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NUMERICAL RESEARCH ON BUILDING VENTILATION SPACE IN THE LAYOUTS OF RESIDENTIAL AREA

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ABSTRACT: Building density in a master plan directly affects the outdoor physical environmental quality in residential area. Inappropriate design of a layout may cause impact on external comfort, such as lack of air movement. To tackle this problem, a dimensional variable, named as ventilation space was defined to feature the building density in a master plan. It consists of the gable space and fore-and-aft space. The Reynolds averaged equations and the renormalization group (RNG) κ-ε turbulence model was used to simulate the wind condition in some typical layouts under the weather condition in Hangzhou, China. The simulated wind conditions were assessed using the criteria, the wind speed ratio at some key locations on pedestrian level. The effects of the ventilation space on the air movement were discussed and an optimal space was derived for each of the modeled layouts. The set of results were expected to be used as a rule of thumb by architects and planners in master planning stage.

Keywords: Wind environment, building space, natural ventilation, layout, residential area.

INTRODUCTION

With the accelerating urbanization process and the continuous improvement of construction techniques, a variety of high-rise buildings with different layout emerged in large numbers and the resulting environmental problems of outdoor wind environment have become increasingly prominent (Murakami 1986; Ping 1997; Yoshiea et al. 2007). For example, high wind velocity of the narrow channel within the high-rise buildings and increased wind velocity would make pedestrians uncomfortable or even bring potential risk; Improper building layout or building size contributes to the formation of a "dead air eddy zone" between the buildings, which affects the conductivity of air flow and waste the heat gas emission. Therefore, it is necessary to explore the formation mechanism and improve the adverse wind environment.

Compared with others, the indicator “wind” has the strongest relation with architectural spatial factor, especially in outdoor environment (Stathopoulos 1997). The main approaches to predict the wind environment around buildings are field measurement, wind tunnel test and numerical simulation (Stathopoulos et al. 1996; Chang 2003). At present, there are still some errors in predicting the subtle pressure of building surface by using numerical simulation, but the overall wind environment has been simulated with high accuracy and practical value (Stathopoulos et al. 1996; Leighton et al. 1997). Stathopoulos applied the numerical simulation to seven rectangular, parallel group buildings; the resulting wind velocity distribution around the building was in good agreement with wind tunnel test results. Chang et al. (2003) applied Fluent (a software) and four different κ-ε models in calculating the vortex condition within the street canyon where the high-rise residential buildings were arranged in parallel and he analyzed the influence on the width-height ratio of street high-rise residential buildings (Chang et al. 2003). Stathopoulos et al made research upon the influence of height variation of street central building on wind velocity around the streets by using wind tunnel test. Cheng-Hu et al. (2005) further used Phoenics to carry out numerical simulation. The results showed that when the central building and the surrounding buildings were at the equal height, both the calculated value and experimental value agreed with each other while the error was evident if the heights were unequal. Taking the impact of different building spacing into account, Li (2001) used Fluent on three high-rise buildings arranged in the work for the numerical

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simulation. In general, the current studies mainly focus on a single or simple layout of the building analysis and evaluation of wind environment, yet no systematic analysis and assessment about the impact of a series of layout changes on wind environment are available.

Oke (1973) and his partners, who have done a lot of research in terms of the relevant urban form and urban thermal environment, presented the residential area patterns' effect on the outdoor air temperature; Hartranft et al. (2003) pointed out that the pattern of significant land use would affect the microclimate changes in city; Further, Voogt and Oke (2003) noted the mechanism of impact from outdoor landscape on urban climate in 2003. In the same year, Atkinson (2003) discussed the computing model of heat island effect on urban areas at the size of 20 km^2. Overall, their research focused on the larger urban scale and didn't consider the thermal environment issues on residential area in small scale, which should be greatly concerned as the residential area constitutes the major part of urban construction in a developing city.

On the other hand, Coceal et al. (2006 and 2007) mentioned the building layout in small scale, taking four homogeneous building cubes with staggered layout as the computing model (building density λ=0.25). The distribution of surrounding air and eddy was observed; in the study of 2008, they expanded the layout of the building cubes to the other homogeneous form, alignment and orthogonal, and compared with air flow of each other. Kono et al. (2010) continuously studied on the homogeneous distribution layout in 2010. The six layouts of different building density λ, changed from 0.05 to 0.33, were simulated and compared. Claus et al. (2010) focused on the case of building layout model with same height. They recorded the difference in the airflow field by changing the initial wind direction to the model. Ying (2013) carried out study to analyze the wind environment around the building group consisting of six square cross-section high-rise buildings. In a word, their studies were all confined to the buildings with simple plane and same height, and did not cover buildings with different plane or height.

In this article, a CFD simulation tool, Phoenics is implemented to study the influence of different building ventilation space in the layout of residential area around the wind environment by using the Reynolds averaged equations and the renormalization group (RNG)κ-ε turbulence model. Through analyzing and comparing with the wind velocity ratios at pedestrian level (1.5m), the relationship between wind environment condition and the layouts is obtained, which provides reference and evaluation indicator for layout construction in residential area.

SIMULATION MODEL

Governing Equations

The mathematical model of basic assumptions: outdoor air of residential area is incompressible Newtonian fluid; the impact of power quality has been taken into consideration for simulation; the flow is assumed to be single-phase flow turbulence.

Based on these assumptions, by using the steady-state standard κ-ε turbulence model, we adopt the hybrid difference scheme to solve the model. In the aspect of computing the object outside fluid, its accuracy is not as good as large eddy simulation, but the standard κ-turbulence model can accurately describe the outdoor air environment. Although the outdoor wind environment is constantly changing, the steady-state model has been able to explain the addressed problems in this paper; therefore a steady state model is applied. During the calculation, the relaxation factor is automatically adopted by the software.

The governing equations (Yakhot 1992) can be written as follows:

In the equations, x_i and y_i $(i=1,2,3)$ are the component of axes x and y. $U_i (i=1,2,3)$ are the average velocity component along the axes x, y, z respectively; κ and ε are turbulent kinetic energy and turbulent dissipation rate respectively; P is mean pressure, ρ is air density, S_{ij} is mean strain tensors component, ν is the

$$\frac{\partial U_j}{\partial x_j}=0 \tag{1}$$

$$U_j\frac{\partial U_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}[(\nu+\nu_t)\frac{\partial U_i}{\partial x_j}]+\frac{\partial}{\partial x_j}(\nu_t\frac{\partial U_j}{\partial x_i}) \tag{2}$$

$$U_j\frac{\partial \kappa}{\partial \kappa_j}=\frac{\partial}{\partial x_j}[(\nu+\frac{\nu_t}{\sigma_\kappa})\frac{\partial \kappa}{\partial x_j}]+\nu_t(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i})\frac{\partial U_i}{\partial x_j}-\varepsilon \tag{3}$$

$$U_j\frac{\partial \varepsilon}{\partial x_j}=\frac{\partial}{\partial x_j}[(\nu+\frac{\nu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}]+C_1\frac{\varepsilon}{\kappa}\nu_t(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i})\frac{\partial U_i}{\partial x_j}-C_2\frac{\varepsilon^2}{\kappa}+R \tag{4}$$

Where:

$$R=-\frac{C_\mu\eta^3(1-\eta/\eta_0)\varepsilon^4}{(1+\beta\eta^3)\kappa}\ ,\eta=S\kappa/\varepsilon\ ,S^2=2S_{ij}S_{ij}\ .$$

kinematic viscosity of. Other parameters are: C_μ=0.085, C_1=1.42, C_2=1.68, σ_k=0.72, σ_ε=0.72, η_0=4.38 and β=0.015.

Boundary Conditions

The approaching wind was created from a power-law model to approximate the mean velocity profile:

$$U(z)=U_G\times\left(\frac{z}{zG}\right)^{0.25} \tag{5}$$

The gradient height z_G was assumed to be 400m and the mean wind velocity U_G at the gradient height was 13 m/s. Since the κ - ε model was used, the values of κ were required to account for the turbulence in the approaching wind. The turbulent kinetic energy κ can be calculated if the turbulence intensity at a given height is known. According to Chang's study (2003), the turbulence intensity was 12-13% at the height of the building (50m) in their wind tunnel experiment; therefore, in the computation, the turbulence intensity was assumed to be 12% at 52m above ground.

The ground at the bottom of the computing domain was simulated with a smooth wall, as it was assumed that the model buildings were mounted on a smooth plate in their wind tunnel test. The log-law wall function was applied to resolve the flow field near walls and building surfaces. The other boundary conditions, such as the outlet and the upper boundary, were not modified so that the default settings were used. The boundary conditions applied in the computing domain are summarized as Table 1.

Table 1 The boundary conditions for the computing domain

Inlet	$U(z) = U_G \times \left(\frac{z}{z_G}\right)^{0.25}$; U_G=13m/s, z_G=400m, $\kappa = \frac{u_*^2}{\sqrt{C\mu}}$; Cμ = 0.09; $\varepsilon(z) = \frac{u_*^3}{\kappa z}$, κ =0.41
Outlet	Gauge pressure=0
Bottom	Smooth wall, using the log-law wall function
Top	Free slip, flux normal to the boundary is zero
Sides	Free slip, flux normal to the boundary is zero; symmetric boundary conditions is applied

Domain Size

There are no explicit rules dictating the size of a computing domain. Many researchers determine their domain size by a trial-and-error approach because the domain size does influence the computed results, as it has been demonstrated by Baetke et al. (2009). Some authors for instance Baskaran and Kashef (1996) suggest that the size of domain can be a multiple of the characteristic height of the building and that the distance between any edge of the domain and the buildings must be at least five times of the characteristic height of the building. If we follow the suggestion, for this study the domain size was 690m× 730m×250m in the longitudinal (x), lateral (y), and vertical (z) directions, respectively, based on the height of 50m (all buildings with identical height).

Building Model Setting

Since the design depth for architects at planning stage is mainly limited to the general layout, the research orientation of our simulation generally contains two situations: gable space simulation and fore-and-aft space simulation. Architectural plane view is adopted in gable spacing model. For research convenience, typical architectural plane has been simplified to model with major characters closely related to wind environment only (Table 2).

Table 2 Typical building plane form in Hangzhou city

Typical building plane	Simplified plane

Gable spacing model

Buildings of three different plane forms have been simulated in gable spacing study, and the details are shown in Fig.1. Buildings in the model are all placed horizontally in a row. Capital letter A, B, C refer to buildings, L refers to building width（L=30m, the width of a common unit）, X refers to the ratio of gable space to building width, XL refers to the gable space between two buildings. When the value of X changes, wind velocity ratio between buildings changes accordingly. In this way, gable space between buildings can be determined according to ventilation demand. Specifically, if considering the actual situation of residential area in Hangzhou, the building models with height of 42m and 21m have been investigated respectively.

Model of fore-and-aft spacing

Three different situations have been simulated in fore-and-aft spacing study. Models are shown in Fig.2.

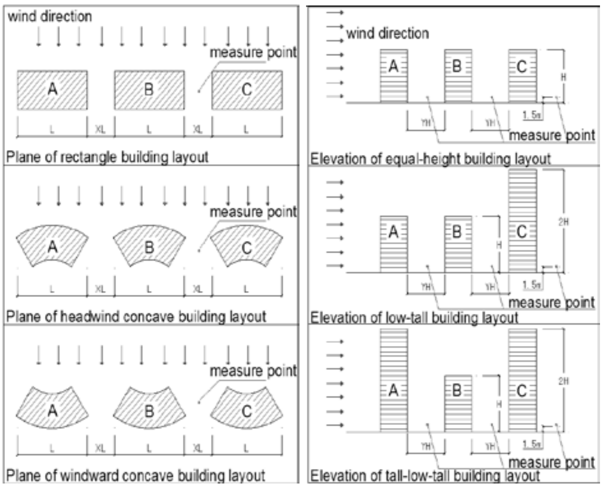

Fig. 1 Gable spacing model: rectangle, headwind concave and windward concave building layout (left)

Fig. 2 Model of fore-and-aft spacing: equal-height, low-tall and tall-low-tall building layout (right)

In this model, the scenario has involved with both multi-storey and high-rise residential building; therefore, the model height H is set at 21m (the height of a common multi-storey unit). Capital letter A, B, C refers to buildings, H refers to building height, YH refers to the fore-and-aft space between buildings. Their planes are all rectangle. By adjusting the value of Y and observing the change of wind speed ratio between buildings in downwind direction, the demand on fore-and-aft space between buildings can be determined.

Evaluation Criterion

This study is to analyze the typical wind condition to buildings in east China monsoon region, where Hangzhou city is located. Although wind is at an unstable state in velocity and directions, there is an evident wind direction in summer or winter which has a significantly higher frequency than that in other seasons, despite the affection of the terrain. Therefore, the case of one wind direction of the prevailing winds is discussed during the analysis.

When comparing wind speeds around different layouts in actual environment, the situation was complicated due to the difference between initial value of wind inflow into the layouts in boundary condition settings and actual wind velocity. Therefore, the wind velocity ratio was introduced, and the impact on wind environment by building layout could be compared. The wind velocity ratio is the ratio of wind velocity (scalar velocity) at each point (height=1.5m) and the wind velocity at the identical height at the inflow boundary18. The calculation of wind velocity ratio could be: R=Vs/V(R is wind velocity ratio, Vs is velocity of a point, V is inflow velocity).

Areas with the wind velocity ratios larger than 2.0 are recognized as a strong wind flow area. In these areas, people would feel uncomfortable. On the other hand, the areas where the wind velocity ratios are less than 0.5 are recognized as a weak wind flow area (Kono et al. 2010; Kubota et al. 2008). Therefore, the comfortable wind velocity ratio's range is from 0.5 to 2.0. It is considered as the main criterion for judging different layouts.

RESULTS AND ANALYSES

Gable Spacing

Three types of gable space model have been studied, and each type has two different building heights (21m and 42m). Six wind velocity variation curves have been obtained from the study, as shown in Fig.3. Figure4 is an example of simulation result.

By initial judgment, one common characteristic in those six curves was that they all had the shape of hyperbola. Take 42m-rectangle model as example, the wind velocity ratio was 0.83 when X=0.5; the wind velocity ratio reduced to 0.73 when X=1. When X=1.75, wind velocity ratio reached its minimum 0.66. When X was enhanced to 2 and 2.25, the wind velocity ratio raised to 0.67 and 0.69. The same trend was also noticed in other models: firstly, the wind velocity ratio decreased as X increased and it reached minimum when X=1.75; At last, it increased while X was increasing. In general, the interval of $1.5<x<2$ was relatively unfavorable. Because when X lied within this interval, the wind velocity ratios in six different models were all below 0.6, which was unfavorable for buildings in back row.

Situation for $X<0.5$ was not simulated because according to the residence fire prevention regulations, the gable space for multi-storey residence must exceed 6m, and 13m for high-rise residence. Take the common point block of one-ladder for two families' type as example, when X=0.5, the gable space was the lower limit satisfying fire prevention regulations. Besides, situation for $X>2.25$ was also not considered because of the space limit. There are very few cases that X=2.5 or even larger in practice.

In general, it was suggested that the value range of X shall be $0.5<X<1.5$ or $X>2$ in residential area planning.

Meanwhile, it was noticeable that curve of rectangle model was at the top among curves with building height of 42m; while the curve of windward concave model was at the bottom; curve of headwind concave model

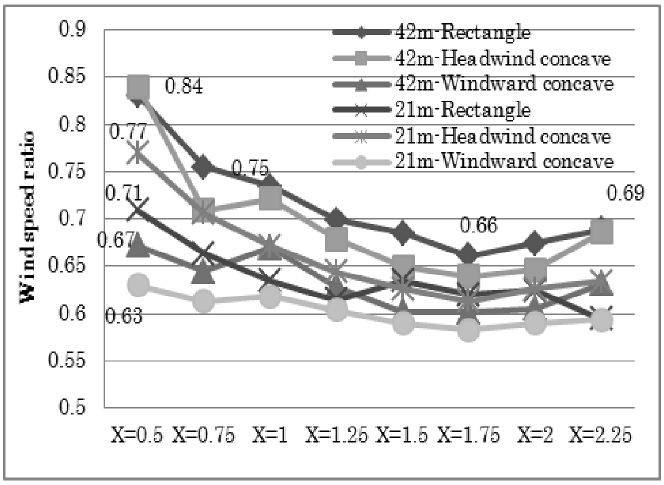

Fig. 3 Wind speed ratio of measure points in six building layouts

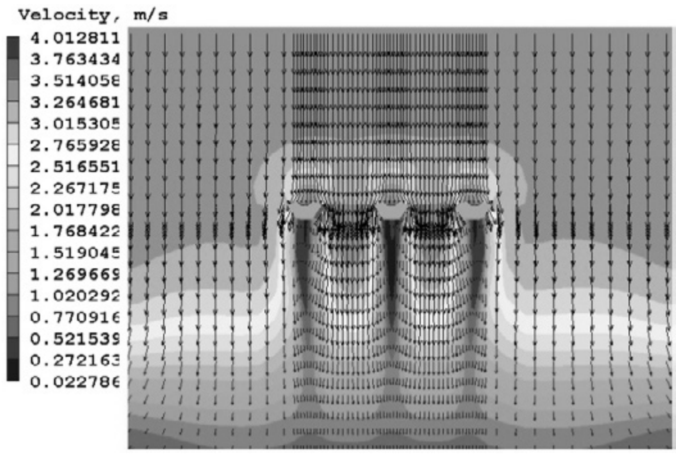

Fig. 4 Wind velocity distribution in simulation result (21m-windward concave building layout case as an example, the current value of X was 1.5)

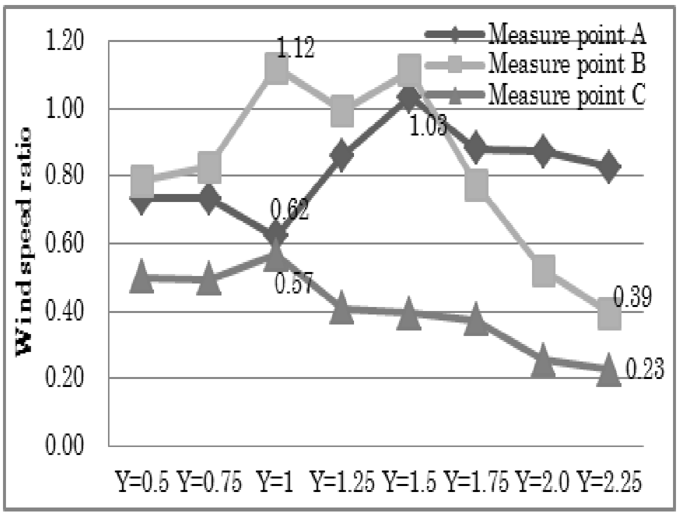

Fig. 5 Wind speed ratio of measure points in equal-height building model

was at the top among curves of building height of 21m, and curve of windward concave was still at the bottom.

Therefore, architects should avoid the building plane form of windward concave. Regular building plane form was recommended in designing high-rise residential building. Although building plane of complete rectangle form may cause unreasonable internal design, architects shall aim at reducing the shape factor of buildings to increase the wind environment of residential area. Building plane form of headwind concave was recommended in designing multi-storey residential area layout.

It is worthy of notice that same building form but different building orientation can also have large influence on natural ventilation. Therefore, the building orientation shall be designed to facilitate ventilation. However, in practice, sunlight shall also be taken in to consideration in residential area planning.

Fore-And-Aft Spacing

Equal-height buildings model

In this model, the wind velocity ratio of measuring point C behind the building C did not change significantly during the period when Y was increasing, showing in Fig.5. The situation of measuring points A and B was different. When Y was raising, the value of point A decreased firstly then increased, and reached the highest value of 1.03 when Y equaled 1.5. It decreased later. The value of point B increased when Y raised, and achieved 1.12 and 1.11 when Y equaled 1 and 1.5, then B decreased. And the wind velocity ratio of point B went under 0.5, which was below comfort zone when Y was over 2.

Both of the ventilation situations of the two buildings should be considered when layouting the community, where the value of Y was 1.5 while point B and C reached their highest. The result showed when Y equaled 2, wind velocity ratio of B was close to 0.5, indicating insufficient nature ventilation. Hence value of Y should be below 2 for community layout.

The situation when $Y > 2.25$ of fore-and-aft distance between two buildings was not considered in the simulation. That was because the limit of the land. According to the experimental data, when wind blows vertically to the front building, the separation distance between the two buildings (Y) should be greater than 6, the wind velocity could recover at the back of the building. Unfortunately it was not possible for a community layout. Hence this situation was not studied.

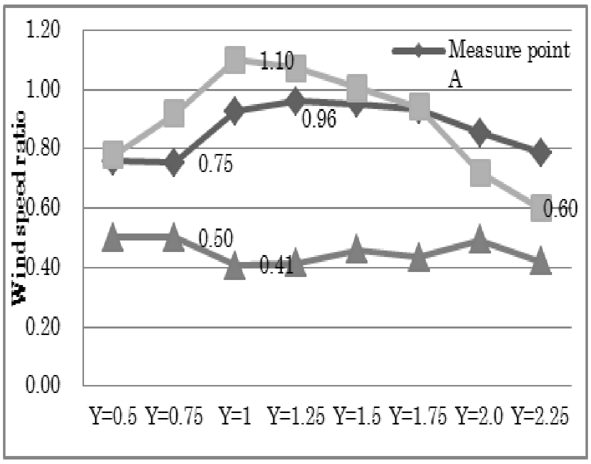

Fig. 6 Wind speed ratio of 3 measure points in low-tall building model

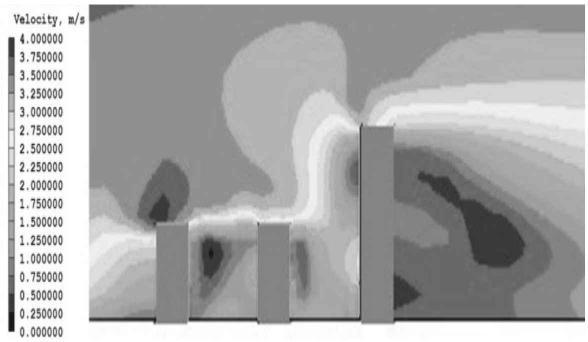

Fig. 7 Wind velocity distribution in simulation result (low-tall building model case as an example, current value of Y was 1.25)

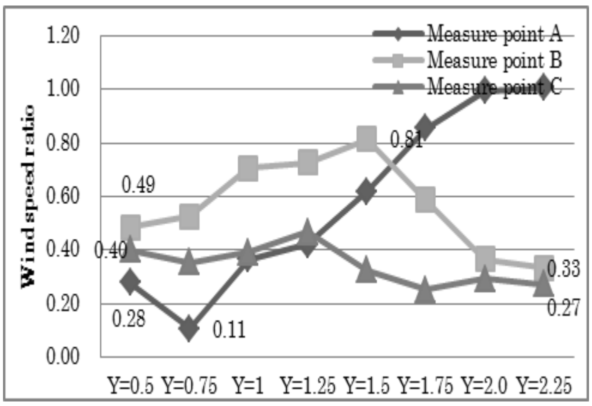

Fig. 8 Wind speed ratio of 3 measure points in tall-low-tall building model

Low-tall buildings model

The data in this simulation was quite similar with which in 3.2.1(Figs. 6 and 7). Measure point C demonstrated a steady fluctuation, and traces of A and B illustrated a parabola shape, which rose firstly and then dropped. The section of Y which was two parabolic peak

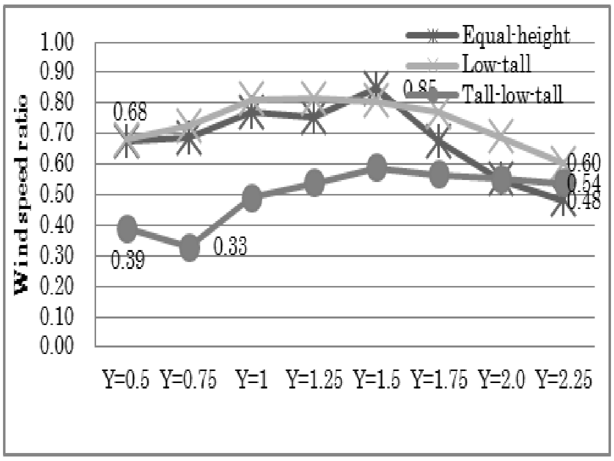

Fig.9 Comparison of average wind speed ratio of all measure points in three building models

was 1~1.25. According to the sunshine spacing requirements, Y should be greater than 1.14 that would fit the rules and regulations of sunshine spacing in Hangzhou. Hence Y was suggested to be 1.25 in this simulation.

Tall-low-tall buildings model

In this model, it showed that the changing of value of Y affected the wind velocity ratio of measure point A significantly but less impact on B and C. That was disadvantage to outside nature ventilation (Fig.8).

Furthermore, compared with the mean wind velocity ratios in three models, the mean wind velocity ratio in tall-low-tall model have lower values between 0.3-0.6, showing the overall situation of surrounding wind velocity was not suitable (Fig.9). Hence this layout method was not suggested.

CONCLUSIONS

Appropriate ventilation space can guarantee the quality of wind environment of residential area in transitional season. However, a lot of researches were based on built indoor and outdoor environments, or their goals were to optimize the design works. In initial design process, such as master plan layout, architects still can get little of guidance. Based on this research, the following suggestions can be made for residential area planning, especially during building plane form selection or buildings spacing adjustment:

[1] For gable space, the recommended value range is 0.5<X<1.5orX>2.

[2] For high-rise residential buildings, the construction plane shall be regulated to reduce the shape factor. For multi-storey residential building planning, headwind concave model is recommended under the condition that the energy saving standard is achieved. Architects shall try to avoid the windward concave building plane form.

[3] For buildings in residential area with the same height, the optimal fore-and-aft space between two buildings is 1.5 times of the building height, and should not exceed 2 times of the building height.

[4] For residential area with low-rise buildings on upwind side and tall buildings on downwind side, the optimal fore-and-aft space is 1.25 times of building height. It is also suggested that the space between two buildings shall not be less than building height or larger than 2 times of building height.

[5] The layout of low buildings surrounded by tall buildings is not recommended.

At the next stage of this study, ventilation space, the new index will be used to assess outdoor comfort in some residential areas. Quantitative correlations are to be derived between wind environment indexes and other indicators of land use, (e.g. the building density and floor area ratio). Consequently, the results are expected to provide some references and suggestions for local government officers in formulating land policies for urban sustainable development in achieving better outdoor air quality as well as more effective use of land resources.

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