

Research on the influence of piloti on residential block's outdoor thermal comfort by questionnaire survey and coupled simulation method in Guangzhou, China

Tianyu Xi*, Hong Jin, Akashi Mochida and Jianhua Ding

*Architecture School of Harbin Institute of Technology, Harbin City, Heilongjiang Province, 150006 P. R. China

*Corresponding author's email: tonny_kid@126.com

Abstract. Piloti is commonly used to optimize the outdoor thermal environment in subtropical climate cities, and there are few studies regarding to the systematic influence of piloti on outdoor thermal comfort. As the outdoor thermal comfort differed by various climates and locations, this work firstly carried out a questionnaire survey in Guangzhou, China, to study on the local acceptance rate (TSV is lower than 1.5) during different SET* intervals. Secondly, a series of cases were simulated by coupled simulation method, which considering convection, radiation and conduction, offering high precision prediction results. At last, by adopting SET* as standard index, taking both of the questionnaire survey result and ASHRAE standard into consideration, the influence of piloti on residential block's outdoor thermal comfort was analysed and discussed.

1 Introduction

1.1 Outdoor thermal environment

Urban heat island is now regarded as one of the most serious environmental problems, and the environmental degradation results in not only the increase of energy consumption in cities but also healthy problem of people. Many ways are adopted and integrated on improving the outdoor thermal environment and thermal comfort, for instance, plant, high reflective capability materials of building envelope, green building walls and roofs, improvement of city ventilation, use of sea wind and decrease of artificial heat [1-6], etc.

1.2 Relative research regarding to piloti

Piloti is commonly used in building design in tropical and subtropical climate zones to gain shadow areas and good ventilation (Fig. 1), but only a few work mentioned piloti's influence on the outdoor thermal environment and thermal comfort. Xi et al. published field measurement results of various human built elements in Guangzhou [7-10], including piloti, but no systematic analysis by simulation was used in those research. The influence of piloti on mean radiant temperature simulated by 3-D unsteady state heat balance radiation calculation method was published by Xi, Hong Jin et al. but no thermal comfort was mentioned [11,12]. Xi, Qiong Li et al. studied on the effects of semi-open space (100 percent ratio piloti) on the outdoor thermal environment of residential communities, by adopting coupled simulation method, but no different piloti ratio cases were compared [13].



This research takes residential blocks in Guangzhou, China, as an example, aiming at study on the comprehensive influence of piloti on outdoor thermal comfort, by a questionnaire survey and coupled simulation cases, offering reference for building design in subtropical climate zones.

2 Method

2.1 Questionnaire survey on local subjective response to outdoor thermal environment

A questionnaire survey on the thermal sensation and thermal comfort was conducted in this study on 14th and 15th July, 2010, designing both of thermal sensation vote (TSV) and thermal comfort vote (TCV) as a 7-level constant vote.

The college students of South China University of Technology took part in this study and their ages ranged from 19 to 21. Each time the students sat on a chair for about 20 minutes and then finished the questionnaires. The parameters of outdoor thermal environment such as temperature, humidity, wind velocity, and globe temperature were recorded. Before the experiment, the students were requested to sit quietly for 30 minutes in shaded place to achieve a uniform metabolic rate. The instruments were set at 1.2 meters high above the ground, less than 3 meters far from the volunteers (Fig. 2). The instruments' information is listed in Table 1, and a total of 114 samples were collected at last.

2.2 Simulation method

The traditional simulation method considers the surfaces as constant value, neglecting the heat transfer of surface radiation, heat conduction in building walls and ground, and latent heat transfer by solid surfaces. The traditional way cannot reflect the situation in true environment, and inevitably will cause calculation omit by only air flow calculation in CFD simulations.

The unsteady state heat balance calculation method was adopted in this paper, which includes 3-dimensional radiation and 1-dimensional conduction calculations. Firstly, non-isothermal CFD analysis is carried out in analysis using data from local meteorological bureau (wind velocity and prevailing wind direction, and air temperature) and observed data (ground and surface temperature). And ground and building surface temperatures are calculated in step 2 based on unsteady state heat balance calculation including 3-dimensional radiation and 1-dimensional conduction calculations. Based on outcomes in above 2 steps, CFD analysis is carried out one more time and more accurate results will be obtained.



Figure 1. Building piloti design in Guangzhou, China.



Figure 2. View of questionnaire survey.

Table 1: Information of test instruments and interval time.

Test Factor	Product	Country	Accuracy	Interval Time
Dry-bulb temperature	TR-72ui	Japan	$\pm 3\% ^\circ\text{C}$	5 min
Relative humidity	& double air duct		$\pm 5\% \text{RH}$	
Wind velocity	QDF-6&flag	Taiwan	$\pm 3\% \text{ m/s}$	5 s
Globe temperature	GL-200 & Globe ball (0.15 m diameter)	Japan	$\pm 0.5\% ^\circ\text{C}$ (20-50 $^\circ\text{C}$) & $\pm 1\% ^\circ\text{C}$ (50-120 $^\circ\text{C}$)	5 min

2.3 Simulated cases design and boundary conditions

5 cases are designed in this study, and the piloti ratio is 0%, 40%, 60%, 80% and 100%. All piloti are centralized arranged in each building, and the buildings are designed to be 21 meters high (7 floors), 15 meters long and 6 meters width. The building coverage ratio of simulated community is 30%, with all buildings parallel arranged.

The domain size, wind direction and building orientation are shown in Figure 3, and the distance between buildings and inflow and wall boundary is set to be 5 times of building height, and the distance between buildings and outlet boundary is set to be 15 times of building height, both of which are set due to AIJ guidelines. The evaluated area is set in the middle of the community to avoid the lateral influence of CFD simulation.

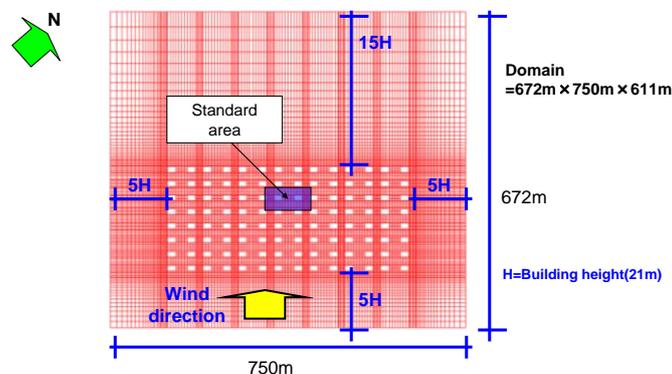


Figure 3. Domain size, wind direction and building orientation of simulated cases.

Based on the whole summer meteorological data from the TMY (typical meteorological year), 24-hour meteorological data are averaged per day to get mean daily data. Consequently, the whole summer mean data are obtained by averaging the cumulated mean daily data. Finally, analysis date is determined by choosing the day whose data are most close to the whole summer mean data (calculating standard deviations by mean daily data and the whole summer mean data). Therefore, 14th July in Guangzhou is selected as a typical day of summer. Analysis time is selected based on at the time when maximum temperature occurred during analysis date, so 15:00 is selected in this study.

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 2).

In step 2, unsteady state heat balance analysis is conducted to obtain ground and building surface temperatures. 3-dimensional radiation and 1-dimensional conduction calculations are included in this

process (Table 3). Tables 4-7 lists ground and building surface properties and structures of building wall, roof and ground.

In step 3, non-isothermal CFD analysis is carried out based on outcomes in Step1 and Step2. More reliable results can be obtained (Table 8).

At last, thermal comfort in target area is evaluated with outcomes in Step3 (wind velocity, air temperature, humidity, MRT) and personal variables (activity and clothing).

Table 2. Boundary conditions in step 1

Date and time	15:00, 14 th July / 12:00, 3 rd August
Temperature	32.4 °C / 29.26 °C
Calculation state	Steady state
Turbulence model	Suga's cubic non-linear k- ε model
Inflow	The wind direction: Southeast $\langle u \rangle: u(z) = U_s \left(\frac{z}{z_s} \right)^a$ $a=0.3, Z_s=10m, \langle u_s \rangle=2m/s$ $\langle k \rangle: k(z) = (I(z)\langle u(z) \rangle)^2$ $I(Z)=0.1(Z/Z_0)^{(-a-0.05)}, Z_0=450m$ $\epsilon: \epsilon(z) = C_\mu^{1/2} k(z) \frac{\langle U_s \rangle}{Z_s} \alpha \left(\frac{z}{z_s} \right)^{(\alpha-1)}$ $C_\mu=0.09$
Outflow	$\langle u \rangle, \langle v \rangle, \langle w \rangle, k, \epsilon$: zero gradient
Lateral and upper surfaces	$\langle u \rangle, \langle v \rangle, k, \epsilon$: zero gradient $\langle w \rangle=0$
Ground and building surfaces	Logarithmic law Ground surface temperature:44 °C Building surface temperature:37 °C
Advection term scheme	$\langle u \rangle, \langle v \rangle, \langle w \rangle, k, \epsilon, T$: MARS
Coupling algorithm	SIMPLE

Table 3. Boundary conditions in step 2.

Date and time	0:00 -24:00 on 14 th July
Calculation state	Unsteady state
Temperature	The daily temperature change mode
Convective heat transfer coefficient	Indoor: 5W/m ² ·K Outdoor: 12W/m ² ·K

Table 4. Ground and building surface properties.

	Long-wave emissivity	Albedo
Building wall and roof (by Mortar)	0.95	0.3
Ground (by concrete)	0.90	0.2

Table 5. Wall structure and its thermal parameters.

	Depth (mm)	Thermal conductivity (W/m·K)	Specific heat (W/m ³ ·K)
Exterior mortar	25	0.93	1890
Aerated concrete	200	0.22	735
Interior mortar	25	0.87	1785

Table 6. Roof structure and its thermal parameters.

	Depth (mm)	Thermal conductivity (W/m·K)	Specific heat (W/m ³ ·K)
Exterior mortar	25	0.93	1890
Fine-stone concrete	40	1.51	2116
cement mortar	20	0.93	1890
Insulation layer	30	0.036	41.4
Reinforced concrete	100	1.74	2300
Interior mortar	25	0.87	1785

Table 7. Ground structure and its thermal parameters.

	Depth (mm)	Thermal conductivity (W/m·K)	Specific heat W/m ³ ·K
Asphalt	240	1.50	3100
Gravel	200	0.62	1500
Soil	200	1.28	1900

Table 8. Boundary conditions in step 3.

Date and time	15:00, 14 th July
Calculation state	Steady state
Turbulence model	Suga's cubic non-linear k-ε model
Inflow boundary,	<u>, <v>, <w>, k, ε, T:
Lateral and upper surfaces	Outcomes in step 1
Outflow	<u>, <v>, <w>, k, ε: zero gradient
Surfaces of ground and building walls	Logarithmic law Temperature: outcomes in step 2
Advection term scheme	<u>, <v>, <w>, k, ε, T: MARS
Coupling algorithm	SIMPLE

2.4 Thermal comfort index

Some studies have found that thermal perceptions and preferences for outdoor people cannot solely be explained by energy balance of human's body, it is significantly affected by the psychological and behavioral factors such as experience, expectation, perceived control, cultural reasons, time of exposure, etc., which is so called thermal adaptation [14-17]. Thus a local subjective response to outdoor thermal environment need to be surveyed, and a thermal comfort index should be selected.

Several indices integrating thermal environmental factors and the energy balance of the human body were applied to assess the outdoor thermal comfort, e.g., predicted mean vote (PMV) [18], the ET*, the SET* [19], OUT_SET* [20, 21], and the physiologically equivalent temperature (PET). Currently, the most broadly used indices in recent studies on outdoor thermal comfort are SET*, PMV, and PET. Ishii et al. [22] compared several thermal comfort indices and concluded that SET* is better suited in evaluating outdoor comfort. Kinouchi also found that SET* can be used as an index for the outdoor environment [23]. In this research, SET* is applied to evaluate the outdoor thermal comfort.

For the questionnaire survey, the mean radiant temperature was calculated via the globe temperature measured by GL-200 and globe ball, adopting the equation suggested by ASHRAE as shown in Equation 1:

$$MRT = \left[\left((t_g) + 273 \right)^4 + \frac{1.01 \times 10^8 \langle V \rangle^{0.6}}{\varepsilon D^{0.4}} \left((t_g) - \langle \theta \rangle \right) \right]^{1/4} - 273 (^\circ C)$$

(1)

Where θ_g , V , θ , ε , and D refer to the globe temperature ($^{\circ}\text{C}$), wind velocity (m/s), air temperature ($^{\circ}\text{C}$), emissivity (0.95), and the diameter of the globe thermometer (0.15 m), respectively.

In both of the questionnaire survey and CFD simulation, the heat convective coefficient is calculated by equation given by Mitchel in 1974 [24], as shown in Equation 2:

$$\begin{cases} \alpha_c = 3.1 & (0 \leq \langle V \rangle \leq 0.2) \\ \alpha_c = 8.3 \langle V \rangle^{0.6} & (0.2 \leq \langle V \rangle \leq 4.0) \end{cases} \quad (2)$$

Where α_c and V are the convective heat transfer coefficient and wind velocity, respectively.

Both of the metabolic rate of survey and simulation was set to be 1.2. The cloth insulation was set following the instructions of the ASHRAE Standard in the questionnaire survey [25], and underwear was supposed to be medium. For the simulation, the cloth insulation was set to be 0.9 clo.

3 Results and analysis

3.1 Local subjective response to outdoor thermal environment

When thermal sensation vote (TSV) is between -1.5 and 1.5, the thermal environment is considered as acceptable, which is put forward by Fanger [18]. An 83 out of 114 samples vote their thermal sensation lower than 1.5, and the occupied percentage of TSV lower than 1.5 in different SET* intervals is shown in Table 9. It is shown that, a hundred percent acceptable rate is observed when SET* is lower than 30 $^{\circ}\text{C}$ in outdoor. When SET* is lower than 32 $^{\circ}\text{C}$, a 78% acceptable rate is expected to be achieved in Guangzhou, and when SET* is between 32 $^{\circ}\text{C}$ and 34 $^{\circ}\text{C}$, the acceptable rate is expected to be about 65%. The acceptable rate decreases sharply to be about 30% when SET* is higher than 34 $^{\circ}\text{C}$.

Table 9. TSV lower than 1.5 in different SET* intervals.

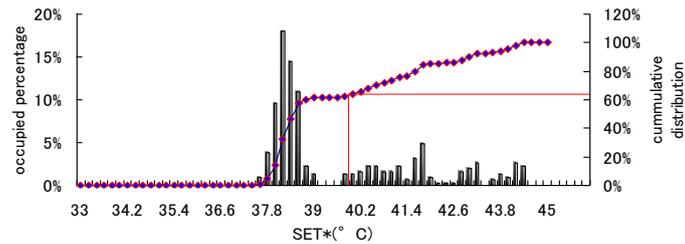
SET*	Acceptable rate	Number of samples (samples TSV \leq 1.5/total samples)
SET* \leq 30 $^{\circ}\text{C}$	100%	27/27
30 $^{\circ}\text{C}$ <SET* \leq 31 $^{\circ}\text{C}$	77%	10/13
31 $^{\circ}\text{C}$ <SET* \leq 32 $^{\circ}\text{C}$	78%	14/18
32 $^{\circ}\text{C}$ <SET* \leq 33 $^{\circ}\text{C}$	65%	17/26
33 $^{\circ}\text{C}$ <SET* \leq 34 $^{\circ}\text{C}$	67%	8/12
34 $^{\circ}\text{C}$ <SET* \leq 35 $^{\circ}\text{C}$	33%	6/18

3.2 Computed cases simulation result

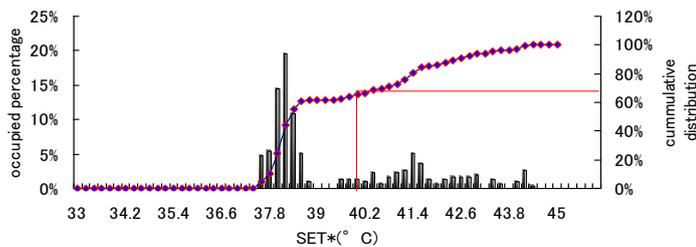
3.2.1 Evaluation standard. According to the result of questionnaire survey, there are 3 SET* values seem to be the inflexion point of local acceptance rate to the outdoor thermal environment: 30 $^{\circ}\text{C}$ (inflexion point of 100% and 80%), 32 $^{\circ}\text{C}$ (inflexion point of 80% and 65%), and 34 $^{\circ}\text{C}$ (inflexion point of 65% and 30%).

Because it is difficult for people to take part in the questionnaire survey in too hot environment, the SET* limit in this study is less than 35 $^{\circ}\text{C}$. ASHRAE defined that, when SET* between 35 $^{\circ}\text{C}$ and 40 $^{\circ}\text{C}$, people will feel hot and very hot, and 40 $^{\circ}\text{C}$ is the limit people can suffer, because when SET* is over 40 $^{\circ}\text{C}$, the peripheral nervous system will be in poor circulation, and people will be in poor body temperature regulation. Both of questionnaire survey result and ASHRAE standard will be taken into consideration in evaluation of outdoor thermal comfort.

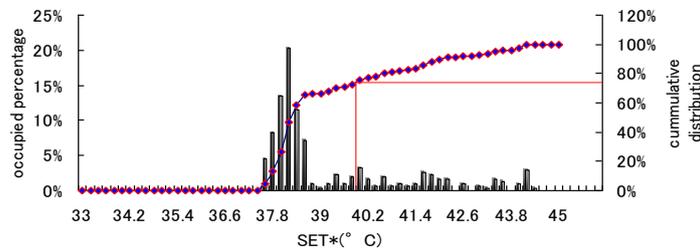
3.2.2 Results of area out of piloti. The cumulative distribution of SET* of area out of piloti is plotted in Figure 4. It shows that, the SET* keeps decreasing with the increase of piloti ratio (the bar graph moves from right to the left). Because the climate is super-hot in Guangzhou, in most of the cases there are some area where SET* is beyond 40 °C limit. The area percentage that SET* in the 40 °C limit for each case is about 62% (0% piloti ratio), 65% (40% piloti ratio), 72% (60% piloti ratio) and 85% (80% piloti ratio). It is noticed that when piloti ratio reaches 100 percent, the SET* in all area is in the 40 °C limit. About 50% area is expected to gain 30% acceptance rate (35°C), and about 10% area reach the need of 65% acceptance rate (34°C).



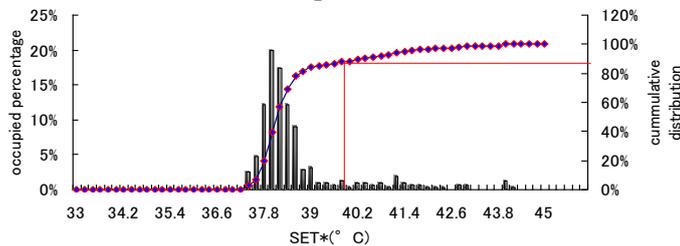
a) 0% piloti ratio.



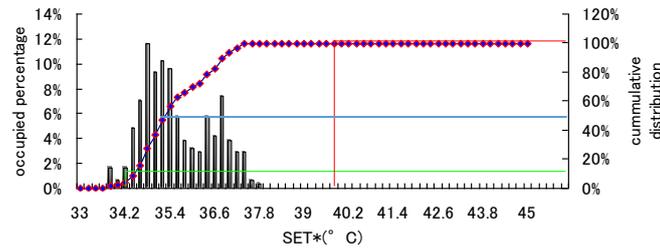
b) 40% piloti ratio.



c) 60% piloti ratio.

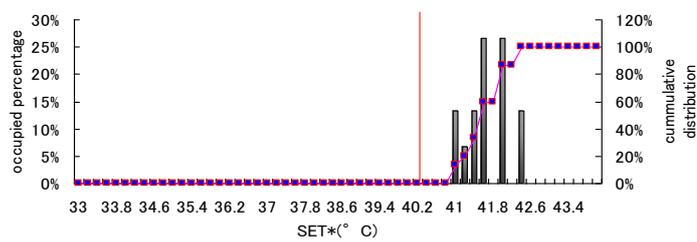


d) 80% piloti ratio.

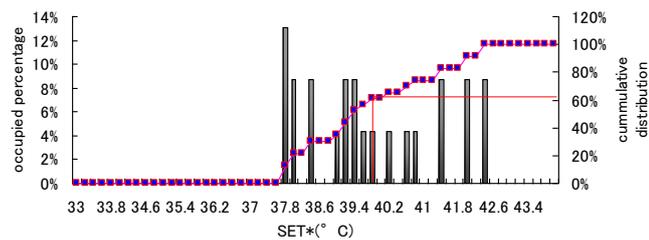


e) 100% piloti ratio.

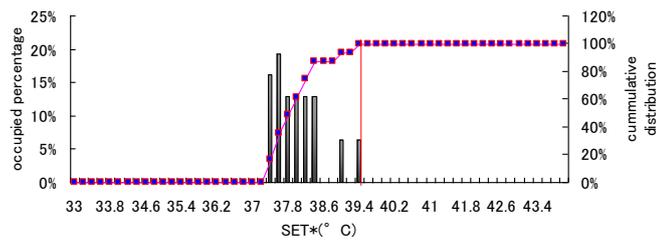
Figure 4. Cumulative distribution of SET* out of piloti area.



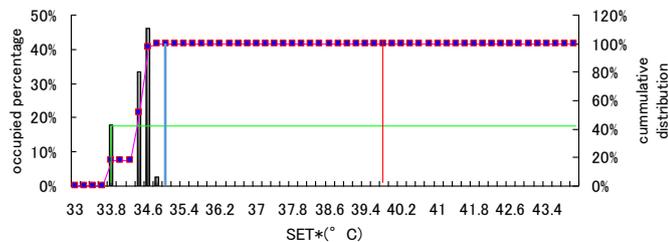
b) 40% piloti ratio



c) 60% piloti ratio.



d) 80% piloti ratio.



e) 100% piloti ratio.

Figure 5. Cumulative distribution of SET* under piloti area.

3.2.3 Results of area under piloti. The cumulative distribution of SET* under piloti area is plotted in Figure 5. It shows that, each 20% piloti increase optimize the outdoor thermal environment a lot. The outdoor thermal environment is very strict when piloti ratio is 40%, and even no area is in the 40 °C SET* limit, this should be due to the very low wind velocity under piloti (Fig, 6). The area which in the 40°C limit of 60% piloti ratio case is about 62%, and for 80% and 100% piloti ratio cases, it is 100%. Due to high wind velocity and shadow influence, 100% area of 100 percent piloti ratio case meet the need of 30% acceptance rate (35°C), and about 40% area meet the need of 65% acceptance rate (34°C).

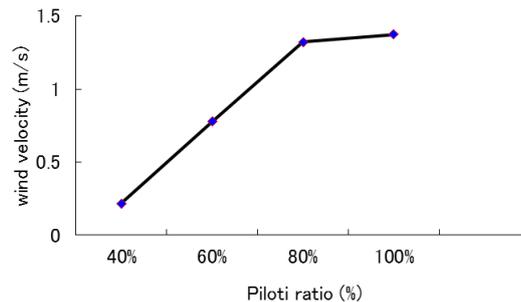


Figure 6. Average wind velocity (piloti area).

4 Conclusions

This work studied on the influence of piloti on outdoor thermal comfort by both of a local questionnaire survey and CFD simulation. The questionnaire survey showed that 3 SET* values seem to be the inflexion point of local acceptance rate to the outdoor thermal environment: 30 °C (inflexion point of 100% and 80%), 32°C (inflexion point of 80% and 65%), and 34 °C (inflexion point of 65% and 30%).

Both of the SET* index value under piloti and out of piloti area decreased with the increase of piloti ratio. A 100% piloti ratio can highly optimize the local outdoor thermal comfort. For the area out of piloti, the SET* in all area is in the 40 °C limit, and about 50% area is expected to gain 30% acceptance rate (35°C), and about 10% area reach the need of 65% acceptance rate (34°C) . For the area under piloti, 100% area meet the need of 30% acceptance rate (35°C), and about 40% area meet the need of 65% acceptance rate (34°C). It is noticed that, when piloti area is 40%, no area is in the 40°C limit, which should be due to the very low wind velocity under piloti area.

Acknowledgements

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