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Improving wind environment design based on assessing spatial distribution of ventilation efficiency in regional space

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Abstract

This paper discusses the influence of design variations on spatial distribution of Ventilation Efficiency (VE) in idealized residential building groups. Series of design cases referring building length and spacing changing are investigated using Computational Fluid Dynamics (CFD) simulation method. Air change rate (ACH) and purging flow rate (PFR) are adopted as evaluation indices of ventilation efficiency. Simulation results indicate that these design changes have evident effects on distribution of spatial ventilation efficiency. Widening building spacing could improve ventilation efficiency of different spaces. However, the benefit is not linear improved as spacing distance increases. When the distance is higher than 15m, improving extent of spatial ventilation efficiency decreases evidently. Variations of building length also has effect on distribution of spatial ventilation efficiency. As building length increase, less wind could reach into space between south and north buildings, which lead to the decrease of wind ventilation for middle residential-unit. Preliminary study indicates that building length should be restricted within 5 residential-unit.

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Keywords: Residential building; Length and spacing design; spacial ventialtion efficiency; CFD simulation

1. Introduction

Wind conditions of exterior spaces relate closely to outdoor air quality and thermal environment. Good wind conditions around buildings can effectively dilute pollutants and excess heat. On the other hand, outdoor air quality and temperature can also affect indoor air quality and temperature by mechanical and/or natural ventilation. The indoor

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and outdoor air quality and temperature relate closely to people's thermal comfort and healthy, and will ultimately influence building's energy consumption. It is especially important for residential area. Optimizing urban form (building shape, spacing and layout patterns) is accepted as an effective mean of providing a better outdoor ventilation condition [1]. But how to create good ventilation conditions through appropriate urban design poses a challenge for architects. Therefore, an understanding of relationship between urban design parameters and spatial ventilation efficiency (VE) is essential for architects to optimizing exterior wind environment.

Based on measurement and numerical simulation, numerous studies had discussed the influence of design variations on spatial ventilation efficiency. Bady et al. [2] uses two-building and building array geometrical models to assess effects of urban street width to height ratio and layout patterns on ventilation efficiency of selected local domains. Kato and Huang [3] further evaluates ventilation efficiency in complex urban street space, and spatial ventilation efficiency of four local domains are analysed. Hang et al. [4,5] used some simple idealized city models to explore effect of city shape and street configuration on flow mechanism and pollutant dispersion. Furthermore, influence of building height variability on pollutant dispersion in idealized high-rise urban city models were also studied by Hang et al. [6]. Buccolieri et al. [7,8] also studied spacing change on air exchange rate using numerical modelling. Similar studies have been performed by Sabatino et al. [9], Ramponi et al. [10], Razak et al. [11] and Lee et al. [12]. Beside the ventilation studies of urban-like building groups, recent studies had also discussed influence of micro-scale building arrangements on exterior wind environment, such as building sizes and distances [13], layouts [14] and street building configurations [15]. But it needs to point out that most of these studies have been concerned with proposing an evolution method of measuring effects of design variations on outdoor wind environment. For spatial ventilation efficiency study, only several typical spaces are investigated under several design cases. Rare studies had discussed series design various on spatial distribution of wind ventilation efficiency. However, it is very important to provide good wind environment for each residential living unit.

This study is attempted to probe into the correlation between residential building design various (building length and spacing) and spatial distribution of wind ventilation efficiency. The multi-residential building district is selected as an example for ventilation performance, as they account for the largest proportion in current China. Series of design cases of residential building groups are established to discuss the effect of lateral spacing and building length change on spatial distribution of wind ventilation efficiency. As for the evaluation indices of ventilation efficiency, air exchange rate (ACH) and purging flow rate (PFR) adopted. These indices are selected as they are two of the commonly used evaluation indices in previous urban ventilation studies [2-5]. To calculate these ventilation performance indices, ANSYS-Fluent is adopted in this study. It is a widely used Computational Fluid Dynamics (CFD) simulation tool, which can provide whole-flow field data.

2. Method

2.1. Description of the building configurations

For sizes of individual residential building, Liu and Ding made a systematic summary of different types of living units of newly built residential building in China [16]. Based on their study, the minimum length of residential building is set as 28.8m, which is a single living-unit building. The maximum length of residential building is 86.4m, which consists of 4~5 residential-unit. Building breath and height are 11m and 18m respectively.

Based on these residential building sizes, a 6 x 5 building groups model is set up as the simulation object, as shown in figure 2a. The interested area is between the 3rd and 4th row buildings, which have two rows of upstream buildings for all wind directions. The longitudinal, namely south-north spacing b is 24m, which meets the requirement of design code, i.e. 1:1.33 coefficient of sunlight spacing, while the east-west spacing d is determined as 7.2 m according to fire protection design code. The length of surrounding building is set as constant (a=72 m). For the central studied area, the length of buildings (L) and east-west spacing D1 and D2 varies as the study demand. To discuss the influence of building length and spacing changing on spatial distribution of wind ventilation efficiency. Three types of building layout changes are established, as shown in Fig 2b. Case A denotes the varying building length while Case B (Case B1 and Case B2) and Case C (Case C1 and Case C2) stand for two types of spacing varying based on variation of Case A. Wind direction is perpendicular to building long façade, which is set as the worst wind condition [17].

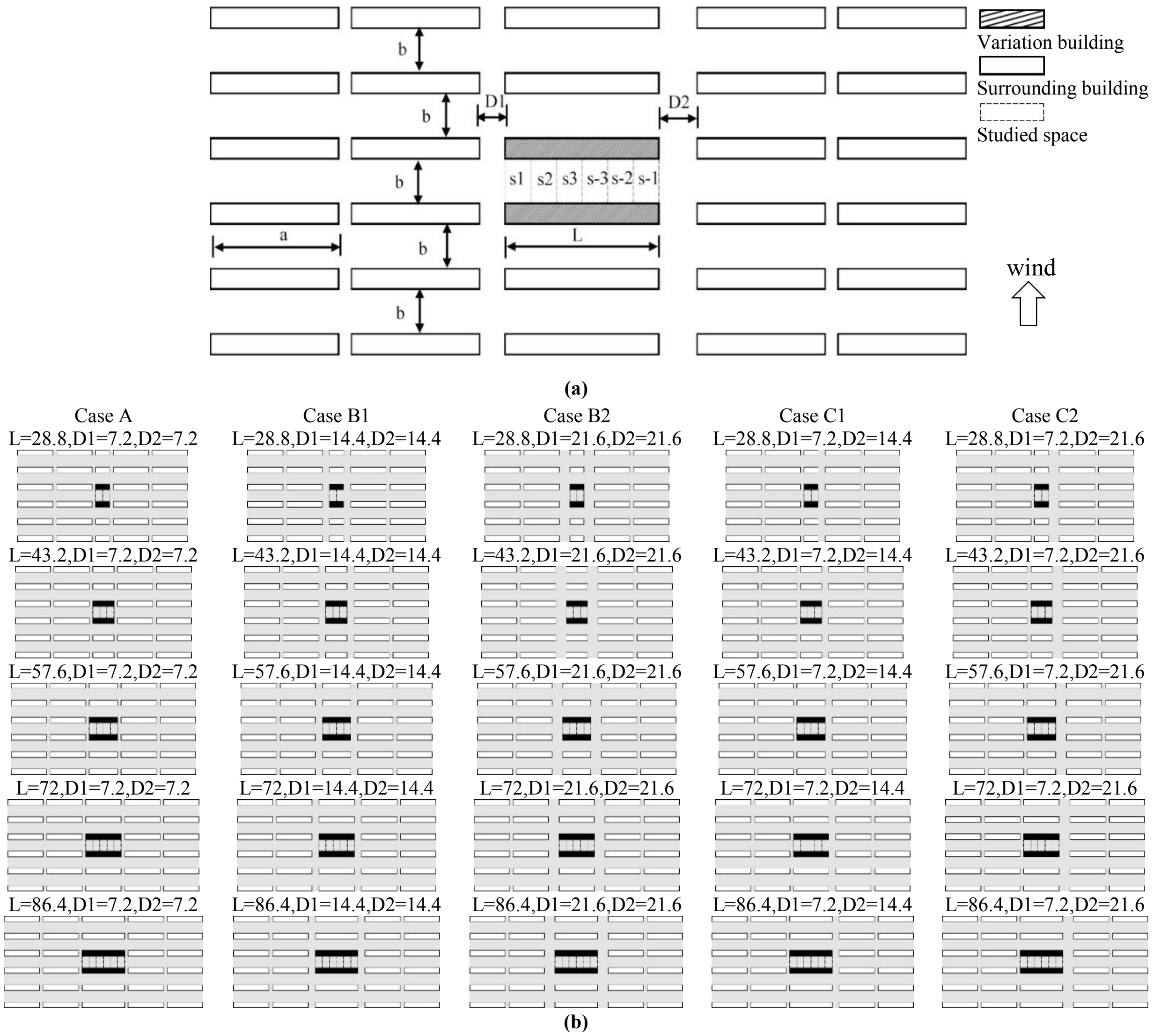

Fig. 1. (a) Residential building group setup; (b) Design variation cases

2.2. CFD modeling

For CFD numerical simulation, the study refers the guidelines of Architectural Institute of Japan (AIJ) as well as some simulation researches about urban ventilation [4,7,18]. The computational domain is 5H (H is the building height) in lateral spacing and 6H in vertical direction. The inlet and outlet boundary are set respectively 5H and 20H away from the buildings. Hexahedral elements are applied in the computational domain (about 2 million). The minimum grids in vertical and horizontal directions between grids are respectively 0.022H and 0.044H, and the maximum expansion factor is below 1.2. Lateral sides and top are symmetrical boundaries while floor and building walls are non-slipping walls. Pressure-outlet is used for domain outlet. At the domain inlet, the vertical profile of velocity (U_z) can be approximated by a power-law form $\mathrm{U_{(z)}} = \mathrm{U_H}(\mathrm{z/H})^{\alpha}$. Turbulent kinetic energy $k_{(z)} = U_f^2/C_\mu^{1/2}$ and its dissipation rate $\varepsilon_{(z)} = C_\mu^{3/4} k_{(z)}^{2/3}/\kappa_v \mathrm{z}$ are all calculated according Hang et al. in their urban ventilation study [12]. In the formula α=0.25, ground roughness z_0=0.001, reference wind speed $U_{(H)}$ at building height H is 4.0m/s, C_μ=0.09, U^*=0.33, κ_v is Karman constant, which is determined as 0.4.

For selection of turbulence model, Large Eddy Simulation (LES) is relatively accurate for simulating wind field characteristics around buildings than the Reynolds-Averaged Navier-Stokes (RANS) approaches. But LES method is higher complicated and time-consumption than RANS approaches. As RANS turbulence models are more time-saving and can provide reasonable good results for spatial flow properties, in this study, RANS approach with standard k-ε turbulent model is adopted [4,8]. 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)

2.3. Calculation of ventilation efficiency parameters

Air change rate (ACH) of urban space can be indicated as the ratio between "fresh" air volume entering the calculated region per unit time (1h). According to the law of conservation of mass, air input (Q_{in}) for certain area equals to air output (Q_{out}), we set overall air change volume as Q_T and ACH can be calculated as:

$$\mathrm{ACH} = \frac{360 \times Q_T}{Vol} = \frac{360 \times \int_A \vec{V} \cdot \vec{n} dA}{Vol} \tag{1}$$

Where $\vec{V}$ is wind speed vector, $\vec{n}$ is the vertical angle between wind speed and inlet (outlet) air plane at boundary of local area, A is the area of inlet (outlet) air plane at area boundary. Vol is volume of the studied domain (m^3).

Purging flow rate (PFR) is defined as the effective airflow rate required to purge the air pollutants from the domain. For calculation of PFR, a "homogeneous emission method" is adopted [4]. This method means that pollutant source with uniformly distributed emission rate, is set in studied domain, and ventilation parameters of the studied domain can be calculated from local pollutant concentration in certain wind field. The calculation of PFR (m^3/s) is as [2,3]:

$$\mathrm{PFR} = \frac{q_p}{C_p \cdot \rho} = \frac{c \cdot Vol}{C_p \cdot \rho} \tag{2}$$

Where q_p denotes pollutant generation rate (kg/s), C_p stands for domain's average concentration (kg/kg), ρ the air density (kg/m^3), and c denotes pollutant generation intensity (kg/m^3-s). As the air flow is not influenced by diffusion of pollutants, the flow field can be firstly calculated and this calculated flow field is used in estimating the PFR. The calculation consists of three steps: First, calculate and obtain flow field; secondly, determine the pollution source within studied domain, and calculate the concentration distribution of pollutants with mass transfer equation; and thirdly, calculate the VE indicators via formulas.

3. Simulation results and analysis

3.1. Effects of building length

Fig 2 shows the effect of building length (L) change on ventilation efficiency of different domains for equal lateral spacing (Case B1 and Case B2) and unequal lateral spacing (Case C1 and Case C2). From the simulation result, it can be seen that the influence of building length on spatial VE distribution relates closely to the type of lateral spacing. When the distances of building lateral spacing are equal, wind flow entering form the left and right sides of the studied domain could be beneficial for the side spaces' VE (domain S1, S-1 and S2, S-2). Under this condition, the exterior space of middle residential units could reach relatively lower ventilation efficiency. In subplot (a), when lateral spacing D1 and D2 are 7.2m, as building length increases, ACH of the middle space (domain S2, S-2 or S3, S-3) decreases evidently, take L=43.3m and L=86.4m as an example, when building length increases from 43.3m to 86.4m, ACH of the middle exterior space decreases by 13.7%. When lateral spacing widens, wind flow from two side of the studied domain could reach more depth of the space. But when building length decreases, these air flows could effect on each other. For example, when building length is less than 60m, air flow entering form one side dominates the spatial VE distribution, and better ventilation space (higher ACH and PFR) moves towards to this air entering side.

When distances of building lateral spacing are different, the distribution of spatial ventilation efficiency generally increases form the space adjoining to the narrow lateral spacing (D1) to that adjoining to the widen one (D2). Take D1=7.2m and D2=14.4m for example, when building length are 57.6m and 86.4, the ACH (PFR) of the domain S-1 increases by 54% (42%) and 235% (114%) respectively, comparing with that of domain S-1 (Fig 2c-d).

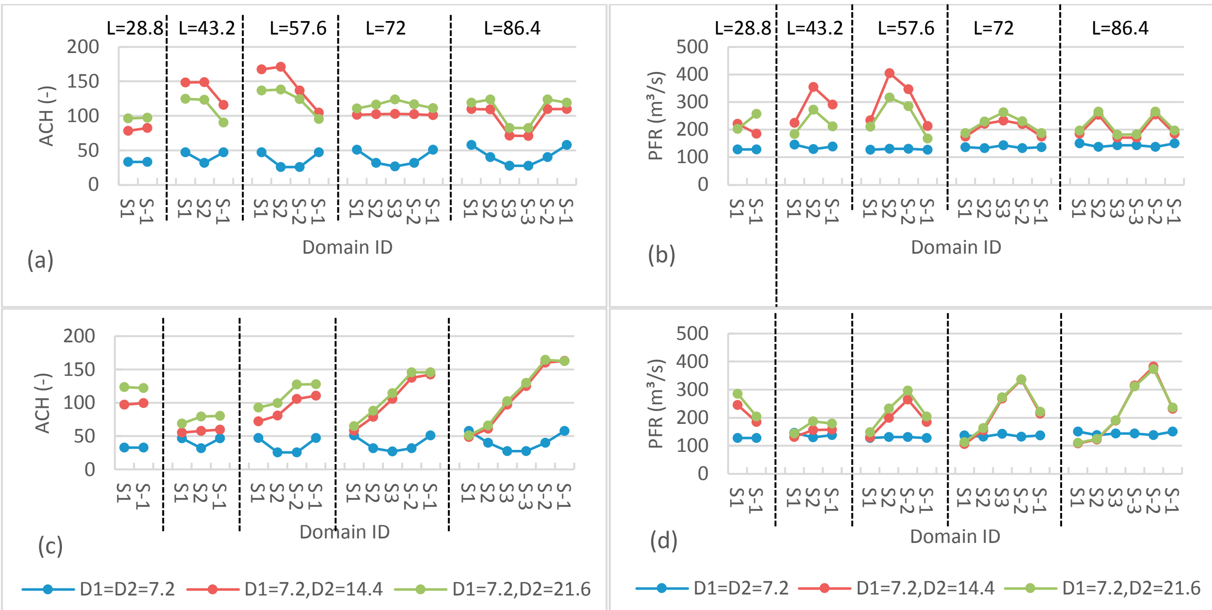

Fig. 2. Influence of building length change on spatial ventilation efficiency, (a) ACH and (b) PFR of different domains under equal lateral spacing; (c) ACH and (d) PFR of different domains under unequal lateral spacing (Unit: m)

3.2. Effects of lateral spacing

To avoid influence of building length on ventilation efficiency of different domains, the design cases with building lengths (L) of 86.5m, are select as the analytical objects. Spatial VE of different domains are investigated under the change of building lateral spacing. Fig. 3 shows the simulation results for these design cases under south wind direction. From these figures, it can be seen that lateral spacing is a very important factor for the distribution of spatial ventilation. Widening lateral spacing will evidently improve ventilation performance of side spaces. For example, in figure 3a and 3b, when lateral spacing D1 and D2 are all 7.2m, only side domains S1 and S-1 could be more beneficial from the induced wind flow, and ACHs and PFRs of these domains increase slightly comparing to other domains. When lateral spacing D1 and D2 increases to 14.4m, more domains could be beneficial from the induced air flow, and trend lines indicate that spaces around S2 and S-2 domains could reach the highest ventilation performance. When lateral spacing D2 increases, while D1 keeps constant, the improvement of ventilation in S-1 and S-2 domains is much larger than that when spacing D1 and D2 all increase to 14.4m (Fig. 3c-d). Take domain S-2 for example, when D2 increases form 7.2m to 14.4m, ACH of S-2 domain increase by 298%, while D1 and D2 all increase form 7.2m to 14.4m, ACH of S-2 domain only increases by 172%. It is mainly due to the interaction of airflow entering from sides of the studied domain. What’s more, it should be pointed that the improvement of ventilation efficiency is not linear related to the lateral spacing increase. When the distance is higher than 15m, the improving extent of VE decreases evidently.

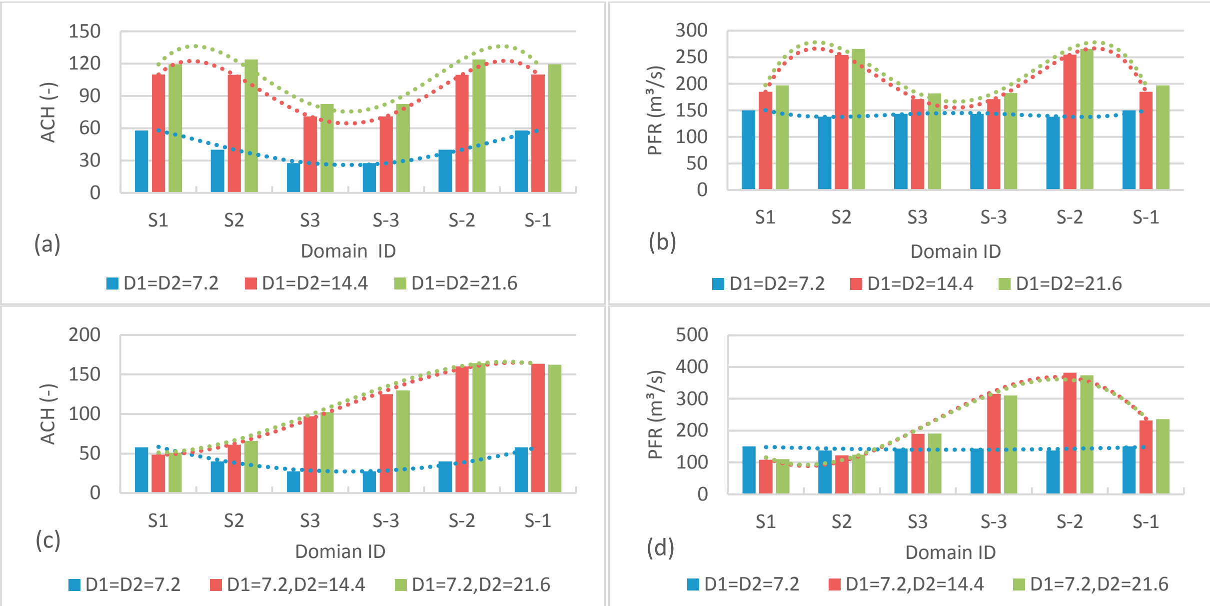

Fig. 3. Influence of lateral spacing change on spatial ventilation efficiency, (a) ACH and (b) PFR of different domains under equal lateral spacing; (c) ACH and (d) PFR of different domains under unequal lateral spacing (Unit: m)

4. Conclusion

Using CFD simulation, this paper discusses the influence of design variations (building length and spacing) on spatial distribution of ventilation efficiency under south wind direction. The simulation results show that building length has considerable influence on outdoor ventilation efficiency of middle-living units, while lateral spacing effect greatly on outdoor ventilation efficiency of side-living units. Increasing building length will not benefit the middle living units' outdoor ventilation and according to the preliminary study, the residential building should be restricted within 5 residential-unit combination. Widening lateral spacing could improve side residential-units' outdoor ventilation and the beneficial amount of side-living unit depend greatly on the distance of lateral spacing. When lateral spacing is 7.2m, only 1 residential-unit can be evidently improved. When lateral spacing increases to 14.4m, 2 residential-unit can be improved. The improvement of side residential-unit' VE is not not linear related to the lateral spacing increase. When the distance is higher than 15m, the improving extent of VE decreases evidently.

This research preliminary analyses the influence of several design changes on outside space's ventilation. The conclusions are constrained to these studied patterns. Due to urban form complexity, more researches should be carried out in the following studies. In addition, the thermal comfort and energy will also be discussed in the following studies.

Acknowledgements

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