THERMAL COMFORT MODELS OF VENUE IN HOT AND HUMID SUBTROPICAL REGIONS

by

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In order to improve the design effect of venues, this paper establishes the evaluation model of indoor thermal comfort for the humid and hot subtropical areas, which provides theoretical reference for venue design. This paper investigates the thermal sensation of basketball players by questionnaire, analyzes the relationship between thermal sensation vote and standard effective temperature, predicted mean vote, and wet bulb globe temperature, and develops an index called predicted thermal sensation by using the least square method. The relationship between outdoor air temperature and indoor working temperature under neutral conditions is obtained by measuring data. The results show that the correlation between thermal sensation vote and air temperature is the strongest, R^2 is 0.753, while the relationship between thermal sensation vote and air speed is weak, R^2 is 0.012. Thermal sensation vote and set, predicted mean vote and wet bulb globe temperature are not suitable for athletes in the field environment.

Key words*: thermal comfort model, questionnaire survey method, least square method, hot-humid subtropical region*

Introduction

Indoor thermal comfort in venues is directly related to public health as well as energy consumption [1]. Currently, the current researches on this field mainly focus on the existing evaluation indices, which is used for evaluating the stress extremum under the prolonged work. Therefore, targeting the hot and humid subtropical region, this paper aims to establish an evaluation model of indoor thermal comfort of venues to provide a theoretical reference for venue designs [2].

Zhang *et al*. [3] studies the subjective thermal comfort evaluation characteristics of different outdoor spaces in hot and humid areas in summer. Taking the city of Guangzhou, China as an example, the thermal environment level and subjective thermal comfort evaluation characteristics of six different outdoor spaces are obtained through thermal environment test and thermal comfort survey. The statistical results show that the open square space receives more solar radiation, and the residents vote the most for the heat. The results showed that the correlation coefficient between the thermal perception and solar radiation was more

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than 0.718. In addition, there are scholars put forward the index of standard effective temperature (SET). They are currently adopted by the ASHRAE Standard-55, ISO7730 Standard and the Chinese Thermal Comfort Standard. In addition, some indices are based on the thermal parameters [4]. Tropical summer index and equivalent temperature. Afterwards, through a large number of practical measurements, Dear and Brager [5], Humphreys and other researchers, see in [5],found that the human body has a thermal comfort adaptability in natural ventilation environment. Therefore, the climate adaptive model was proposed.

A thermal comfort model that is applicable to venues was established and compared with the models of SET, predicted mean vote (PMV) and wet bulb globe temperature (WBGT). In addition, thermal neutral temperature was discussed. By comparing with the previous studies, the difference of climate adaptive model was verified among regions and an adaptive model applicable to venues in hot and humid climates was established.

Materials and Methods

Study site

Figure 1 shows the relationship between the monthly average temperature and humidity in Guangzhou. The monthly average temperature and humidity in Guangzhou are high, and the period with high temperature and high humidity is long [6].

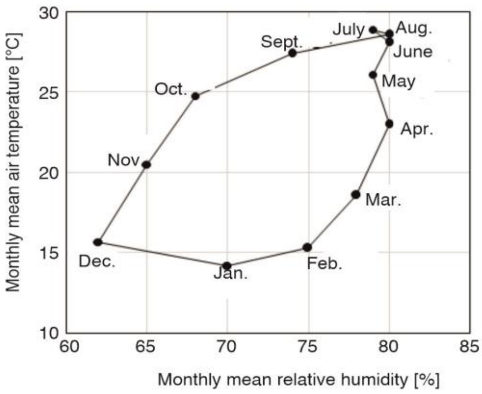


Figure 1. Climograph of Guangzhou, China

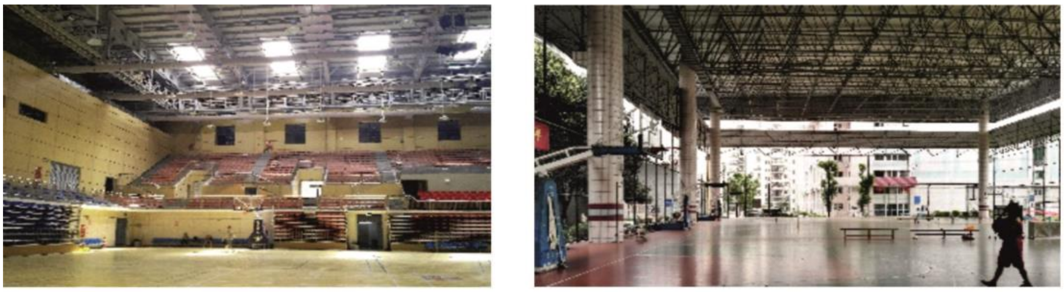
Figure 2 present the interior views and floor plans of the two venues (Venue T and Venue W) studied in this paper. Both venues are located at the downtown area of Guangzhou. Venue T was built in 2010 with the structure of reinforced concrete [7]. It is an arena, with a size of 75 m × 60 m × 20.8 m in length, width, and height respectively. Venue W was completed in 1996 with the structure of steel. It is open on the south, east, and north sides. There are three basketball courts in each of the venues and are mainly used for athletes' daily training and exercises [8]. Therefore, the research objective is the thermal comfort of the basketball athletes in the venues [9].

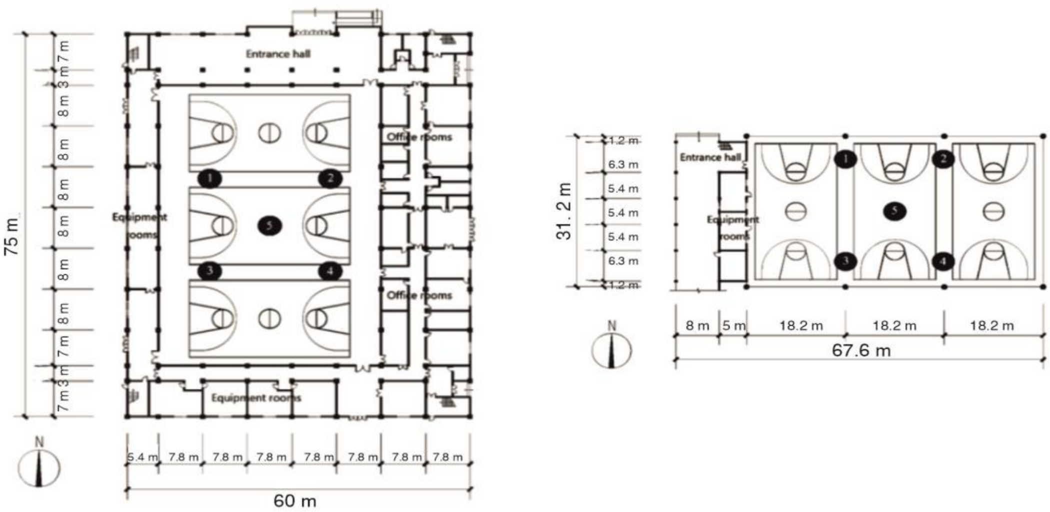
Individual Factors

During the survey, the subjects wore long-sleeves and trousers during winter and shorts during the other seasons, thus the clothing insulation in a state of rest is 0.74 clo and 0.36 clo, respectively, according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards [10]. The clothing insulation is reduced when relative air-flow exists between the human body and the ambient air during physical exercises, and the change in clothing insulation can be estimated by eq. (1) [11]. Thus, the clothing insulation when playing basketball is 0.3 clo during winter and 0.11 clo for the other seasons when air-flow is considered. Lastly, by taking the time weighting of active and resting periods, the clothing insulation is 0.39 clo during winter and 0.16 clo in the other seasons:

$$\Delta I_{\mathrm{cl}} = -0.504 I_{\mathrm{cl}} - 0.00281 V_{\mathrm{walk}} + 0.24 \tag{1}$$

where ΔI_{cl} [clo] is the change in clothing insulation, I_{cl} [clo] – the clothing insulation in a state of rest, and V_{walk} – the intensity of air-flow.





(a) (b)

Figure 2. Plans of measured venues (Points 1 to 5 in each Venue represent the locations of the measuring instruments); (a) Venue T and (b) Venue W

Results

Values of thermal parameters

Mean radiant temperature was calculated with the air temperature, global temperature and air velocity [12], as shown:

$$T_r = T_g + 2.37\sqrt{V_a}(T_g - T_a) \tag{2}$$

where T_r [°C] is the mean radiant temperature, T_g [°C] – the globe temperature, V_a [ms^{-1}] – the air velocity, and T_a [°C] – the air temperature .

Humidity ratio was calculated and used in the following discussion instead of relative humidity, because it is a variable independent to the air temperature.

The correlation between thermal sensation vote and indoor thermal parameters

The measured thermal sensation vote (TSV) was linearly fitted with the indoor thermal parameters, establish a thermal comfort model for the basketball athletes in the venues [13].

The correlation between the TSV and the four thermal parameters are summarized in figs. 3-6. Each plot in these figures represents a sample of measurement. There is strong correlation between the TSV and the air temperature, with the R^2 value of 0.753, indicating that the change of air temperature has the greatest influence on human thermal sensation. The relationship between TSV and humidity ratio is positively correlated, with the R^2 value of 0.366. Figure 6 demonstrates that the relationship between the TSV and the air velocity is weak, with the R^2 value of 0.012.

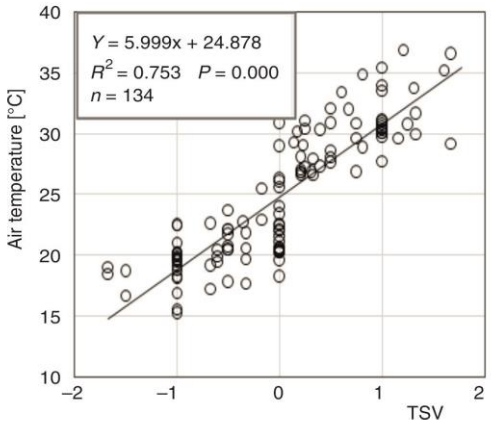


Figure 3. The relationship between TSV and air temperature

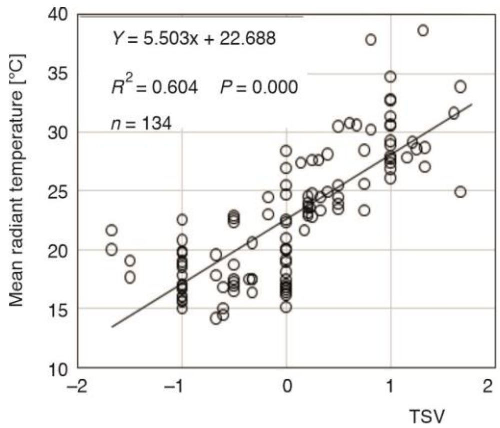


Figure 4. The relationship between TSV and mean radiant temperature

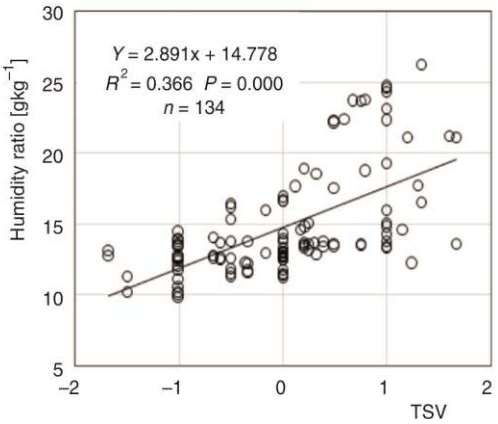


Figure 5. The relationship between TSV and humidity ratio

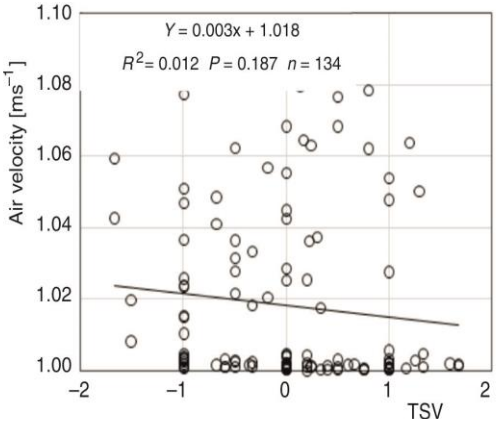


Figure 6. The relationship between TSV and air velocity

The correlation between TSV and SET, PMV, and WBGT

In order to verify the applicability of the thermal indices originally suggested for offices and so on, relations between the TSV and SET, PMV, and WGBT are demonstrated in figs. 7-9. Each plot in these figures represents a sample of measurement [14]. Among these indices, the correlation between the WGBT and the TSV is the strongest with the R^2 value of 0.701. The reason for the weak correlations with other indices is probably that the SET and PMV are suggested for the low metabolic rates and steady-state environments.

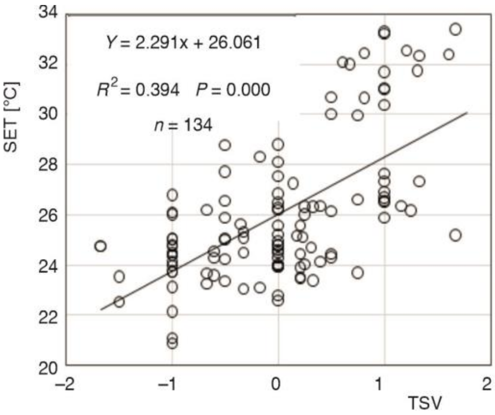


Figure 7. The relationship between TSV and SET

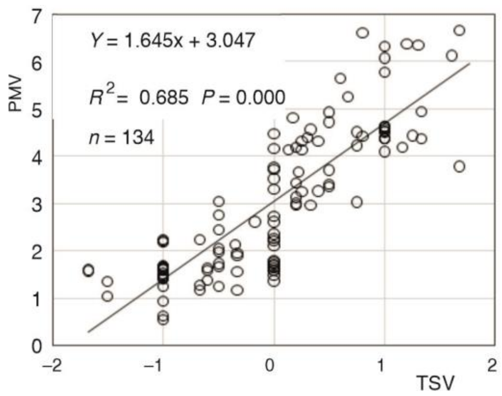


Figure 8. The relationship between TSV and PMV

Proposal for a new index for athletes in venues

As aforementioned, the existing thermal indices are not applicable to the athletes in venue environments. Using the least square method, an index called the predicted thermal sensation (PTS) is developed. The derivation process has been shown in eq. (3). Firstly, a multiple linear regression model is created:

$$PTS = C_0 + C_1 T_a + C_2 T_r + C_3 x + C_4 V_a \tag{3}$$

where C_0, C_1, C_3, and C_4 are the partial regression coefficients.

Set the partial derivative in 0, and obtain the optimal solutions of C_0 to C_4. This part of calculation can be done by SOLVER in excel. Finally, the index of PTS is established as:

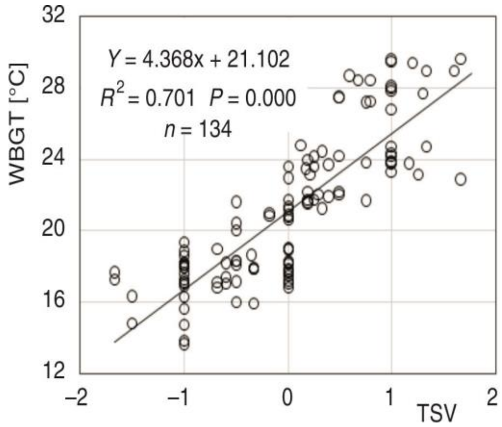


Figure 9. The relationship between TSV and WBGT

$$PTS = 3.304 + 0.132T_a + 0.023T_r + 0.021x - 7.264V_a \tag{4}$$

The RMSE is 0.419, which shows that the PTS fits the TSV well. The R^2 value (0.777) is smaller than that for other indices, which implies that the PTS index can be used to evaluate the thermal sensation of athletes in venue environments with limited errors.

Similar to the index of WBGT, the PTS index is established basing on the statistics of thermal elements due to the certain values on individual factors. Moreover, the factors of human physiology are already reflected in the PTS index by means of thermal parameters. For instance, the evaporation on human body is related to the humidity and air velocity; The convection on human body is related to the air temperature and air velocity [15]. Therefore, the index of PTS is more precise than WBGT and other existing indices when applied to the venues in hot and humid climates.

Neutral temperature

Dear found that the neutral temperature of naturally ventilated buildings changes with the outdoor air temperature, as described by the adaptive model. Each plot represents a sample under neutral condition (While TSV = 0). The regression equation between the indoor operative temperature under the thermal neutral condition and outdoor air temperature is established:

$$T_n = 0.90T_0 + 3.5 \tag{5}$$

where T_n [°C] is the indoor operative temperature under the thermal neutral condition and T_0 [°C] – the outdoor air temperature.

Equation (5) is close to that of Ministry of Hosing and Urban-Rural Development (MOHURD) of China which is established based on the hot and humid areas in China. However, the equations of Dear and Brager [5] and Humpherys are established based on various areas around the world where different adaptive responses on human are shown. It therefore demonstrates that the equations of Dear and Brager [5] and Humpherys are more widely used but less precise when apply on the hot and humid areas.

Discussion

The thermal sensation of basketball players was investigated using questionnaire surveying;

The correlation between TSV and the air temperature is strongest, with the R^2 value of 0.753, while the relationship between the TSV and the air velocity is weak, with the R^2 value of 0.012.

The relationships between TSV and SET, PMV and WBGT were analyzed and found that these thermal indices are not applicable to the athletes in venue environments. Therefore, using the least square method, an index called the PTS is developed. the PTS model is established for venues in hot and humid regions, as shown in eq. (4).

The relation between outdoor air temperature and indoor operative temperature under neutral conditions in venues was obtained by the measured data, as shown in Equation (5). In addition, a comparison between eq. (5) and the equations of Dear and Brager [5], Humphreys and MOHURD of China was given. It shows that the eq. (5) is close to that of MOHURD of China which is established based on the hot and humid areas in China.

Conclusions

The two models established in this paper, eqs. (4) and (5), are based on measured data. Due to the certain limitations of the measurement conditions, the previous developed models should be limited in its use. First of all, the measurement sites were venues in Guangzhou, locating in the hot and humid subtropical region. Therefore, these models should be confined to venues in hot and humid subtropical region.

Secondly, the subjects of this research were basketball athletes. Therefore, these models should be limited to basketball athletes or people involved in exercise equivalent to playing basketball.

As the next step, we would conduct more measurements at different locations and discuss about the types of sports and the physical characteristics of athletes including gender, height, weight, *etc*.

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