H14-124

EVALUATION OF THE ROLE OF VEGETATION ON THE AIR QUALITY IN HIGH DENSE URBAN AREAS

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Abstract: Vegetation is generally considered as an essential component for a sustainable city as it helps improve its microclimate environment and reduce greenhouse gases emissions. However, there is some evidence suggesting that negative effects may be imposed by tree-planting in an urban street canyon. Vegetation may act as an obstacle impairing the air circulation and pollutant removal processes at the pedestrian zone of some shallow urban canyons. Accordingly, we intend to examine the effect of vegetation on the air quality of two deep canyons (i.e. with aspect ratios H/W = 2 and 4) under the perpendicular approaching wind condition. In addition, we also aim to examine the effects of different tree configurations on air circulation and pollutant removal processes inside these canyons by constructing a Computational Fluid Dynamics (CFD) model. Our findings suggest that tree planting at street levels may not always enhance the pollutant removal process, and therefore the location of the trees should be carefully planned in order to mitigate the potential negative impacts. The findings should be of great significance to urban planners in planning a sustainable city.

***Keywords:** Vegetation; Tree configurations; Deep canyons; Pollutants dispersion; CFD;*

INTRODUCTION

Massive building construction has become a byproduct of rapid urbanization in many metropolitan cities. Excessive unplanned constructions in a city lead to many environmental problems such as urban heat island and air pollution problem. The situation is worsened in those urban street canyon areas where tall buildings are aligned along the heavy trafficked roads. Tree-planting campaigns are often launched with an objective to improve the environmental quality within urban cities. As a result, outdoor thermal comfort can be enhanced by moderating the solar heat gain to the urban area through building parks (Dimoudi, A. and M. Nikolopoulou, 2003), green roof and green walls (Alexandri, E.and P.Jones, 2008; Lin, B. et al., 2008; Robitu, M. et al., 2006). The amount of air pollutants deposited on the plant surface could be reduced by vegetation (Fujii, S. et al., 2005; Ottelé, M. et al., 2010; Yang, J. et al., 2008). Despite so, there is some contradictory evidence showing that actual pollutant concentration level inside canyons would be higher if road traffic was found near to tree-plantings (Litschke, T. and W. Kuttler, 2008). The wind velocity decreased and the average pollutant concentrations increased as trees acted as obstacles which blocked the wind flow and trapped the pollutants inside canyons (Gromke, C. et al., 2008; Buccolieri, R. et al., 2009; Ries, K. and J. Eichhorn, 2001; Buccolieri, R. et al., 2011).

However, only few studies investigated the effect of in-canyon tree-planting on pollutants dispersion, and most of them were only focused on canyons with low aspect ratios (i.e. with aspect ratios of (H/W) 0.5 or 1). Accordingly, this study aims at examining the impact of vegetation and its pattern on the pollutant dispersion inside deep canyons (i.e. with aspect ratios higher than 2). The study was initiated by first comparing the CO concentrations between the tree-free case and tree-lined case for deep canyons, and followed by varying the green coverage areas inside the canyons.

METHODOLOGY

Model description

Simulation models were constructed to investigate the impact of vegetation on the pollutants dispersion inside deep canyons. In this study, we focused on three different canyon geometries - with aspect ratios (AR) (ratio of building height to road width) 1, 2 and 4. As many possible combinations of building and road configurations exist under a specific aspect ratio, various configurations were constructed by varying the building height while holding both the street width H and the building façade length L ($10H$) constant. The results obtained were compared against those obtained for the tree-free configuration (i.e. street canyon without any trees). Figure 1a show the model sketch of tree-free case with traffic source in the mid-axis of the canyon. Different tree models were then built to compare with the base case. Models in tree cases were used for portraying a scenario that the trees lined along the mid-axis of the canyon and the tree crown was directly located on top of the traffic source. The dimension of tree crowns were assumed to be 9m (W) x 6m (L) x 6m (H) in all simulated cases. Figure 2 shows the cross-sections of the tree models for canyons with aspect ratios of 1 or 2. In addition, three different percentages of green coverage (which is defined as the percentage of occupied greenery area in the canyon in the x-y plane) (i.e. 12%, 25% and 50%) were modeled by varying the total number of trees planted insides street canyons. Figures 1b to 1d show the relevant sketches and cross-sections of the model used to simulate the tree-lined cases at different green coverage. A 12% green coverage was achieved by planting 7 trees inside the studied canyons ,a 25% coverage was achieved by planting 15 trees, , and a 50% green coverage was achieved by planting 30 trees. In addition, the effects of vegetation on the pollutants dispersion under 90° approaching wind directions were also examined. In total, 12 different configurations (3 baseline configurations and 9 test cases) were modeled and analyzed.

Numerical set-up

ANSYS FLUENT 12.0 (ANSYS 2009), which is a computational Fluid Dynamics (CFD) commercial code, was utilized to perform a series of three-dimensional (3D) flow simulations. FLUENT solves the steady flow field and pollutants dispersion based on Reynolds-Averaged Navier-Stokes (RANS) equations, standard k-ε turbulence model (Launder, B. and D.B. Spalding, 1974). The advection diffusion (AD) module was applied to model the pollutants transport. The selected sizes of hexahedral meshed elements for x-, y-, z- directions were 0.02 H. Finer grid sizes were used near the building walls, and the mesh size was then expanded from the building walls to outer part with a ratio of 1.2. All of the applied settings were complied with the COST Action 732(2005-2009) and AIJ guidelines (Tominaga, Y. et al., 2008). For the computational domain, the inlet boundary was set to at 8H from the upstream building of the street canyon, while the outflow boundary was set to at 30H from the downstream building. Top domain was set to be 7H from the building roof and the lateral domains were 5H from the building side walls. Other parameters, like the vertical profile of wind velocity, turbulent kinetic energy (k) and dissipation rate (ε) were also input to the model. The wind profile was assumed to obey power law and is represented in Eq.(1). The inlet speed was defined according to the inlet profile reported in the wind tunnel experiment (CODASC, 2008). As suggested by Solazzo, E. et al. (2009), the turbulent kinetic energy (k) and dissipation rate (ε) is calculated as Eq.(2) and Eq.(3) respectively.

$$\frac{u(z)}{u_H} = \left(\frac{z}{H}\right)^{\alpha} \tag{1}$$

$$k = \frac{{u_*}^2}{\sqrt{C_\mu}}\left(1 - \frac{z}{\delta}\right) \tag{2}$$

$$\varepsilon = \frac{{u_*}^3}{\kappa z}\left(1 - \frac{z}{\delta}\right) \tag{3}$$

where $u(z)$ is the wind velocity (in ms^{-1} at height z (in m)), u_H is the flow velocity at building height H, is equal to 4.7ms^{-1}. δ is the boundary layer depth, u^*= 0.52 ms^{-1} is the friction velocity, κ is the von Kàrmàn constant and has a value of 0.4, and C_μ is a constant and is equal to 0.09.

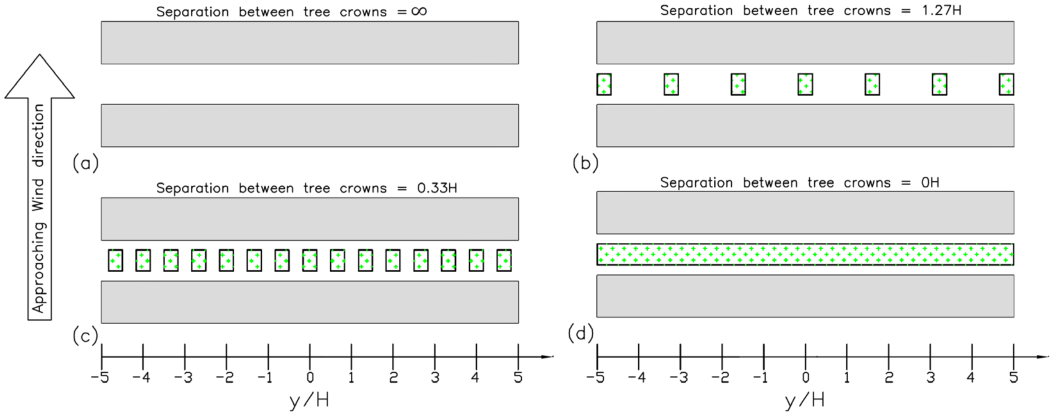

Figure 1. Sketches of the x-y plane of the simulated street canyon models (Top view) of a) Tree-free case; b) Tree-lined case with 12% green coverage; c) 25 % green coverage and d) 50% green coverage

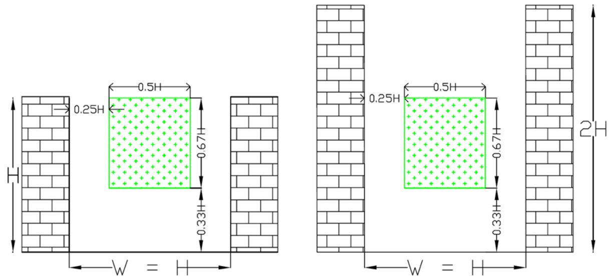

Figure 2. Cross-section sketches of the tree models in aspect ratio 1 (left) and 2 (right)

The vegetation model in our study was constructed by using the new modeling approach proposed by Gromke, C. (2010). This modeling approach has also been applied successfully in other studies to model plantings in canyons (Buccolieri, R. et al. 2009; Gromke, C. et al. 2008). Under this approach, the tree canopy is modeled as a porous medium. Pressure loss coefficient (l) is used as a measure of porosity of a tree, and is determined to be 200m^{-1} in a recent study. When wind flows through the tree canopy, air flow velocity is reduced and is resulted in a pressure loss over the medium.

In this study, the traffic induced pollutants were modeled by inserting one Carbon Monoxide (CO) line source with an emission rate of 10gs^{-1} in the center of the canyon. The normalized averaged concentrations at windward and leeward wall as well as the normalized volume-averaged pollutants at pedestrian zone (C_{avg}) were used to present the simulation results. The average concentrations derived from the CFD results were firstly normalized according to

$$C^+ = \frac{c * u_H * H}{Q} \tag{4}$$

where c is the mean pollutant concentration, u_H is the undisturbed flow velocity at building height H, and Q is the emission source strength.

RESULTS AND DISCUSSION

Model validation

Our models were first validated against the wind tunnel experimental data obtained from CODASC – Concentration Data of Street Canyon (CODASC, 2008). The experimental data chosen are those obtained for tree-free canyons and tree-lined canyons which have an aspect ratio of 1 and under 90° approaching wind. Our simulated results are highly correlated with the experimental results as the Pearson correlation coefficient values in all compared scenarios are higher than 0.85. Furthermore, the dispersion patterns of our simulation results were also in good agreement with the wind tunnel results reported by Gromke, C. et al. (2008). Figure 3 shows a comparison of the experimental and simulation results for tree-free case and tree-lined case under perpendicular approaching wind flow. The contour plots show the normalized concentration at windward side and leeward side obtained from the wind tunnel experiment and our simulation. Similar patterns are observed for the two cases. All these results led us conclude that our simulation model can predict the pollutant concentration inside the canyons to a high accuracy.

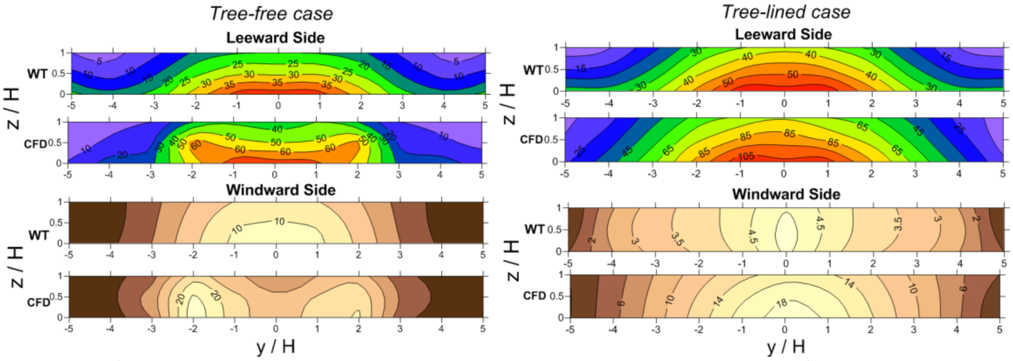

Figure 3. Contour plots of the normalized concentration at the leeward side and windward side in the tree-free and tree-lined case

The effect of tree-planting on the pollutant dispersion for different canyon geometries

In our study, the averaged normalized concentrations at windward wall, leeward wall and at the pedestrian zone (z = 1.5m) were used as proxies for monitoring the pollutant concentrations inside street canyons. Table 2 shows the normalized concentrations for both tree-free and tree-lined cases in canyons AR1, AR2, and AR4. The deviations in concentration (ΔC) between the tree-free case and tree-lined case were determined by [(C_{tree}-C_{ref})/ C_{ref} x100%], where C_{tree} and C_{ref} are the average concentrations of the tree-lined cases and tree-free case respectively (i.e. the base case). A number of findings are revealed. First of all, the averaged pollutant concentration at pedestrian zone was higher if trees were lined inside the canyons for all the studied canyon geometries. The CO concentration levels for tree-lined canyons AR1 and AR2 were 38% higher than that for tree-free case, and the concentration level for canyon AR4 was 27% higher. Tree-planting acts as obstacles in reducing the amount of air flow through the cavity, and is resulting in low ventilation rates. Compared with the tree-free case, tree-planting in canyons AR1 and AR2 led to significant increases in CO levels at the leeward sides but led to a small drop in CO levels at the windward sides. This is in line with those reported in other studies (Gromke, C. and B. Ruck, 2007; Buccolieri, R. et al. 2009). However, the result is found to be different for tree planting in canyon AR4 as its averaged concentrations were observed to be higher at both leeward and windward walls. This is because the dispersion mechanism occurred in AR4 is different from the ones occurred in AR1 or AR2. In tree-free AR1 and AR2 canyons, the vertically rotating vortices push the pollutants upwards and diluted by the air exchange near roof level (Gromke, C. and B. Ruck, 2007). However, the tree crowns blocked the air flow from windward to leeward side. Insufficient air flow reduced the ventilation performance around the area near leeward side. As a result, the CO concentration in the leeward side was higher. In contrast, for a deeper canyon AR4, more counter-rotating vortices generated within the canyons render the dispersion mechanism to be significantly different (Kovar-Panskus, A. et al., 2002; Eliasson, I. et al. 2006).The major pollutant dispersion mechanism for deeper canyons like canyon AR4 is by diffusing vertically and exchanging through the vertical counter-rotated vortices. High concentration levels were observed at both leeward and windward sides of the canyon due to the existence of trees in deep canyons obstructs the upward flow process of the pollutant dispersion.

Table 2 Comparison of the normalized concentration level at leeward side, windward side and pedestrian zone

Aspect Ratio	1			2			4		
	Tree-free	Tree-lined	ΔC	Tree-free	Tree-lined	ΔC	Tree-free	Tree-lined	ΔC
Leeward side	33.80	60.17	+78%	27.05	43.58	+61%	34.51	59.06	+71%
Windward side	15.85	10.49	-34%	65.22	46.77	-28%	42.50	60.74	+43%
Pedestrian zone	37.57	51.98	+38%	94.01	129.88	+38%	243.75	310.50	+27%

Effect of green coverage within the canyons

In the second part of this study, the green coverage area of the canyon was varied to investigate its impact on the pollutants dispersion. Green coverage is defined here as the percentage of total greenery area divided by the canyon width. Figure 4 shows the normalized volume-averaged concentration level at pedestrian volume for different green coverage. A tree-free cased was used as the base case (i.e. with 0% green coverage). Our findings reveal that the CO concentration level of a tree-lined canyon is higher than the tree-free case irrespective of the tree configurations for all the studied canyon geometries.

Higher pollutant concentration was found in the pedestrian zone of the trees lined canyon with spacing between trees (i.e. 12% and 25% green coverage cases) and maximum concentration level occurred for 25% green coverage. This was mainly due to the wind flow pattern changed by introducing separation distances between the tree crowns. For the case without separation (i.e.50% green coverage), two different circulation paths were observed at above and below the tree canopy layer. Below the tree canopy, the air entrained through the two street ends and towards the leeward side. The air flow near the leeward side rose up towards the roof level could help the pollutant removal. The polluted air rising above the tree crown then mixed with the air entrained from the canyon-roof interface, and the circulating vortices formed on top of the tree canopy increased the exchange rate. However, the flow pattern on and above the tree canopy layer changed if a lower green coverage was introduced by separating the tree crowns by a distance. The circulation path on top of the canopy layer disappeared, and the flow pattern below the tree canopy also changed. The air started flow downwards from the canyon-roof interface to the canyon cavity through the gaps between tree crowns. This reversed entrainment mixed with the air entered from two street ends and go towards the center of the canyon. The circulation path appeared in 50% green coverage case was obstructed. Thus, the pollutant cannot advect towards the leeward side and thus blocking the upward diffusion. This results in an accumulation of the pollutants at the bottom part of the street canyon.

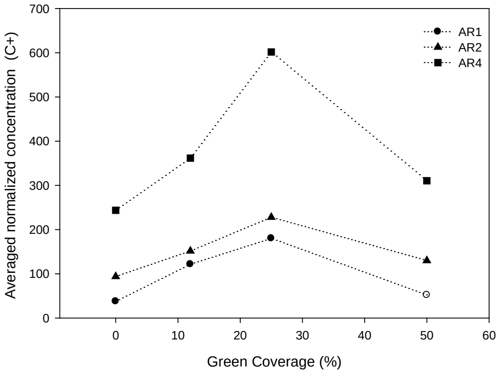

Figure 4. Normalized concentration profiles at the pedestrian zones for different green coverage scenarios

CONCLUSION

This study investigates the effects of street level vegetation on the pollutant dispersion characteristics in two deep canyon geometries under the perpendicular approaching wind. Street level tree-planting tends to increase the CO concentration level at the pedestrian zone for all the studied canyon geometries. Tree crowns act as obstacles in blocking the wind flow and altering the original dispersion path. In particular for deep canyons, tree crowns block the rising pollutants exchange path and the pollutants trapped at the pedestrian zone. Contrary to our original expectation, the ventilation performance inside deep canyons cannot be enhanced by increasing the separation distance between trees. Indeed, the reversed flow lowered the original ventilation performance and worsened the air quality inside.

These led us conclude that the aerodynamic effect of vegetation as street level tree-planting cannot be overlooked as it has a profound influence on the ventilation process inside deep canyons. In this regard, urban planners should strike a good balance between the positive effect on the temperature reduction, energy saving and the negative effect on the air quality of the vegetation. Trees are not recommended to plant along the centerlines of deep street canyons as the trees may act as an obstacle of the ventilation process. Furthermore, our study demonstrated the successful of applying CFD tools for analyzing the aerodynamic effect of the vegetation in different canyon configurations. However, only the aerodynamic impact of the vegetation was considered in our study. More studies should be conducted to extend our findings with considering the other effect such as the deposition and thermal effect of the vegetation.

ACKNOWLEDGMENTS

The authors would like to thank the Hong Kong Polytechnic University for her funding support through the Central Allocation Grants nos: GU-683.

REFERENCES

Alexandri, E. and P. Jones, 2008: Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment* ,**43**,480-493.

ANSYS, 2009: ANSYS FLUENT 12.0. http://www.fluent.com.

Buccolieri, R., C. Gromke, S. Di Sabatino and B. Ruck, 2009: Aerodynamics effects of trees on pollutant concentration in street canyons. *Science of the Total Environment*, **407**, 5247-5256.

Buccolieri, R., S. M. Salim, L. S. Leo, S. Di Sabatino, A. Chan, P. Ielpo, G. de Gennaro and C. Gromke, 2011: Analysis of local scale tree–atmosphere interaction on pollutant concentration in idealized street canyons and application to a real urban junction. *Atmospheric Environment,* **45**, 1702-1713.

CODASC Database, 2008: Concentration Data of Street Canyon, internet database, http://www.codasc.de.

COST Action 732, 2005-2009: Quality assurance and improvement of micro-scale meteorological models. http://www.mi.uni-hamburg.de/Home.484.0.html.

Dimoudi, A., and M. Nikolopoulou, 2003: Vegetation in the urban environment: microclimatic analysis and benefits. *Energy and Buildings*, **35**, 69-76.

Eliasson, I., B. Offerle, C. Grimmond, and S. Lindqvist, 2006: Wind fields and turbulence statistics in an urban street canyon. *Atmospheric Environment,* **40**, 1-16.

Fujii, S., H. Cha, N. Kagi, H. Miyamura, and Y. Kim, 2005: Effects on air pollutant removal by plant absorption and adsorption. *Building and Environment,* **40**, 105-112.

Gromke, C., and B. Ruck, 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., R. Buccolieri, S. Di Sabatino and B. Ruck, 2008: Dispersion 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. 2010: A vegetation modeling concept for Building and Environmental Aerodynamics wind tunnel tests and its application in pollutant dispersion studies. *Environmental pollution,* **159**, 2094-2099.

Kovar-Panskus, A., L. Moulinneu, E.Savory, A. Abdelqari, J.F. Sini, J.M. Rosant, A.Robins and N.Toy, 2002: Influence of geometry on the mean flow within urban street canyons–a comparison of wind tunnel experiments and numerical simulations. *Water, Air, & Soil Pollution: Focus,* **2**, 365–380.

Launder, B, and D.B. Spalding, 1974: The numerical computation of turbulent flows. *Computer Methods in Applied Mechanics and Engineering,* **3**, 269-289.

Lin, B, X Li, Y Zhu, and Y Qin, 2008: Numerical simulation studies of the different vegetation patterns' effects on outdoor pedestrian thermal comfort. *Journal of Wind Engineering and Industrial Aerodynamics,* **96**, 1707-1718.

Litschke, T. and W. Kuttler, 2008: On the reduction of urban particle concentration by vegetation – a review. *Meteorologische Zeitschrift,* **17**, 229-240.

Ottelé, M., D. Hein, V. Bohemen and A. L.A. Fraaij, 2010: Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecological Engineering*, **36**, 154-162.

Ries, K. and J. Eichhorn, 2001: Simulation of effects of vegetation on the dispersion of pollutants in street canyons. *Meteorologische Zeitschrift,* **10**, 229-233.

Robitu, M., M. Musy, C. Inard, and D. Groleau, 2006: Modeling the influence of vegetation and water pond on urban microclimate. *Solar Energy*, **80**, 435-447.

Solazzo, E., X. Cai, and S. Vardoulakis, 2009: Improved parameterisation for the numerical modelling of air pollution within an urban street canyon. *Environmental Modelling & Software,* **24**, 381-388.

Tominaga, Y., A. Mochida, R. Yoshie, H. Kataoka, T. Nozu, M. Yoshikawa and T. Shirasawa, 2008: AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of Wind Engineering and Industrial Aerodynamics,* **96**, 1749-1761.

Yang, J., Q.Yu and P. Gong, 2008: Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment,* **42**,7266-7273.