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Climatically Adapted Piloti Arrangement and Ratio of Residential Blocks in a Subtropical Climate City

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1. Introduction

In recent years, because of the urban heat island and extreme weather, the outdoor thermal environment is becoming worse and worse, and outdoor thermal comfort is becoming an increasing concern for residents.

Many studies have been conducted to clarify the influences of green and water spaces on outdoor thermal comfort in residential area. Uchida et al. [1)] carried out measurements in the summers of 2007 and 2008 in and around a biotope, and clarified the thermal effects of a biotope with a pond and green space. Furthermore, a questionnaire survey was conducted at the measurement site to look into the principal causes that affected human thermal comfort. Hwang et al. [2)] carried out field comfort surveys of 3839 interviewees in tree-shaded spaces throughout a year and aimed to obtain a better understanding of human thermal comfort response outdoors as well as to propose an adaptive comfort model for tree-shaded spaces. Chen et al. [3)] investigated the actual situation of the outdoors thermal environment in summer in an apartment block in Shenzhen City using field measurements, and examined the effect of schemes to improve the outdoor thermal environment in this apartment block, such as changing the building shapes, planting arrangements, etc. through simulations.

Relationships between outdoor environment and building density/arrangement also have been researched. Kubota et al. [4)] carried out wind tunnel tests on the relationship between building density and pedestrian-level wind velocity. The results of wind tunnel tests on 22 residential neighborhoods selected from actual Japanese cities were presented. There was a strong relationship between the gross building coverage ratio and the mean wind velocity ratio. The wind environment evaluation for case study areas was performed by using the wind tunnel results and the climatic conditions of several major Japanese cities. The development method of guidelines for realizing acceptable wind environment in residential neighborhoods using the gross building coverage ratio was proposed. Xuan et al.[5)] and Yang et al. [6)] studied climatically adapted building arrangement to maximize thermal acceptability of outdoors at different Latitudes. The optimal ratio of building distance (D) to building height (H), D/H from the viewpoints of urban ventilation and sun-shading in Sendai, Japan and Guangzhou, China was analyzed. The results showed that the distributions of wind velocity around buildings became polarized as building distance decreased and the proportion of low wind velocity grew larger which was the main cause of poor ventilation and thermal discomfort. But on the other hand, the significant cooling effects of building shade were observed in closely packed arrangements. The optimal values of D/H in Guangzhou and Sendai were around 0.24.

However, the research on piloti space, which is an important part of building in area with hot and humid summer has not been studied sufficiently. Piloti space can improve wind environment and provide cooler activity space in city with hot and humid summer. This study aims to propose climatically adapted piloti arrangement and ratio for design of residential area. Through coupled simulations, the optimal piloti arrangement and relationships between piloti ratio and outdoor thermal environment (wind, MRT, SET*) are discussed.

2. Analysis outline

2.1 the city of Wuhan

Wuhan is the capital of Hubei Province, People's Republic of China, located at 113°41′-115°05′ East, 29°58′-31°22′ North. It lies at the east of the Jianghan Plain at the intersection of the middle reaches of the Yangtze and Han Rivers (Fig.1). Wuhan is well known for its oppressively hot and humid summer. Fig.2 shows the daily average temperature, maximum temperature, minimum temperature, and relative humidity in Wuhan in 2001.

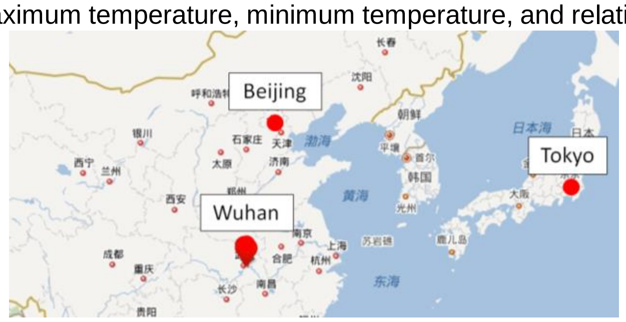

Fig. 1 Location of Wuhan

The temperature ranges from -3°C to 38°C and relative humidity is consistently high. Summer season is from June to August, and there are 44 hot days (daily maximum temperature is above 30°C), 19 extremely hot days (daily maximum temperature is above 35°C) during these three months.

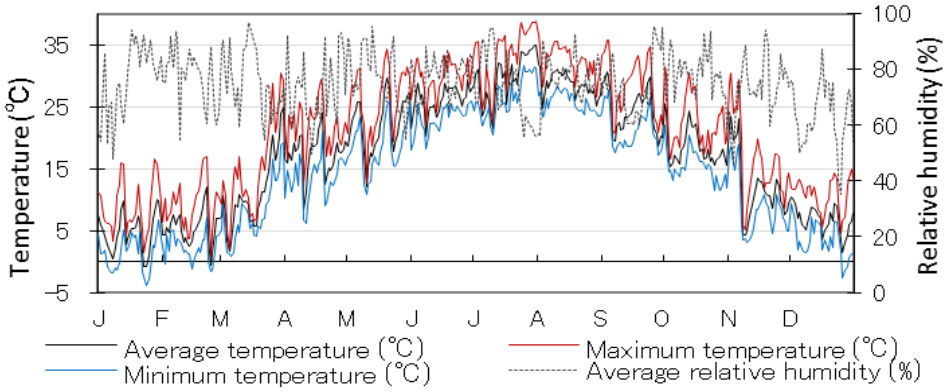

Fig.2 Daily temperature and relative humidity in Wuhan (2001)

2.2 Prediction method on outdoor thermal environment

Fig. 3 shows the flowchart of a coupled approach applied in the paper. There are two domains, large and small, and the small one is belonged to the large one. It is a 2-stage coupled analysis. Firstly, CFD analysis is conducted in the large area with measurement outcomes as boundary values. The $k-\varepsilon$ revised turbulence model is selected. Therefore, boundaries values of the small area belonged to the large area are obtained. And then the temperatures of ground and building surfaces are calculated in analysis domain 2 based on unsteady state heat balance calculation including 3-dimentional radiation and 1-dimentional conduction calculations. With outcomes in the above two steps, CFD analysis is carried out again in the small area. Finally, in order to evaluate outdoor thermal comfort, a comprehensive index, SET* is calculated in target area which is located in the center of analysis domain 2.

In this paper, a numerical simulation system is set up by integrating STAR-CD/RADX with additional codes. The prediction methodology is similar with as mentioned above.

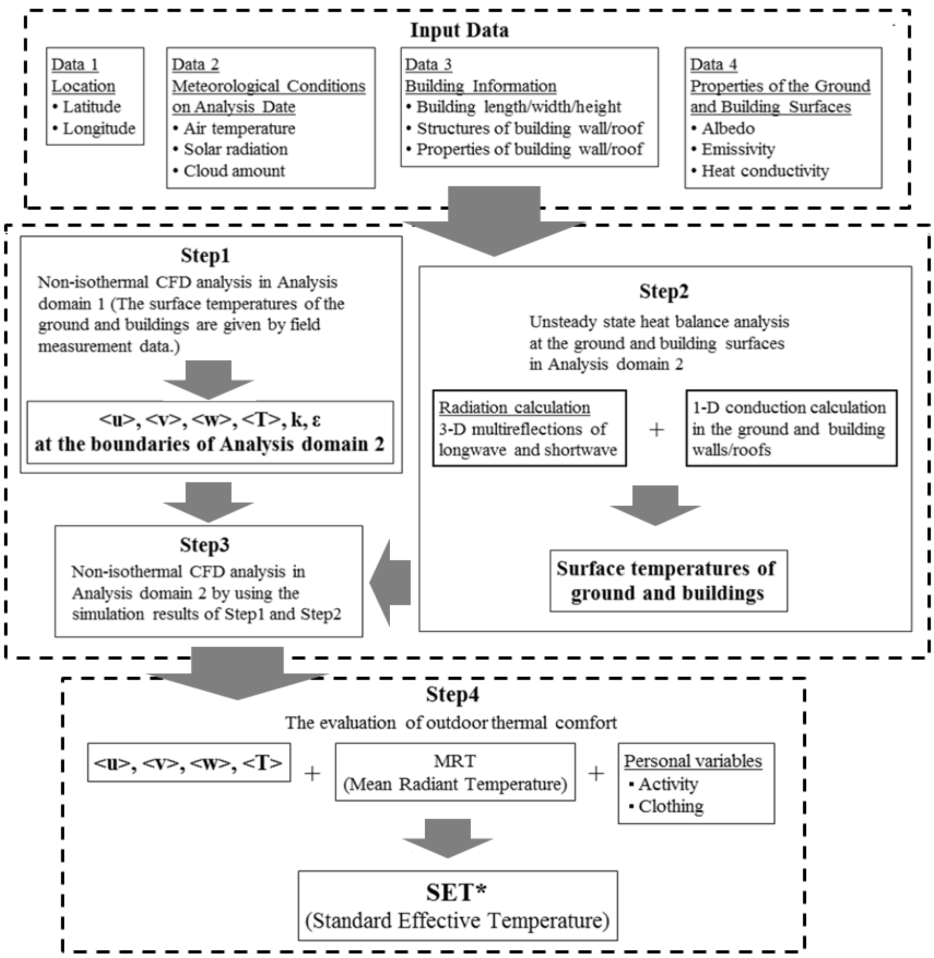

Fig.3 The flowchart of prediction method on outdoor thermal environment

2.3 Analysis boundary conditions

In step 1, non-isothermal CFD analysis is carried out. Meteorological conditions on analysis date and time (air temperature, wind velocity and prevailing wind direction), and ground and building surface temperatures observed in the actual environment are used as initial and boundary conditions (Table 1).

In step 2, unsteady state heat balance analysis is conducted to o16:00, 1st July btain ground and building surface temperatures. 3-dimensional radiation and 1-dimensional conduction calculations are included in this process (Table 2).

In step 3, non-isothermal CFD analysis is carried out based on outcomes in Step1 and Step2. Boundary conditions in step 3 are shown in Table 3.

In step 4, thermal comfort in Target area is evaluated with outcomes in Step3 (wind velocity, air temperature, humidity, MRT) and personal variables (activity and clothing).

Table 1 Analysis boundary conditions in step 1

Date and time	16:00, 1st July
Calculation state	Steady state
Turbulence model	Suga cubic non-linear k-εmodel
Inflow	The wind direction: South Air temperature: 33.5℃ <u>: $U(z) = \langle U_s \rangle (z/z_s)^{\alpha}$ $\alpha=0.25$, $z_s=10$m, <Us>=1.25m/s <k>: $k(z) = (I(z)\langle u(z)\rangle)^2$ $I(z)=0.1(z/z_G)^{(-a-0.05)}$, $z_G=470$m ε: $\varepsilon(z) = C_\mu^{1/2} k(z) \frac{\langle U_s \rangle}{z_s} \alpha \left(\frac{z}{z_s}\right)^{(\alpha-1)}$ Cμ=0.09
outflow	<u>, <v>, <w>, k, ε, zero gradient, <w>=0, T: adiabatic
Lateral and upper surfaces	<u>, <v>, k, ε: zero gradient, <w>=0
Ground and building surfaces	Summer: 48℃(ground surface), 39℃(building surfaces)
Advection term surfaces	<u>, <v>, <w>, k, ε, T: MARS
Coupling algorithm	SIMPLE

Table 2 Boundary conditions in step 2

Date and time	0:00 on 1st July ~ 24:00 1st July
Calculation state	Unsteady state
Temperature	The daily temperature change mode in 1st July
Convective heat transfer coefficient	Indoor: $5W/m^2$•K Outdoor: $12W/m^2$•K

Table 3 Boundary conditions in step 3

Date and time	16:00, 1st July
Calculation state	Steady state
Turbulence model	Suga cubic non-linear k-εmodel
Inflow boundary, Lateral and upper surfaces	<u>, <v>, <w>, k, ε, T: from Step 1
outflow	<u>, <v>, <w>, k, ε, T: zero gradient
Ground and building surfaces	Logarithmic law $T_{surface}$: from Step 2
Scheme for advection term	<u>, <v>, <w>, k, ε, T: MARS
Coupling algorithm	SIMPLE

2.4 Analysis model and cases

Coupled simulations for residential buildings in Wuhan were carried out using STAR-CD/RADX with additional codes. The analysis model is shown in Fig.4. Size of the computational domain was determined according to AIJ guidelines [7)]. The most common six-floor residential buildings were taken as the research object. The density of buildings was about 30% and the height of the first floor was 3.6 m, height of other floors is 3 m. As seen in Fig.5, four different piloti arrangements in the target area were considered in order to determine the optimal one. Then the relationship between piloti ratio and wind environment was investigated based on the optimal piloti arrangement. All the analysis cases are listed in Table 4. Piloti ratio of Case 1-S- Case 4-S was 40%. Case 4-20-S, Case 4-60-S and Case 4-80-S were set with different piloti ratio based on the piloti arrangement of Case 4-S.

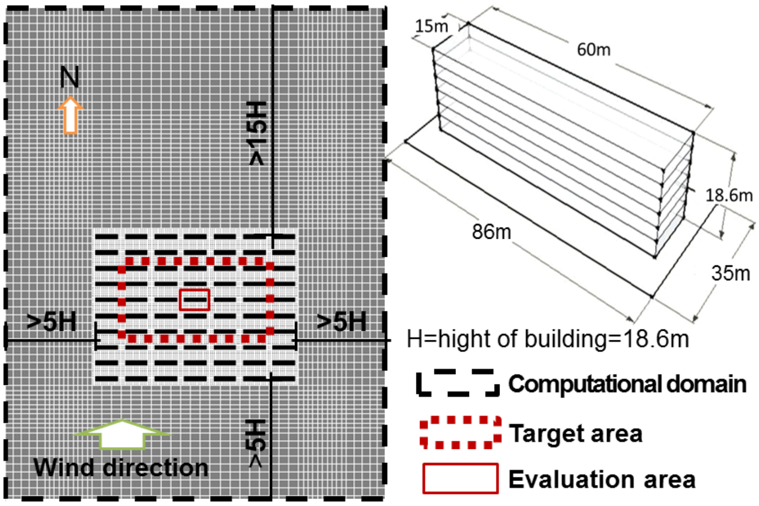

Fig.4 Analysis model

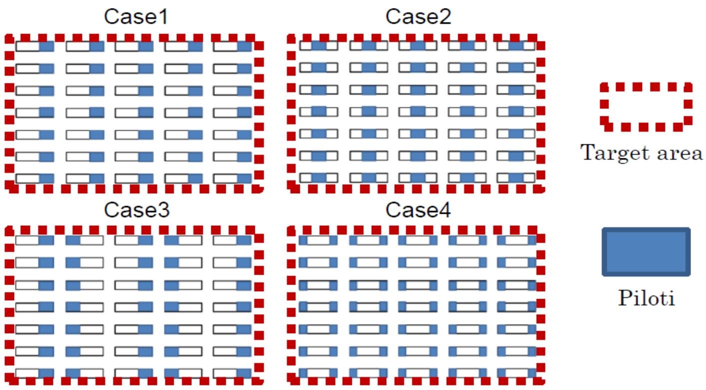

Fig.5 Different piloti arrangement in target area

Table 4. Analysis cases

Case name	Analysis date and time	Inflow wind velocity (m/s)	Piloti arrangement	Politi ratio (%)
Case 0-S	7/1 16:00	1.25m/s (at 10m, prevailing wind direction: South)	no piloti	0
Case 1-S			in the east end of building	40
Case 2-S			in the middle of building	40
Case 3-S			in one end of building	40
Case 4-S			in the two ends of building	40
Case 4-20-S				20
Case 4-60-S				60
Case 4-80-S				80

3. Results and discussion

3.1 The optimal piloti arrangement

Fig.6 presents the distributions of wind velocity at 1.5m from Case 0-S to Case 4-S and Fig.7 indicates the probability density and cumulative distribution of wind velocity from Case 0-S to Case 4-S in the evaluation area shown in Fig.4. When piloti ratio is 0 (Case 0-S) or piloti is in the middle of building (Case 2-S), the portion of wind velocity less than 0.5m/s occupies about half of the cumulative distribution. When piloti is in the two ends of building (Case 4-S), wind velocity which is over 0.5m/s occupies over 75% of the cumulative distribution. Case 4-S can improve the wind environment significantly. Therefore, it is concluded that piloti in the two ends of building is the optimal piloti arrangement.

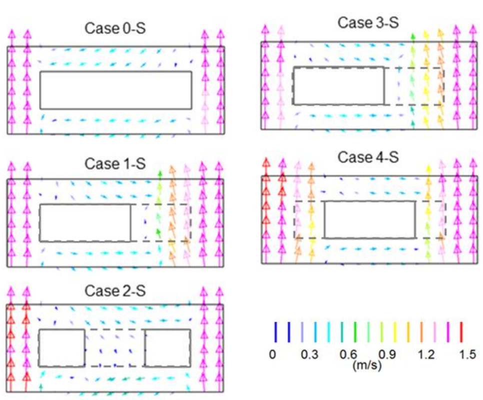

Fig. 6 The distributions of wind velocity at 1.5m from Case 0-S to Case 4-S

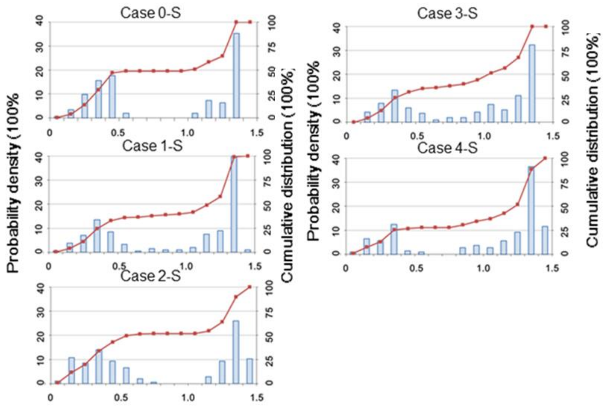

Fig. 7 The probability density and cumulative distribution of wind velocity at 1.5m

3.2 The relationships between piloti ratio and outdoor thermal environment

3.2.1 Wind velocity

Fig. 8 shows the distributions of wind velocity at 1.5m from Case 0-S to Case 4-80-S. Wind path is formed along the south to north direction. With the increasing of piloti ratio, the wind path is enlarged. The wind velocities beside the south and north side of building are very weak, and the enlarged wind path improve the wind velocity of this area. The average wind velocities of non-piloti area of each case are 0.83 m/s, 0.89 m/s, 1.01 m/s, 1.04 m/s and1.05 m/s, respectively. The wind environment is improved with the increasing of piloti ratio in summer. The wind velocity in the red dashed parts (weak wind area) changes greatly. The average wind velocities of red dashed area of each case are 0.35 m/s, 0.47 m/s, 0.59 m/s, 0.61 m/s and0.62 m/s, respectively.

3.2.2 MRT

The distributions of MRT from Case 0-S to Case 4-80-S are displayed in Fig. 9. With the increasing of piloti ratio, MRT decreased. Under the piloti shaded space are formed. In Case 0-S the temperature of west wall in the first floor is high, so the MRT beside the west wall is very high. After adding piloties, west wall in the 1st floor is under the piloti , so the temperature of west wall in the 1st floor is not so high, and because of the shaded space under the piloti, the MRT beside the west wall is low .

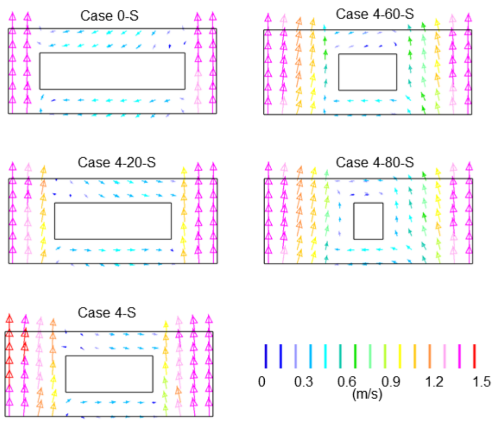

Fig. 8 the distributions of wind velocity at 1.5m from Case 0-S to Case 4-80-S

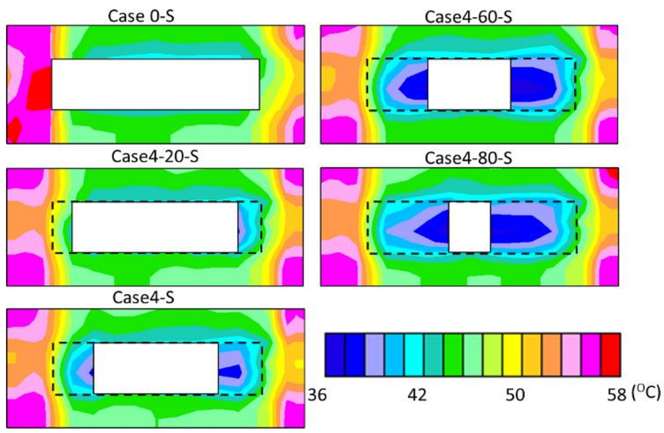

Fig. 9 The distributions of MRT from Case 0-S to Case 4-80-S

3.2.3 SET∗

Fig. 10 shows the distributions of SET* from Case 0-S to Case 4-80-S. Piloti can provide shaded place and decrease the set* rapidly. Beside the south and north sides of building, because the wind velocity is very weak, the set* is very high. In the red dashed area, the SET* is not so high.

Fig. 11 presents the probability density and cumulative distribution of SET* (non-piloti area) in summer cases. The minimum SET* value is about 31 ℃, and the maximum SET* value is about 42 ℃. The average SET*s of non-piloti area are 38.7 ℃, 36.9 ℃, 36.0 ℃, 35.4 ℃, 35.1 ℃, respectively. The average SET*s of red dashed area are 35.8 ℃, 34.4 ℃, 33.6 ℃, 32.9 ℃, 32.6 ℃, respectively.

3.3 Assessment

Fig. 11 shows the relationship between different SET* intervals and acceptable rate in summer (from a subjective response to outdoor thermal environment in Wuhan), according the calculated average SET* values of different cases, the corresponding acceptable rate can be gain. Red lines refer the situation of non-piloti area, and orange lines refer the situation of red dashed area. When acceptable rate is 50% of red dashed area, it can be calculated that the piloti ratio is about 31%.

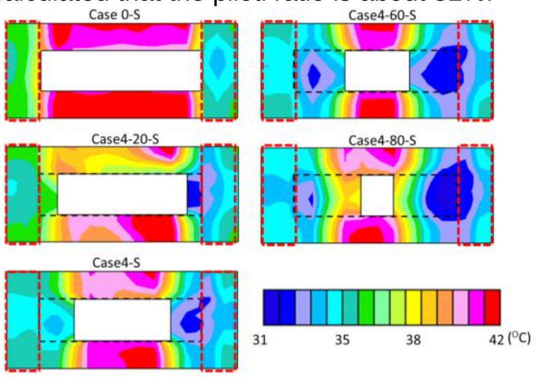

Fig. 10 The distributions of SET from Case 0-S to Case 4-80-S*

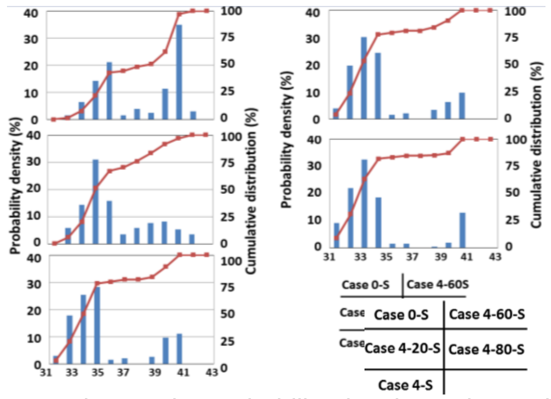

Fig. 11 The probability density and cumulative distribution of SET (non-piloti area) in summer*

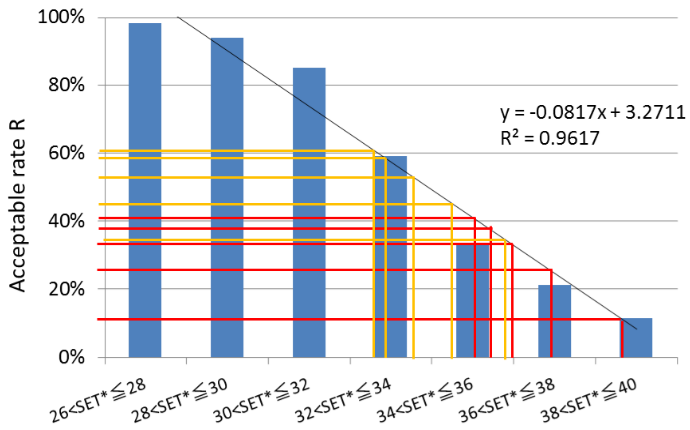

Fig. 11 Relationship between different SET intervals and acceptable rate (summer)*

4. Conclusion

Outdoor thermal environment in the hottest month (July) in Wuhan was researched. Piloti set in the two ends of building is the optimal piloti arrangement in residential area of row layout. Pedestrian wind environment improves and the SET＊decreases with the increasing of piloti ratio. The appropriate piloti ratio is about 31% in residential area of row layout.

Acknowledgment

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References

1) Uchida M, Mochida A, Sasaki K, Tonouchi T. Field measurements on turbulent flowfield and thermal environment in and around biotope with pond and green space. The seventh International Conference on Urban Climate, Yokohama, Japan; 2009
2) Hwang R-L, Lin T-P, Cheng M-J, Lo J-H. Adaptive comfort model for tree-shaded outdoors in Taiwan. Building and Environment,2010; 45:1873-1879
3) Chen H, Ooka R, Harayama K, Kato S, Li X. Study on outdoor thermal environment of apartment block in Shenzhen, China with coupled simulation of convection, radiation and conduction, Energy and Buildings 2004; 36:1247–58
4) Tetsu Kubota, Masao Miura, Yoshihide Tominaga, Akashi Mochida. Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: Development of guidelines for realizing acceptable wind environment in residential neighborhoods, Building and Environment 43 (2008) 1699–1708.
5) Xuan Y., Li Q. Yang G, Mochida A. Fundamental Study on Building Arrangement to Maximize Thermal Acceptability of Outdoors at Different Latitudes Part 1: The Characteristics of Wind Velocity Distributions in Different Building Arrangements in Guangzhou and Sendai. Technical papers of annual meeting of Architectural Institute of Japan, 873-874, 2013-08-30
6) Yang G, Li Q, Xuan Y, Mochida A. Fundamental Study on Building Arrangement to Maximize Thermal Acceptability of Outdoors at Different Latitudes : Part 2: The Change of Outdoor Thermal Environment in Different Building Arrangements in Guangzhou and Sendai. Technical papers of annual meeting of Architectural Institute of Japan, 875-876, 2013-08-30
7) Yoshihide Tominaga, Akashi Mochida, Ryuichiro Yoshie, Hiroto Kataoka, Tsuyoshi Nozu, Masaru Yoshikawa, Taichi Shirasawa. AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings, Journal of Wind Engineering and Industrial Aerodynamics 96 (2008) 1749–1761