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Improving Wind Environment of Residential Neighborhoods by Understanding the Relationship between Building Layouts and Ventilation Efficiency

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Abstract

This research attempts to probe into the correlation between the residential building layout and ventilation performance of various spaces in an operative level. To quantify the influence of design change on outdoor ventilation, numerical modeling technology is adopted with ANSYS-Fluent as the simulation tool. As to evaluate the ventilation efficiency of exterior space, local mean age of air (L-MAA), which is common used in recent urban form studies, is further discussed for local region's ventilation efficiency in residential neighborhoods. Using this ventilation index, several cases are calculated and three types of building layout changes (lateral spacing, building lengths and stagger of location) are discussed. The simulation results show that L-MAA is a useful ventilation index to access the design changes on urban space ventilation and these design changes have great effects on exterior space ventilation. Building length has great influence on ventilation efficiency of different spaces, while the influence of lateral spacing and stagger of location changes varies greatly in different local regions.

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keywords: Residential building; Layout design; Ventilation efficiency; CFD simulation

1. Introduction

Ventilation efficiency of building exterior space is important for both interior and exterior air qualities and thermal comforts. Good ventilation condition around buildings can effectively dilute pollutants and

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remove excess heat. On the other hand, air quality and temperature of exterior space also affect those of interior space, which is closely relevant with building's energy consumption and pollutants emission. A thorough understanding of the relationship between the building layout and ventilation efficiency is therefore essential for architects to improve building's air qualities and/or thermal comfort.

Based on computer simulation and experiments, effect of building layouts on ventilation and pollutants dispersion of exterior space within street canyons and densely built-up areas has been extensively discussed [1, 2]. Recent studies have analysed the role of urban street width to height ratio [3], building shape [4], density [5], building spacing and height variation [6], building roof geometry [7] and tree planting [8]. What's more, some studies have also analyzed building layout patterns, shapes and height variation for residential buildings [9, 10]. However, most of these studies have been concerned with proposing an evolution method while the guidance value for practice in term of design operation is very limited. For example, most studies on urban canyon are limited to discuss overall effect on ideal urban form with models of homogeneous texture. In studies on street-scale, the computational models are usually two strip-shaped buildings with lengths exceeding 7m and even infinite 2D ones, which falls a wide gap behind the design operations in reality. What's more, most studies on building layout perform simulation by simply combining several individual buildings without considering the blocking effect of surrounding buildings.

This research is attempted to probe into the correlation between the residential building layout and ventilation performance of various spaces in an operative level. Several cases of residential building groups are established to discuss the effect of lateral spacing, building length and stagger of location change on ventilation efficiency in various typical regions. To assess the influence of varying designs on ventilation efficiency of exterior spaces, computational fluid dynamics (CFD) simulation method is adopted with ANSYS-Fluent as the calculation tool, a frequently used commercial calculation software. As for the evaluation index of ventilation efficiency, local mean age of air (L-MAA) is commonly used in recent urban form studies [3, 5]. It shows great potential in accessing ventilation efficiency of urban spaces. In this study, the very concept age of air is further developed and applied to evaluate local region's ventilation efficiency.

2. Research Method

2.1. Building configuration description

This study mainly focuses on optimization of exterior wind environment of strip-type multi-floor residential area, which accounts for a large proportion in that of current China. For the configuration 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 [11]. Based on their study, the minimum length (L) of residential building is set as 28.8m, which means a single living-unit building. The maximum length of residential building is 79.2m, which is consisted of 4~5 living-units. The breadth of the building is 11m and the height of building is determined as 18m.

Based on these residential building sizes, three types of building layout changes are established, as shown in Fig 1. Case A denotes the varying lateral spacing while Case B and Case C stand for the varying of building lengths and stagger of location. The longitudinal spacing is restricted by the sunshine conditions and land use economy, which is therefore set as 24m. In order to compare the effects of design variation on ventilation efficiency in different domains, some typical areas (R1~R4) are selected for comparison. For example, A-R1 and A-R3 respectively represent the outdoor spaces of outer and inner side living units in Case A, B-R2 represent outdoor space of central living units in Case B. C-R4 represents space at intersection of buildings in Case C. What's more, to consider the blocking effect of surrounding buildings on design changes, Case A3 is set around the studying cases. The road widths around the studied area are set respectively as 24m and 10.8 m precisely according to the national specification [12].

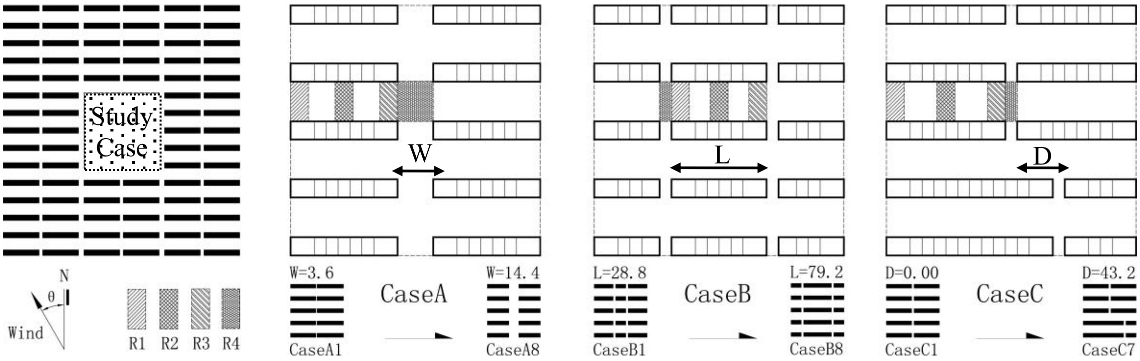

Fig 1. Study cases setting

2.2. CFD simulation model setting

For the setup of numerical modeling, the study refers to the guidelines of Architectural Institute of Japan (AIJ) as well as some simulation researches of urban morphology [4, 13] and calculation domain and boundary conditions are shown in Fig 2. Minimum grid control is 0.022H in direction z and 0.044H in direction x-y. Maximum expansion factor between grids is 1.15. According to AIJ standard wind tunnel test [12], in the formula α=0.25, thickness of atmospheric boundary layer δ=1m, ground roughness $Z_0=4.8\times10^{-4}$H (H is the building height), which indicates that thickness of atmospheric boundary layer under actual conditions is 250m, Z_0=0.12H (scale 1:250), reference wind speed $U_{(H)}$=7.8m/s, thickness at atmospheric boundary layer H=δ, C_μ=0.09, U^*=0.33, K_v is Karman constant, which is determined as 0.4. For turbulence model selection, despite its less accuracy in simulating wind field characteristics around buildings than large eddy simulation (LES), the Reynolds-Averaged Navier-Stokes (RANS) model is applied in this study due to its less time consumption and less complexity in boundary condition setting with standard k-ε model [5, 6] as the turbulent model.

Turbulent model		standard k-ε model
Mesh		Structured grid: total 400,000
Scheme		SIMPLE
Spatial discretization		Second order; Second order upwind
Boundary condition	Inflow	$U_{(z)} = U_{(H)}(z/H)^{\alpha}$, $k_{(z)} = U_f^2 / C_\mu^{1/2}$, $\varepsilon_{(z)} = C_\mu^{3/4} k_{(z)}^{3/2} / \kappa_v z$
	Outflow	Pressure-outlet
	Top/side	Symmety
Convergence residual		1e-5
Contaminant		Passive contaminant

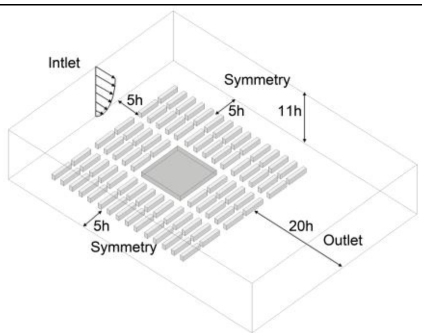

Fig. 2. Computational domain and boundary conditions

2.3. Calculation of local-mean age of air

The local mean age of air (L-MAA) refers to the time it takes for a parcel of air to reach an arbitrary point after entering an airflow system. In CFD numerical modeling, L-MAA is based on pollution source uniform release method [4, 5]. If uniform pollution source is assumed within a local region investigated, L-MMA of a local region under certain ventilation conditions can be obtained through calculation of pollutant concentration in such region, with the following formula:

$$\text{L-}MAA = C_p \times \rho / S_c \tag{1}$$

Where C_p means the mean concentration of pollutants (kg/kg) in the studied area, ρ the air density, and S_c the release rate of uniform pollutants (10-5kg/m3-s). Change of L-MAA reflects the change effect of air flow characteristics such as wind speed, eddy of flow field in a local region, which can better reveal the effect of design parameters on wind field conditions and detention time of pollutants in a local region.

3. Simulation results and analysis

3.1. Lateral spacing change

Lateral spacing changing (W) has certain influence on ventilation efficiency of outside space between buildings under the south wind direction, as shown in Fig 3a. The results reveal that the intersection space (A-R4) and outdoor space of inner side living units (A-R3), which is adjacent to the changing intersection space, is more affected by lateral spacing changing. The changing extent of A-R3 and A-R4 on L-MAA can reach respectively more than 33.4% and 71.9%. However, the outdoor space ventilations 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 lateral spacing changing. Under southeast 30° wind direction, the influence of lateral spacing changes on outside ventilation of different domains also varies (Fig 3b). As the lateral spacing increases, L-MAA of the domain A-R4 increases, while that of other spaces remains constant. This is mainly because that the wind flow enters from west side into the in-between space of the south and north buildings. And as the lateral spacing increases, more wind hit the east side wall of the western building, which arouses eddy flows at the building corners that decrease the wind speed in this domain.

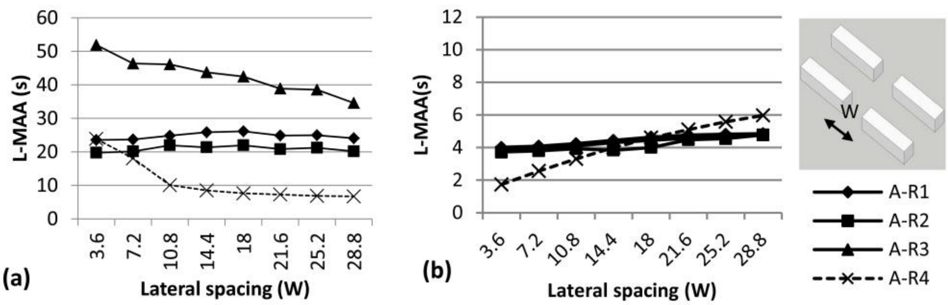

Fig 3. Influence of lateral spacing change on local mean age of air under (a) south and (b) southeast 30° wind directions

3.2. Building length change

Fig 4a shows the effects of building length (L) change on ventilation efficiency of different regions under south wind direction. The simulation results show that as the building length increases, L-MAA of

B-R2 decreases evidently, with variation amplitude of 19.7%, while L-MAA of B-R1 remains constant initially, but increases greatly when building length reaches more than 50m. The change range reaches as much as 42%. The main reason might be that as the building length increases, region B-R1 gradually approaches to the edge of the study area, which leads to acceleration of wind speed in this region. Fig 4b shows the effects of building length change on ventilation efficiency under southeast 30° wind direction. As building length increases, L-MAA of the region B-R3 and B-R4 increases, while the other two regions B-R1 and B-R2 keep constant. The reason might be the same as that of building lateral spacing changing. When the domain B-R3 approaches to 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 region B-R4.

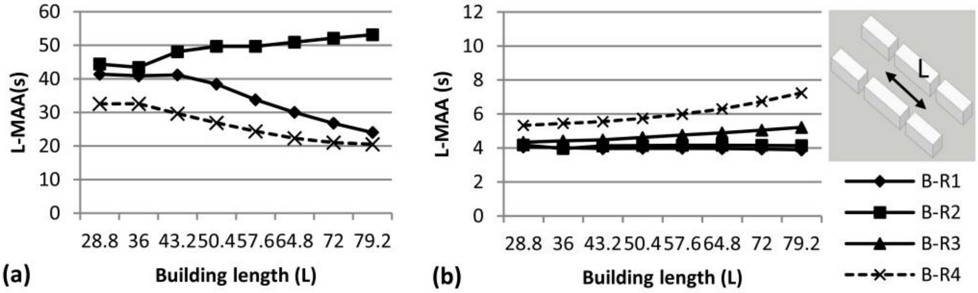

Fig. 4. Influence of building length change on local mean age of air under (a) south and (b) southeast 30° wind directions

3.3. stagger of location change

Fig 5a shows the effects of building stagger of location change on ventilation efficiency of different domains under south wind direction. The simulation results show that building stagger of location change has relatively less effects on urban space ventilation. As building stagger size increases, L-MAA of C-R4 obviously increases with variation amplitude of 62.8%, while that of other spaces keeps nearly constant under south wind direction. And under the southeast 30° wind direction, as shown in Fig 5b, stagger of location change nearly has little effects ventilation efficiency, L-MAA of all regions keeps constant, with variation amplitude less than 8%.

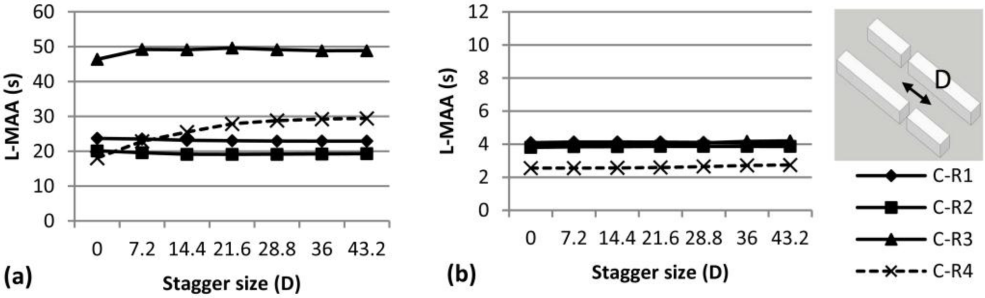

Fig. 5. Influence of stagger size change on local mean age of air under (a) south and (b) southeast 30° wind directions

4. Conclusion

Using CFD simulation method, this paper discusses the effect of design variations such as length, lateral spacing, and stagger of locations of residential buildings on local mean age of air in different outdoor spaces under south and southeast 30° wind direction. The simulation results show that L-MAA is a useful ventilation index to access the design changes on urban space ventilation. These design changes have great effects on the air quality reflected by L-MAA. Building length has certain influence on ventilation efficiency of outside space, which is especially true for those buildings located in the middle of the residential area. While the influence of lateral spacing and stagger of location changes varies greatly in different local regions. Variation of lateral spacing has certain effect on ventilation efficiency of two adjacent domains. And the building stagger of location change can affect intersection space of buildings under the south wind direction.

Acknowledgements

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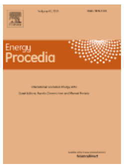

Biography

Dr. Wowo Ding is a professor in school of architecture and urban planning, Nanjing University, China. Her current research interests include urban morphology and optimization of sustainable urban design.