IMPACT OF BUILDING PERMEABILITY ON POLLUTANTS REMOVAL EFFECTIVENESS IN URBAN STREETS

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ABSTRACT

Improper city planning has a tremendous impact on urban air quality. Tall buildings aligned along two sides of the street canyon affect the pollutant dispersion process. Efforts have been spent on exploring strategies to mitigate air pollution problem within street canyons. However, there is still in need of consensus on which types of road and building geometry will enhance air circulation. In this study, we aim to investigate the effects of building permeability and approaching wind directions on the pollutant removal ability for different canyon geometries. A numerical model was constructed using standard k-ε model under the Computational Fluid Dynamics (CFD) flow and dispersion simulation. Pollutants reductions at the pedestrian levels were examined for different building permeability ratios and wind directions. It is found that pollutant reduction has a linear relationship with the building permeability for a canyon with an aspect ratio of 2 when the approaching wind is perpendicular to the street axis. However, such relationship is not found for canyon with an aspect ratio of 6. Increasing building permeability in deep canyons may not necessarily enhance the pollutant removal ability in street canyons. When the approaching wind direction is parallel to the street axis, wind will be channeled and washed out the pollutants towards the street end. However, spacing between building blocks interrupted this process so that pollutants cannot be removed effectively. The pollutants are accumulated at the street ends and the pollutant reduction capability is reduced. Open spaces may not always favor the removal process and the approaching wind direction should also be considered during urban planning stage to ensure effective pollutant removal from the site. These findings should be of particular significance to city planners as they help reveal the impacts of building permeability on the pollutants removal effectiveness.

KEYWORDS

Street canyons, Pollutants removal, Computational fluid dynamics, Building permeability.

INTRODUCTION

Traffic-related air pollution is the common problem observed in some high-dense urban cities especially in some metropolitans e.g. Tokyo, Hong Kong. In energy aspect, high density urban design is recommended since the consumption was found less than those low-density designs (O'Brien et al. 2010; Steemers, 2003). However, high density urban design worsened the air quality especially within the street canyon. Street canyons are common in urban cities which were formed by aligning tall buildings along the trunk road. Hence, attention has been drawn to suggest some strategies to mitigate the pollution problem in urban street canyon. Previous studies examined the wind flow and pollutants dispersion pattern in street canyons by field measurement (Kumar et al. 2008a; Zhou & Levy, 2008), computational simulation (Buccolieri et al. 2010; Hang et al. 2009; Kim and Baik 2004) or wind tunnel experiments (Chang & Meroney, 2003; Heist et al. 2009; Kastner-klein & Plate, 1999). These studies explored the role of different parameters like wind direction (Kim & Baik, 2004; Kumar et al. 2008b), thermal effect (Cheng et al. 2009; Xie et al. 2007), building packing density (Di Sabatino et al. 2007; Cheng et al. 2007) and special canyon design (Assimakopoulos, 2003; Xie et al. 2005) on the pollutant removal ability. However, few studies have focused on the effect of building permeability (i.e. ratio of building separation distance to the total façade length) on air quality even though it can be used to enhance the air movement and the pedestrian comfort at ground level (Ng, 2009). Furthermore, limited street canyon studies extended their examination to the deep canyon which aspect ratio is greater 4. To overcome these research gaps, this study aims at investigating the effects of building permeability on air quality in urban canyons. More specifically, this study is intended to study how a change in building permeability can induce a change in wind flow characteristics, ventilation effectiveness and the pollutant reduction capability in deep canyons.

METHODOLOGY

Model Description

To investigate the impact of building permeability on the air quality, sets of models were built and Figure 1 shows the configuration of the street canyons that examined in this study. In this study, we only focused on two canyons having aspect ratios (ratio of building height to road width) 2 and 6. For each aspect ratio, the effect of building permeability '*p*' (in terms of the ratio of building separation *S* to the building façade length *L*) on air quality was modeled by varying different permeability values (i.e. 5%, 10%, 20%, 25% and 35%), As many combinations of building and road configurations are possible for a specific aspect ratio, various configurations were constructed by altering the building height while holding both the street width *H* and the building façade length *L* (10*H*) constant. The results obtained for the five different permeability values were compared against those obtained for the baseline configuration i.e. buildings with a zero permeability value. Besides, the effects of the building permeability on the pollutants removal capability under 0°and 90° approaching wind directions were also examined. Due to resources constraints, we only focused on the effect of building configurations when the wind speed was 4.7m/s. In total, 24 different configurations (4 baseline configurations and 20 test cases) were modeled and analyzed.

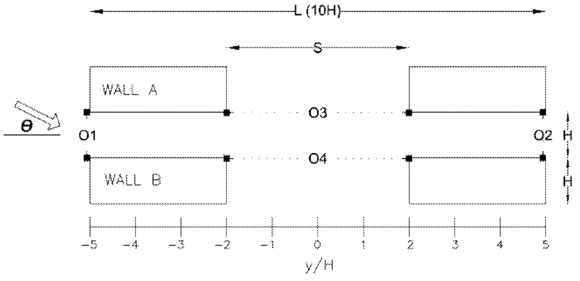


Figure 1 Modeled street canyon configuration

Numerical set-up

Computational Fluid Dynamics (CFD) commercial code ANSYS FLUENT 12.0 (*FLUENT*, 2009) performed 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-e turbulence model (Launder & Spalding, 1974) and pollutants transport equations. The adopted size of hexahedral meshed elements for x-, y-, z- directions were 0.02 H and finer grid size were found near the building walls. The mesh size was then expanded from the building walls to outer part in a ratio of 1.2. All of the applied settings were complied with the COST Action 732(2005-2009) and AIJ guidelines (Tominaga 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. The schematic diagram of the computational domain is shown in Figure 2.

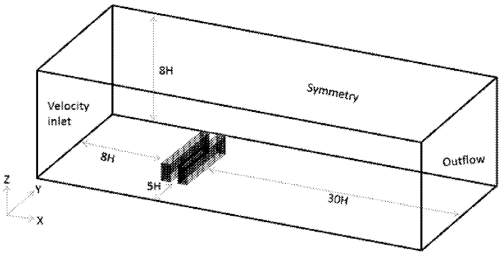


Figure 2 Schematic diagram of the computational domain with boundary conditions

The vertical profile of wind velocity, the turbulent kinetic energy (k) and dissipation rate (ε) are required to input to the model. For the wind profile, it is assumed to obey power law and shown in Eq.1. For the turbulent kinetic energy (k) and dissipation rate (ε) is calculated as Eq.2 and Eq.3 which is introduced by Solazzo et al. (2009).

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

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

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

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

Dispersion set-up

To simulate the traffic-related pollutants emitted from vehicles, line source with carbon monoxide emission rate of $10\ \mathrm{gs}^{-1}$ was constructed. The dispersion process was modeled by solving the species transport equation together with the turbulence model equations. The mass diffusion process was analyzed based on the following equations:

$$J = -\left(\rho D + \frac{\mu_t}{Sc_t}\right)\nabla Y \qquad (4)$$

$$Sc_t = \frac{\mu_t}{\rho D_t} \qquad (5)$$

$$\mu_t = \rho\left(\frac{C_\mu k^2}{\varepsilon}\right) \qquad (6)$$

where J is the diffusion flux of the mixture, ρ is the density of the mixture; D is the molecular diffusion coefficient of the pollutant in the mixture; Y is the mass fraction of the pollutants; μ_t is the turbulent viscosity and its value is determined from Eq. 6; turbulent Schmidt number Sc_t is set to 0.7.

Air quality parameter

A number of indicators (e.g. ACH, ventilation flow rates) have been applied for evaluating the air quality in previous street canyon studies (Cheng et al. 2008; Hang & Li, 2010; Yim et al. 2009). Pollutant reduction capability at pedestrian level was computed in this study to investigate the impact of building permeability on pollutants. The pollutant reduction capability 'R' is determined by:

$$R = \frac{(C' - C)}{C} \times 100\% \qquad (7)$$

where C' is the average CO concentration in the canyon when the building permeability is at a specific value and C is the average CO concentration in the canyon when the permeability value is 0% at pedestrian level.

RESULTS AND DISCUSSION

Model validation

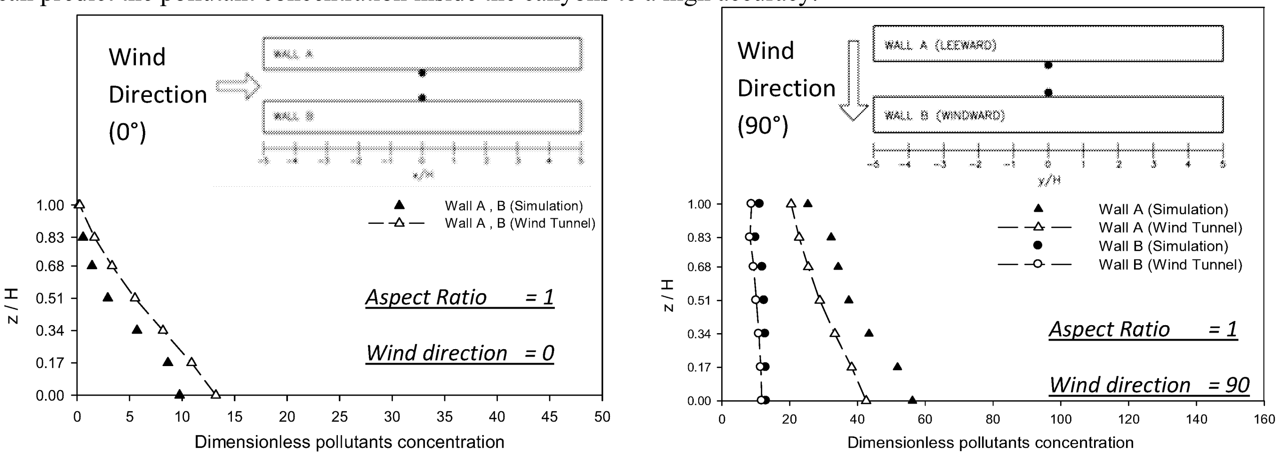
Our models were first validated against the wind tunnel experimental data collected from CODASC – Concentration Data of Street Canyon (Gromke et al. 2008). The experimental data chosen for our validation are those obtained for canyons having aspect ratio 1 under three different approaching wind directions. Pearson correlation coefficient (R) was also used to evaluate the linear dependence between the wind tunnel and simulated results. Correlation coefficient value of '+1' suggests a perfect correlation between the simulated and wind tunnel results. On the contrary, correlation coefficient value of '0' suggests the correlation between the simulated results and the wind tunnel results is insignificant. Table 1 show the statistical evaluation of the simulated results. The correlation coefficients in all compared scenarios are more than 0.9 which indicated our simulated results are highly correlated with the experimental results.

Table 1 Statistical analysis results

'R' Correlation coefficient

	Aspect ratio = 1		
Wind direction	0	45	90
Wall A / Leeward side	0.97	0.91	0.91
Wall B / Windward side	0.97	0.94	0.95

Furthermore, the trends of the results from our simulations were compared with the wind tunnel results collected by Gromke et al. (2008) to ensure the quality of the applied CFD code. Figure 3a and 3b show the comparison of the experimental and simulation results under parallel and perpendicular approaching wind flow. Similar trends are observed for two different approaching wind directions. All these results led us conclude that our simulation model can predict the pollutant concentration inside the canyons to a high accuracy.



(a) Parallel approaching wind (b) Perpendicular approaching wind

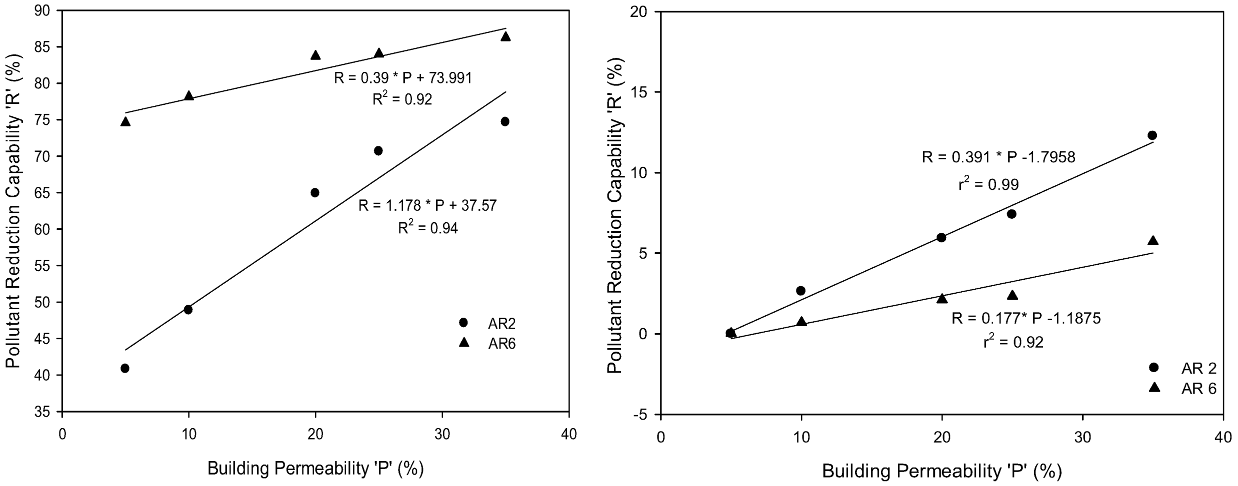
Figure 3 Comparison of the concentration profile obtained from experimental results (Grmoke et al., 2008) and simulation results

Effect of building permeability on pollutant dispersion and removal

Given the pollutant dispersion path changes with air flow pattern, the location of the highest pollutant concentration observed along the street canyon is also found to vary with building permeability and wind directions. The results for all the test cases were compared with those from the respective baseline configurations, i.e. with zero building permeability street canyon configurations in AR2 and AR6 under both perpendicular and parallel approaching wind flow. Results derived from all the 20 cases are presented in Figure 4a and 4b.

First of all, the pollutant reduction capabilities of the two canyon geometries were analyzed under perpendicular approaching wind flow. Figure 4a shows the relationship between pollutant reduction capability and the building permeability. A parametric relationship between building permeability (P) and pollutant reduction capability (R) have been formulated. Pollutant reduction capability increases linearly with building permeability for both canyon geometries but higher rate of increase is observed for AR2. For the same building permeability value, the pollutant reduction capability of canyon AR6 is almost twofold as that of AR2. Around 70%-86% of the pollutants can be removed from canyon AR6 if the building permeability value is raised above 5%. However, only 40%-75% can be removed from canyon AR2. Furthermore, the rate of increase for canyon AR2 is larger than for canyon AR6. This suggests that the change in pollutant reduction capability is less sensitive to the change in building permeability value in canyon AR6. Higher building permeability value results in higher pollutant reduction capability for canyon AR2. However, the pollutant reduction capability of canyon AR6 only increases slightly with increasing building permeability.

The models were then simulated under parallel approaching wind flow. The pollutant dispersion pattern under parallel wind flow is different from that under perpendicular flow. For the configurations with zero building permeability, the channeled wind flow pushes the pollutants towards the street ends. The lowest pollutant concentration is found near the entry of the canyon while the highest concentration is found near its exit. Pollutant dispersion pattern does not vary with building permeability for both canyon geometries. Channeled wind flow pushes the pollutants towards the street ends. However, some complex vortex structures formed inside the separation between building blocks produce lateral wind flow which reduces the channeling force. Figure 4b shows the effects of building permeability of the canyon on the pollutant reduction capability. Unlike the perpendicular, building permeability had less impact on the pollutant reduction capability. The flow resistance induced by the gaps between building blocks increased with the separation distance (Princevac et al. 2010). The removal mechanism by the channeled wind will be changed such that pollutants cannot be removed from the canyon effectively. Compared to the non-permeable building under 90° wind flow, fewer pollutants can be removed.



(a) Perpendicular approaching wind (b) Parallel approaching wind

Figure 4 Relationship between pollutant reduction capability 'R' and building permeability 'P'

CONCLUSION

This study investigates the effects of building permeability on the wind flow and pollutant dispersion characteristics in two canyon geometries under different approaching wind directions. Upon a closer examination of the air quality inside the canyons, a number of important findings can be drawn from this study and should have far-reaching implications for urban planners.

The effects brought about by increasing building permeability along a street canyon strongly depend on the approaching wind direction. Contrary to our original expectation, higher ventilation effectiveness and pollutant removal capability of the canyon are not necessarily the direct results of increasing the building permeability along canyons. Linear increasing relationship can only be reckoned when the approaching wind direction is 90°. On the contrary, an insignificant relationship is reckoned between ventilation effectiveness and pollutant reduction capability, and building permeability under parallel wind flow. This suggests that it is not appropriate for uniformly applying the same building permeability value in city planning as prevailing wind direction is shown to have a profound influence on its ventilation effectiveness. Urban planners can apply our findings for newly designed some high-rise urban area or enhanced the existing polluted street canyons. Despite so, more studies should be conducted to extend our findings to more complicated street canyon geometries and different wind speeds.

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