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ANNUAL AVERAGE IMPACT OF TREES ON AIR QUALITY IN STREET CANYONS

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Abstract: The influence of vegetation on the concentrations of traffic pollutants in urban street canyons is examined using numerical simulations with the CFD code OpenFOAM. This CFD approach is validated against literature wind tunnel data on traffic pollutant dispersion in street canyons. The impact of avenues of trees is simulated for a variety of vegetation types and the full range of approaching wind directions at 15° interval. All these results are combined in meteostatistical analysis, including effects of seasonal leaf loss, to determine the annual average effect of trees in street canyons. This analysis is performed for two pollutants, elemental carbon (EC) and PM10, using background concentrations and emission strengths for the city of Antwerp, Belgium. The results show that due to the presence of trees the annual average pollutant concentrations increase with about 8% (range of 1% to 13%) for EC and with about 1.4% (range of 0.2 to 2.6%) for PM_{10}. The study also indicates that this annual effect is considerably less than earlier estimates which are generally based on steady state results based on a specific set of governing conditions (1 wind direction, full leafed trees, peak hour traffic emissions). This implies that the adverse air quality effect of street canyon trees may not be as harmful as previously assumed.

Key words: *Computational Fluid Dynamics – Pollutant dispersion – Street Canyons – Validation – Urban Vegetation*

1. INTRODUCTION

The last few decades have been characterized by an intense urbanization, caused by the growing population of the world and rural migration. The interest in the urban living environment is therefore increasing with an important focus on air quality. Densely populated city centers have a road network of which a significant fraction consists of street canyons. Traffic emissions in these street canyons are a large contributor to local pollutant concentrations (Vos et al., 2013). Trees have the capacity to remove air pollutants by dry deposition. This positive effect on air quality can however be locally overshadowed by the disturbance of the flow field by these same trees. Tree canopies can form a barrier between the street level where the traffic emits and the atmospheric wind above the roofs. The reduced ventilation leads to an increase in the concentration of pollutants emitted by the traffic in the street canyon.

Microscale studies of these effects request building resolving models to capture the urban environment in sufficient detail. Computational Fluid Dynamics (CFD) is therefore chosen to simulate the flow, turbulence and dispersion.

Gromke et al. have investigated the effects of vegetation on the air quality in street canyons through a combinations of wind tunnel experiments and CFD simulations (Buccolieri et al., 2011, 2009; Gromke et al., 2011, 2009). They quantified the change in pollutant concentrations from canyon emissions for wind directions perpendicular, parallel and 45° inclined to the canyon axis for varying street canyon aspect ratios, the ratio between the street width (W) and the building height (H). The experimental results have been made available through an online database (CODASC, 2008). Our objective continues from these findings and aims to quantify the year round effects of trees on urban air quality. CFD simulations are presented for all wind directions at a 15° interval and variety of trees. A range of leaf area densities and deposition velocities have been investigated to cover the variety in deciduous urban trees. Further, the seasonal effects on these trees are considered. Through intelligent meteo-statistical averaging, hourly concentrations with and without canyon vegetation are summarized as annual average influences. The microscale pollutant concentrations in cities are however strongly influenced by the background concentrations and all other traffic and non-traffic emissions in the complete city. For atmospheric particulate matter with a diameter of 10 µm or less, PM_{10}, and elementary carbon, EC, all these contributions have been considered for a busy urban street canyon in Antwerp, Belgium, during 2012.

2. NUMERICAL MODEL

2.1 Computational grid, boundary conditions and solution method

Three-dimensional steady state simulations to study the air quality effect of urban trees in street canyons have been performed using the OpenFOAM CFD package. The COST action 732 report has been used as guideline for the numerical simulation setup.

The simulations are validated against the CODASC wind tunnel database (CODACS, 2008). The street canyon dimensions have therefore been chosen to represent the full scale street canyon the wind tunnel model simulates. The buildings have a height of 18 m (H), a length of 180 m (10H) and a width of 18 m (H). Two different street canyon widths of 18 m and 36 m have been investigated, with respective street canyon width over height ratios (W/H) of 1.0 and 2.0.

The dimensions of the computational domain consist of an approach flow region of 8 H, the street canyon region and a downwind region of 15 H. The distance from the buildings to the side boundaries of the domain as well as the top boundary is 5 H. A regular hexahedral grid within 1 H distance of the street canyon is combined with an irregular grid outside this region. Inside and around the canyon, the highest resolution is requested and here a constant grid resolution of z/H = 0.028 and x/H = y/H = 0.05 is chosen with regular hexahedral cells. To keep the amount of cells in the domain manageable the cell size increases by an expansion ratio of maximum 1.2 outside this central region and cells become irregular. It is ensured that increasing the resolution of the grid does not improve the results.

SimpleFoam, an OpenFOAM steady-state RANS solver for incompressible, turbulent flow has been used as basis to develop a solver for the air flow through vegetation. Further, through coupling with the *scalarTransportFoam* solver, the dispersion of pollutants is added as a passive scalar. A standard k-ε model has been applied as turbulence model. Our use of a k-ε model including vegetation terms is here considered a sufficiently accurate model given the large variation and uncertainties in vegetation and street configurations. The goal of this study is not to model this problem at the highest level of detail; we aim at validating the *k-ε* approach to have a validated tool for annual average urban air quality results at micro-scales.

The boundary conditions are chosen to reflect an atmospheric boundary layer, in the absence of temperature effects, such as used in the CODACS wind tunnel experiments (CODASC, 2008), similar to other CFD simulation studies of the same data set (Buccolieri et al., 2009). The simulations are iteratively solved and all residuals dropped below 10^{-6}, indicating full convergence has been reached. Second order upwind discretization schemes have been applied for k, ε, pressure and momentum.

As described in literature, it is important to correctly specify the wall roughness of the ground surface to avoid stream wise gradients in the atmospheric boundary layer flow. The equivalent sand-grain roughness height, $k_S = 0.12\ m$, and the roughness constant, $C_S = 8$, are thus optimized to avoid these stream wise gradients. This combination represents an aerodynamic roughness length of 0.1 m. This seems to agree quite well to the wind tunnel set up where roughness elements have been introduced. It is known that the turbulent Schmidt number, Sc_T, has a significant influence on the simulation of pollutant concentrations using a k-ε model. The optimum values for Sc_T vary with the flow characteristics, here the Sc_T number is optimized for each wind direction and W/H aspect ratio, the range of values is 0.3- 1.0.

2.2 Modelling vegetation

By including the vegetation module, the effect of trees and other vegetation types can be incorporated in the simulation. Vegetation zones lead to a perturbation of the air flow and the removal of pollutants from the air. The presence of vegetation is implicitly represented by introducing additional terms in the governing equations in order to mimic the effects of vegetation. As such, the steady RANS equations (closed by the standard k-ε model) are augmented with source/sink terms. Vegetation zones affect the momentum equation (sink), the turbulence equations (source/sink) and the dispersion (deposition). The physical properties of a tree in the simulations are defined through a momentum sink, $C_x = LAD * C_d$, and deposition term, $LADv_d = LAD * v_d$. LAD, C_d and v_d represent the leaf area density, the drag coefficient and the deposition velocity. The momentum sink (same as pressure loss coefficient), and deposition term are assigned to the cells in the computational domain occupied by the tree crowns.

3. Model performance against wind tunnel data

The pollutant dispersion in idealized street canyons with and without trees is simulated, analyzed and validated against the majority of the cases presented in the CODASC databank. We validate against the results for both W/H = 1.0 and 2.0, for the three different wind directions with an angle between the inlet flow direction and the street canyon axis of 90°, 45° and 0°, for the cases without trees and with porous trees with varying pressure loss coefficients. For each case the concentrations inside the canyon at planes close to both buildings are analysed and discussed. The normalized concentration profiles from the CFD simulations can be compared with the respective profiles from the wind tunnel database, measured inside the canyon close to both building walls. In Figure 1, an example of such a comparison is given.

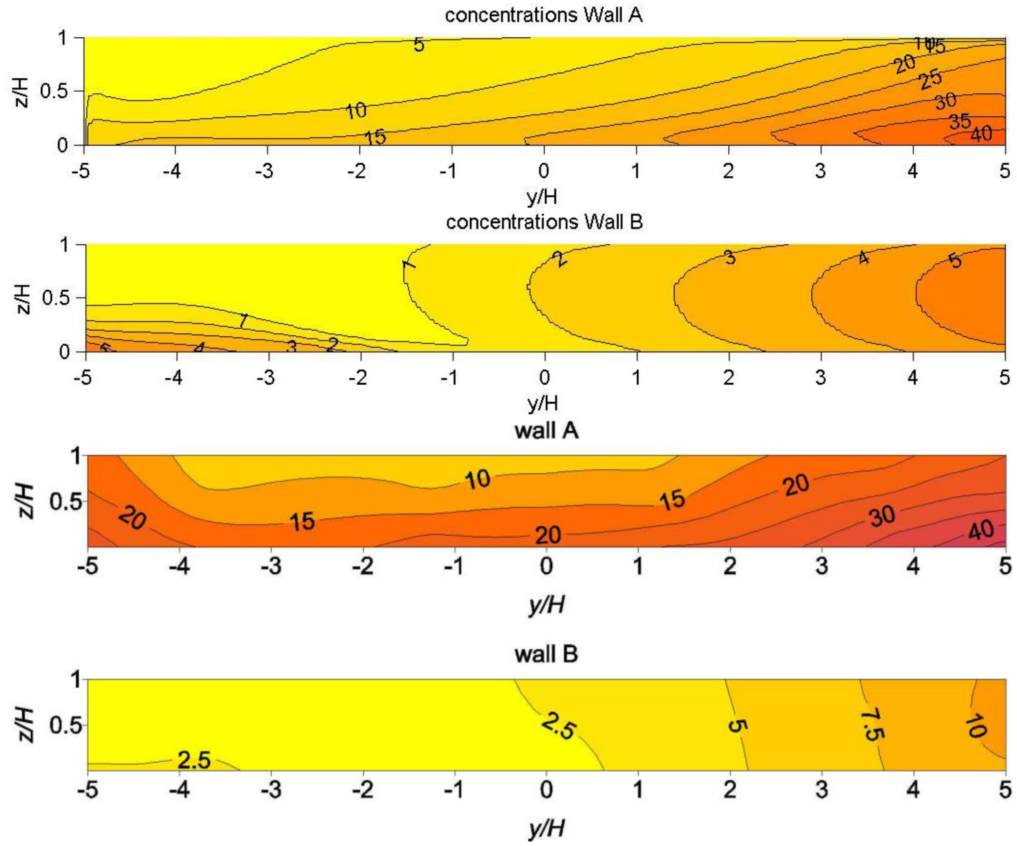

Figure 1. Normalized concentration profiles inside the street canyon near the walls of both buildings for W/H = 1.0, 45°, no trees. Top two profiles are from the CFD simulations, bottom two reproduced from CODASC, 2008.

Table 1. Summary of the wall average normalized concentrations near the buildings inside the idealized street canyon *W/H = 1.0*, presented CFD results vs. the wind tunnel (WT) results (CODACS, 2008). For each case the coefficient of determination of a scatter plot of the simulations against the experimental data and the relative difference (diff.) between the simulation and the exp. value is included. All trees have a momentum loss $C_x = 1.33\ m^{-1}$.

Angle	**Wall**	**No trees**				**Trees**				**Effect Trees**	
		WT	*CFD*	*diff.*	*R^2*	*WT*	*CFD*	*diff.*	*R^2*	*WT*	*CFD*
90°	*A*	19.7	23.0	17%	0.78	32.7	35.0	7%	0.77	66%	52%
90°	*B*	5.34	8.03	50%	0.95	2.69	7.10	169%	0.83	-50%	-12%
45°	*A*	18.4	14.3	-22%	0.81	31.0	21.6	-30%	0.75	69%	51%
45°	*B*	3.70	2.41	-35%	0.80	5.27	11.6	120%	0.27	42%	380%
0°	*A/B*	7.10	7.22	2%	0.88	9.73	12.2	26%	0.88	37%	70%

All results for the street canyon aspect ratios *W/H = 1.0 and 2.0* have been summarized in Table 1 and 2, comparing the average normalized concentrations of the wind tunnel results and the presented CFD simulations. All trends observed in the wind tunnel experiments are reproduced by the CFD simulations using a $k - \varepsilon$ epsilon model. The trees affect the flow pattern leading to an increase in pollutant concentrations for all situations except the leeward wall for a perpendicular wind direction. Discrepancies between the CFD results and wind tunnel data arise probably due to differences in the flow patterns. The larger differences in wall maximal normalized concentrations are partly canceled out when comparing wall average concentrations. The comparison of the change in concentrations upon introduction of trees leads to a further cancellation of errors. The approach of applying a k-ε model for the screening of the effects of trees for a large variety of wind directions and type of trees can therefore be considered a valid strategy.

Table 2. Summary of the wall average normalized concentrations near the buildings inside the idealized street canyon *W/H = 2.0*, presented CFD results vs. the wind tunnel (WT) results (CODACS, 2008). For each case the coefficient of determination of a scatter plot of the simulations against the experimental data and the relative difference (diff.) between the simulation and the exp. value is included. All trees have a momentum loss Cx = 1.33 m^{-1}.

Angle	**Wall**	**No trees**				**Trees**				**Effect Trees**	
		WT	*CFD*	*diff.*	R^2	*WT*	*CFD*	*diff.*	R^2	*WT*	*CFD*
90°	*A*	15.0	10.8	-28%	0.68	20.9	19.5	-7%	0.73	40%	81%
90°	*B*	5.14	8.23	60%	0.73	3.46	5.88	70%	0.93	-33%	-29%
45°	*A*	9.84	9.83	0%	0.45	18.4	13.2	-29%	0.80	87%	34%
45°	*B*	0.87	0.89	2%	0.55	3.77	3.28	18%	0.59	218%	269%
0°	*A/B*	1.46	1.16	-21%	0.83	2.10	2.42	15%	0.82	44%	109%

4. Annual average effects of trees on air quality

The validated OpenFOAM CFD model has been used to study the year round effect of trees. This study focuses on the broader street canyons W/H = 2.0 as this type of canyon is more relevant for Western and Northern European cities. Besides the three wind directions studied for validation, 90°, 45° and 0°, cases with 15°, 30°, 60° and 75° have been added. For each wind direction both vegetation parameters, momentum sink C_x and deposition term $LADv_d$, have been varied. From the variety of reported leaf area densities, *LAD*, deposition speeds and drag coefficients, we have selected ten combinations to cover the range of values. These three parameters depend on the type of tree, time of the year, location and type of pollutant. All seventy simulations, combination of seven wind directions and ten vegetation settings, have been completed using the validated *k*-ε approach in OpenFOAM. Significant changes in wall average concentrations are observed when including trees for all wind directions. The momentum sink effect of trees hinders the inflow of fresh air, lowering the wind velocities in the canyon and its ventilation, leading to increased concentrations. Even for the high deposition velocities, an overall increase is observed.

The next step is to use annual statistics to consider the year round effect of trees. We are considering the influence of the change of the leaf area density throughout the year for deciduous trees, different deposition speeds and several orientations of the street canyon with aspect ratio *W/H = 2.0*. The wind directions can be split up in 24 sectors of 15°. The hourly meteo data for the year 2012 from the meteo station Luchtbal near Antwerp in Belgium have been used. For each hour the normalized concentrations are used from the respective wind sector to come to a year average concentration. As wind directions are unevenly distributed, the orientation of the street canyon influences the year average result. We have therefore considered four different orientations along the cardinal and intercardinal directions.

We have approximated here the seasonal effect by using the results with trees for the period from the 15th of April to the 1st of November. For the winter period the results without trees are used, as no deposition is possible and the disturbance of the flow is significantly reduced.

The concentrations of pollutants emitted by traffic are significantly affected by sources outside of the immediate surroundings of an urban street. The background concentration in an urban street canyon is made up of dispersion of all other pollution sources in the city of interest and longer distance transport.

We applied for EC and PM_{10} the annual average urban background concentrations determined in the city of Antwerp, Belgium, for the year 2009, respectively 1.81 µg m^{-3} and 29.32 µg m^{-3}. The emissions of both pollutants are the estimations of the MIMOSA4 model (Mensink et al., 2000) for the busy urban street Frankrijklei in Antwerp, respectively 11.22 and 22.45 µg s^{-1} m^{-1}. These values have been used together with the wind velocities of the 2012 meteo data of Luchtbal, Antwerp, to calculate absolute EC and PM_{10} concentrations, combining with the background concentration.

The effects of trees on the annual average EC and PM_{10} concentrations for the different combinations of vegetation parameters have been summarized in Figure 2. The emission from a busy urban street canyon form 40% of the EC concentrations inside the canyon. Taking into account EC background values, the annual effect of trees ranges from 1% to 13% increase, depending on the orientation and type of vegetation. For PM_{10} the contribution of the emissions inside the canyon is limited to about 7.5% of the total concentrations. The effect of trees on the PM_{10} concentrations is therefore only a 0.2% to 2.6%

increase. In Figure 2, the values for an average Belgian tree are connected by a line, the spread of the values showing the range for vegetation effects. Further, a worst-case influence is indicated in the graphs. This is definied as the influence of trees for one specific set of governing conditions (perpendicular wind direction, full leafed trees). Year-round effects of trees are thus significantly smaller than the large changes in concentrations identified for a single configuration and wind direction.

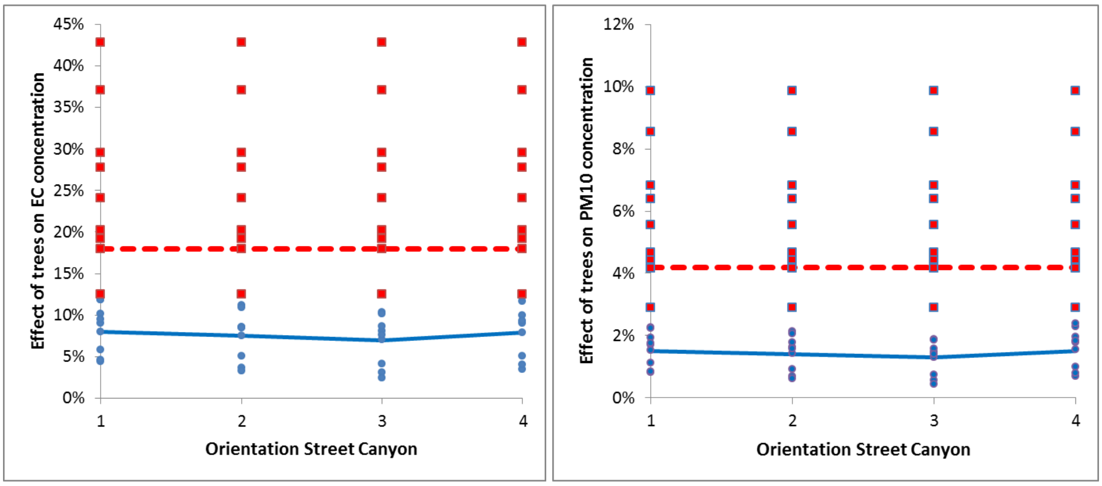

Figure 2. The annual effect of trees on EC and PM_{10} concentrations in an urban street canyon, for each street canyon orientation (N-S, W-E, NE-SW, NW-SE) data for 9 different vegetation types (blue dots) are presented and an average Belgian vegetation type is shown by the full line. Red squares represent worst-case-scenario of perpendicular wind direction and full-leaved trees, the dashed line indicates worst-case-influence for average vegetation.

5. CONCLUSIONS

The presented results agree with prior studies that the positive effect of street canyon vegetation on pollutant deposition is surpassed by the flow disturbance limiting the ventilation. The annual effects prove however fairly small, 0.2% to 2.6% increase for PM_{10} concentrations and 1% to 13% for EC, depending on the type of vegetation. Urban vegetation has several positive environmental impacts, traffic pollutant exposure mitigation for street canyons is however not one of them. We like to stress urban trees are not the source of increased pollutant concentrations in street canyons, as this is the local traffic.

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