Numerical modeling of flow and pollutant dispersion in street canyons with tree planting

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Abstract

Numerical simulations of the impact of tree planting on airflow and traffic pollutant dispersion in urban street canyons have been performed using the commercial CFD (Computational Fluid Dynamics) code MISKAM. A $k-\varepsilon$ turbulence model including additional terms for the treatment of vegetation, has been employed to close the Reynolds-averaged-Navier-Stokes (RANS) equations. The numerical results were compared to wind tunnel data. In the case of the investigated wind direction perpendicular to the street axis, the presence of trees lead to increased pollutant concentrations inside the canyon. Concentrations increased strong on the upstream side of the canyon, while on the downstream side a small concentration decrease could be observed. Lower flow velocities and higher pollutant concentrations were found in the numerical simulations when directly compared to the experimental results. However, the impact of tree planting on airflow and concentration fields when compared to the treeless street canyon as a reference configuration were simulated quite well, meaning that relative changes were similar in the wind tunnel investigations and numerical computations. This feature qualifies MISKAM for use as a tool for assessing the impacts of vegetation on local air quality.

Zusammenfassung

Numerische Simulationen über die Auswirkungen von Baumpflanzungen auf die Strömungsverhältnisse und die Ausbreitung von Verkehrsemissionen in städtischen Straßenschluchten wurden mit dem kommerziellen CFD (Computational Fluid

**Keywords:** MISKAM, model validation, $k$-$\epsilon$ turbulence model, vegetation module, trees, leaf area density, street canyon, pollutant dispersion, vortex core detection

### 1 Introduction

Traffic emissions are the predominant source of air pollution in urban areas. An efficient removal of these pollutants is needed to ensure the quality of life and health of the residents. In general, the natural ventilation guarantees a sufficient dilution and dispersion of traffic emissions. However, natural ventilation is often hindered by building arrangements. Especially, urban street canyons formed by multi-storey buildings with relatively narrow spacings are disadvantageous. When the flow is perpendicular to the canyon axis, the air exchange between the urban canopy layer and the layer above the roof level is limited. Near-ground traffic exhausts get trapped in the street canyon resulting in high pollutant concentrations. In this context, the question arises how avenue-like tree planting in urban street canyons affect the natural ventilation and traffic pollutant concentrations.

So far, pollutant dispersion in empty street canyons, i.e. without tree planting, has been addressed in numerous studies. Beside wind tunnel investigations (Meroney et al., 1996; Gerdes and Olivari, 1999; Kastner-Klein and Plate, 1999; Dezső-Weidinger et al., 2003), numerical simulations employing standard RANS turbulence closure schemes (Baik and Kim, 1999; Di Sabatino et al., 2007) and also more sophisticated turbulence modeling
approaches like LES (Liu and Barth, 2002; So et al., 2005) have been performed. While in the above mentioned references, flow and dispersion of passive, non-reactive scalars were studied, Baik et al. (2007) included the transport and photochemical transformations of the main traffic-originated gaseous pollutants in their numerical study.

Pollutant dispersion and wind characteristics in street canyons with tree planting have been investigated by only a limited number of researchers. In Gromke and Ruck (2007) and Gromke and Ruck (2008), pollutant concentrations and flow field characteristics measured on a small scale wind tunnel model of an isolated street canyon were presented. In the first study, tree crowns of spherical shape were arranged along the street axis, forming an avenue-like planting pattern. Crown diameter, crown porosity, tree spacing and tree height were systematically varied. Additionally, the influence of traffic-induced turbulence on pollutant dispersion was accounted for, while in Gromke and Ruck (2008) a new method for tree modeling in wind tunnels was introduced, and the effect of tree porosity on the canyon concentrations was investigated in detail. In Gromke et al. (2008) numerical results, obtained by using the FLUENT code with the standard $k$-$\varepsilon$ turbulence model and the Reynolds Stress Model (RSM) were compared with wind tunnel data. Generally, the numerical results predicted higher pollutant concentrations and lower flow velocities inside the street canyon when compared to experimental data. The RSM closure performed better than standard $k$-$\varepsilon$.

Gross (1997) investigated the influence of trees planted along building walls using the numerical code ASMUS. In ASMUS, the Reynolds-averaged Navier-Stokes equations (RANS) are closed using a $k$-$\varepsilon$ turbulence model. Tree crown porosity is accounted for by additional vegetation terms in the conservation equations. These vegetation terms are based on characteristic aerodynamic parameters of trees, such as leaf drag, the distribution of leaves within the crown and the tree stand density. In the presence of trees, increased pollutant concentrations and decelerated flow velocities near the building walls were found.

Performing numerical computations with MISKAM, Ries and Eichhorn (2001) studied a tree planting arrangement comparable to that of Gross. A one-equation turbulence model based on a differential transport equation for the turbulent kinetic energy $k$ and an algebraic equation for the dissipation rate $\varepsilon$, involving the Blackadar mixing length formula, was used to close the RANS equations. As before by Gross (1997), additional terms for modeling porous tree crowns were incorporated in the flow equations. They found an increase of local pollution concentration at the canyon walls and reduced flow velocities inside the street canyon. However, since no experimental data were available from small scale wind tunnel or from large scale field studies, the results of the numerical works could not be validated.
In the present article, the numerical model MISKAM (EICHHORN, 1989) has been used to simulate flow and pollutant concentrations in street canyons with tree planting. MISKAM has been employed and validated for several pollutant concentration studies in urban environments, such as KETZEL et al. (2000), SAHM et al. (2002), and GORICSÁN et al. (2009). A \( k-\varepsilon \) turbulence model has been employed to close the RANS equations. Trees are treated by a special vegetation parameterization. Extra terms, based on characteristic aerodynamic parameters of trees, are added to the conservation equations of momentum, turbulent kinetic energy \( k \) and dissipation \( \varepsilon \). MISKAM simulations of the flow and dispersion in an urban setting with vegetation were compared and validated for the first time with an extensive wind tunnel data set documented in GROMKE et al. (2007) and GROMKE and RUCK (2008), now also available in the CODASC database.

While the effects of vegetation on the flow field are considered in the numerical model, the deposition of non-gaseous pollutants, e.g. dust particles on leaves is not taken into account. According to the recent review of LITSCHKE and KUTTLER (2008) on the filtration effect of urban vegetation, average concentration decrease due to particle deposition is only about 1% in urban areas. In order to have a remarkable filtration effect, unrealistic high vegetation coverage would be necessary in street canyons. From these findings it can be concluded that using a passive, non-reactive gaseous scalar is appropriate to model exhaust emissions.

2 Model and Approach

2.1 MISKAM model description

The roots of the MISKAM model (Microscale flow and dispersion model, also known as MISCAM) go back to EICHHORN (1989). It is mostly used by consulting engineers for environmental studies, urban planning or regulatory purposes. The model solves the Reynolds-averaged Navier-Stokes (RANS) equations on a rectilinear grid with the \( k-\varepsilon \) turbulence closure, with modifications proposed by KATO and LAUNDER (1993) and LÓPEZ (2002) to obtain a 3D wind field. Using this wind field, the dispersion of pollutants (a passive scalar) can be calculated by solving the Reynolds-averaged advective-diffusion (RAAD) equation. A detailed description of the employed release of MISKAM (5.02a) can be found in EICHHORN (2008).

MISKAM’s boundary conditions are mostly predefined, allowing the user to control them by only a few parameters. At inlet boundaries, MISKAM generates a logarithmic velocity profile based on a reference velocity at a certain height, which can be modified by a stability factor in order to model non-neutral atmospheric conditions. The remaining boundaries, with the exception of the top boundary, have no flux conditions, i.e. normal gradients of any quantity are forced to vanish. At the top boundary, the corresponding
values of the inlet velocity and turbulence profile are assigned. On solid surfaces (ground and buildings), velocity components vanish (no-slip) and roughness lengths have to be prescribed.

2.2 Modeling of trees in MISKAM

Vegetation affects the flow field by changing mean velocities and modifying the production rates of turbulent kinetic energy $k$ and dissipation $\varepsilon$. As written by RIES AND EICHHORN (2001), in grid cells containing vegetation, the momentum equations and the transport equations for $k$ and $\varepsilon$ are modified by additional vegetation terms in MISKAM. For the momentum equation in vegetation cells, the drag force per cell volume $F_{\text{veg},i}$ is defined as

$$F_{\text{veg},i} = \rho n_c^3 c_{d0} b u_i |u|$$  \hspace{1cm} (Eq. 1)

with $\rho$ - fluid density; $n_c$ - vegetation coverage, being the fraction of surface covered by the vertical projection of trees (in MISKAM simulations usually 0 or 1 in a grid cell); $c_{d0}$ - leaf drag coefficient defined by the leaf drag force and the leaf surface area. GROSS (1993) mentioned values between 0.2 and 2, with larger values corresponding to smaller velocities, and vice versa. In MISKAM, $c_{d0}$ is set to 0.2; $b$ - leaf area density (LAD), defined as projected leaf surface area per unit volume

$$b = \frac{A_{\text{leaves}}}{V_{\text{cell}}} \left[ \frac{m^2}{m^3} \right]$$  \hspace{1cm} (Eq. 2)

with $A_{\text{leaves}}$ - single-sided leaf area; $V_{\text{cell}}$ - cell volume. Literature sources (GROSS, 1993; LARCHER, 2001) give values for $b$ between 0.5 and 1.6 (which is the average value for the tree crown) for forest areas and 1.7 - 3.3 for shrubbery. The distribution of LAD with height is not constant and shows differences between deciduous and coniferous trees.

With Eq. 1 and Eq. 2, the original momentum equation (EICHHORN, 2008) is extended by the following term:

$$\left. \frac{du_i}{dt} \right|_{\text{reg}} = -n_c^3 c_{d0} b u_i |u|$$  \hspace{1cm} (Eq. 3)

The transport equations for turbulent kinetic energy $k$ and dissipation rate $\varepsilon$ are modified with the following additional vegetation terms:

$$\left. \frac{dk}{dt} \right|_{\text{reg}} = n_c^3 c_{d0} b |u|^3 - 4 n_c^3 c_{d0} k |u|$$  \hspace{1cm} (Eq. 4)
\[
\frac{dE}{dt}_{\text{reg}} = \frac{3}{2} \varepsilon n_c^3 c_{d0} b |u|^3 - 6n_c^3 c_{d0} \varepsilon |u| 
\]  
(Eq. 5)

From Eq. 4 and Eq. 5 it can be seen that the chosen parameterization of the vegetation accounts for increased and decreased turbulent kinetic energy production and dissipation rates.

2.3 Boundary conditions of street canyon geometry and incident flow

The street canyon geometry was taken from a wind tunnel model of scale \( M = 1:150 \) (GROMKE et al. (2007)), with buildings of quadratic cross-section, a building height \( H \) to street width \( W \) ratio of \( H/W = 1 \) and a street length \( L \) to width \( W \) ratio of \( L/W = 10 \) (Fig. 1). The MISKAM CFD simulations were carried out for real scale dimensions with \( H=18m \) building height. A roughness length of \( z_0 = 0.1m \) was assigned to the ground, and \( z_0 = 0.01m \) to the building surfaces, corresponding to the smooth acrylic surface of the wind tunnel model. The computational domain had the dimensions of 500x300x300m, fulfilling the recommendations given in FRANKE et al. (2007), i.e. 10\( H \) in front of, 15\( H \) behind and 15\( H \) above the buildings of height \( H = 18m \). The span wise width was set to 300m according to the width of the test section of the boundary layer wind tunnel. The blockage ratio in the numerical model, defined as the ratio of the projected area of buildings in flow direction and the total cross section area of the computational domain, amounts to 3.5%.

The inlet velocity profile was perpendicular to the street length axis and fitted to the profile measured in the wind tunnel. In MISKAM, the law of the wall (logarithmic approach) is employed to describe the inlet velocity profile. A best fit was achieved with \( u_{ref} = 4.75m/s \) at the reference height \( H=18m \) and a ground roughness length of \( z_0 = 0.1m \) (Fig. 2). The turbulence intensity for the MISKAM turbulence profile was defined as

\[
I_{xyz} = \frac{2}{3} \frac{k}{u^2} 
\]  
(Eq. 6)

Pollutant sources are modeled in MISKAM as volume sources. In this case, the source containing grid cells are situated along the lowermost layer of the 4 lanes (Fig. 1), without having any vertical momentum.
Figure 1: Arrangement and dimensions of the investigated street canyon.

Figure 2: Vertical profiles of velocity $u$ (normalized to $u_{\text{ref}}$, velocity at building height $H$) and turbulence intensity $I_{xyz}$ (Eq. 6) at the domain inlet boundary.

### 2.4 Relationship between the pressure loss coefficient $\lambda$ and the leaf area density (LAD)

In the wind tunnel study, tree crowns were simulated by using porous media. The aerodynamic characteristics of porous media can be described by their permeability to wind expressed in terms of the pressure loss coefficient $\lambda$ [Pa (Pa m$^{-1}$)]. This coefficient is the ratio of the static pressure difference $\Delta P_{\text{stat}}$ between the porous media's windward and
leeward side in forced convection conditions and the dynamic pressure $p_{dyn}$ divided by the body’s streamwise depth $l$, according to

$$\lambda = \frac{\Delta P_{stat}}{p_{dyn} l} = \frac{P_{lw} - P_{lee}}{(1/2) \rho u^2 l}$$  \hspace{1cm} (Eq. 7)

with $u$ - mean velocity component in the streamwise direction. With this, the drag force field $F$ acting on the flow in the vegetation zone is

$$F_{veg, i} = \frac{1}{2} \rho \cdot u_i \cdot |u| \cdot \lambda$$  \hspace{1cm} (Eq. 8)

On the other hand, in MISKAM the force in a vegetation zone is given by Eq. 1. Setting these equations equal to each other one gets

$$\lambda = 2 \cdot c_d \cdot n_i^3 \cdot b$$  \hspace{1cm} (Eq. 9)

In order to parameterize the vegetation in MISKAM the specification of the leaf area density $b$ is needed. By transferring the pressure loss coefficients $\lambda$ determined for the wind tunnel scale according to Eq. 7 into full scale, the leaf area density $b$ required for the MISKAM simulations can be calculated by Eq. 9. Claiming that the ratio of drag force to inertia force has to be equal in model and full scale, results in the following similarity criteria

$$\begin{bmatrix} \Delta p \\ P_{dyn} \end{bmatrix}_{\text{model}} = \begin{bmatrix} \Delta p \\ P_{dyn} \end{bmatrix}_{\text{full scale}} \quad \Leftrightarrow \quad [\lambda \cdot l]_{\text{model}} = [\lambda \cdot l]_{\text{full scale}}$$  \hspace{1cm} (Eq. 10)

which gives with the wind tunnel model scale $M = l_{\text{model}} / l_{\text{full scale}} = 1:150$

$$\lambda_{\text{full scale}} = M \cdot \lambda_{\text{model}}$$  \hspace{1cm} (Eq. 11)

From Eq. 9 and Eq. 11, the leaf area density $b$ required for the MISKAM simulations was determined (Table 1).

**Table 1: Vegetation parameters for all investigated cases: pressure loss coefficient $\lambda = \Delta p / (p_{dyn} l)$ of the trees modeled in wind tunnel and in the full scale simulation; calculated leaf area density $b$.**

<table>
<thead>
<tr>
<th>case</th>
<th>vegetation density</th>
<th>$\lambda_{\text{model}}$ [Pa m⁻¹]</th>
<th>$\lambda_{\text{full scale}}$ [Pa m⁻¹]</th>
<th>$b$ (LAD) [m² m⁻³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>no vegetation</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>ultra-low</td>
<td>n. a.</td>
<td>0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>very low</td>
<td>n. a.</td>
<td>0.3</td>
<td>0.75</td>
</tr>
<tr>
<td>4</td>
<td>low</td>
<td>80</td>
<td>0.53</td>
<td>1.33</td>
</tr>
<tr>
<td>5</td>
<td>medium</td>
<td>200</td>
<td>1.33</td>
<td>3.33</td>
</tr>
<tr>
<td>6</td>
<td>high</td>
<td>250</td>
<td>1.67</td>
<td>4.17</td>
</tr>
</tbody>
</table>
In this article, cases (1) and (4) - (6) of Table 1 are analyzed in detail, while (2) and (3) are only partially discussed. Case (1) represents the reference case, a treeless street canyon. The vegetation zone is arranged in the middle of the street canyon, filling 1/3 of its volume (Fig.1).

2.5 Grid sensitivity study

Several test runs were performed for the reference case employing 5 different computational grids. The grids varied in terms of resolution, in the street canyon and near the building walls. An overview of the grids is given in Table 2. The finest grid covered only half of the domain divided by the mid plane, using the symmetrical arrangement of the tested configuration.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Smallest cell size at the windward edge of building A</th>
<th>Average cell size in the street canyon</th>
<th>Grid cells x y z</th>
<th>No. of grid cells [million]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x y z [m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coarsest</td>
<td>1/1/1</td>
<td>1/1/1</td>
<td>142/240/67</td>
<td>2.3</td>
</tr>
<tr>
<td>medium</td>
<td>0.5/0.5/0.5</td>
<td>0.5/1.5/0.5</td>
<td>195/234/86</td>
<td>3.9</td>
</tr>
<tr>
<td>fine</td>
<td>0.5/0.5/0.5</td>
<td>0.5/1.3/0.5</td>
<td>221/249/98</td>
<td>5.4</td>
</tr>
<tr>
<td>refined</td>
<td>0.1/0.2/0.1</td>
<td>0.5/1.3/0.5</td>
<td>232/249/100</td>
<td>5.8</td>
</tr>
<tr>
<td>finest*</td>
<td>0.1/0.1/0.1</td>
<td>0.4/1/0.4</td>
<td>250/154/137</td>
<td>5.3* (10.6)</td>
</tr>
</tbody>
</table>

*Half model, hence equivalent cell number would be the double.

The numerical results of the street canyon without trees showed strong grid dependency. For finer grids, the separation bubble at the top of the windward building was resolved quite well (Fig. 3), allowing the canyon vortex to extend partly out of the canyon and increase the air exchange with the above-roof flow. However, even for the finest grid, the numerically predicted separation bubble showed smaller extension than measured in the wind tunnel. The same can be stated about the bolster eddy in front of the windward building.
The corresponding pollutant concentrations $0.04H$ in front of the inner canyon walls are shown in Fig. 4 as normalized concentrations $c^*$. The concentrations have been normalized according to

$$c^* = \frac{c \cdot u_{ref} \cdot H}{Q/L}$$

(Eq. 12)

with $c$ - measured or simulated concentration, $u_{ref}$ - inlet velocity taken at reference height $H$ and $Q/L$ - line source strength. Since the concentration distributions were always symmetrical to the mid plane, only one half of the canyon wall is depicted.
In all cases the maximum concentration was observed in the middle of the canyon \((y/H = 0)\) near the ground of the leeward wall. Concentrations on the windward wall were about 3-5 times lower than on the leeward wall, as it was reported for the wind tunnel measurements of Kastner-Klein and Plate (1999). As stated above, refining the grid resulted in an increased separation bubble at the top of the windward building. This was accompanied by lower concentrations at the canyon walls, indicating the importance of the windward edge separation on the pollutant dispersion process inside the street canyon. However, even with the finest grid employed, the computed separation bubble was smaller and the concentrations were higher than in the wind tunnel experiment.

To quantify the deviation of the numerical from the experimental concentration data, the root mean square deviation, (RMSD) of the simulated concentrations with regard to the measured ones was calculated and normalized by the mean of the measured concentrations giving the coefficient of variation \(CV(RMSD)\) (Fig. 5).
From the results in Fig. 5, a strong grid dependency of CV(RMSD)-values can be found for numerical grids consisting of less than 5.8 million cells. Although the amount of virtual cells in the case of the finest half domain grid is nearly doubled as compared to the fine grid case (Table 2), a slightly higher CV(RMSD) is present, indicating that a finer grid resolution does not yield to any further improvement. Therefore the refined grid with 5.8 million grid cells was selected for the further investigation of street canyons with tree planting.

3 Results and Discussion

3.1. Effect of tree planting on the wind field in street canyons

The measured and numerically calculated vertical velocities $w$ have been analyzed in a vertical cross section within the street canyon at $y/H = 0.5$. Normalized vertical velocities $w^* = w/u_{ref}$ obtained from laser-Doppler-velocimetry (LDV) measurements are shown together with MISKAM results in Fig. 6.

Figure 6: Distribution of the dimensionless vertical velocity component $w^* = w/u_{ref}$ in the street canyon at $y/H = 0.5$ (near the mid plane) measured in the wind tunnel and simulated by MISKAM in the reference case and for high leaf area density. Above-roof wind comes from the left.
Regarding the experimental data in Fig. 3, a downward flow component above the canyon can be expected due to the flow separation at the leading edge of the windward building and the bending of the streamlines. This is clearly reflected in the velocity plots in the left column of Fig. 6 showing the LDV measurements. In contrary, the MISKAM results in the right column show a downward directed flow in the above-roof region only in front of the windward wall of the leeward building. This phenomenon can be explained by the smaller separation bubble at the top of the windward building predicted by the numerical computations and little streamline bending (Fig. 3).

Both modeling methods state the existence of the street canyon vortex, which causes the upward flow on the leeward side and downward flow on the windward side of the canyon. MISKAM predicts significantly lower velocities in general. One can recognize from the gradient of $w^+$ on the side walls that the wall boundary layer in the wind tunnel is much thicker than in the numerical simulations. MISKAM results show that with increasing leaf area density, the velocities inside the crown tend to zero. Outside the crown in front of the windward wall, velocities decrease, whereas in front of the leeward wall, velocities remain almost constant (wind tunnel) or are even increased (MISKAM).

For the analysis of complex three-dimensional flow fields, obtained either from measurements or from numerical simulation, several methods have been developed and are widely used nowadays, see e.g. LohÁsz et al. (2006). In this study, visualization with streamlines and detection of vortex cores were performed. When applying this method to a street canyon configuration, where the tree planting has a high leaf area density ($b = 4.17 \text{m}^{-1}$), several vortex structures can be identified. Following the streamwise direction these are: the bolster eddy in front of the windward building, which is a part of the horseshoe vortex, the leading edge separation eddies at the top and sides of the windward building, the corner eddy which interacts with the street canyon vortex as well as the wake vortex in the recirculation zone behind the leeward building (Fig. 7). At low and medium leaf area densities the same vortex structures are present, with an almost unchanged main canyon vortex and small differences in the position of the corner eddies.
Figure 7: Flow features in and around the street canyon in case of high leaf area density \((b = 4.17 \text{m}^{-1})\): 2D streamlines (thin black lines with arrows in the symmetry plane), 3D streamlines (thin grey lines without arrows) and vortex cores (thick greyscale rods, on which darker colors correspond to stronger vortices).

3.2 The effect of tree planting on the concentration field in street canyons

In Fig. 8 and Fig. 9, results from the wind tunnel concentration measurements and the MISKAM simulations at the inside of the canyon walls are shown. Since in the wind tunnel data the distributions were only slightly asymmetrical to the mid plane, left and right side results were averaged and the figures show concentration distribution of the leeward wall on their left side and concentration distribution of windward wall on their right side.

![Figure 8: Distribution of concentration \(c^* = (c \cdot u_{ref} \cdot H)/(Q/L)\) at the canyon walls obtained from wind tunnel measurements for different leaf area densities.](image-url)
Regarding the wind tunnel (Fig. 8) and MISKAM results (Fig. 9), we can state the following:

- **Leeward wall:**
  - an increase in concentration with increasing LAD can be seen at the entire wall
  - the increase is highest in the middle of the canyon
  - neither the experimental nor the numerical results show any significant deviations between the medium and high LAD
  - in the reference case, small areas of concentration increases at the ends of the street can be found, which are due to a stable dead water zone created by the shedding of the corner eddies at the vertical building edges. This dead water zone shows low exchange rates, indicating that pollutant concentrations get trapped in this area

- **windward wall:**
  - a decrease in concentration is predicted with the increasing LAD
  - in the MISKAM results, a pronounced decrease in near-ground concentrations is evident
In order to facilitate the identification of tree planting impacts on concentrations, the relative changes in concentration $\delta^{+}_{veg}$, in regard to the reference case of the treeless street canyon, have been calculated according to

$$
\delta^{+}_{veg} = \frac{c^{+}_{veg} - c^{+}_{ref}}{c^{+}_{ref}}
$$

(Eq. 13)

Fig. 10 and Fig. 11 show the relative changes in concentration $\delta^{+}_{veg}$ at the leeward and windward wall, respectively. Here the figures are composed of wind tunnel and MISKAM results.

By analyzing Fig. 10 and Fig. 11, the following quantitative observations can be made:
• leeward wall:
  - concentrations increase up to 100% (wind tunnel) and up to 140% (MISKAM) in the low, medium and high leaf area density cases
  - in MISKAM, relative changes at the leeward wall are steadily increasing with increasing LAD
  - at the end of the canyon, a decrease in concentration with increasing LAD is present (more pronounced in MISKAM). This is due to the disappearance of the dead water zones, since the corner eddies are hindered by the tree crowns in entering the street canyon
  - two peaks of concentration increases can be observed at \( y/H = 0 \) and \( y/H = 3.5 \) in the upper part of the wall. This effect is clearly realized in both methods

• windward wall:
  - concentrations decrease in all areas except at the canyon ends. The measurement results show an average decrease of about 40%, while the MISKAM results show an average decrease of about 60%. These changes are however rather small, because concentrations were generally small
  - the concentration decreases are relatively independent of LAD

In order to summarize the vegetation effects, the average concentrations along the building walls are shown in Fig. 12. Although over predicted by the numerical simulations, the concentration increase at the leeward wall is comparable to the wind tunnel data for growing LAD, while at the windward side an almost perfect agreement can be seen. The wall-average relative concentration change \( \delta_{\text{veg,wall}} \) (cf. Eq. 13) emphasizes the quality of the vegetation module of the CFD code (Fig. 13). Similar trends for both the wind tunnel and numerical data are evident with low LADs having already a significant impact on the concentration changes and an almost independency for higher LADs. Regarding the average over both walls (total average), a good agreement is found. However, the vegetation module overestimates the influence of tree planting, giving enhanced concentration increases at the leeward wall and larger decreases at the windward wall.
Figure 12: Wall-averaged normalized concentration $c^* = (c_{u_{ref}} H) (Q/L)$ as a function of full scale leaf area density.

Figure 13: Wall-averaged relative concentration change $\delta^+_{veg, wall} = (c^+_{veg} - c^+_{ref}) / c^+_{ref}$ [%] as a function of full scale leaf area density.

Finally, the linear regression and correlation coefficients between experimental and numerical data have been calculated for the normalized concentrations $c^*$ and the relative concentration changes $\delta^+_{veg}$ (Fig. 14). In both cases, correlation coefficients of above 0.8 have been found, suggesting that an approximate linear relationship between wind tunnel and MISKAM results exists. Moreover, the correlation analyses shows that, on average, the numerical computations overestimate the experimental pollutant concentrations by
about 60% and the relative changes in concentration due to the impacts of tree planting by about 30%.

![Figure 14: (a) Correlation of measured and simulated concentrations $c^* = (c_{u_{ref}} H)/(Q/L)$; (b) correlation of measured and simulated relative concentration changes $\delta^*_{veg} = (c^*_{veg} - c^*_{ref})/c^*_{ref} [%]$](image)

Validation metrics, proposed e. g. in the COST Action 732 “Quality Assurance and Improvement of Micro-Scale Meteorological Models” (BRITTER and SCHATZMANN, 2007) were calculated using the BOOT software (CHANG and HANNA, 2004). The results shown in Table 3 prove the statement above. While most criteria are fulfilled, improvement of hit rate is necessary.

Table 3: Validation metrics as given by CHANG and HANNA (2004) of the normalized concentrations $c^* = (c_{u_{ref}} H)/(Q/L)$

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Aim value</th>
<th>Range of acceptance</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>correlation coefficient (R)</td>
<td>1</td>
<td>&gt; 0.8</td>
<td>0.92</td>
</tr>
<tr>
<td>factor of two (FAC2)</td>
<td>1</td>
<td>&gt; 0.5</td>
<td>0.63</td>
</tr>
<tr>
<td>normal mean square error (NMSE)</td>
<td>0</td>
<td>&lt; 4</td>
<td>0.98</td>
</tr>
<tr>
<td>fractional bias (FB)</td>
<td>0</td>
<td>[-0.3; 0.3]</td>
<td>-0.35</td>
</tr>
<tr>
<td>geometric mean bias (MG)*</td>
<td>1</td>
<td>[0.7; 1.3]</td>
<td>0.94</td>
</tr>
<tr>
<td>geometric variance (VG)*</td>
<td>1</td>
<td>&lt;1.6</td>
<td>1.46</td>
</tr>
<tr>
<td>hit rate (q)**</td>
<td>1</td>
<td>&gt;0.66</td>
<td>0.40</td>
</tr>
</tbody>
</table>

* with threshold of measurement error ($\Delta c^* = 2$)

** hit rate defined with allowed deviation smaller than 25% or the measurement error.

4 Conclusion

MISKAM was able to qualitatively reproduce the essential flow and pollutant patterns in isolated street canyons with and without avenue-like tree planting, as found in the wind tunnel studies. Characteristic flow field structures, such as the windward building roof top
separation and the street canyon vortex, were resolved as well as pollutant concentration distributions at the canyon walls. However, a more quantitative consideration reveals lower flow velocities and higher traffic pollutant concentrations in the numerical results, when directly compared to experimental data. Despite these partially significant deviations, MISKAM, including the vegetation module, holds the capability to simulate the impact of tree planting on pollutant dispersion inside the street canyon. Based on the treeless street canyon, as a reference configuration, relative changes in concentration due to tree planting were in acceptable agreement with the corresponding wind tunnel data. This feature qualifies MISKAM for use as a tool for roughly assessing the impacts of vegetation on local air quality in contrast to the no-vegetation scenario.

Both methods, wind tunnel and numerical modeling showed that dense vegetation in urban canyons can cause an average concentration increase of 20% - 40% compared to the treeless case. On certain locations almost double as high values, but also decreased concentrations could be observed. Tree planting campaigns in urban areas with heavy car traffic should be therefore accompanied by local emission reduction. From the air quality view, tree species of rather low leaf area density are favorable. On the other hand, urban planners should also consider the positive effects of vegetation on urban climate, e. g. on temperature or humidity. This gives also motivation for the further development of micro scale numerical models.

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