaced and formed to porous crowns of spherical shape. Different porosities were realized by the amount of filamentous material used to form the crown. They demonstrated that the approach enables the aerodynamic modeling of trees in terms of drag and wake characteristics.

3 MODELING APPROACH

3.1 *Vegetation modeling approach*

Tree-avenues were modeled for wind tunnel investigations of pollutant dispersion in urban street canyons. For this purpose, a line-like lattice cage construction of street canyon length with equally sized cells was built and filled with a filamentous synthetic wadding material (Figure 1). Trunks were not modeled as they are fairly small compared to the crowns and their influence on the flow past trees is negligible.

The approach allows to model tree-avenues of different stand density (trees per unit length) and crown porosity (pore volume fraction), see also [15], [16]. Different stand densities can be realized by filling every n th cell ($n = 1, 2, 3, \dots$) and different crown porosities by filling the cells with defined masses of the wadding material. For the present study, tree-avenues of maximum stand density ($n = 1$) and crown porosities with pore volume fractions of $P_{Vol} = 97.5\%$ and $P_{Vol} = 96.0\%$, typical for deciduous trees, e.g. [17], [18], were realized.

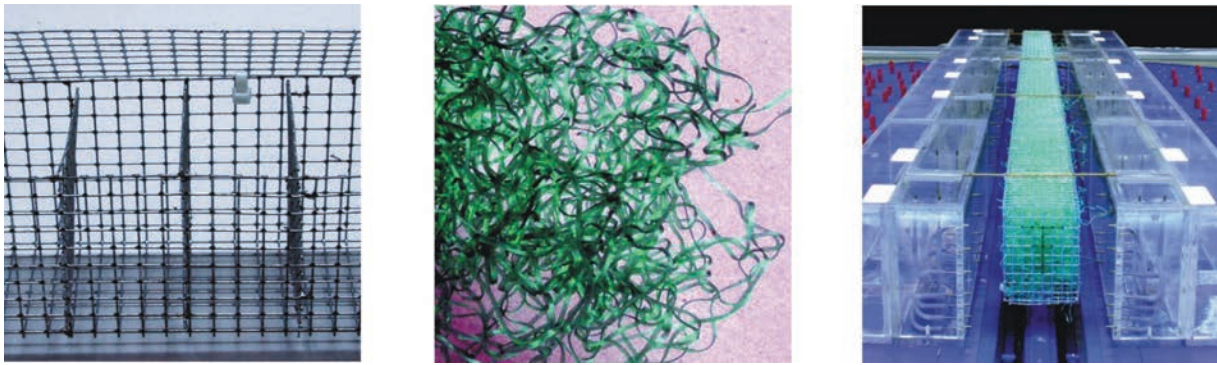


Figure 1. Close-up of lattice cage, filamentous wadding material, and street canyon model with tree-avenue.

In addition to the pore volume fraction, the texture of porous media, i.e. the form, arrangement and size distribution of the pores and their wall roughness as well as their orientation to the flow influence the wind permeability. A definite measure for the permeability of porous media is given by the pressure loss coefficient λ [m^{-1}]. The pressure loss coefficient is determined in forced convection flows, see Figure 2 (left), according to

$$\lambda = \frac{\Delta p_{st}}{p_{dyn} d} = \frac{p_{windward} - p_{leeward}}{0.5 \rho u^2 d} \quad (1)$$

where Δp_{st} is the static pressure drop [Pa] over the porous media of streamwise thickness d [m], p_{dyn} is the dynamic pressure [Pa] and u is the bulk velocity [ms^{-1}].

Figure 2 (right) shows the measured pressure loss coefficients λ for different flow speeds. No pronounced dependency of λ on u is visible for both porosities. The slight decreases in λ with increasing u for $P_{Vol} = 96.0\%$ is attributed to viscous effects. A deformation or compaction of the wadding material samples was not observed in the tested flow speed range. From these measurements, the pressure loss coefficients were determined to $\lambda = 80 \text{ m}^{-1}$ and $\lambda = 200 \text{ m}^{-1}$ for the tree model crowns of high ($P_{Vol} = 97.5\%$) and low ($P_{Vol} = 96.0\%$) porosity, respectively.

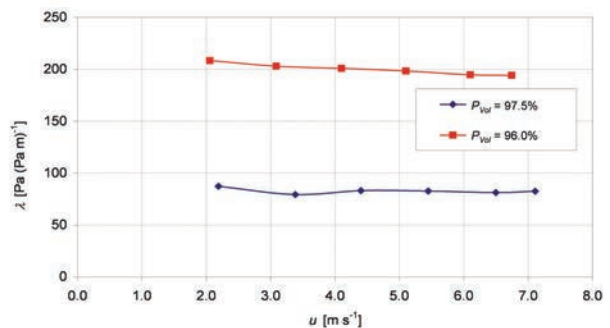
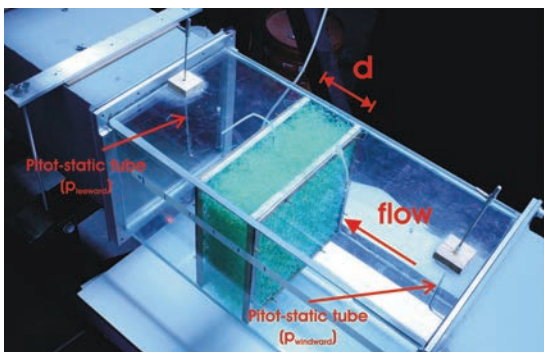


Figure 2. Forced convection flow setup for measuring pressure loss coefficient λ [m^{-1}], and pressure loss coefficient λ vs. flow speed u .

As already stated in the introduction, fluid dynamical similarity is required in order to transfer the wind tunnel model results to full-scale. In the present modeling approach, a similarity criterion is established based on energy considerations. Postulating equality in the normalized static pressure drops $\Delta p_{st}/p_{dyn}$ for forced convection flows in full-scale (fs) and in small-scale (ss), i.e.

$$\left[\frac{\Delta p_{st}}{p_{dyn}} \right]_{fs} = \left[\frac{\Delta p_{st}}{p_{dyn}} \right]_{ss} \quad (2)$$

ensures that the flow potential energy which is extracted by the resistance of the porous media relative to the flow kinetic energy is equal in both scales. This gives with Equation 1

$$\frac{\lambda_{fs}}{\lambda_{ss}} = \frac{d_{ss}}{d_{fs}} = M \quad (3)$$

with M [-] the wind tunnel model scale.

Applying Equation 3 to the tree models, results with the wind tunnel model scale $M = 1:150$ in up-scaled pressure loss coefficients of $\lambda_{fs} = 0.53 \text{ m}^{-1}$ and $\lambda_{fs} = 1.33 \text{ m}^{-1}$. For the purpose of comparison and validation, pressure loss coefficients λ of vegetation shelterbelts formed by broad-leaved trees measured in forced convection flows by [19] are provided in Table 1. It has to be noted that these shelterbelt values are the most appropriate data available as pressure loss coefficients of tree crowns lack.

Table 1. Pressure loss coefficients $\lambda [\text{m}^{-1}]$ for leaved vegetation shelterbelts [19].

density ρ_s^a	1.33	1.00	0.67
poplar	1.2 - 3.6	0.8 - 2.4	0.5 - 1.5
Norway maple	1.5 - 3.5	1.1 - 2.5	0.7 - 1.6
field maple	4.7 - 8.9	3.5 - 6.9	2.2 - 4.0
small-leaved lime	1.5 - 4.0	0.9 - 2.3	0.4 - 1.5
bird cherry	1.5 - 13.4	1.2 - 6.5	0.6 - 3.1

^a density ρ_s refers to the branch arrangement in the shelterbelt. $\rho_s = 1.00$ is the 'normal density'.

From Table 1 it can be seen that the up-scaled tree model pressure loss coefficients λ_{fs} are in agreement with the values of [19] for thinned out shelterbelts ($\rho_s = 0.67$). The reason for employing the thinned out values is that the branch and foliage arrangement in ground-near shelterbelts of rather shrub-like stature appears to be denser and more uniform than in elevated tree crowns. In elevated tree crowns, most of the foliage is concentrated at the crowns' envelopes whereas the crowns' interiors are almost empty. Based on this argument it is hypothesis that the thinned out shelterbelt pressure loss coefficients are more adequate for the validation.

3.2 Urban street canyon model

The line-like lattice cage was positioned in a generic urban street canyon model with aspect ratios $W/H = 1$ and $L/H = 10$ ($H = 0.12 \text{ m}$). The whole setup was placed in a wind tunnel and subjected to perpendicular approaching flow simulating an urban-type atmospheric boundary layer of model scale $M = 1:150$ (Figure 3). For more detailed information on the boundary layer wind tunnel characteristics, the reader is referred to [20] or to the internet database CODASC - Concentration Data of Street Canyons [21].

The Reynolds number Re based on the velocity u_H of the undisturbed flow at building height H is equal to 37000, ensuring a Reynolds number independent flow field. Traffic emis-

sions were simulated by tracer gas emitting line sources according to functional principle described in [22]. Sulfur hexafluoride SF_6 was used as tracer gas. Measurement taps were applied along the leeward and windward canyon walls (hereafter referred to as wall A and wall B, respectively) to sample the near-façade canyon air. Mean concentrations were measured with Electron Capture Detection (ECD), model Meltron LH108. The measured concentrations c [-] were normalized according to

$$c^+ = \frac{c u_H H}{Q_T / l} \quad (4)$$

where Q_T/l [$\text{m}^3\text{s}^{-1}\text{m}^{-1}$] is the tracer gas source strength per unit length.

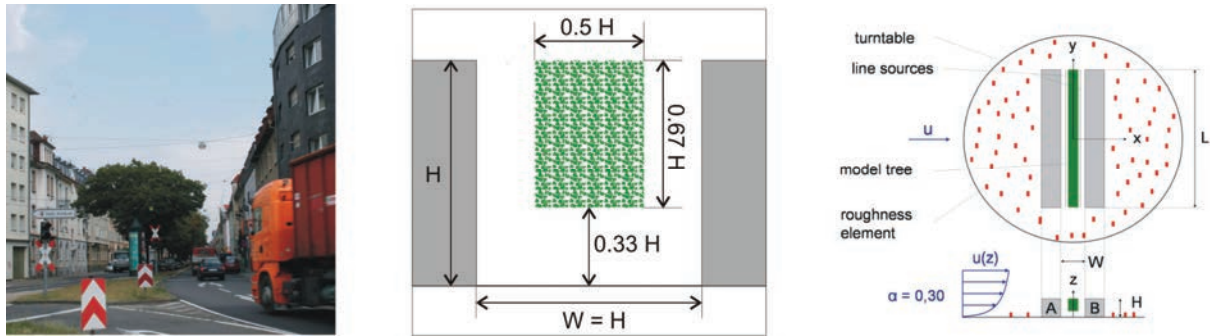


Figure 3. Urban street canyon with tree-avenue and geometry of generic model setup.

4 APPLICATION TO POLLUTANT DISPERSION STUDIES

Figure 4 shows contour plots of normalized pollutant concentrations c^+ [-] at the canyon walls A and B for tree-avenues of maximum stand density ($n = 1$). Starting with the tree-free street canyon at the top (a), tree crowns with decreasing permeability, i.e. increasing pressure loss coefficients λ were investigated, with $\lambda_{ss} = 80 \text{ m}^{-1}$ in (b) and $\lambda_{ss} = 200 \text{ m}^{-1}$ in (c). Finally, in (d), the tree-avenue model was formed by a solid block corresponding to an infinite pressure loss coefficient. The latter was considered as a limiting case revealing the highest possible concentrations. Please note that the vertical dimension z [m] and the along street dimension y [m] are normalized by the building height H and that only one half of the building walls is shown ($-5 < y/H < 0$) utilizing symmetry.

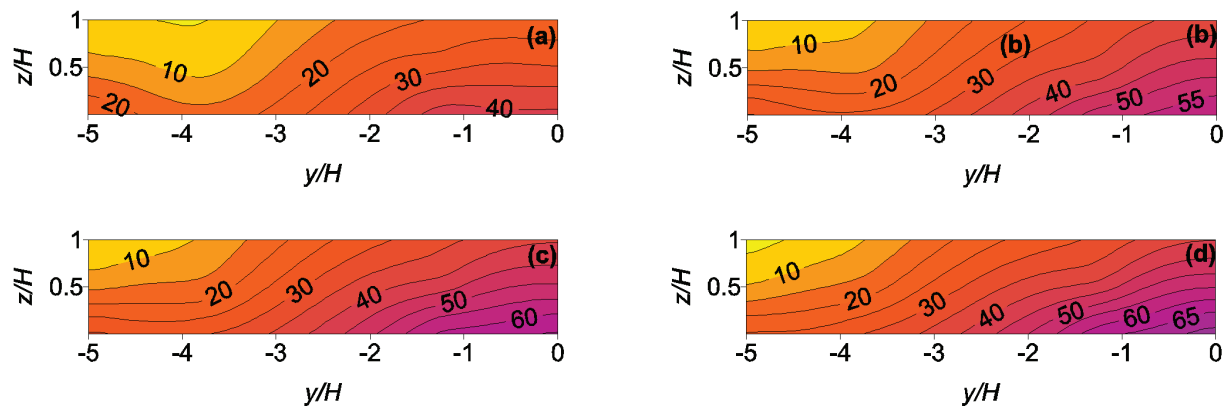


Figure 4. Normalized pollutant concentrations c^+ [-] at building wall A for (a) tree-free street canyon, (b) tree crown with $\lambda_{ss} = 80 \text{ m}^{-1}$, (c) tree crown with $\lambda_{ss} = 200 \text{ m}^{-1}$, and (d) solid block ($\lambda_{ss} = \infty$).

The contour plots of Figure 4 reveal the general implications of tree-avenues and crown permeability on traffic pollutant concentrations in urban street canyons. At the leeward canyon wall A, increasing traffic pollutant concentrations with decreasing crown permeability, i.e. increasing pressure loss coefficient λ , are visible. Both the wall average pollutant level and the peak concentration increase continuously.

In order to understand the influence of tree-avenues on the canyon wall concentrations, it is useful to consider the dominating flow and dispersion processes in the tree-free street canyon first. The flow field in the tree-free street canyon is dominated by two vortex structures, the canyon vortex and the corner eddies. Driven by the above roof wind, a clockwise rotating canyon vortex forms and entrains air into the street canyon in front of the windward wall B. On the reverse flow from wall B to wall A, the canyon vortex accumulates traffic exhaust emissions. Thus, the upward flow in front of the leeward wall A contains increased pollutant concentrations which are then partially entrained and mixed into the above roof wind before re-entrained into the street canyon again. At the street ends additional air exchange is provided by the corner eddies leading to reduced pollutant concentrations [23], [24]. In street canyons with tree-avenues, flow and pollutant dispersion are also dominated by the canyon vortex and corner eddies as was found by Laser Doppler velocimetry (LDV) measurements [23] and by CFD simulations [25], [26], [27]. However, the presence of trees leads to smaller flow velocities inside the street canyon and modified air exchange with the surroundings at the canyon roof and ends. Smaller flow velocities implicate a reduced volume flux of the canyon vortex. Consequently, the traffic exhaust emissions are less diluted and the concentrations in the upward flow in front of the leeward wall A are higher. The contour plots of Figure 4 indicate that these effects are stronger pronounced with decreasing crown permeability, resulting in continuously increasing traffic pollutant concentrations at the leeward wall A. Additionally, the tree crowns partly block the corner eddies and reduce the lateral air exchange which is reflected by increased concentrations at wall A close to the street canyon ends.

Figure 5 summarizes the influence of tree-avenues on pollutant concentrations at wall A. Shown are the relative changes $\Delta c/c_{ref}$ [%] in wall average and peak concentrations with crown permeability λ [m^{-1}] according to

$$\frac{\Delta c}{c_{ref}} = \frac{c_{trees} - c_{tree-free}}{c_{tree-free}}. \quad (5)$$

Steady increases in wall average and peak concentrations with increasing pressure loss coefficient can be seen. The incremental increases are strongest for small values of λ . For larger pressure loss coefficients, the wall average and peak concentrations asymptotically approach their upper limits given by the solid block tree model (dashed lines in diagram).

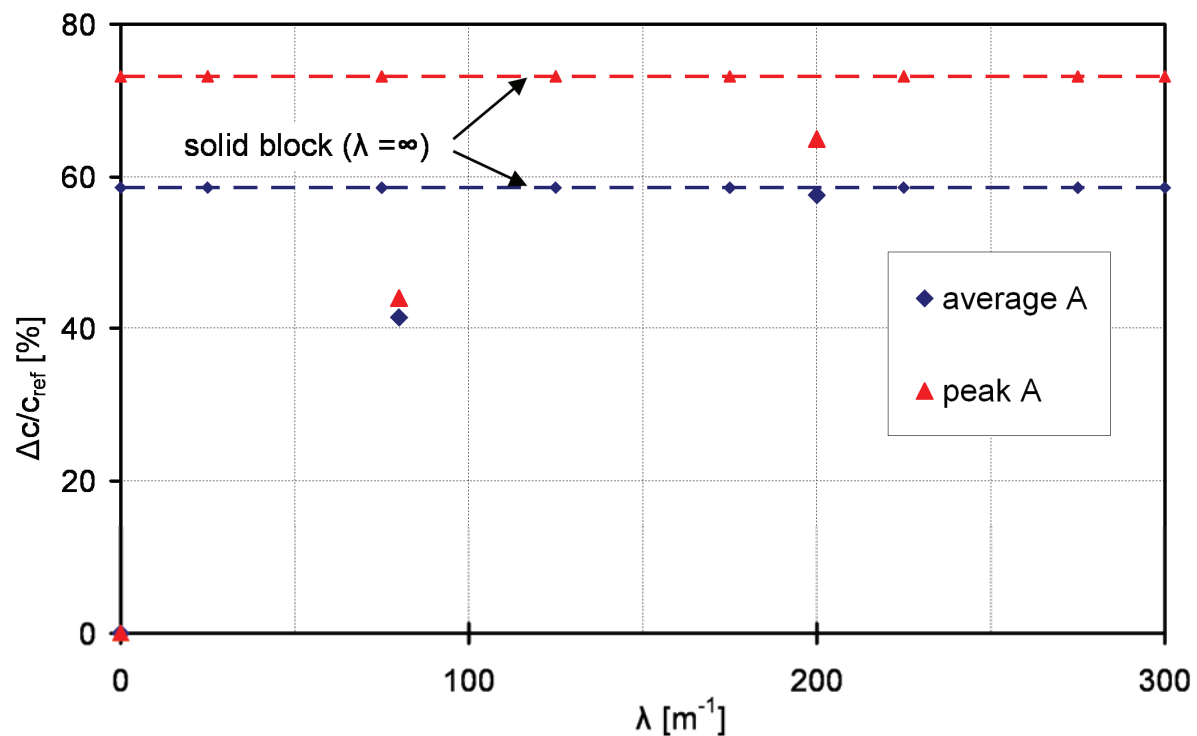


Figure 5. Rel. changes $\Delta c/c_{\text{ref}}$ [%] in wall average and wall peak concentrations with crown permeability λ [m^{-1}].

5 CONCLUSIONS

A new vegetation modeling approach was introduced and successfully applied in Wind Engineering small-scale pollutant dispersion studies. The transferability of the small-scale wind tunnel results to the full-scale was ensured by compliance with fluid dynamical similitude requirements. The permeability to wind was identified as relevant for the aerodynamic of vegetation. Consequently, the similarity criterion was set up based on the pressure loss coefficient which is a measure for permeability.

In this study, the modeling approach was employed to model tree-avenues in an urban street canyon and to study pollutant dispersion. The wind tunnel dispersion experiments a posteriori proved the vegetation modeling approach to be practicable and provided strong evidence for its reliability. Beyond the scope of the investigation presented herein, the approach can also be applied to other vegetation types, such as single trees, shrubs, hedges, forest stands or field crops, in diverse Wind Engineering wind tunnel studies, concerning e.g. pedestrian wind comfort or wind loads on structures.

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REFERENCES

- 1 B. Ruck, Über die Aerodynamik der Bäume, In: C. Egbers, L. Jehring, T. von Larcher, B. Ruck, A. Leder, D. Dopheide (Ed), Proc. 13. GALA-Fachtagung Lasermethoden in der Strömungsmesstechnik, Brandenburg University of Technology, Cottbus, Germany, 2005, pp. 49.1-49.7.
- 2 M. Rudnicki, S.J. Mitchell, M.D., Novak, Wind tunnel measurements of crown streamlining and drag relationships for three conifer species. *Canadian J. Forest Research* 34 (2004) 666-676.
- 3 S. Vollsinger, S.J. Mitchell, K.E. Byrne, M.D. Novak, M. Rudnicki, Wind tunnel measurements of crown streamlining and drag relationships for several hardwood species. *Canadian J. Forest Research* 35 (2005) 1238-1249.
- 4 W. Agster, B. Ruck, The influence of aerodynamic properties of forest edges and stands on the pressure pattern within a forest, In B. Ruck, C. Kottmeier, C. Mattheck, C. Quine, G. Wilhelm, (Ed), *Int. Conf. Wind Effects on Trees*, Karlsruhe, Germany, 2003, pp. 25-32.
- 5 C. Frank, B. Ruck, Numerical study of the airflow over forest clearings. *Forestry* 81 (2008) 259-277.
- 6 R.N. Meroney, Characteristics of wind and turbulence in and above model forests. *J. App. Meteorol.* 7 (1968) 780-788.
- 7 R.N. Meroney, Wind-tunnel simulation of the flow over hills and complex terrain. *J. Ind. Aerodyn.* 5 (1980) 297-321.
- 8 G.R. Stacey, R.E. Belcher, C.J. Wood, B.A. Gardiner, Wind flows and forces in a model spruce forest. *Bound.-Layer Meteorol.* 69 (1994) 311-334.
- 9 J.M. Chen, T.A. Black, M.D. Novak, R.S., Adams, A wind tunnel study of turbulent airflow in forest clearcuts, In M.P. Coutts J. Grace (Ed) *Wind and Trees*. Cambridge University Press, Cambridge, 1995, pp. 71-87.
- 10 S. Aubrun, B. Leiti, Development of an improved physical modelling of a forest area in a wind tunnel. *Atmos. Env.* 38 (2004) 2797-2801.
- 11 S. Aubrun, R. Koppmann, B. Leiti, M. Möllmann-Coers, A. Schaub, Physical modelling of a complex forest area in a wind tunnel - comparison with field data. *Agricult. Forest Meteorol.* 129 (2005) 121-135.
- 12 M. Zashke, B. Ruck, A wind tunnel investigation of the flow across a forest edge, 12th Int. Conf. on Wind Engineering, Cairns, Australia, 2007, pp. 1055-1062.
- 13 C. Frank, B. Ruck, Numerical study of the airflow over forest clearings. *Forestry* 81 (2008) 259-277.
- 14 C. Gromke, B. Ruck, Aerodynamic modeling of trees for small scale wind tunnel studies. *Forestry* 81 (2008) 243-258.
- 15 C. Gromke, A vegetation modeling concept for Building and Environmental Aerodynamics wind tunnel tests and its application in pollutant dispersion studies. *Environ. Poll.* 159 (2011) 2094-2099.
- 16 C. Gromke, B. Ruck, Pollutant concentrations in street canyons of different aspect ratio with avenues of trees for various wind directions. *Bound.-Layer Meteorol.*, in press.
- 17 G. Gross, A numerical study of the air flow within and around a single tree. *Bound.-Layer Meteorol.* 40 (1987) 311-327.
- 18 B. Ruck, F. Schmidt, Das Strömungsfeld der Einzelbaumumströmung - Abschätzung von Depositionswahrscheinlichkeiten für Feinsttröpfchen. *Forstwissenschaftliches Centralblatt* 105 (1986) 178-196.
- 19 F. Grunert, D. Benndorf, K. Klingbeil, Neuere Ergebnisse zum Aufbau von Schutzpflanzungen. *Beiträge für die Forstwissenschaft* 18 (1984) 108-115.
- 20 C. Gromke, B. Ruck, Die Simulation atmosphärischer Grenzschichten in Windkanälen, In C. Egbers, L. Jehring, T. von Larcher, B. Ruck, A. Leder, D. Dopheide (Ed) *Proceed. 13. GALA-Fachtagung Lasermethoden in der Strömungsmesstechnik*, Brandenburg University of Technology, Cottbus, 2005, pp. 51.1-51.8.
- 21 CODASC, Concentration Data of Street Canyons. Internet database. Karlsruhe Institute of Technology KIT, Germany, 2008, www.codasc.de.
- 22 R.N. Meroney, M. Pavageau, S. Rafailidis, M. Schatzmann, Study of line source characteristics for 2-D physical modelling of pollutant dispersion in street canyons. *J. Ind. Aerodyn.* 62 (1996) 37-56.
- 23 C. Gromke, B. Ruck, Influence of trees on the dispersion of pollutants in an urban street canyon - experimental investigation of the flow and concentration field. *Atmos. Environ.* 41 (2007) 3387-3302.
- 24 C. Gromke, B. Ruck, Effects of trees on the dilution of vehicle exhaust emissions in urban street canyons. *Int. J. Environ. Waste Management* 4 (2009) 225-242.
- 25 M. Balczó, C. Gromke, B. Ruck, Numerical modeling of flow and pollutant dispersion in street canyons with tree planting. *Meteorol. Zeit.* 18 (2009) 197-206.
- 26 R. Buccolieri, C. Gromke, S. Di Sabatino, B. Ruck, Aerodynamic effects of trees on pollutant concentration in street canyons. *Science Tot. Environ.* 407 (2009) 5247-5256.
- 27 C. Gromke, R. Buccolieri, S. Di Sabatino, B. Ruck, 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. *Atmos. Environ.* 42 (2008) 8640-8650.