A Field Study of Thermal Comfort in Outdoor and Semi-outdoor Environments in a Humid Subtropical Climate City

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Abstract

Very few studies exist on the outdoor thermal environment and thermal comfort impact of a semi-outdoor environment—under a piloti—in a humid subtropical climate city. Subjective data was collected using questionnaires both in a square and under a piloti during June and July 2011 in Wuhan. The aims were to obtain a better understanding of human thermal comfort response while outdoors and to clarify the effect of piloti on thermal comfort in a humid subtropical climate city. It was found that mean radiant temperature (MRT) plays a more important role than air temperature in the subjective response of people to the outdoor thermal environment. The relationship between the standard effective temperature (SET*) and thermal sensation vote (TSV) was clarified, and the neutral SET* was calculated as being about 24.8°C. Being under a piloti has a notable impact, reducing the heat effect by ameliorating the microclimate and enhancing human thermal comfort outdoors. When the maximum air temperature exceeded 35°C during daytime, the SET* decreased by 9°C under the piloti in a humid subtropical climate city relative to that in a nearby square, and the acceptance rate of the outdoor thermal environment under the piloti was more than twice that in the square.

Keywords: outdoor thermal comfort; piloti; standard effective temperature; humid subtropical climate

1. Introduction

In recent years, the accelerated rate of urban growth has produced a large number of residential areas. A study by Tolley et al. (2001) indicated that walking for health is a trend that is becoming increasingly popular, and this popularity is likely to continue to increase. Therefore, outdoor thermal comfort is becoming an increasing concern for residents.

Previous research regarding outdoor thermal comfort mainly focused on two fields: (1) the relationship between human behavior and outdoor thermal environment and (2) the relationship between biophysical environments and subjective states of thermal comfort. Ishii et al. (1988) conducted an experimental study on the comfort perception of people in outdoor environments. Nikolopoulou et al. (2001) conducted a study of subjective human responses to their outdoor environments following de Freitas’ study (1985). Murakami et al. (1986) conducted long-term observations of wind-induced problems around a high-rise apartment building located in a built up area in Tokyo, in cooperation with many inhabitants of the area. They also proposed a method for assessing the wind environment at ground level. Spagnolo and de Dear (2003) researched the relationships between biophysical environments and subjective states of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney, Australia. Their study found that the thermal neutrality in terms of the thermal comfort index of outdoor standard effective temperature (SET*) of 26.2°C was significantly higher than the indoor SET* counterpart of 24°C (Gagge et al. 1986). Mayer and Höppe (2003) performed biometeorological measurements simultaneously in three different urban structures within the city of Munich and in the trunk space of a nearby tall spruce forest to research the thermal comfort of humans in different urban environments. Because different thermal sensations depend on regional and climate differences in the outdoor environments, an outdoor thermal comfort database is necessary (Katzschner, 2006).

In order to alleviate the outdoor thermal environment, researchers have reviewed the impact of green space and water. Chen et al. (2004) investigated the actual situation of the outdoor thermal environment in summer in an apartment block in Shenzhen City.
using field measurements. They then 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. Uchida et al. (2009) 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-based survey was conducted at the measurement site to look into the principal causes that affected human thermal comfort. Hwang et al. (2010) 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. Zhou et al. (2011) analyzed the impact of inland water body changes from 1965 to 2008 on the local climate and environment of Wuhan, China. As mentioned above, in recent years, research into outdoor thermal comfort while considering green space and the presence of water has increased. However, the impact of the presence of pilotes, which are an important part of buildings in areas with hot summers, has not been studied sufficiently (Xi et al. 2012). The present research collected data using questionnaires filled in by young people in a square and under a piloti in Wuhan City, China, during June and July (summer) 2011. The aim was to clarify the individual preferences of people and identify the neutral SET* in a humid subtropical climate city, as well as to clarify the effect of being in a semi-outdoor environment—under a piloti—on the subjective thermal sensation.

2. Methodology

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 east of the Jianghan Plain at the intersection of the middle reaches of the Yangtze and Han Rivers.

The climate of Wuhan is humid subtropical with abundant rainfall and four distinctive seasons. Fig. 1 shows the daily average temperature, maximum temperature, minimum temperature, and relative humidity in Wuhan in 2001. The temperature ranges from -3°C to 38°C and relative humidity is consistently high. The summer season is from June to August, and there are 44 hot days (daily maximum temperature is above 30°C), including 19 extremely hot days (daily maximum temperature is above 35°C), during these three months.

2.2 Questionnaire and instruments

Subjective thermal sensation and thermal comfort data were collected using a questionnaire (Table 1.) that was adapted from appendix E of BSR/ASHRAE Standard 55P (2003). Some items were not part of previous ASHRAE questionnaires, such as question 3 that inquires about sun/shade preferences.

Objective environmental physical measurements and subjective measurements, using questionnaires, were carried out simultaneously. The measurement instruments used in this study for each influence variable are listed in Table 2. Solar radiation data was provided by the Wuhan weather station.

Table 1. Questions Included in the Questionnaire Used to Collect Data in this Study

| Question 1 | Please tick the scale to indicate how you feel at the moment. |
|------------|---------------------------------------------------------------|
| Cold       | Cool             | Slightly cool | Neutral | Slightly warm | Warm    | Hot     |
|-3          | -2               | -1            | 0       | 1             | 2       | 3       |

Would you like to be (circle appropriate answer)?

Warmer No change Cooler

Question 2 Would you like (circle appropriate answer)?

More air movement No change Less air movement

Question 3 Would you like (circle appropriate answer)?

More sun No change More shade

Question 4 Activity

For the last half hour have you been mainly:
Sleeping Sitting Standing Walking

Question 5 Please tick the scale to indicate how you feel at this moment

Comfortable Slightly uncomfortable

0 Slightly comfortable 1 2 Uncomfortable 3
2.3 Method of data collection using questionnaires

The investigations were carried out on days with suitable weather (to avoid windy or rainy days, during hot days or extremely hot days) from June to July 2011 in a square and under a piloti in Wuhan. Because thermal sensitivity declines with age (Stevens and Choo, 1998), young students between the ages of 19 and 27 were invited to complete the questionnaire as volunteers. Each time, 4 or 5 students were seated on a chair within the square or under the piloti for about 20 min and then given the questionnaires. Simultaneously, the physical factors of the outdoor thermal environment, such as temperature, humidity, wind velocity, and globe temperature, were recorded. Before starting the investigation, the volunteers were requested to sit quietly in an indoor place, located a 1 min walk from the test site, for 30 min in order to obtain a uniform metabolic rate. The instruments were set at a height of 1.2 m from the ground, less than 3 m from the volunteers (Fig.2.). Each volunteer took part in the investigation several times, and in total, 386 samples were collected.

2.4 Calculation method of SET*

The SET* is adopted for the assessment of thermal comfort in this study, and the mean radiant temperature (MRT) is calculated by the following equation (BSR/ASHRAE Standard 55P, 2003).

\[
MRT = \left[ \left( \frac{\theta_g}{\epsilon} + 273 \right)^4 + \frac{1.015 \times 10^5 \rho \epsilon^8 \epsilon}{\rho D^4} \left( \theta - \theta' \right) \right]^{1/4} - 273 \quad \text{[°C]} \tag{1}
\]

Here, \( \theta_g \), \( V \), \( \theta \), \( \epsilon \), and \( D \) denote the globe temperature (°C), wind velocity (m/s), air temperature (°C), emissivity (0.95), and the diameter of the globe thermometer (0.15 m), respectively. The method used in this paper was one of the main ways for calculating MRT and was used in many previous studies (ISO 7726, 1998, Xi et al. 2012). But, it should be noted that the MRT value estimated by using the globe temperature overestimates the incoming solar radiation compared to the MRT value calculated by using the results of 3D radiant heat transports, when the actual short-wave absorptivity is small (Yumino, 2012).

The convective heat transfer coefficient \( \alpha_c \) is calculated by the equation given by Mitchell (1974).

\[
\alpha_c = 3.1 \left( 0 \leq \langle V \rangle \leq 0.2 \right)
\]

\[
\alpha_c = 8.3 \langle V \rangle^{0.6} \left( 0.2 \leq \langle V \rangle \leq 4.0 \right)
\]

\( \alpha_c \) and \( V \) denote the convective heat transfer coefficient and wind velocity value, respectively. The metabolic rate is set to 1.2 and clothing insulation is calculated according to Table B2 in BSR/ASHRAE Standard 55P (2003).

3. Results and Analysis

3.1 Individual preferences

| Variable                  | Measurement instruments | Manufacture location | Accuracy                          |
|--------------------------|-------------------------|----------------------|-----------------------------------|
| Air Temperature (\( \theta \)) | Hygrothermograph (TES-1365) | Taiwan              | ±0.5°C                            |
| Relative Humidity (RH)    | Hygrothermograph (TES-1365) | Taiwan              | ±0.5% RH (25°C 30~95% RH)         |
| Wind Velocity (V)         | Hot-wire Anemograph (TES-1341) | Taiwan              | ±5% RH (25°C 10~30% RH)           |
| Globe Temperature (\( \theta_g \)) | GL-200 & Globe Ball (0.15 m diameter) | Japan               | ± 0.5% (20~50°C)                  |
|                          |                         |                      | ± 7% (50~120°C)                   |

Fig.2. Views of Questionnaire Procedure in Wuhan

Fig.3. Individual Preferences of Young Students

(a) -1.5 < TSV < 1.5

(b) 1.5 < TSV ≤ 3
When the TSV is between -1.5 and 1.5, the thermal environment is considered acceptable, as given by Fanger (1970). In this study, 301 out of 386 young people identified their TSV as lower than 1.5, which shows that they found the thermal environment acceptable. These personal preferences are plotted in Fig.3. (a). It is seen from Fig.3. (a) that when the thermal environment is considered acceptable, 59% and 56% of the subjects choose the option "no change" for sun/shade and air movement, respectively, whereas 61% of the subjects choose the option "cooler" regarding the parameter of air temperature. When the TSV is higher than 1.5 (Fig.3. (b)), almost all of the subjects (n = 80) choose the option "cooler" for air temperature. Therefore, most people (n = 265, 69%) feel that the air temperature is unacceptable in Wuhan in hot summers.

3.2 Relationships between biophysical environments and subjective states

Table 3. lists the outdoor data for the questionnaire period in Wuhan. The questionnaire procedure was performed on hot sunny days, and the maximum global solar radiation, air temperature, and globe temperature were 922.2 W/m², 36.5 °C, and 50.2 °C, respectively.

Table 3. Outdoor Data for Period during which Questionnaire was Conducted

| Parameter                        | Mean   | Max   | Min   | Stdev |
|----------------------------------|--------|-------|-------|-------|
| Global solar radiation (W/m²)    | 490.6  | 922.2 | 0     | 345.8 |
| Ta (°C)                          | 33.4   | 36.5  | 29.8  | 1.91  |
| RH (%)                           | 55.7   | 71.2  | 29.1  | 8.27  |
| Vel (ms⁻¹)                       | 0.87   | 3.85  | 0.01  | 0.74  |
| Tglobe (°C)                      | 36.1   | 50.2  | 29.8  | 5.49  |
| MRT (°C)                         | 40.4   | 81.4  | 29.8  | 12.2  |
| CLO (clo)                        | 0.38   | 0.51  | 0.29  | 0.07  |

The relationship between the air temperature and the TSV is plotted in Fig.4. In this study, the TSV in Wuhan is shown for air temperatures ranging from 27°C to 37°C in an outdoor environment. However, no clear relationship is found between the air temperature and the TSV (Fig.4.). This is because the TSV is not only dependent on air temperature but is also affected by other factors, such as wind speed and availability of shade. Considering several parameters influencing thermal comfort, the following equation could be obtained:

\[
\text{TSV} = -0.105 \times \text{Ta} - 2.7 \times \text{RH} + 0.11 \times \text{Tg} - 0.016V + 1.996
\]

\[(R^2 = 0.53)\]

The relationship between the MRT and the TSV is plotted in Fig.5. When the MRT is low (28°C~42°C, the rectangular area), the range of the TSV is very wide, from 0 to 2.5. When the MRT is higher than 45°C (the elliptic area), the range of the TSV is mainly from 1.5 to 3. The MRT correlates with the TSV more closely than the air temperature correlates with the TSV. The linear relation between the MRT and the TSV is

\[
\text{TSV} = 0.04 \times \text{MRT} - 0.63 \quad (R^2 = 0.49)
\]

The relationship between the SET* and the TSV is plotted in Fig.6. The globe temperature within a square rises quickly at noontime in Wuhan (Fig.8. (a)), so the values of the SET* are mainly in the range of 26°C~33°C and 35°C~40°C. It is shown that the TSV of young people varies by about 0.15 with a 1 unit change in the SET* in a humid subtropical climate city in summer, and the thermal sensation correlates well with the SET*. The neutral SET* in Wuhan in summer is about 24.8°C. The linear relation between the SET* and the TSV is

\[
\text{TSV} = 0.15 \times \text{SET*} - 3.48 \quad (R^2 = 0.54)
\]

Fig.6. Relationship between SET* and TSV

Fig.7. compares the TSV with the thermal comfort vote (TCV). It shows that though the thermal comfort is influenced by many factors other than the thermal environment, such as psychological factors, acoustic and light environments, air quality, and human
behaviors and purposes, thermal comfort correlates well with thermal sensation. The TCV varies by about 0.79 for a 1 unit change in the TSV. When the TCV is 0, the TSV is about -0.18. This means that in summer, people will feel comfortable when their thermal sensation is slightly low. The linear relation between the TCV and the TSV is
\[ TCV = 0.79 \times TSV + 0.14 \quad (R^2 = 0.71) \]

3.3 Effect of piloti on thermal comfort
The air temperature, MRT, and relative humidity both under the piloti and in the square on July 2\textsuperscript{nd} (sunny) are shown in Fig.8. (a). From 7:00 to 10:00, because of the weak solar radiation, there were only small differences among the four temperatures. After the solar radiation became stronger, from 10:00 to 17:00, the four temperature curves were different. The MRT in the square increased rapidly, the highest MRT reaching 81.4°C at 15:00, and the maximum MRT difference between under the piloti and in the square was about 45.3°C. The air temperatures and the MRT under the piloti were relatively close. After 17:00, when the solar radiation weakened, the difference between the four temperature curves became small. The curves of MRT were also affected significantly by the wind velocity. Relative humidity values under the piloti and in the square were almost the same throughout the day.

Fig.8. (b) shows the wind velocity both in the square and under the piloti on July 2\textsuperscript{nd}. The wind velocity in the square was less affected by the wind direction, and the wind became strong during the afternoon. The wind velocity under the piloti was more affected by the wind direction.

Fig.9. shows a comparison of the SET* under the piloti and in the square on July 2\textsuperscript{nd}. The trend of the SET* was similar to the globe temperature, but with the influence of wind velocity and relative humidity,
the values of SET* under the piloti and in the square showed irregular differences. The SET* in the square increased rapidly after 10:00, and reached the maximum value of 38.8°C at 13:40. The maximum SET* difference between under the piloti and in the square was about 9°C at 13:20.

Fig.10. (a) shows a comparison of the TSV under the piloti and in the square from 7:00 to 10:00 and after 17:00 on July 2nd. More than 60% of the TSVs reported in the questionnaire responses in this timeframe were less than 0.5, and the difference was very small between under the piloti and in the square. This means that when the solar radiation is not very strong, in the morning and evening, thermal sensations under the piloti and in the square are almost the same.

A comparison of the TSV under the piloti and in the square from 10:00 to 17:00 is shown in Fig.10. (b). The values of the TSV under the piloti were mainly from 0 to 1.5, with an average value of 1.03, while the values of the TSV in the square were mainly from 1.5 to 2.5, with an average value of 1.75. This indicates an outdoor thermal environment acceptance rate of 77% under the piloti; in comparison, in the square, the acceptance rate was only 35%.

Therefore, when the solar radiation is intense during the day, the piloti can effectively reduce the solar radiation relative to the square, thereby more than doubling the acceptance rate of the outdoor thermal environment.

4. Conclusions

This paper presented the findings of an extensive field comfort questionnaire used to collect data during the summer within a square and under a piloti in Wuhan. The main findings are as follows:

(1) Individual preferences are consistent with people's thermal sensation. When the thermal environment is considered unacceptable, change in three factors will be necessary: shade, airflow, and temperature. Most people consider that the air temperature is unacceptable in Wuhan in hot summers.

(2) SET* correlated well with TSV during the hot and humid summer in the outdoor environment of Wuhan, and the neutral SET* was found to be about 24.8°C in Wuhan. TSV correlated well with TCV, and people will feel comfortable when their thermal sensation is slightly low in summer.

(3) When the air temperature exceeded 35°C in the daytime, the maximum MRT difference between under the piloti and in a nearby square was about 35.3°C, and the SET* while outdoors it decreased by 9°C when under a piloti in a humid subtropical climate city—Wuhan. The acceptance rate of the outdoor thermal environment while under a piloti is nearly twice that when in a square.
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