Assessment of outdoor space’s ventilation efficiency around residential building: Effects of building dimension, separation and orientation

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Abstract: This paper probes into the influence of varying lateral spacing and serial lengths in residential buildings on ventilation efficiency in various typical outdoor spaces. To assess ventilation efficiency around residential buildings, purging flow rate (PFR), visitation frequency (VF) and air residence time (TR) are calculated with the computational fluid dynamics (CFD) method. The calculation tool is ANSYS-Fluent. Simulation results show that in comparison with length and lateral spacing, building orientation exerts relatively more effect on ventilation efficiency of outdoor spaces. When the angle between the long facade orientation and wind direction exceeds 30 degrees, the ventilation performance of different domains sees great improvement. Building length has certain influence on ventilation efficiency of outdoor space, especially for the buildings located in the middle of the residential area. The varying range of PFR could reach 16%. Lateral spacing in varying has a relative limited effect on the ventilation efficiency of various outdoor spaces, among which those closer to the varying area generally receive higher effect this way, in the meanwhile dependent on the layout pattern of surrounding buildings.

Keywords: Residential building; Layout design; Ventilation efficiency; CFD simulation.

1. Introduction

Ventilation efficiency of outdoor space is very important for both interior and exterior air qualities. Good ventilation condition around buildings means effective pollutant dilution and highly exterior air quality, which again affects the interior air quality by mechanical or natural ventilation. As most people spend most of their daytime and all nighttime indoors, a good ventilation condition around residential buildings proves importance for residents’ health. But how to create good ventilation conditions through appropriate building layout poses a challenge for architects. On the other hand, although research has revealed the effect of design variables on air flow pattern around buildings, the wind environment still remains beyond control of the architect as with the sunlight in deciding the orientation, length and spacing [Sanaieian et.al 2014]. It is partially because of the complexity of forms and design. So the trial-and-error method is adopted primarily at present during layout design of residential
buildings to improve the exterior wind environment of residential area. In order to help designers in effective decision-making for ventilation design of exterior spaces, the relationship between design parameters and exterior ventilation efficiency requires intensive research in an operable level.

Factors such as the size, spacing, orientation and location of residential buildings are important in the layout design. Effect of such design factors on ventilation and pollutants dispersion of exterior space has been discussed extensively in many studies in the field of urban forms and street canyon. For studies on urban forms, for example, Mfula et al. (2005) discussed the effect of spacing variation between buildings on diffusion of pollutants at different locations within urban space through wind tunnel tests. Buccolieri et al. (2010) employed numerical modelling to examine the spacing variation as to air exchange rate. These studies are mostly focussed on influence of building density on overall urban wind flows, choosing the square building arrays equally spaced in longitudinal and lateral directions in uniform variation as the simulation object. Buccolieri et al. (2015) also chose square arrays while respectively investigating the influence of the longitudinal and lateral spacing. Hang et al. (2015) conducted similar researches on street widths and building height studies. In the field of street canyon study, Oke et al. (1988) identified three characteristic flow field types on the basis of width / length (w/h) ratio of street section as early as in 1988. Then, Sini et al. (1996) discussed different characteristics of wind field with and without heating of walls for street canyon of infinite length with the technique of numerical modelling and studied street canyon simulation under different w/h ratios of street section, confirming the conclusion of Oke et al. again and finding the change of wind field characteristics when windward facade walls were heated. Similar studies also include that of Simoëns and Wallace (2008) on diffusion of pollutants. Besides w/h ratio of street section, Chan et al. (2001) also studied the effects respectively of different w/h ratios of building facade and change of building height on diffusion of pollutants at different locations, and results showed the facilitation of non-uniform building heights to urban ventilation and a maximum of building facade w/h ratio recommended to control within the range of 5. With most studies concerned with proposing an evolution method, the guidance value for practice in term of design operation is relatively limited. Most studies of urban form are restricted in discussing overall effect on ideal urban form with models of homogeneous fabric. In the street canyon field, long-strip buildings with w/h ratio of building facade over 7 were applied in most calculation models, and sections of street of infinite length were investigated even with 2D calculation model, which differed considerably from the design of residential buildings.

In addition, a number of studies related to residential building layout design have been carried out in recent years. For example, Hong and Lin (2015) simulated and compared 6 layout patterns of multilayer residential buildings under same density and coverage, and results showed that the building layout and orientation had significant effect on outdoor wind environment at pedestrian level. Yang et al. (Yang et al. 2015) analysed the effect of standard and staggered layout of roadside multi-floor buildings on diffusion of pollutants with numerical modelling. Ying (Ying et al. 2013) and Iqbal (Iqbal and Chan 2016) also conducted comparisons of high-rise residential building layout patterns. However, most of them performed simulation by simply combining several individual buildings without considering the blocking effect of surrounding buildings. What’s more, very few systematic studies have been conducted to characterize the effects of serial design changes.

In the last decade, evaluation method on urban ventilation has developed rapidly. Different parameters have been proposed and applied to assess ventilation efficiency of urban areas. Most of those parameters were developed from indoor ventilation studies (Bady et.al 2008, Hang et.al 2015, Buccolieri 2010, 2015), such as mean age of air (MAA), purging flow rate (PFR), visitation frequency (VF) and air residence time (TR). MAA in urban area can be defined as the time it takes for the urban external
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“fresh” air to reach a given location. PFR is defined as the effective airflow rate required to purge the air pollutants from the domain. TR means the time a pollutant takes from once entering or being generated in the domain until leaving it. A high value of MMA or AR implies a poorly ventilated domain. And a low PFR means that the domain is weakly ventilated. VF represents the number of times a particle enters the domain and passes through it. A high VF indicates poor removal efficiency of the pollutants. These parameters provide effective analysis methods for this study.

This research is attempted to probe into the correlation between varying design parameters and various spaces’ ventilation performances for design in operative level, so as to facilitate the designer in terms of ventilation design of outdoor space around residential buildings. This paper is focussed on the influence of varying lateral spacing and serial lengths in residential buildings on ventilation efficiency at various typical positions within the outdoor space. In consideration of the likely impacts from blocking effect of surrounding buildings, the cases were all set with similar surrounding conditions, namely residential districts with similar layouts. As for the residential district types, the slab-type and multi-story buildings are mainly paid attention to as accounting for the largest proportion in current China. To assess the influence of varying designs on ventilation efficiency of outdoor spaces, computational fluid dynamics (CFD) simulation method is adopted, and the calculation tool is ANSYS-Fluent, an extensively used commercial calculation software. As for the evaluation parameters of ventilation efficiency, there are some limitations with layout design researches of partial residential districts due to the fact that MMA is meant for fresh air areas. PFR, VF and TR are employed as indicators to evaluate the ventilation efficiency, which fully reflect air flow features of the calculated domain.

2. Simulation method

2.1. CFD model setting

For the setup of CFD model, the study refers to the guidelines of Architectural Institute of Japan (AIJ) as well as some similar studies (Tominaga et.al 2008, Hang et.al 2015). The computational domain is 5H (H is the building height) in lateral spacing and 6H in vertical direction. The distances are respectively 5H between inlet boundary and buildings and 20H between outlet boundary and buildings. Hexahedral elements are applied in the computational domain (about 3 million). The minimum grids in vertical and horizontal directions and maximum expansion factor between grids are respectively 0.022H, 0.044H and 1.15. The boundaries of air inlet and outlet are respectively velocity-inlet and pressure-outlet. Lateral sides and top are symmetrical boundaries while floor and building walls are non-slipping-outlet. Inlet vertical wind speed and turbulence distribution are determined according to formula (1) - (3).

\[ U(z) = U_H \left( \frac{z}{H} \right)^{\alpha} \]  
\[ k(z) = U_i^2 / C_{mu}^{1/2} \]  
\[ \varepsilon(z) = C_{mu}^{3/4} k(z)^{3/2} / \kappa z \]

According to AIJ standard wind tunnel test (Tominaga et.al 2008), in the formula \( \alpha=0.25 \), thickness of atmospheric boundary layer \( \delta=1m \), ground roughness \( Z_0=4.8 \times 10^{-4} h \) (\( h \) is the building height), which indicates that thickness of atmospheric boundary layer under actual conditions is 250m, (scale 1:250), reference wind speed \( U_H=7.8m/s \), thickness at atmospheric boundary layer \( H=\delta \), \( C_{mu}=0.09 \), \( U_i=0.33 \), \( K_v \) is Karman constant, which is determined as 0.4.
For selection turbulence model, large eddy simulation (LES) is relatively accurate for simulating wind field characteristics around buildings according to literatures. In consideration of the higher complicatedness and time-consumption of the LES, the more stable RANS model is introduced. Turbulent model is the standard k-\( \varepsilon \) model [Santiago et.al 2010]. All transport equations are discretized by the second order upwind scheme. The SIMPLE scheme is used for the pressure and velocity coupling. CFD simulations are run until all residuals become constant (equal to or below 1e-05).

2.2. Calculation of ventilation parameters

For calculation of ventilation efficiency parameters, a “homogeneous emission method” is introduced into numerical simulation (Hang et.al 2009). The homogeneous emission method means that pollutant source, such as carbonic oxide (CO) with uniformly distributed emission rate, is set in the studied domain, and the ventilation parameters of the studied domain can be calculated from the local pollutant concentration in certain wind field. As the air flow is not influenced by diffusion of pollutants, the flow field can be firstly calculated and then utilized in estimating the ventilation parameters. So the calculation of ventilation efficiency parameters consists of three steps: First, calculate and obtain flow field within the distribution area; secondly, determine the pollution source of overall or local area according to demand of parameter calculation, and calculate the concentration distribution of pollutants within flow field with mass transfer equation; and thirdly, calculate the parameters of ventilation efficiency via various calculation formulas.

The calculation formulas of PFR (m\(^3\)/s), VF and TR (s) are as follows [Bady et.al 2008]:

\[
PFR = \frac{q_p}{(C_p \cdot \rho)} \tag{4}
\]

\[
\Delta \frac{q}{q} = 1 + \frac{\Delta q_p}{q_p} \tag{5}
\]

\[
TR = \frac{Vol}{(PFR \cdot VF)} \tag{6}
\]

Where \( q_p \) denotes pollutant generation rate (kg/s), \( C_p \) stands for domain’s average concentration (kg/kg), \( \rho \) the air density (kg/m\(^3\)), \( \Delta q_p \) the inflow flux of pollutants into the domain (kg/s) and Vol the domain volume (m\(^3\)).

As the research deals with ventilation efficiency parameter calculations of different cases in various investigated regions, setting of pollution sources and calculation of ventilation parameters are quite complicated and time-consuming. To improve the calculation efficiency, the user-defined- function (UDF) of ANSYS-Fluent is applied here to help set the pollution sources and post-process the data.

3. Residential building configurations

3.1. Living units and combination

Configuration of residential buildings sizes (width L, depth D and Height H in Fig. 1a) involves the selection of living unit and their combination. Liu and Ding (2012) had made a systematic summary of different types of living units in newly built residential region in China (Liu and Ding 2012). According to their study, three common used living units are selected to compose the multi-floor residential buildings, as shown in Figure 1b. They represent two-bedroom (U1), three-bedroom (U3), and four-bedroom (U3) units. The living unit depth D is namely that of the residential units (D=12m). Building width L is subject to the unit composition. The unit composition types include single-unit composition and multi-unit
composition. The pattern of single-unit composition determines the minimum width of residential units, and residential units with greater width are configured with multi-unit grouping, as shown in Fig. 2c. To simplify the modeling, the partial undulations are excluded from consideration while plane of residential buildings is determined as rectangular, the floors as six in number and 2.8m in height and totaling in 18m in addition of the parapets and height difference between the interior and exterior heights.

3.2. Calculated residential buildings group setup

The latest residential districts in China share a noticeable fabric characteristic as shown in Figure 2a. The configuration derives from the designer’s initiative responses to the site shape, functions, sunshine and fire control requirements. Based on the striped fabric, residential building groups arrayed in 3*3 is assumed as the calculation object. The middle group serves as the studied area for the residential building length and varying spacing while the surrounding groups take part too, only as the surrounding conditions. To conveniently divide the grid to attune to the Fluent model, the surrounding groups are all arrayed in 2*3, each building sized 72x11m, with 3~4 units, duly oriented southward, spaced laterally (s1) in 7.2m and longitudinally (s2) in 24m particularly to meet the very sunshine spacing coefficient from the national specification. The road widths around and within the groups (r1 and r2) are set respectively as 24m and 10.8m precisely according to the national specification (GB50180-93 2002).

Figure 2: Calculated model setup (unit: m)
3.3. Building lateral spacing and length variation

To investigate the influence of varying building lateral spacing and lengths on the ventilation in outdoor space, two steps are adopted in this study. First, a common used design case is simulated under different wind direction to decide the typical wind directions. Then different cases with varying lateral spacing and lengths are performed in these typical wind directions. As shown in Figure 3, Case A denotes the varying lateral spacing while Case B stands for the varying lengths. The longitudinal spacing is restricted by the sunshine conditions and land use economy, therefore fixed in 24m. To examine the effect of design variables on ventilation efficiency in different domain, some typical areas are selected for comparison. A-R1 and A-R3 represent outdoor space of outer and inner side living units in Case A, B-R2 represent outdoor space of central living units in Case B.

![Figure 3: Calculated model setup (unit: m)](image)

4. Simulation results and analysis

4.1. Influence of wind direction changes

To assess the influence of wind direction on space ventilation, Case A2 is taken as the simulation object with a building size and spacing commonly used in the residential layout design. The wind direction variation is set form south direction ($\theta=0^\circ$) to east ($\theta=90^\circ$), with an interval of 30 degrees. Figure 8 shows the MMA, VF and TR of different domains all through the wind direction variation. It is noticeable that as the wind angle increases, these indices change evidently. VF and TR in all domains decrease while PFR rises rapidly. It implies the ventilation ability improves as the wind direction gradually tend to parallel to the building’s long facade. This is mainly due to the strip-shaped spatial structure with a duly north-south directed ventilation corridor as a result of the sunlight requirement. As the wind direction turns parallel to the ventilation corridor from being perpendicular, the wind flow entering the space between residential buildings increases greatly. However, effect on ventilation efficiency caused by wind direction variation does not show the rule of linear variation. When the angle between building facade orientation and wind direction exceeds 30 degrees, amplitude of variation of ventilation parameters decreases gradually, especially obvious in term of visitation frequency and air resistance time. Taking A-R1 for an example as well, when wind direction turns from south to 30 degrees of southeast, VF and TR reduce by 32% and 79% respectively, while when wind direction turns from 30 degrees of southeast to east, the change range of VF and TR are all blow 1%. What’s more, the ventilation efficiencies of different domains also vary greatly, especially when wind direction is perpendicular to the long facade of buildings. The variation range of VF and TR can respectively reach more than 23% and 32%.
It can be concluded from the simulation that building orientation is an important factor for improving outdoor ventilation of multilayer residential buildings. In the design process the local prevailing wind direction should be seriously considered, and when the angle between the main facade orientation and wind direction exceeds 30 degrees, the ventilation efficiency of different domains improves greatly. So in the following studies, the cases are all calculated in the wind directions of south and southeast 30°.

4.2. Lateral spacing change

Lateral spacing variation (S) also has a certain influence on ventilation efficiency of outdoor space between the buildings, but the influence range varies greatly in different domains. As the study cases are symmetrical in the southward wind direction, three typical domains between the western two buildings are calculated, as shown in Figure 5a-c. The results reveal that the outdoor space of inner side living units (A-R3), which is adjacent to the changing middle space, is more affected by lateral spacing variation. The change range of A-R3 on PFR, VF and TR can exceed 50%, 25% and 35%. However, the outdoor space ventilation of outer side living units (A-R1) and central living units (A-R2), which are far away from the changing middle space, are less affected by the lateral spacing variation. The change range of A-R1 on PFR, VF and TR are 9%, 4%, and 7%, and that of A-R2 are 17%, 1% and 18%. As the lateral spacing increases, the PFR of A-R3 rises gradually. These simulation results show that an increasing lateral spacing can improve the ventilation in limited areas. Besides, when the lateral spacing goes beyond 10.8 meter, the range decreases evidently perhaps as a result of the lateral spacing of the surrounding buildings, which is located in the south of the target area.

In southeast wind direction (30°), the influence of lateral spacing variation on outdoor ventilation of different domains also varies (Figure 5d-f). As the lateral spacing increases, PFR of the domain between buildings at the west end decreases, while that of the east keeps constant. Take the outdoor space of the living units on the inner side (A-R3 and A-R4) for an example, PFR of the west-end domain A-R4 decreases by 20% while that of the east-end domain A-R5 decreases only by 5%. This is mainly because that the wind flow enters from the west side into the in-between space of the south-oriented buildings. And as the lateral spacing increases, more wind flows hit the east interface of the western building, bringing about eddy flows at the building corner, which decreases the wind speed in the very domain.
4.3. Building length change

Figure 6a–c shows the effects of building length (L) variation on ventilation efficiency in different domains in the south wind direction. As the study cases are also symmetrical in the south wind direction, two typical domains (B-R1 and B-R2) between the two middle buildings are calculated. The simulation results show that as the building length increases, PFR of the outdoor space of middle living units (B-R2) decreases evidently, with variation amplitude of 16%. PFR of the outdoor space of outer side living units (B-R1) initially keeps nearly constant, but when building length reaches more than 50 meters, it increases greatly. The change range reaches as much as 60%. The main reason might be that as the building length increases, domain B-R1 gradually approximates the edge of the study area, which leads to acceleration of wind speed in this domain. Meanwhile, the vortex flow weakens as shown in Figure 6b. As building length increases, VF decreases slightly. So it can be concluded that increasing building length will not benefit the improvement of space ventilation when wind direction is perpendicular to the main building facade, especially for the middle located buildings.

Figure 6d–f shows the effects of building length variation on ventilation efficiency of different domains in southeast wind direction. As building length increases, PFR of the domain B-R3 decreases, while the other two domains B-R3 and B-R4 remain constant. The reason might be the same as that of the building lateral spacing variation. As the domain B-R3 approaches the east side of studied area, more wind flows hit the east side wall of the middle south and north buildings, which leads to more rotation in vortex flow at domain B-R4 as clearly shown in Figure 6e.
5. Conclusion and discussion

This paper discusses the effect of design variables such as orientation, length and lateral spacing on ventilation efficiency of outdoor spaces under the conditions of blocking effect from surrounding buildings. Based on CFD simulation, the pollutant purging flow rate, visitation frequency and air resistance time of different domains are calculated for serial design variation under typical wind directions. These indices show relatively favorable effect of design variables on the ventilation in outdoor space. The findings are concluded as follows.

- Building orientation exerts relatively more effect on ventilation efficiency of outdoor spaces. In the design process, local prevailing wind direction should be considered seriously, and when the angle between building main facade orientation and wind direction exceeds 30 degrees, the ventilation performance of different domains improves greatly.
- Building length has a certain influence on ventilation efficiency of outdoor space. It is especially true for the buildings which are located in the middle of the residential area. Decreasing building length will benefit the ventilation performance of outdoor space around the middle living units when the wind direction is perpendicular to the main building facade, and the improvement of purging flow rate could reach 16%.
- Lateral spacing variation have a relatively limited effect on ventilation efficiency of outdoor spaces and a certain effect on that of two adjacent domains. Besides, the improvements are restricted by lateral spacing of the surrounding buildings, which is located in the windward direction of the studied area.

This research preliminary analyses the influence of several design changes on outside space’s ventilation. Due to urban form complexity, the conclusions are constrained to these studied patterns. In further research, more numerical simulations should be carried out to check whether the conclusions...
drawn above changed or not. For example, housing blocks with staggered layout buildings and trees arrangement should be considered in both studied area and surrounding conditions. Building heights variation and leisure square design will also be discussed in the following studies. What’s more, only the predominant wind characteristics are discussed in this study. In subsequent research, local wind rose data should be considered to discuss the influence of annual wind direction and speed variation.

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