CFD Simulations of Pollutant Dispersion for Optimized Half Open Spaces in Ideal Urban Street Canyons

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SUMMARY
Earlier studies have demonstrated the possibility to improve urban ventilation efficiency by integrating half open spaces into building configurations. Considering as a major form of half open spaces, an optimized arcade design configuration was evaluated to greatly reduce air pollutant dispersion in ideal urban street canyons, as compared to the case of a typical arcade design. This paper employed the optimization procedures from our former study based on the multivariable regression correlation to maximize $ACH^*$ for achieving the optimized arcade arrangement. CFD simulations were then extended to consider the buildings with the optimized arcade designs for examining the effectiveness of half open spaces to resolve an issue of air pollutant dispersion over urban street canyons.

INTRODUCTION
Motor vehicle emissions are now one of the largest sources of urban air pollution in towns and cities throughout the world. Some of the worst air contaminations resulting from vehicular emissions can occur over a road edged by tall buildings (i.e. a “street canyon”). Air pollutant dispersion in a street canyon is different from that in a flat open region or a complex terrain. The vertical/horizontal turbulence intensities having similar values in a street canyon are much weaker than those in flat open lands. Specifically, the turbulence scale influencing the concentration fluctuation is limited in street canyons (Du et al., 2017). Good ventilation in the urban canopy layer (UCL) can transport a cleaner airflow from the rural areas into the UCL to decrease the negative effects of pollutants and urban heat island (UHI), and thereby to improve the air quality in outdoor and semi-outdoor pedestrian zones (Ai & Mak, 2016, 2017; Cui, Mak, Kwok, & Ai, 2016; Du et al., 2017).

Wind flow over convoluted urban areas has a central role in ventilation and breathability of cities, which is closely related to the quality of life and health benefits. As one of main forms of semi-open spaces, corridor is a partially open comfortable space, which is prevalent in the regions with hot and humid climates including Japan, China, Malaysia and Taiwan. It can facilitate good quality ventilation in the pedestrian pathway layer (PPL) to transport a clean airflow for easing the harmful impacts of contaminant spreading (Jian Hang, Li, Buccolieri, Sandberg, & Di Sabatino, 2012; J. Hang, Sandberg, & Li, 2009; Wen et al., 2017). The integration of semi-open spaces into building configurations could be one of the promising solutions to mitigate the UHI effect. Half open spaces have been extensively investigated by several researchers (Ali-Toudert & Mayer, 2007; Carrilho da Graça, Martins, & Horta, 2012; Kim, Kim, & Kim, 2010; Niu et al., 2015; Thompson, 2002; Wen et al., 2017). In our previous research to explore urban ventilation in idealized urban street canyons (Wen et al., 2017), the predictions evidently showed an enhancement of ventilation efficiency in the UCL through adding the arcade arrangement. Moreover, there is a 60% increase of the $ACH$ in the PPL by incorporating an arcade into the same street canyon layout. An integrated approach using the CFD numerical modelling and a ventilation index of $ACH$ was confirmed effective to quantitatively study various design impacts of the arcade layout on UCL ventilation. The simulated results were then processed by the multi-variables linear regression analysis to come up with a correlation of the above studied outcome as a basis, it is still needed to evaluate the pollutant dispersion around the buildings with the arcade design. Considering as an important shape of half open spaces, an optimized arcade layout was appraised to greatly alleviate air pollutant dispersion in ideal urban street canyons, as compared to the situation using a conventional arcade form. This paper applied the procedures from our past study based on the multivariable regression correlation to maximize $ACH^*$ for achieving the optimized arcade layout. After that, CFD simulations were extended to investigate the effectiveness of buildings with the optimized arcade design for resolving the issue of air pollutant dispersion over urban street canyons.

METHODS
High-rise urban areas geometry
To accurately resolve the pollution concentrations in built-up areas, we need the details about the height and width of the buildings, their configurations, the spacing between them, street widths, etc. There is no universally accepted scheme of urban classification for traffic pollution modelling purposes. Figure 1 shows a schematic of the building array geometries. The building model was made up of a 3×3 array with the featured parameters of building width (B), building height (H) and street width (W). In this research, a rectangular building array was numerically explored with B= W= 30 m and H= 90 m. This scenario was to take the UCL parameters in high
In the aforementioned equations, \( u_i \) denotes the velocity component in the \( i \) direction; whereas \( \rho, \rho, \nu, \nu_{\text{ref}} \) and \( g \) stand for the pressure, density, effective kinematic viscosity \( \nu \) and turbulent kinematic viscosity \( \nu_t \) and gravitational acceleration, respectively. In view of as the most prevalent, well-established and widely used turbulence model, a standard \( k-e \) two-equation turbulent model (Richards & Hoxey, 1993) was adopted for turbulence closure, as follows:

\[
\frac{\partial u_i}{\partial x_j} = 0 \cdot (4)
\]

\[
\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \left( \frac{\partial p}{\partial x_j} + g_i + \frac{\partial}{\partial x_j} \left[ V + u_i \right] \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right). (3)
\]

The production term was given as

\[
P = \nu_i \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right). (6)
\]

At the inlet of the computational domain, the measured velocity profile in the upstream free flow was used (in Eq. (1)) (Lin et al., 2014). It denoted a neutral atmospheric boundary layer (ABL). The inlet profiles of the turbulent kinetic energy \( k \) and its dissipation rate \( (\varepsilon) \) were calculated by Eqs. (7) and (8):

\[
k(z) = \frac{\nu^*}{C_{\mu}} \left( \frac{U_{\text{ref}}}{H} \right)^{2/3} (z / H)^{4/3}; (7)
\]

\[
\varepsilon(z) = C_{\mu} \left( \frac{U_{\text{ref}}}{H} \right)^{5/3} (K_v z). (8)
\]

Figure 1. Building array geometries

density areas with \( H/W=3 \) into account. Therefore, this paper aims to explore the phenomena of urban ventilation and air pollutant dispersion on the basis of the UCL model of high density urban street canyons. A ideal 3D building array was performed using the CFD software ANSYS/Fluent® to solve the above equations, and the wind environment adjacent to the subject building with half open spaces, numerical computations were performed using the CFD software ANSYS/Fluent® to solve the wind structure characterized by the interaction of airflow with buildings having half open spaces for examining the pollutant dispersion over urban canyons. Taking the inlet boundary condition into consideration, the atmospheric boundary layer (ABL) flow was employed to model the associated atmospheric processes (Yang, Wen, Juan, Su, & Wu, 2014). The theoretical analysis was based on the steady-state three-dimensional conservation equations of mass and momentum for the incompressible isothermal turbulent airflow over the calculation domain (Blocken, 2015). The governing equations are stated as follows:

\[
\frac{\partial u_i}{\partial x_i} = 0 \cdot (2)
\]

\[
\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \left( \frac{\partial p}{\partial x_j} + g_i + \frac{\partial}{\partial x_j} \left[ V + u_i \right] \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right). (3)
\]

This study adopted the wind velocity ratio (VR) as one of ventilation indices which denoted the dimensionless velocity magnitude. It was defined as the ratio of the wind velocity at the pedestrian level to a reference wind velocity (Hu & Yoshie, 2013), as below:

\[
VR = \frac{U}{U_{\text{ref}}}. (9)
\]

Where \( U \) and \( U_{\text{ref}} \) were the velocity magnitude and reference velocity of 3 m/s for all cases at \( z = H \) of the inflow boundary. Since ventilation refers to the continuous flow of air, the wind VR was then chosen to evaluate the ventilation efficiency in the street canyons (Ai & Mak, 2017; Hiyama & Kato, 2012).

\( ACH \) was used as another important factor to quantify the volumetric air exchange rate of the entire pedestrian pathway layer (PPL), \( Q_h \), to evaluate the effectiveness of aeration. The \( ACH \) is defined as follows.

\[
ACH = \frac{3600 Q_h}{V}. (10)
\]

Here, the \( ACH \) has a unit of \( h^{-1} \) and \( V \) denotes the volume of an entire PPL. \( Q_h \) was obtained by integrating over the whole computational domain with 77 buildings. Notably, the total flow rate that enters the PPL \( (Q_h) \) through the control volume boundaries equals that which is leaving the PPL \( (Q_{\text{out}}) \), due to flow balance.
In this investigation, we defined the uniform volume pollutant sources (PM\textsubscript{10}) with a total length of L (i.e. length of building array) at the entire pedestrian level from z = 0 to z = 0.1B (i.e. from 0 to 3 m) to simulate the perfectly-mixed near-ground pollutant emissions. The pollutant emission rate in the passive volume sources was 3 \times 10^{-11} \text{ kg/m}^3\text{s} for all cases to ensure that the source release produced little disturbance to the flow field (Jian Hang, Sandberg, Li, & Claesson, 2009). The steady transport equation for the time-averaged pollutant concentration (C, kg/m\textsuperscript{3}) is:

\[
\frac{\partial C}{\partial x_j} = -\frac{\partial}{\partial x_j}\left(K_{ij} \frac{\partial C}{\partial x_i}\right) + S_j. \tag{11}
\]

where \(u_i\) is the time-averaged velocity components, \(S_c\) is the pollutant emission rate \((3 \times 10^{-11} \text{ kg/m}^3\text{s}), K_{ij}\) is the turbulent eddy diffusivity of pollutants, \(v_i\) is the kinematic eddy viscosity, \(S_{ct}\) is the turbulent Schmidt number (here \(S_{ct} = 0.7\)).

As an important flow variable to analyse pollutant dispersion, pollutant concentration can be substantially affected by both flow field and source arrangements (locations and release strength). Therefore, it can’t be used to quantify and compare the ventilation capacity of pollutant removal independent of pollutant sources. In a zone where a passive contaminant source is formed with uniform release strength, the purging pollutant sources. In a zone where a passive contaminant source is formed with uniform release strength, the purging pollutant source is defined with the reference flow rate \((PFR, m^3/s)\) is the net flow rate by which this zone is purged out of pollutants (Sandberg, 1984). In case passive pollutants are uniformly released \((S_c = 3 \times 10^{-11} \text{ kg/m}^3\text{s})\) at the pedestrian level from 0 m to 3 m above the ground, the pedestrian purging flow rate (PFR) is defined as (Wen et al., 2017):

\[
PFR = \frac{S_c \times Vol}{C} = \frac{S_c \times Vol}{\int_{Vol} dxdydz / Vol}. \tag{12}
\]

Here the sign \(C\) is the spatially-averaged concentration in the entire pedestrian air volume \((Vol)\). Bady et al. has used this concept for assessment of ventilation in urban spaces (Bady, Kato, & Huang, 2008). It is noted that PFR is independent of the source strength \((S_c)\) at the pedestrian level, and shows the net capacity of removing contaminant pollutants owing to both mean flow and turbulent diffusion.

Because PFR is relatively small in this study, we normalized it \((PFR^*)\) by the reference flow rate \((Q_\infty = 0.00233 \text{ m}^3\text{s}^{-1})\) as below:

\[
PFR^* = \frac{S_c \times Vol}{(C)Q_\infty}. \tag{13}
\]

**RESULTS**

Numerical calculations were conducted by resolving the wind field at the pedestrian level for examining the influence of the buildings with half open spaces on the aeration and pollutant dispersion process in urban street canyons to improve the microclimate around the residential area. This research used the hexahedral cells so that the grid size close to the street grounds is around 0.4 m with a grid expansion ratio of 1.2 to characterize large variations of the flow properties associated with the interaction of the wind with structures.

The predicted velocities and turbulent kinetic energy by using standard, realizable, RNG k-ε and SST k-ω turbulence model are compared with the measured data from wind tunnel experiments in the open literature for computer software validation. It can be observed from results that the calculated X velocity and turbulent kinetic energy profiles from the standard k-ε models are relatively more accurate than those from the realizable, RNG and SST k-ω models. The prediction capability of the standard k-ε turbulence model demonstrates the best results in which there is optimal agreement between the CFD simulations and wind tunnel measurements.

**Optimization of arcade design in typical street canyons**

As indicated in our prior paper (Wen et al., 2017), buildings with an arcade design can improve the aeration performance of the PPL. To resolve an issue of air pollutant dispersion over urban street canyons through optimization of the arcade design, this study then implemented the design guidelines in terms of correlations obtained from a multivariable regression analysis (Wen et al., 2017) to determine an optimum aspect ratio of the arcade arrangement that could be modified from a typical urban layout. For a high density urban condition, the volumetric air exchange rate of a full-scale building array was numerically resolved with UCL parameters extents of H/W = 3. Accordingly, ACH* was defined as the ratio of ACH to a characteristic frequency, obtained from the reference velocity of the far upstream free flow divided by the reference building height, as the same definition in our previous study (Wen et al., 2017).

![Figure 2. 3D response surface of ACH* using multivariable regression against h and w in high density areas with H/W=3.](image)
Table 1. Calculated $ACH^*$ values for the typical and optimized arcade layouts (Wen et al., 2017)

<table>
<thead>
<tr>
<th>Scenario of urban layouts</th>
<th>Arcade layout</th>
<th>$ACH^*$</th>
<th>RPS Response</th>
<th>CFD Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H(m)</td>
<td>W(m)</td>
<td>Case</td>
<td>H(m)</td>
</tr>
<tr>
<td>Typical</td>
<td>90</td>
<td>30</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Optimized</td>
<td>90</td>
<td>30</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

Because the arcade design usually has a height of 3 m on the ground floor in regions with hot and humid climates such as Japan, China, Malaysia and Taiwan. An optimized arcade layout was $h= 4$ m and $w= 9$ m, which is rounded off the best design to the nearest integer (the best design when $h= 4.3$ m and $w= 9$ m). With the same configuration of urban street canyons, the predicted $ACH^*$ values for the typical and optimized arcade layouts were 229.162 and 854.127, respectively. As a result, the $ACH^*$ of the optimized arcade layout was therefore expected to be much higher than that of the typical arcade layout. For a wider arcade, it as found that the $ACH^*$ is greatly increased because more fresh air is transported into the PPL. The CFD predictions of the $ACH^*$ for typical and optimized arcade layouts confirm that the best ventilation outcome has maximum values of 926.552, thus revealing the effectiveness of utilizing the correlations from multivariable regression as a guideline to design an arcade in buildings for improving urban ventilation. It was also found that the CFD predictions provided 155% higher $ACH^*$ values than those of the typical arcade layout.

To further analyze the influences of arcade layout on the flow pattern, the velocity magnitude contours (Fig. 3) were predicted and probed in a vertical cross-sectional view of PPL for the cases of the typical (left) and optimized (right) arcade layouts. It could be clearly observed that the arcade design in Case 2 tended to generate higher airflow velocities in the central core and wake region, as compared to the flow pattern in Case 1. As a result, the simulated results in Case 2 indicated a much higher volumetric flow rate $Q_v$ and $ACH$ through the inlet opening and arcade.

The external clean air flowed across the windward opening to enter PPL, and some fraction of air passed through street roofs to leave the PPL volume. Along the main streets, the flow was channelled forward with a slightly vertical upward motion. In those secondary streets, it was observed that 3D helical flows produced upward and downward air exchange and turbulent fluctuations across street roofs. Moreover, the pollutants were transported across low levels of the interfaces from the canyons into the channels, leading to the outcome.

Figure 3. Predicted Velocity magnitude contours for typical (Case 1) and optimized (Case 2) arcade layouts

Figure 4. Predicted dimensionless pollution accumulation
that the main fraction of pollutants was removed out via the airflow along the central street in this case. Such processes of pollutant transport were consistent with the flow pattern and ventilated flow rates in Hang and Li [16]. Figure 4 illustrates the PM10 concentration contours in a vertical plane at y= 0 m for Case 1 with the typical arcade layout and Case 2 with the optimized arcade layout, from the simulations at S= 0.7. It should be noted that the upper limit of the colour bar was set at 2.2 ng/m². It was expected that local concentrations were relatively higher at lower wind speeds. It was observed that the pollutant accumulation outcome was greatly reduced in the center core and the wake region for the arcade design in Case 2, as compared to that in Case 1. Consequently, the simulated results in Case 2 indicated a much lower pollutant accumulation and higher PFR for the wind flow through the opening and arcade layouts. Table 1 illustrates the computed PFR values for Case 1 and Case 2 of pollutant gathering of the PPL. The predictions indicated that the PFR value in Case 2 was higher than that in Case 1 by around 5% due to relatively lower pollutant accumulation in the PPL. It was thus found that the arcade design can positively augment purging flow rate in the PPL.

DISCUSSION

The limitations of this study are listed as follows and will be addressed in future work.

(1) In this study, the CFD validation was performed using just one direction of the wind velocity, which agreed with the wind tunnel data. This is attributable to the lack of available on-site measured data of the wind directions as the wind only blew in one direction during the measurements.

(2) This study only focused on the effective ACH* and PFR indicators to determine the frequency with which a given volume of air can be completely replaced with fresh air for analyzing city breathability. Future works should apply and compare different ventilation and pollutant indices to assess urban ventilation and urban air pollutant dispersion.

(3) Steady-state calculations were performed to simulate the scenario of a mean summer condition for the incompressible isothermal turbulent flow. This may neglect the temporal fluctuations in the wind flow velocity, direction and diurnal temperature amplitude. Besides, the effects of solar radiation on street canyon ventilation were negligible for the isothermal condition. In spite of these limitations, the issue of concern here is on the appropriateness of using the optimized arcade layout obtained from our preceding study based on the multivariable regression correlation to maximize ACH* for resolving the issue of air pollutant dispersion over urban street canyons. This integrated approach by applying a ventilation index of ACH into the CFD numerical modeling is confirmed effective to quantify urban ventilation for various design impacts of the arcade layout. It provides practical implications for the urban planners, designers and policymakers to utilize the arcade design in conjunction with optimization of the street geometry and urban morphology for enhancing city breathability and resolving air pollutant dispersion.

CONCLUSIONS

Pollution simulation has been considered in this study which can be performed by examining the realistic capacity of city breathability and the induced flow exchange processes inside an actual urban area. It can focus on quantifying the removal capability of air pollutants to appraise the effectiveness of the optimization procedures in designing the arcade buildings that enhance city breathability. From the aforementioned studies investigating the efficacy of half open spaces in ideal street canyons on urban ventilation and air pollutant dispersion, these lead to the following conclusions.

1) CFD simulations were performed to verify the effectiveness of implementing the design concept of arcade in buildings for removing pollutants via natural ventilation.

2) To measure the influences of arcade design on the airing performance and pollutant transport rates, we showed the ACH and PFR of the entire PPL for buildings with and without the arcade design. A comparison of the simulated results for two versions suggested a significant increase in the ACH* value up to 155% and the PFR* value up to 5% by uniting the arcade design into a building for enhancement of the ventilation performance.

ACKNOWLEDGEMENT

This study represents part of the results obtained under the support of National Science Council, Taiwan, ROC (Contract No. MOST 105-2221-E-027-098).

REFERENCES


