https://doi.org/10.1016/j.scs.2018.10.022

Investigation into the differences among several outdoor thermal comfort indices against field survey in subtropics

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Highlights

- Different thermal comfort indices were compared based on the fundamentals.
- Field surveys were carried out for validation of the thermal comfort indices.
- The relationships between the indices and MTSV were undetermined for hot outdoor environments
- The ranges of heat stress category and PMV need to be modified for hot outdoor environments.

Abstract: Comfortable and healthy outdoor microclimates are beneficial to sustainable urban development. Based on a comprehensive comparison of some currently frequently used thermal comfort indices, including PMV, WBGT, PET, SET*, and UTCI, the differences among these indices are significant in dealing with the fundamental energy balance model, descriptive equations, and application boundary conditions. In order to validate these indices, a subjective questionnaire survey with field measurements was carried out on a university campus in Guangzhou in southern China. Results revealed strong linear relationships between operative temperature and mean radiant temperature (T_{mrt}), WBGT, PET, SET*, UTCI, as well as PMV. However, the relationships between these thermal comfort indices and the mean thermal sensation vote (MTSV) are not clear for a hot outdoor environment, especially when the operative temperature was above 34 °C. The ranges of the heat stress category and PMV need to be modified for the evaluation of hot outdoor environments.

Keywords: Microclimatic parameters; Outdoor thermal comfort; Thermal comfort indices; Operative temperature; Thermal sensation

Nomenclature

T_a	Air temperature, °C	$\Delta q_{m,bas}$	Changes in the local basal metabolism, W/m^3
T_w	Wet bulb temperature, °C	$q_{m,sh}$	Metabolism of shivering, W/m^3
T_g	Globe bulb temperature, °C	$q_{m,w}$	Metabolism of exercise, W/m^3
T_{cl}	Clothing surface temperature, °C	I_{cl}	Thermal resistance of clothing, m^2·°C /W
T_{mrt}	Mean radiant temperature, °C	f_{cl}	Clothing area factor,
T_M	Mean body temperature, °C	h_c	Convective heat transfer coefficient, W/(m^2·°C)
Tc, t_{cr}	Core temperature, °C	v_a	Air velocity, m/s
T_{sk}, t_{sk}	Mean skin temperature, °C	$skbf$	Peripheral blood flow, L/(h·m^2)
T_{bla}	Arterial blood temperature, °C	m	The body mass, kg
T_i	Tissue temperature, °C	$C_{p,b}$, c_k	Specific heat capacity of body, kJ/kg
T_{bs}	Surface temperatures of the body sector, °C	θ	Time, s
T_{op}	Operative temperature, °C	α	The body mass fraction in the skin compartment
H,M	Internal heat produced by the metabolism, W	ω	Skin wittedness
E_D	The latent heat lost due to diffusion of water vapor, W	h_s	Standard heat transfer coefficient, W/(m^2.°C)
E_{SW}	The latent heat lost due to evaporation of sweat, W	GE	The body mass, kg
E_{Re}	Latent heat lost due to respiration, W	v_b	Blood flow from the core to the skin, m^2/s
L	Sensible heat lost due to respiration, W	A_{Du}, A_D, A_{sk}	Surface area of the skin, m^2
K	Conductivity, W	A_{Be}	Surface area of the clothed body, m^2
R	Sensible heat loss from skin by radiation, W	Δt	Time step
C	Convection, W	h_e	Latent heat transfer coefficient, W/(m^2·kPa)
S	Heat content in the body, W	VP_a, pa,	Ambient water vapor pressure, kPa

E	Sum heat lost due to evaporation, W	SVP_{Tsk}	Saturation vapor pressure of skin temperature, kPa
$R+C$	Sum sensible heat loss from skin, W	c	Tissue heat capacitance, J/(kg·°C)
W	Heat lost due to mechanical work, W	ρ_b	Density of blood, kg/m^3
S_{cr}	Rate of heat storage in core compartment, W/m^2	A	Temperature factor
C_{res}	Dry respiratory heat loss per unit area, W/m^2	PMV	Predicted Mean Vote
E_{res}	Rate evaporative heat loss from respiration, W/m^2	$WBGT$	Wet Bulb Globe Temperature, ºC
S_{ck}	Rate of heat storage in the skin node, W/m^2	$SET*$	Standard Effective Temperature, ºC
E_{sk}	Total rate of evaporative heat loss from skin, W/m^2	PET	Physiological Equivalent Temperature, ºC
S_{sk}	Rate of heat storage in skin compartment, W/m^2	$UTCI$	Universal Thermal Climate Index, ºC
H_{sk}	Heat loss from the skin, W/m^2	$MTSV$	Mean Thermal sensation vote
F_{cs}	Energy flux from the body core to the skin surface, W	D	Globe diameter, mm
SW	Sweat rate, kg/s	cl	Clothing
ε_g	Globe emissivity,	β	Efficiency
I	Clothing insulation, clo	A_1	Efficiency
M_{shiv}	Metabolic heat generation by shivering, W	y_0	Intercept
q_m	Metabolism rate, W/m^3	j	A certain one of subjects
Δq_m	Any additional heat gain, W/m^3	n	The number of the subjects

1. Introduction

Outdoor spaces are important for sustainable and livable cities. In the developed world, people are willing to spend more and more time outdoors on their recreational activities enjoying the sunshine and natural wind. Outdoor thermal comfort, as one of the main factors affecting the quality of life and livability of the outdoor space, is attracting a great deal of attention in urban planning and design (Golasi et al., 2018). More comfortable micrometeorology benefits cities from various perspectives, including physical, environmental, economic, and social aspects as to encourage more people in outdoor spaces (Hakim et al., 1998; García-López et al., 2015), leading to energy savings due to a reduction in the use of air conditions (Lai et al., 2014). Due to the serious Urban Heat Island (UHI) effect, the energy consumption for providing air conditioning in urban areas has been dramatically increased (Morakinyo et al., 2018; Costanzo et al., 2016). Based on the statistics, the average Global Energy penalty per unit of surface and degree of UHI intensity was estimated as 0.74 kWh/(m^2/K) while the average total energy load of representative buildings consumed for heating and cooling purposes had increased by 11% between 1970 and 2010 (Santamouris et al., 2014). Additionally, the effects of outdoor thermal environment on human health must also be paid attention (Kovats et al., 2008). Studies as Salata et al. (2017) revealed an increase in the death rate when air temperature reached high values. Therefore, it is important for architects and planners to reconsider these variations of the urban microclimate during building design to create thermally comfortable outdoor built environments.

In recent decades, a number of outdoor thermal comfort investigations were carried out for evaluating the outdoor thermal conditions. Thermal comfort indices, based on the energy balance equations for the human body and heat transfer mechanisms, have been developed to describe different thermal comfort levels. These indices vary on many aspects: from steady state to dynamic process, and from one node, two nodes to multi-nodes and multi-elements (George et al., 2015). It was easy to find that in the one node model only based on the heat balance equation. In this model, the heat is generated in the body and lost from the skin and lungs. It is transferred through clothing where it is lost to the environment. Thus, it can be calculated from the six basic parameters (t_a, T_{mrt}, RH, v_a, I_{clo}, Met). Two node model includes equations for the thermal resistance provided by clothing over the body. It considers the effects of the inner core and an outer shell of the body on the heat balance. Thus, the skin temperature and the core temperature, as the main factors, were considered in the model. Multi-node models were applied in the dynamic human thermal model for the prediction of the thermal comfort responses. In this model, the whole body was divided into many compartments and nodes. The effects of the skin temperature, core temperature and rate of change of skin temperature on the thermal comfort were considered.

One of the most popular thermal indices applied to the outdoor thermal environment without much verification and validation is the Predicted Mean Vote (PMV) (Fanger, 1970), mainly developed for the indoor environment (Gao et al., 2017). The PMV was measured on a seven-point scale to obtain the mean thermal response of human being and introduced in the International Organization for Standardization (ISO) standard (ISO 7730, 2005), which was used to assess the outdoor thermal comfort in some earlier studies (Nikolopoulou et al., 2001; Cheng et al., 2012).

The Physiological Equivalent Temperature (PET), which is based on the Munich Energy-balance Model for Individuals (MEMI) (Höppe et al., 1984). PET is use to define as the air temperature in a typical indoor condition, at which the human body's thermal perceptions is the same as that under a complex outdoor condition (Höppe, 1999). Meanwhile, independent physiological parameters, such as height, age, and activity, were considered in calculating the metabolic rate and sweat rate in the PET index. Matzarakis et al. (1999) provided the PET for different grades of thermal perceptions in Europe, and further Lin and

Matzarakis (2008) reported the different PET neutralities and grade of thermal perception in a subtropical region, highlighting the adaptive comfort effect on human thermal perception across diverse climatic settings. A number of studies were also reported its applications in the evaluation of the complex outdoor environment in different climatic regions (Mayer et al.,2008; Niu et al., 2015; Yang et al., 2017; Amindeldar et al., 2017; Pantavou et al., 2018)

The Wet Bulb Globe Temperature (WBGT) index, as one of the most extensively used thermal indices, was proposed more than 50 years ago (Yaglou and Minard, 1957). It was first used during the 1950s as the index for evaluation of training camps of the United States Army and Marine corps, and then also for evaluation of the outdoor thermal environment (Grahame, 2008).

The Standard Effective Temperature (SET*) simplified the complicated radiation environment into a "standard" environment, based on the Pierce two-node model (Gagge et al., 1986). This index treats the thermoregulation of the human body into two isothermal parts (skin and core). Core temperature, skin temperature, and mean body temperature can be derived by their deviation from the set points. It has also been applied in many field studies on the outdoor thermal environment (Zhu et al., 2007; Tian et al., 2010; Zhao et al, 2016)

The recent chapter in the history of heat-balance modelling of outdoor thermal comfort is the Universal Thermal Climate Index (UTCI) which develops a multi-node heat budget-based approach and is increasingly used by biometeorological researchers (Gerd, 2012). Based on Fiala's multi-node human physiology and thermal regulation model (Fiala, et al., 1999; 2001) and combined with the clothing model of Havenith et al. (Havenith et al., 2012), following the precedents of SET^*, the concept of the equivalent temperature is used in UTCI to characterize outdoor thermal comfort (Gerd et al., 2012). The UTCI index calculates the combined thermal effects of air temperature, wind, direct, diffuse and reflected solar radiation, infrared long-wave radiation, humidity, and then back-calculates an air temperature of a reference uniform environment in which an average person would experience the same physiological strain as in the actual environment.

In recent years, a team of researchers at UC-Berkeley worked to create a mathematical model of the human-body thermoregulatory system for calculating the comfort conditions, based on a number of experimental data. This model was proposed to assess complex thermal environments with considering individual physiological differences, and further developed and clarified the relationships of the local thermal sensation and local thermal comfort of individual body parts, and the whole body's sensation and comfort for uniform, non-uniform and transient environments (Zhang, 2003). However, it has not been used in the assessment and prediction of the outdoor thermal comfort conditions.

Most of the earlier studies on human thermal comfort were conducted indoors (Yang, 2015; Fang et al., 2018), while substantial differences existed between the indoor and outdoor thermal environments. Outdoor environmental parameters typically include variations of the sunshine and shade, changes in air temperature, wind speed, and direction. Furthermore, the metabolic rate and clothing level of human beings are quite different from those indoors. On the other hand, thermal comfort studies have revealed that a purely physiological approach is inadequate to characterize outdoor thermal comfort conditions. Thermal adaptation, which involves behavior adjustments (personal, environmental, technological or cultural), physiological factors (genetic adaptation or acclimatization) and psychological factors (habituation or expectation) (Fang et al., 2018), should also be considered (Marialena and Koen, 2003). At the same time, only a few studies have been conducted on the outdoor thermal comfort for subtropical China. However, few studies compared the differences among thermal comfort indices of adaption.

Based on the above reviews, most of the thermal comfort indices are developed in the temperate zone based on the experimental data collected under a definite climate. The deviations may exist between the results of thermal comfort in southern China and the predictions of these thermal indices. In the present study, thermal comfort indices, including PMV, SET*, WBGT, UTCI, and PET, are compared against field survey data. The objective of this study is to analyze the adaptions of different thermal comfort indices for evaluation of the outdoor thermal environments in built environments of subtropical China.

2. Methodology

2.1Field measurement and survey sites

This investigation was carried out on the campus of Guangzhou University, which is located in southern China at longitudes between 112.8 ^{o}E and 114.2 ^{o}E, and latitudes between 22.3 ^{o}N and 24.1 ^{o}N. Based on the statistical data from 2010 to 2015 (2345 weather report, 2016), air temperature (T_a) was 28.4 °C in July. Relative humidity (*RH*) was around 83% in summer and 70% in winter (Zhang, 2013) (Figure 1). Climatically Guangzhou was a typical subtropical city with uniformly high temperatures, high humidity, and abundant summer rainfall. Guangzhou University is one of the ten universities clustered in the Guangzhou University City, located on Xiaoguwei Island in Panyu District in central-south of Guangzhou.

To study human subjective responses for evaluating the influence of microclimatic conditions, sites were chosen to cover different microclimatic conditions (i.e., shaded, unshaded, meadow, concrete-paved areas, *etc*.) were identified and used. Thus, the areas included squares, teaching building blocks and a large open ground floor, as shown in Figure 2. This investigation included two parts: measurement of outdoor thermal environment parameters and thermal comfort questionnaire collection.

2.2 Environmental measurement and survey method

2.2.1 Overall introduction

A series of field surveys and measurements were carried out from June to July in 2016. The field survey and measurement lasted 9 hours from 8:30 to 18:30 every day. Three thermal parameters, including air temperature (T_a), *RH*, and globe temperature (T_g) were continuously measured and automatically recorded every minute. Air velocity (V_a) was continuously measured and recorded every five minutes. While the microclimate parameters were being collected, the subjects near the measurement sites were randomly invited to answer the questionnaire. At first, an introduction of the questions was given to every subject. After understanding all questions, the subject filled out the questionnaire. 674 questionnaires were collected in this field survey. Four different locations (A-D) in Figure 2 were chosen in the present field survey. The numbers of surveying days at the four different locations were 6, 3, 4, and 6, respectively. The detailed information of the surveying days was shown in Table 1.The numbers of subjects were 58, 85, 82, and 97 respectively. 30 questionnaires were discarded during the screening process because they were not completed. Thus, the total number of valid questionnaires was 644. The detailed information is shown in Table 1.

2.2.2 Measurement parameters and instruments

The main microclimatic parameters collected according to ASHRAE Standard 55-2017 included T_a, *RH*, T_g, and V_a (ASHRAE 55, 2017). These measurements were carried out at the height of 0.6 m with the subjects seated and at the height of 1.1 m with those standing (ISO 7726, 1998) near the subjects. During the measurements, T_a, and *RH* were recorded by a temperature and humidity sensor named ZDR-20. T_g was recorded by a globe thermometer named JTR10. The globe temperature was recorded by the instrument named JTR 10. JTR 10 is the standard black globe thermometer with the diameter of 150 mm, and the emissivity (ε_g) is 0.95. The response time of the standard globe thermometers is near 15 min to reach equilibrium, which meets the requirement of this investigation. However, globe temperature obtained from globe thermometers with 38 mm diameter is affected more by convection instead of radiation, which caused poor accuracy of T_{mrt} (Yang et al., 2017). In addition, the performance of JTR 10 meets the requirement of ISO 7726 (1998). Kanomax Model KA22, a hot wire anemometer was used to record the wind speed. It has two measurement ranges, including low wind speed range from 0 to 4.99

m/s, and high wind speed range from 5 to 50 m/s. The accuracy is ± 2 %. The wind speed of the investigated locations was always lower than 5 m/s. Thus, in this investigation, the wind speed was recorded by Kanomax Model KA22 with the low wind speed range from 0 to 4.99 m/s. All sensors were calibrated before the measurement. The detailed information of micrometeorological measurements, including the ranges and accuracies, were summarized in Table 2.

The operative temperature (T_{op}), with consideration of the effects of air temperature, mean radiation temperature, and air velocity, is calculated by the following equation (ISO 7730, 2005; ASHRAE 55, 2017):

$$T_{op} = AT_a + (1 - A)\, T_{mrt} \tag{1}$$

In Equation (1), A is the mean weight coefficient of the air temperature and mean radiant temperature, which depends only on V_a, shown in Table 3.

T_{mrt}, which considers both short-wave and long-wave radiation and represents the weighted average temperature of an imaginary enclosure that gives the same radiation as the complex urban environment, has a strong influence on human thermal comfort (Yahia and Johansson, 2013). According to ISO 7726 (1998), T_{mrt} was calculated by Equation (2). In Equation (2), ε_g was assumed to be 0.95, and black globe thermometer diameter (D) was 150 mm.

$$T_{mrt} = \{(T_g + 273)^4 + \left[\frac{(1.1 \times 10^8 \times V_a^{0.6})}{(\varepsilon_g \times D^{0.4})}\right] \times (T_g - T_a)\}^{1/4} - 273 \tag{2}$$

In this investigation, the clothing insulation was the total insulation. In the ASHRAE Handbook (2013), it was reported that the most accurate ways to determine clothing insulation by measurements on heated mannequins (Olesen and Nielsen, 1983; McCullough and Jones, 1984) and active subjects (Nishi, 1975). However, clothing insulation was not easily measured for most engineering applications. A list clothing insulation for individual garments commonly worn could be derived from the ASHRAE Handbook, while the total insulation of an ensemble was estimated from the individual values using a summation formula (Olesen and Nielsen, 1983) as:

$$I_{cl} = 0.835 \sum_i I_{clu,i} + 0.161 \tag{3}$$

Where $I_{clu,i}$ was the effective insulation of garment i, and I_{cl}, as before, was the insulation for the entire ensemble. A simpler and nearly accurate summation formula (Olesen, 1985) was:

$$I_{cl} = \sum_i I_{clu,i} \tag{4}$$

In this survey, the total clothing insulation was calculated by Equation (4). The detail of the information of the clothing insulation was collected in the field survey.

2.2.3 Questionnaire

Each subject was requested to answer a questionnaire while the physical measurement taking place in the present study. All subjects were volunteers. The questionnaire consisted of three sections. The first section collected demographic information, including age, gender, height, and weights. The second section recorded respondents' thermal adaptation, including their thermal experience, activity type, and clothing. The third section questioned thermal respondents. The relevant issues were checked, and the questionnaire survey was approved by the University Research Office. The scope of the questionnaire was according to the thermal environment stipulated in ASHRAE Standard 55 (2017) and ISO 7730 (2005). The traditional ASHRAE 7-point scale rated thermal sensation vote as follows: -3: cold, -2: cool, -1: slightly cool, 0: neutrality, 1: slightly warm, 2: warm and 3: hot. Only a few studies used a 9-point thermal sensation scale to evaluate the indoor thermal environment (-4: very cold, -3: cold, -2: cool, -1: slightly cool, 0: neutrality, 1: slightly warm, 2: warm, 3: hot and 4: very hot) (Fang et al, 2018). Zhang et al. also used the 9-point to study the thermal comfort in buildings with split air-conditioners in the hot-humid area (Zhang et al., 2013). In light of the possibility of encountering hot and humid conditions in the survey, the 9-point scale was adopted in the questionnaire for the current study.

In the field survey investigation, while the microclimate parameters were being collected, the subjects near the measurement sites were randomly invited to answer the questionnaire. An introduction of the questions was given to every subject. The subjects were asked to do as the following: please describe your thermal perception at the moment by crossing on the appropriate scale. They finished the questionnaire based on their understanding of all question.

2.3 Thermal comfort assessing indices

In this study, several indices were studied including WBGT, PMV, SET*, PET, and UTCI as listed in Table 4. The differences among these indices are very significant. The PMV as a "static" or "constancy" model was developed in 1970 by Fanger. Based on the heat balance of the human body, it can be calculated using four physical variables (air temperature (T_a), air velocity (V_a), mean radiant temperature (T_{mrt}), and relative humidity (RH), and two personal variables (clothing insulation and activity level). The PMV was developed based on the thermal sensation votes collected from more than 1300 subjects (Fanger, 1970), whereas the WBGT, introduced by Yaglou and Minard (1957), was used in the field by the US army and was the index for training safety orders and adopted by the World Health Organization (Moran et al., 2001). It is calculated using three thermal environmental parameters: T_a, black globe temperature (T_g), and wet bulb temperature (T_w), as shown in Table 4.

The most noticeable difference between the WBGT and other thermal comfort indices is that the WBGT does not incorporate the human energy balance but the environmental conditions only. Both SET* and PET are based on the energy balance of the human body, which the two-node human body model (Gagge, 1986) and the Munich Energy Balance Model for Individual (Höppe, 1984) are adopted for SET* and PET, respectively. The main differences between these two indices are the way for calculating the physiological sweat rate and heat flow from the body surface (Table 4). In SET*, mean skin temperature and skin wittedness equal that of a reference person in the actual environment. The default *RH* of SET* is set as 50%, while PET only assumes the vapor pressure as 1.2 kPa. The default setting of air velocity in SET* is 0.15 m/s, which is slightly higher than the 0.1 m/s of PET. More differences can be listed in the default of clothing insulation and metabolic rate. For SET*, the clothing insulation is 0.6 clo and the metabolic rate is 1.0 met, while the default values of PET are 0.9 clo and 80 W, respectively. Detail information is shown in Table 4.

UTCI, an equivalent ambient temperature, is based on a multi-node model of human thermoregulation (Gerd et al., 2012). Compared with the two-node models, multi-node models simulate the human body in greater detail, predicting both overall and local physiological responses. The original 19-compartment and 342-node model was configured as a symmetric 12-compartment and 187-node model whose left and right extremities and spatial body sectors were merged to lumped entities (Moran et al., 2001). The parameters under analysis included mean skin temperature (T_{sk}), body core temperature (T_c), and all kinds of heat loss. The reference environment is different from that of both SET* and PET. In UTCI model, the default definition is that the reference wind velocity observed 10 m above ground is 0.5 m/s and the mean radiant temperature equals the air temperature, and the humidity is set as 50%. Meanwhile, the metabolic rate is

2.3 met (135 W) higher than that of the other indices (Fiala et al., 2011). All the details of these thermal comfort indices are summarized in Table 4. The effects of different parameters among these thermal indices are listed in Table 5.

In this investigation, the WBGT was calculated by the equation shown in Table 4. Considering the correction of the PMV and SET*, the PMV and SET* were calculated by the Center for the Built Environment (CBE) thermal comfort tool for ASHRAE -55 (http://comfort.cbe.berkeley.edu/). RayMan (Matzarakis et al., 2007), as an available software, was used to calculate the PET. The UTCI equivalent temperature values are available as an operational procedure which was accessible both as software source code and executable program on the project's website (www.utci.org). In order to establish a thermal sensation range for different thermal comfort indices, including WBGT, SET*, PET, T_{mrt}, and UTCI, in the humid subtropical area of China, this study used a method similar to those of previous investigations (Lin and Matzarakis, 2008; Lai et al., 2014; Salata et al., 2016; Wang et al., 2018). The mean thermal sensation votes (MTSV) of respondents in each 0.5 °C thermal indices, including WBGT, SET*, PET, T_{mrt}, and UTCI, were calculated using Equation (5).

$$MTSV = \frac{\sum_n^j TSV}{n} \quad (5)$$

In Equation (5), n was the number of TSV in each 0.5 °C thermal indices. Thus, considering the differences among these different thermal comfort indices, the WBGT, PMV, SET*, PET, and UTCI were compared and analyzed in this investigation.

3. Results

3.1 Meteorological parameters of outdoor thermal environment

Air velocity (V_a) has been proved to be one of the most important thermal environment parameters influencing human thermal comfort. In this study, V_a was recorded, and its variation was shown in Figure 3. Most data fell in the range between 0 and 1 m/s with the maximum of about 2.1 m/s. This indicates that the investigated sites were at a low wind condition most of the time. The possible factor is that some sites are surrounded with buildings, which the shelter effect may reduce the local wind speed at these sites.

In a place of high temperature and humidity, the effect of *RH* on thermal comfort is very significant (Alahmer, 2011). In Figure 4, it was noted that the *RH* was high. Most of the values exceeded 60%. Therefore, the *RH* required to be considered. In Figure 4, the air temperature fell in the range of 27 to

39 °C. The maximum reached 39 °C, which reflected that sometimes the outdoor thermal environment could be severe. For the comfort and especially health, it is recommended avoiding high levels of physical activities, such as outdoor exercise and mechanical work in such environments (ASHRAE handbook, 2017). In addition, the *RH* decreased with the rising of the air temperature. Therefore, in the outdoor thermal environment, the combined effects of air temperature and relative humidity on thermal comfort need to be considered. Figure 5 shows the instantaneous monitoring values of air temperature and RH at Location D on 30th July 2016. When T_a reaches the peak value, the *RH* locates the minimum value. Specifically, the T_a is higher than 36 ºC between 10:30 and 12:00 with the peak value of 37.8 ºC. The *RH* is exceeded 60%, which also indicates that the climate characteristic of Guangzhou is a typical subtropical climate region in summer.

3.2 Differences in terms of Clothing insulation

The effect of clothing insulation on thermal sensation is very significant. As an efficient way to adjust thermal comfort, clothing insulation always varies with T_a (Fanger, 1970). In this investigation, the garments of each subject were collected in the questionnaire. The total clothing insulation was further calculated by the Equation (4). Some previous investigation used this method to determine the clothing insulation (Hadanpour et al., 2018; Li et al., 2016; Lai et al., 2014; Pantavou et al., 2013; ASHRAE Handbook, 2013). From Figure 6, clothing insulation fell in the range between 0.3 and 0.6 clo with the maximum close to 0.8 clo and the minimum close to 0.25 clo. The average clothing insulation was 0.425 clo, which was lower than the standard 0.57 clo for summer as given in ASHRAE 55 (2017). The primary reason was that all the subjects were students at Guangzhou University. The students were dressed casually, which were significantly different from the occupants in offices. Zhang et al. (2013) reported that in hot summer subjects wore light clothing with average insulation of 0.43 clo in the office.

3.3 Thermal sensation vote distribution

Figure 7 shows the percentage of the thermal sensation votes. Most subjects chose the warm sensation (+3), which is exceeded 40% in all the locations. Approximately 10% of the subjects felt hot (+4). One of the possible factors is that the instantaneous air temperature of the outdoor environment could be higher than 36 °C during the survey, as shown in Figure 4. The total of the percentages of +2, +3 and +4 was near 70%. Only few people felt neutral. Thus, in the subtropical climate region, it is necessary to improve the outdoor thermal environment for human outdoor activities.

3.4 The variations of Thermal indices

Based on the survey data, thermal comfort indices, including WBGT, SET*, PET, T_{mrt}, T_{op} and UTCI were calculated. Figure 8 shows the differences among thermal comfort indices with T_{op}. All the thermal comfort indices increased with the rising of T_{op}. However, the slopes of different thermal comfort indices varied significantly. At the same T_{op}, different thermal comfort indices actually predicted different thermal comfort levels. In Figure 8, the range of T_{op} spreads widely, from 27 to 50 °C. Most of T_{op} points fell in the range between 27 and 38 °C. Based on the measurement data, it was found that the average outdoor temperature in summer was 31.8°C, which was quite high. In order to correlate the operative temperature and different thermal comfort indices, simple regression method was used.

Figure 9 shows the fitted linear relationship between the different thermal comfort indices and T_{op}. Based on the previous analysis, the method of linear regression was applied to compare the indices. Shown in Figure 9, all the thermal comfort indices showed strong linear relationships with T_{op}. Every R^2 was much higher than 0.8, except that for the SET*. In addition, the slopes of the linear lines vary, as shown in Figure 8. The slope of T_{mrt} was 1.847 higher than that of other indices. In an outdoor thermal environment, when the solar radiation was strong, although T_a was low, the T_{mrt} was still high, especially in the outdoor spaces without shading. The slope of WBGT was only 0.327 lower than that of other indices. In terms of the formula of WBGT, the weighting of T_w was 0.7, while the weightings of T_a and T_g were 0.2 and 0.1, respectively. However, comparing among the values of T_w, T_a, and T_g, the value of T_w was always lower than those of T_a and T_g (Ma et al., 2015), which led the values of WBGT to be lower than those of the other thermal comfort indices. The T_{mrt} had the steepest slope of 1.847. It was decided by five factors (T_g, T_a, V_a, ε_g, and D). In an outdoor space, the stronger the solar radiation was, the higher the T_{mrt} was. It was found that the slopes of the SET* and UTCI were almost the same. The regression lines of the SET* and UTCI were paralleled. The slope of PET was between those of the T_{mrt} and UTCI. When the

T_{op} was lower than 34 °C, the differences among the SET*, PET, and UTCI were insignificant. However, when T_{op} rose, their differences increased. Therefore, the discrepancies among the thermal comfort indices depended on T_{op}.

3.5 Outdoor thermal comfort indices versus thermal sensation

Figure 10 shows the relationships of the mean thermal sensation vote (MTSV) with different thermal comfort indices. When the thermal comfort indices, including SET*, PET, T_{mrt}, and UTCI, were lower than 38 °C, the MTSV basically kept the same pace with the thermal comfort indices. However, when the thermal comfort indices were higher than 38 °C, The MTSV concentrated in the range between 3 and 3.5. The reason could be that the top scale limit was "very hot" (+4). Most of the subjects voted either "very hot" (+4) or "hot" (+3). Therefore, the relationships between the MTSV and thermal comfort indices were unclear in the hot outdoor thermal environment. In most of the previous investigations (Mahmoud, 2011; Elnabawi et al., 2016; Liu et al., 2016; Salata et al., 2016; Wang et al., 2017; Lin et al., 2011; Hwang and Lin, 2007; Xi et al., 2012; Watanabe et al., 2014), the 7-point scale of ASHRAE 55-2017 was applied to evaluation of the outdoor thermal environment. It was reported that there were strong linear relationships between the MTSV and PET (Yahia and Johansson, 2013; Lin, 2009; Mahmoud, 2011; Mahmoud, 2011; Cohena et al., 2013; Lai et al., 2014; Elnabawi et al., 2016; Liu et al., 2016; Salata et al., 2016; Wang et al., 2017), SET* (Lin et al., 2011; Hwang and Lin, 2007; Xi et al., 2012), and UTCI (Lai et al., 2014; Watanabe et al., 2014; Kriuger et al., 2015; Huang et al., 2016). However, the linear relationships could not cover the range of high outdoor temperatures. Thus, the scale used to evaluate outdoor thermal environment should be extended, at least at the high-temperature end. In addition, the slope of the MTSV vs WBGT was the steepest. When the WBGT was at about 32 °C, the MTSV exceeded 3.0. The linear portion of The MTSV vs WBGT was much shorter than those vs the other thermal comfort indices. The regression models of the different thermal comfort indices were shown in Table 6. From Table 6, most of the R^2 of the regression models were higher than 0.7. The maximum value of R^2 was 0.745. All the p-value of the regression models were lower than 0.01. Thus, the regression models were significant. *PMV and thermal sensation*

The PMV as one of the most popular thermal comfort indices was originally developed to predict indoor thermal sensation. Sometimes, it was used to evaluate outdoor thermal comfort (Hadanpour et al., 2018). In Figure 11, the relationships of the PMV and MTSV with the T_{op} are shown. There was a strong linear relationship between the PMV and T_{op}, which had been found in many previous investigations (ASHRAE

55, 2017). As shown in Table 4, when the PMV was applied to the indoor thermal environments, it needed to meet certain conditions: The PMV range was between -2 and +2, and T_a should not exceed 30 °C. In Figure 11, it was noted that when T_{op} was lower than 34 °C, the PMV predicted quite well. However, the discrepancy between the PMV and MTSV increased with the rising of T_{op}, which was significant at high T_a in outdoor thermal environments. In addition, the relationship between the MTSV and T_{op} was unclear. When T_{op} was lower than 34 °C, the MTSV also increased with the rising of T_{op}. However, when T_{op} exceeded 34 °C, the PMV overestimated the thermal sensation. The primary reason was that the PMV would increase with the rise of the T_{op} without considering the effects of human thermal adaptation in hot thermal environment. However, in actual outdoor thermal environment, Humphreys (1994) pointed out that through various strategies, including physiological adaptation, psychological adaptation, and behavioural adaptation, people sued to adjust their thermal station. People were not inert receivers of the environment, but interact with them to optimize their conditions. From Figure11The MTSV fell at around 3.0 under higher T_{op}. Most subjects felt hot or very hot when the operative exceeded 34 °C. Therefore, if the PMV was used to evaluate the outdoor thermal environment exceeding 34 ^{o}C, it probably needs to be modified.

4. Discussion

4.1Thermal sensation vote scale

In the survey, the subjective thermal sensation votes were very important. An appropriate thermal sensation scale should be adopted. In the previous investigations (as shown in Table 7), the most commonly applied scale was the ASHRAE 7-point scale subdivided as follows: -3, cold; -2, cool; -1, slightly cool; 0, neutral; 1, slightly warm; 2, warm and 3, hot (ASHRAE 55, 2017). In both ASHRAE 55 (2017) and ISO 7730 (2005), the 7-point scale was adopted together with the PMV index to evaluate indoor thermal environments. However, the indoor air temperature was confined within a certain range. In ISO 7730 (2005), the range of indoor T_a was between 10 and 30 °C, and that of T_{mrt} was between 10 to 40 °C. However, the comfort conditions of the ASHRAE Standard stem from the Nevins et al.'s (1966) and Robles and Nevins' (1971) climate chamber trials. They concluded that for all subjects, air temperatures for those conditions rated as comfortable covered the range of 16.7 °C to 36.6 °C (Parsons, 2002). Therefore, the thermal sensation 7-point scale was applied for evaluation of the thermal environment where T_a was higher or close to the limit of the indoor thermal environment. In addition, most of the body surface sweated with hot thermal sensation. Song et al.'s experimental investigation showed similar results (Song et al., 2016). The trials were performed in a climate chamber with a T_a of 34.0 °C, *RH* of 65% and V_a of 0.15 m/s. At the end of the trials, ratings of the maximal overall thermal sensation reached 3.1, and the maximal wetness sensation reached 2.4, close to very wet. Occupants could use a personal cooling system to maintain thermal comfort in a warm indoor environment without HVAC (e.g., T_a < 32.0 °C) (Scheatzle et al., 1989). However, it seemed difficult to keep the human body in thermal comfort zone using personal cooling systems in a hot indoor space where T_a was higher than 34.0 °C (Atthajariyakul and Lertsatittanakorn, 2008). Therefore, the 7-point scale was good enough to evaluate an indoor thermal environment. Meanwhile, the 7-point scaled was also applied to evaluate outdoor thermal environments (Watanabe et al., 2014).

In Table 7, all the surveys were carried out in hot summer. By examining the ranges of the T_a, for most of the investigations into outdoor thermal environments in subtropical cities, T_a exceeded 35 °C (Spagnolo and de Dear, 2003; Lin, 2009; Yahia and Johansson, 2013; Kruger et al., 2015; Huang et al., 2016; Liu et al., 2016; Kruger et al., 2017; Golasi et al., 2018; Hadianpour et al., 2018). On the other hand, T_{mrt} was also higher than 40 °C due to strong solar radiation (Spagnolo and de Dear, 2003; Lin, 2009; Kántor et al., 2012; Yahia and Johansson, 2013; Watanabe et al., 2014; Kruger et al., 2015; Huang et al., 2016; Liu et al., 2016; Zhao et al., 2016; Ndetto and Matzarakis, 2017; Kruger et al., 2017; Wang et al., 2017; Golasi et al., 2018; Hadianpour et al., 2018). Based on these, the subjects probably felt extremely or very hot so that the 7-point scale was insufficient to reflect their thermal sensation. Therefore, in some investigations, considering the larger variation in outdoor climate, a 9-point scale, which was an extension of the ASHRAE 7-point scale, was used to evaluate the outdoor thermal sensation. Table 7 shows four studies using the 9-point vote scale to rate the thermal sensation in an outdoor thermal environment in cool desert climate, subtropical climate, Mediterranean climate and transitional climate. However, at present, the 5-point scale is still being used (Nikolopoulou and Lykoudis, 2006). As shown in Figure 10, the average thermal sensation was higher than 3.0 when the operative temperature exceeded 34 °C. It was more rational to adopt the 9-point thermal sensation vote scale for evaluation of the outdoor thermal environment in this survey investigation.

4.2 Differences in current thermal indices

T_{op}, described in ASHRAE 55 (2017), was the average of T_a and T_{mrt} factored by, respectively, the convective heat transfer coefficient and linearized radiant heat transfer coefficient for the occupant, as shown in Equation (1). It is most commonly used to evaluate the indoor thermal environment in the ASHRAE Standard, ISO-7730 (2005) and GB/T50785 (2012). He et al. (2016) reported that there was a strong linear relationship between T_{op} and thermal sensation in the range of 22 to 30 °C. Wang et al. carried out a survey of the thermal comfort in urban green spaces in a Dutch university campus (Wang et al., 2017). The results also demonstrated that The MTSV can be predicted with T_{op} using a linear model. Shown in Figure 11, the different thermal comfort indices have strong linear relationships with T_{op}, most of the average R^2 are close to 0.85, which indicate that T_{op} could be applied in the evaluation of outdoor thermal environments. In order to compare among the heat stress categories of different thermal comfort indices, the T_{op} of heat stress categories was calculated by the linear regression formulae shown in Figure 9.

Based on a large number of surveys, the T_{op} ranges of the heat stress categories for the different thermal indices were shown in Table 8. It is noted that for different indices, different operative temperatures correspond to the same stress range. This revealed that discrepancies existed. Therefore, if the thermal indices were applied to evaluate the outdoor thermal environments in Guangzhou, the thermal indices need to be modified. However, the T_{op} range of Lin et al.'s investigation is quite close to the present study. Shown in Table 8, T_{op} range of being "hot" in Taiwan is 35.2 to 38.6 ^{o}C (Lin et al., 2008). The range between 31.84 and 35.2 ^{o}C was regarded as "warm" and the range between 28.5 and 31.8 ^{o}C is "slightly warm". For this investigation, it was shown in Figure 10, that when the operative temperature exceeded 34 ^{o}C, the thermal sensation should be "hot". The range between 30 and 34.0 ^{o}C was "warm" and the range between 28 and 30 ^{o}C was "slightly warm". This result agreed well with that found in Taiwan. One of the reasons probably was that the climatic conditions of these two places are similar. Another possible reason was that in Taichung city (Lin et al., 2008), the psychological adaptation, social, economic and cultural factors were similar to those in Guangzhou. Nevertheless, the difference between those found in Guangzhou and the original heat stress categories were significant. Similar deviations were also reported in some earlier studies (Cheng et al., 2012; Lai et al., 2014; Liu et al., 2016). The other thermal comfort indices, including the UTCI, SET*, and WBGT, were also applied in the evaluation of outdoor thermal environment. The ranges of T_{op} were also shown in Table 8. By comparison of T_{op} ranges in these studies, the deviations of T_{op} were also significant (Marianna et al. 2014). Based on the field survey data acquired in Tianjin (Lai et al., 2014), the UTCI range of different stress categories were compared with that of the UTCI-Fiala multi-node model (Brode et al., 2012). The deviation was significant. Pantavou et al. (2013) also reported that the UTCI range of different stress categories was different from the original UTCI stress categories. For example, the range of no thermal stress was from 17.4 ^{o}C to 24.5 ^{o}C, shorter than that of the original UTCI from 9 ^{o}C to 26 ^{o}C (Jendritzky et al., 2012). Therefore, modifications of indices may be required in future studies. In addition, the current regression results only describe the variation of the

MTSV in the warm thermal environment in summer, without other seasons' data in the whole year. Therefore, the prediction models between the MTSV and different thermal comfort indices need to be considered the effects of the different seasons in the whole year. In the future work, the effects of the other different seasons, including spring, autumn, and winter, will be considered.

4.3Different performances for thermal Comfort indices

The restriction to the reference conditions appeared to be justified, because the thermal comfort indices for the actual condition, which were identified by T_a, T_{mrt}, water vapor pressure (P_a), and V_a, were defined in terms of the equivalent temperature as T_a of the reference conditions yielding the same physiological of responses of the thermal comfort indices as for the actual conditions. Thus, in order to conveniently evaluate the thermal environment, the assessment scale categorizing thermal stress needed to be determined. In the previous studies, the Bin method was used for the calculation of the mean thermal sensation for every 1 K interval (Lin et al., 2008; de Dear and Fountain, 1994), which can be applied in thermal sensation evaluation as follows: (a) Binning a particular building's observations into half-degree (K) increments, and working with the bin's mean response, as The MTSV, instead of individual subjects' thermal votes. (b) Fitting a linear regression model between thermal sensations and whatever the x-axis thermal index may be PET, SET*, or UTCI. The regression models weighted each point according to the number of observations within each x-axis bin. In the present study, the first step is binning an observation into 1 degreed (K) increments. The second step is calculated the bin's mean response, as the mean thermal sensation. The relationships between the MTSV and thermal indices are obtained. In most of the previous questionnaire surveys (Table 7), the subjects were asked to report their thermal sensation according to the ASHRAE 7-point scale. Based on the survey data and Bin method, the linear regression models of the MTSV and different thermal indices were obtained (Table 9). However, some were close to unity, and some others were lower than 0.5. The minimal R^2 was only 0.305 (Lin et al., 2011), which indicated a weak correlation between the subject thermal sensations and thermal comfort indices. Elnabawi et al. conducted an investigation into thermal comfort in an urban park in Cairo, Egypt (Elnabawi et al., 2016). The results showed that the thermal responses concentrated around the scale of hot (+3) at the PET largely exceeding 40 °C, in the place of seating and close to a fountain, which was similar to the present study as shown in Figure 10. The primary reason is that when the temperature was very high, the actual thermal responses of the subjects exceed the heat stress limits. The subjects probably had no choice but to choose the highest level of heat stress. The results by Brode et al. (2012) showed that the relationship of dynamic thermal sensation and UTCI was not a strong linear relationship in the range between -50 and 50 °C UTCI.

The situations were similar for other thermal indices. Therefore, when outdoor temperature exceeded 40 °C, the relationships between the thermal sensation and predicted temperatures of different thermal indices were not clearly revealed. In this investigation, the 9-points scale, extending the 7-point scale, was adopted to evaluate the outdoor thermal environment. Based on the survey data, in the extremely hot condition, the MTSV concentrated in the range between +3 and +4, which indicated that the extremely hot scale may instruct the subjects that the edge of the scale indicated the hottest they have ever experienced. Thus, the choice of the thermal sensation scale needs to consider the actual characteristic climate. In tropical zone, some insufferable hot condition may appear. The scale point needs to be modified. The magnitude estimation has no upper limit. Meanwhile, based on the regression models, the heat stress categories of different thermal indices needed to be modified, possibly for different climate zones.

5. Conclusions

The outdoor thermal comfort index is an essential tool in considering the design of urban inhabitability and sustainable development. In this study, a comprehensive comparison of frequently used outdoor thermal indices, including PMV, WBGT, PET, SET* and UTCI was presented. Also, a subjective approach-based TSV questionnaire survey with field measurements was carried out to validate the performances of the aforementioned outdoor thermal indices. The findings are as follows:

(1) Based on the comparison of the different thermal comfort indices versus T_{op}, strong linear relationships are demonstrated between T_{op} and WBGT, PET, SET*, UTCI, T_{mrt} and PMV, where the correlation coefficients are close to 0.9.

(2) The relationships between the different thermal comfort indices and MTSV in the hot outdoor environment are analyzed. The non-linear regression equations may be more appropriate for predicting thermal sensation during the extremely hot environment.

(3) Based on the analysis of several thermal comfort indices by comparing the operative temperature heat stress categories, the difference between the original heat stress and that of the present study is significant. This indicates that the heat stress categories are required to be modified for evaluation of outdoor thermal environments in Guangzhou.

As aforementioned, the impacts of various parameters on outdoor thermal comfort are more complicated than those for indoors. The present study is a validation research so some realistic boundary conditions are reasonably simplified. The next step of study is to consider complex variation parameters on thermal comfort in outdoor environments during different seasons, such as clothing insulation and metabolic rates. In addition, the physiological parameters of the subjects are required to be recorded in outdoor environments under hot and humid climatic conditions and analyzed in order to modify some of the popular thermal comfort indices.

Acknowledgments

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. C5002-14G). The authors would like to express our gratitude to Dr. Tsz-cheung Lee of Hong Kong Observatory for his advice and all the students who participated in the surveys. Special thanks are also given to the anonymous reviewers for their valuable comments on the manuscript.

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Figures

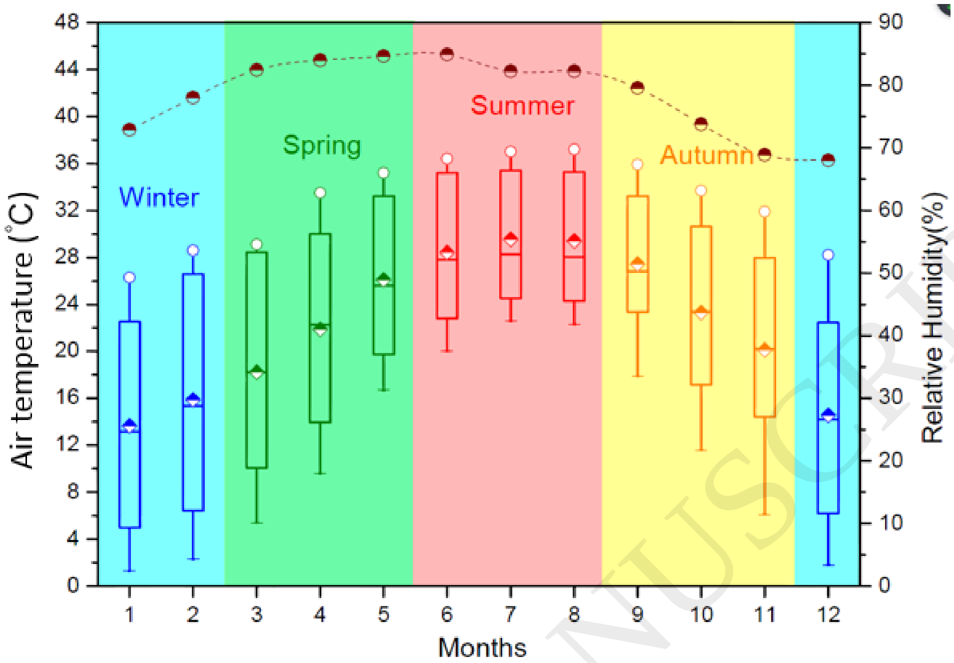

Fig. 1. Monthly variation of air temperature and relative humidity

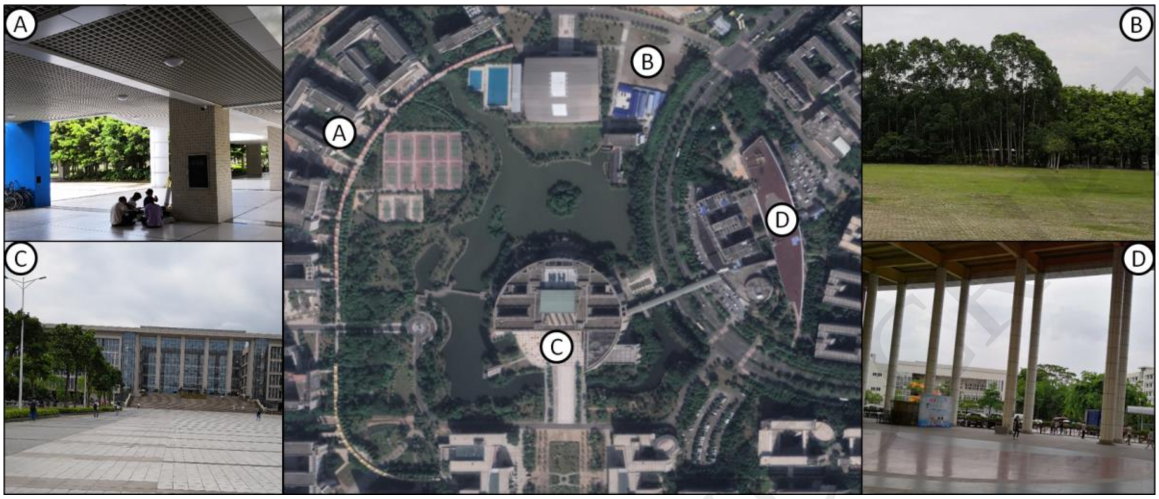

Fig. 2. Sites of survey, (A) open area underneath the elevated building, (B) open area (lawn), (C) square, (D) open area (concrete-paved)

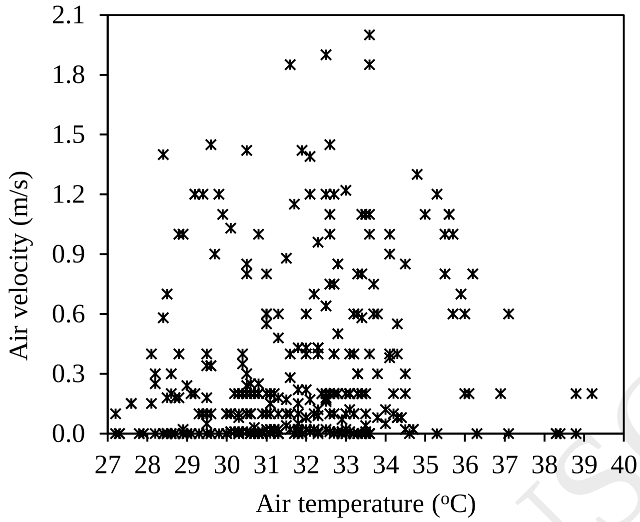

Fig. 3. Air temperature against air velocity

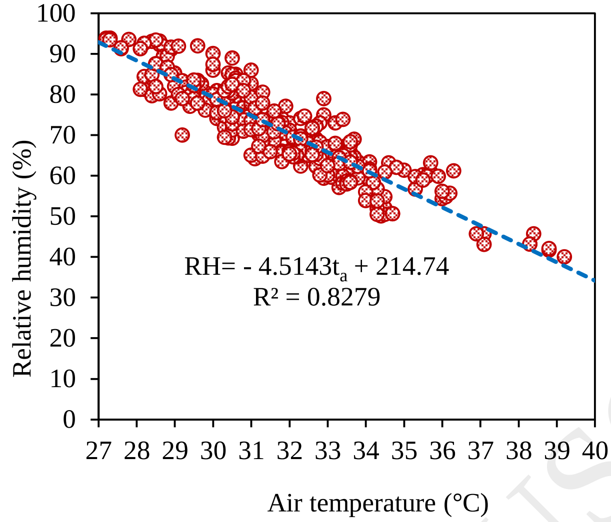

Fig. 4. Air temperature against relative humidity

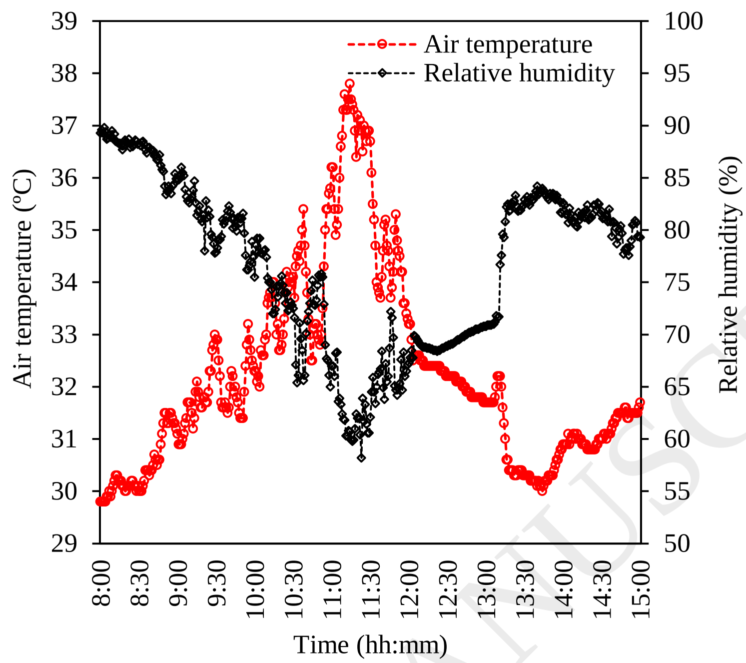

Fig.5. Monitored values of air temperature and RH at Location C on 30th July 2016

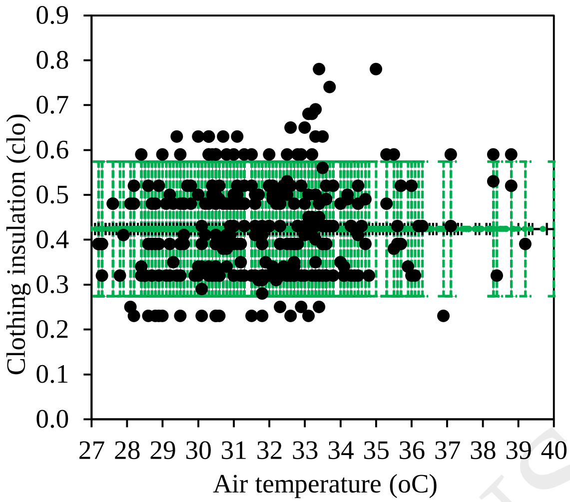

Fig. 6. Clothing insulation against air temperature

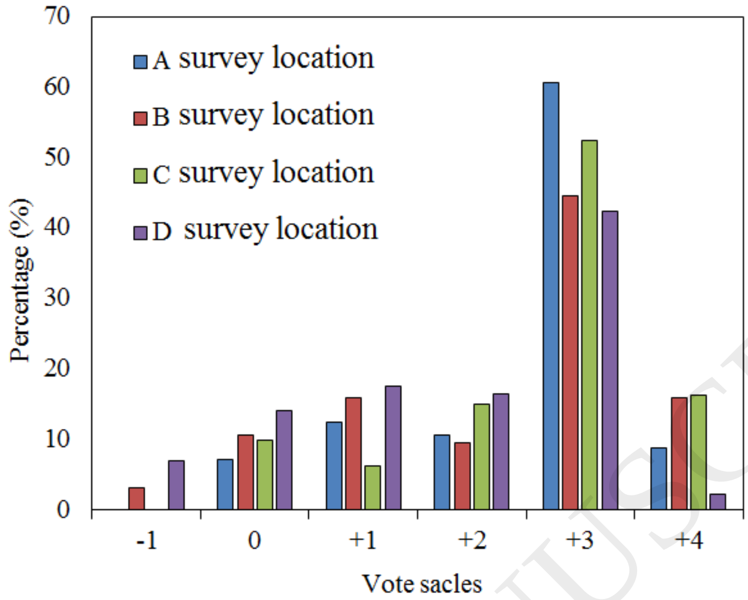

Fig. 7. Percentage of scale voted at different locations

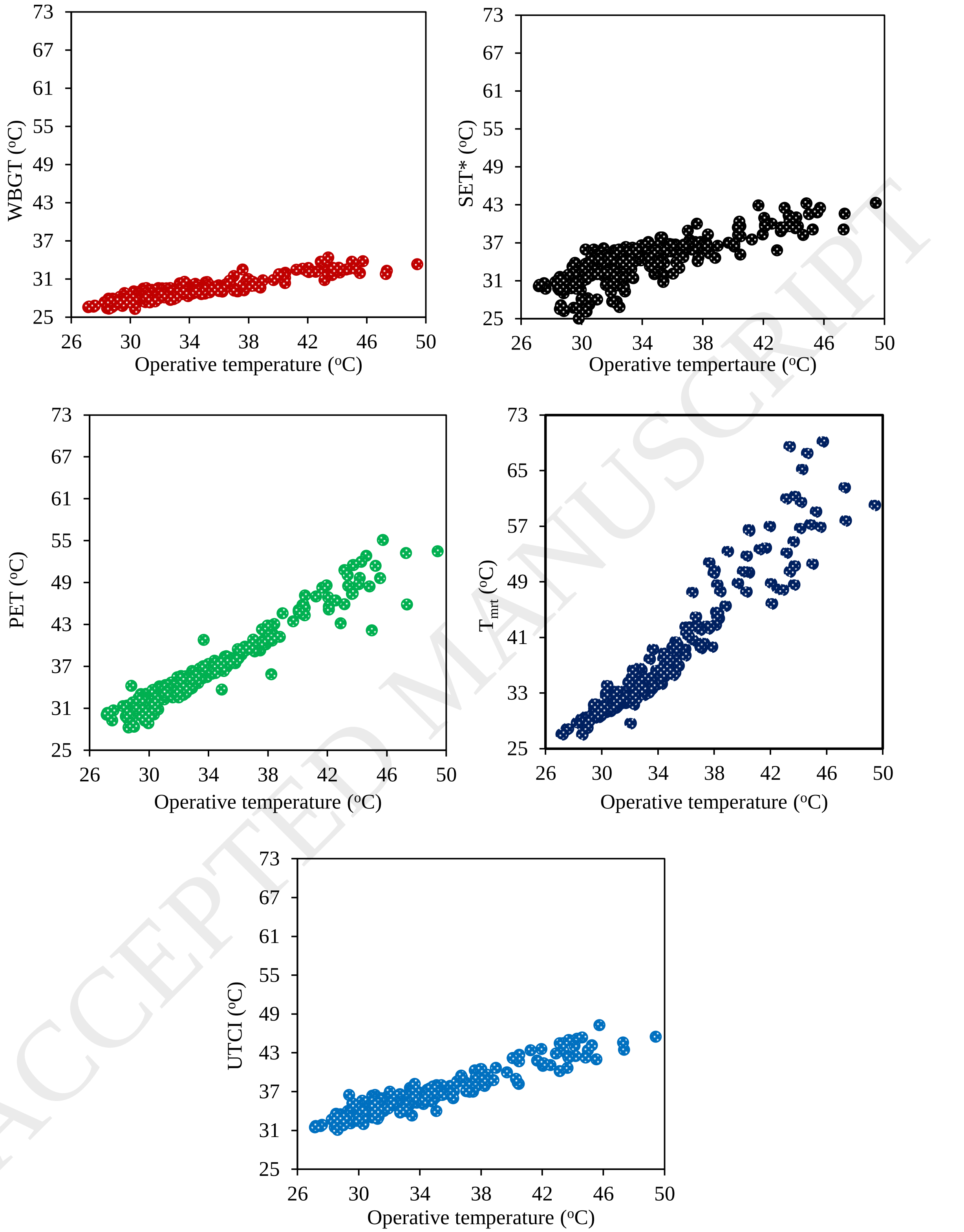

Fig. 8. Different thermal comfort indices vs. operative temperature: (1) WBGT, (2) SET*, (3) PET, (4) T_{mrt} and (5) UTCI

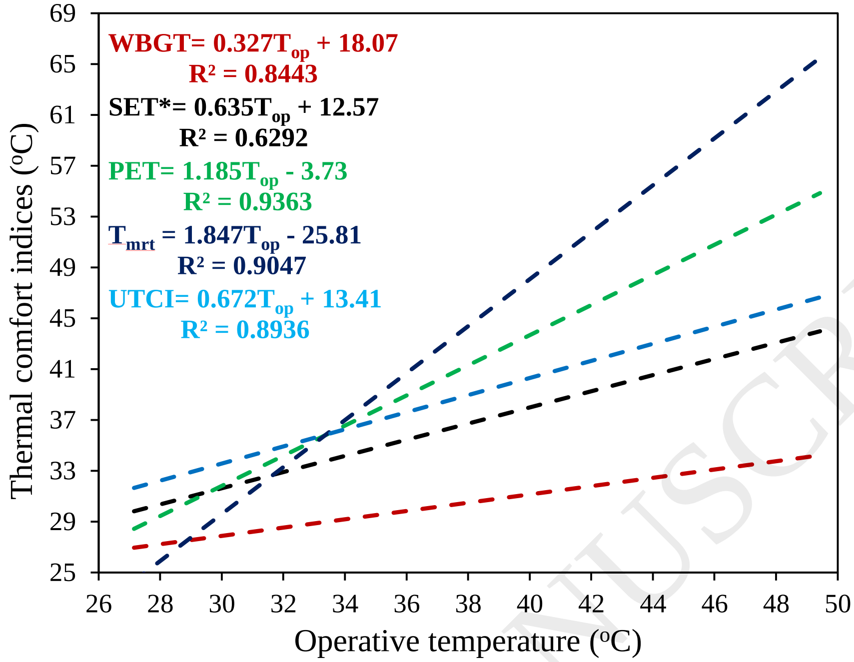

Fig. 9. Relationships between different thermal indices and operative temperature

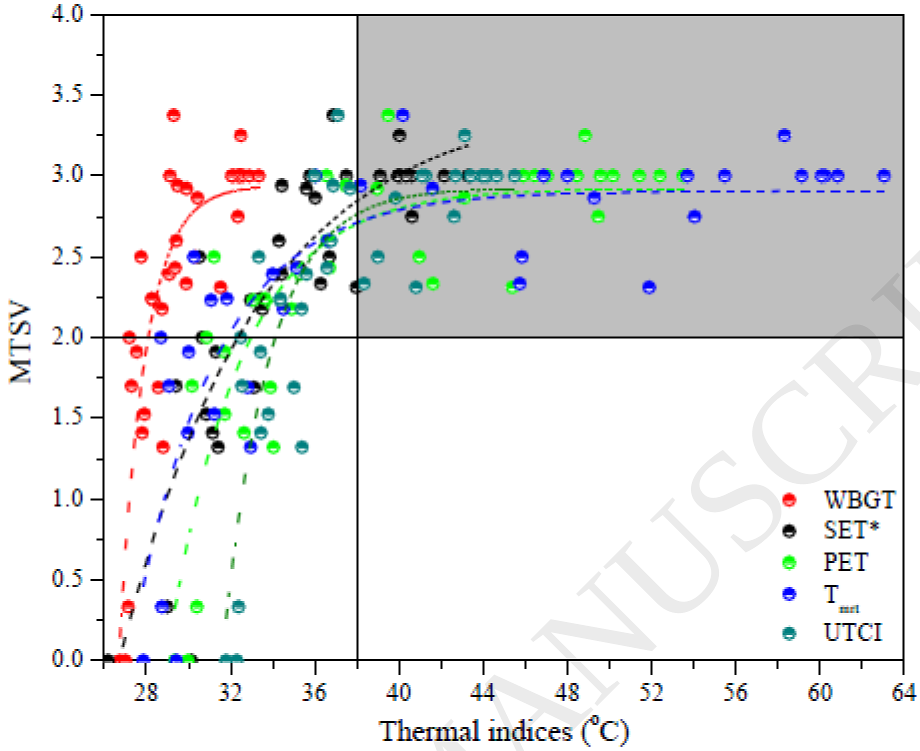

Fig. 10. MTSV versus different thermal comfort indices

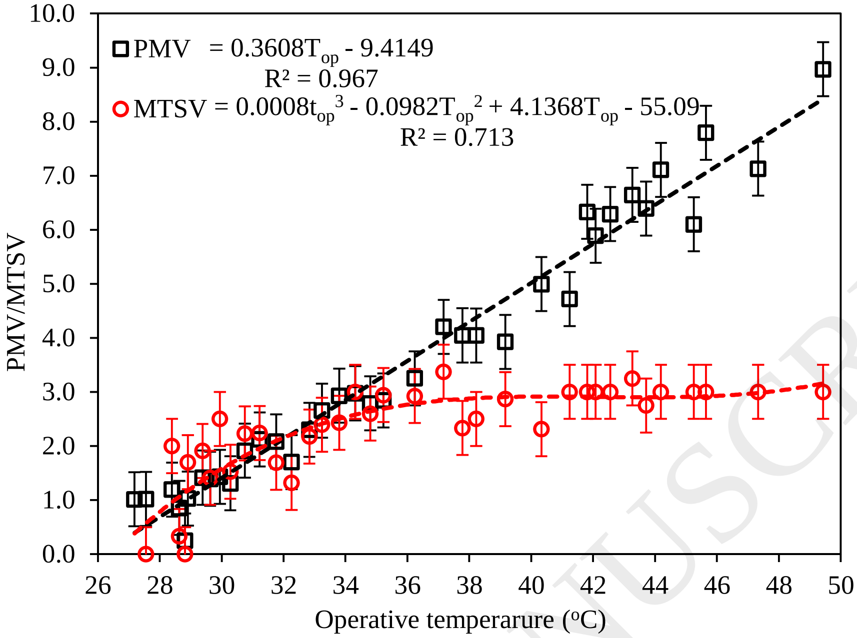

Fig. 11. Difference between PMV and MTSV respectively versus operative temperature

Tables

Table 1 Detail information of field data

Location	Date	Number of subjects		Age
A	13,15,20,22,23,24 July,2016	Male	54	21.8(1.1)*
		Female	62	20.7(1.6)
		Male + Female	116	21.2(1.4)
B	15,20,22,29 July, 2016	Male	132	22.0(3.1)
		Female	45	21.2(1.7)
		Male + Female	177	21.9(2.9)
C	21,22,28 July,2016	Male	103	21.8(1.5)
		Female	52	21.5(2.3)
		Male + Female	155	21.7(1.7)
D	12,13,28,29,30 July; 1 June,2016	Male	108	21.3(1.1)
		Female	91	21.0(1.0)
		Male + Female	199	21.2(1.0)
Total Number			644	

* Standard Deviation

Table 2 Instruments used in micrometeorological measurements

Sensor	Meteorological parameters	Measuring range	Accuracy
ZDR-20	T_a	-40 - 100 °C	± 0.5 °C;
	RH	0 - 100 %	± 3 %
JTR10	T_g	5 - 120 °C	± 0.2 °C
Kanomax Model KA22	V_a	0 – 4.99 m/s, 5 - 50 m/s	± 2 %

Table 3 Coefficient A in different air velocity ranges.

V_a (m/s)	< 0.2	0.2 to 0.6	> 0.6
A	0.5	0.6	0.7

Table 4 Detail information of different thermal comfort indices

Year	index	Author(s)	Model (model type)	Description	Addition
1957	WBGT	Yaglou and Minard (1957)	Statistics	$WBGT=0.7T_w+0.1T_a+0.2T_g$ (outdoor air) $WBGT=0.7T_w+0.3T_g$ (indoor air)	
1970	PMV	Fanger (1970)	Steady-State Energy Balance (One Node model)	$H-E_D-E_{sw}-E_{Re}-L= R+C$ $PMV=(0.028+0.3033e^{-0.036M}).\{(M-W)-3.05[5.733-0.000699(M-W)-Pa]-0.42[(M-W)-58.15]-0.0173M(5.867-Pa)-0,0014M(34-Ta)-3.96.10-8f_{cl}[(T_{cl}+273)4-(T_{mrt}+273)4]-f_{cl}.h_c(T_{cl}-T_a)\}$ $T_{cl}=35.7-0.28(M-W)-0.155I_{cl}[3.9610-3f_{cl}[(T_{cl}+273)4-(T_{mrt}+273)4]-f_{cl}.h_c(T_{cl}-T_a)]$ $hc=2.38(T_{cl}-T_a)^{0.25}$ for $2.38(T_{cl}-T_a)0.25 \geqslant 12.1(v_a)^{0.5}$ or $h_c=12.1v_a^{0.5}$ for $2.38(T_{cl}-T_a)0.25 \leqslant 12.1 (v_a)^{0.5}$ $f_{cl}=1.0+0.2I_{cl}$ for $I_{cl}<0.5$ clo or $f_{cl}=1.05+0.1I_{cl}$ for $I_{cl}>0.5$ clo	PMV : -2 - +2; Metabolic rate : 46 - 232 W/m^2 (0.8 - 4 met); Clothing thermal resistance:0 - 0.310 m^2°C/W(0 - 2clo); Ambient air temperature:10 - 30 °C; Mean radiant temperature :10 - 40 °C; Air velocity: 0 - 1 m/s.
1973	SET*	Gagge et al. (1986)	Two Node model	$S=M-E-R-C-W$ $S_{cr}=M-W-(C_{res}+E_{res})-(t_{cr}-t_{sk})\times(5.28+1.163\times skbf)$ $S_{sk}=(t_{cr}-t_{sk})\times(5.28+1.163\times skbf)-(C+R+E_{sk})$ $S_{cr}=(1-\alpha)mc_{p,b}(dt_{cr}/d\theta)/AD$ $S_{sk}= \alpha mc_{p,b}(dt_{sk}/d\theta)/AD$ $H_{sk}=h_s(t_{sk}-SET^*)+\omega h_s,e(p_{s,sk}-0.5p_{SET^*})$	Ambient air temperature equals mean radiation temperature; relative humidity: 50 %; Air velocity: 0.15m/s; Clothing thermal resistance :0.6 clo; Metabolic rate: 1.0 met; The same mean skin temperature and shin wittedness as the person in the actual complex environment.
1999	PET	Hoppe et al. (1984; 1999)	Munich energy balance model of individuals(Two –Node model)	$H-C-R_N-E_D-E_{SW}-E_{Re}=S=C_k.GE.(dT_M/dt)$ $F_{cs}=v_b.\rho_b.c_b.A_{Du}.(T_c-T_{sk})$ $F_{sc}=(A_{Be}/I_{cl})(T_{sk}-T_{cl})$ $SW=8.47\times10-5.((0.1Tsk+0.9Tc)-36.6)A_{Du}$ $E_{SW}=SW\times r$ $M_{shiv}=19.4\times(34.0–T_{sk})\times(37.0–Tc) A_{Du}$ $E_{SW}=h_e(VP_a-SVP_{Tsk}).A_{Du}$	Ambient air temperature equals mean radiation temperature ; Air temperature : 20 °C Air velocity: 0.1 m/s; The vapor pressure of the ambient air :12hPa Relative humidity: 50%; Metabolism rate: 80W; Clothing thermal resistance: 0.9 clo;

2001	UTCI	Jendritzky et al. (Gerd et al., 2012; Fiala et al., 2011)	UTCI-Fiala model (Multi-node)	$UTCI=f(Ta; T_{mrt}; v_a; p_a)=Ta+Offset(T_a; T_{mrt}; v_a; p_a)$	Ambient air temperature equals mean radiation temperature ; Metabolic rate: 135W/m^2 ; Walking speed of 1.1 m/s. Air velocity: 0.5 m/s (10 m above ground). Relative humidity: 50% ;

Table 5 The parameters' effect on different thermal comfort indices (Fanger, 1970; Höppe, 1984; 1999; Gagge et al., 1986; Gerd et al., 2012; Yaglou and Minard, 1957; Fiala et al., 2011; Psikuta et al., 2012)

Thermal comfort indices	T_a	RH/T_w	V_a	T_{mrt}/T_g	*I*	*Met*	*Skin witting*	T_{sk}	T_c
WBGT	√	√		√					
PMV (One Node model)	√	√	√	√	√	√			
SET* (Two Node model)	√	√	√	√	√		√	√	√
PET (Two Node model)	√	√	√	√	√	√		√	√
UTCI (Multi-Node model)	√	√	√	√	√	√		√	√

Table 6 Detail information of the regression models

Equation:	MTSV= $A_1 \bullet Exp(-x/\beta) + y_0$				
x	A_1	β	y_0	R^2	*p-value*
WBGT	2.94	-8.02•Exp(9)	1.23	0.737	<0.01
SET*	3.46	-1.4•Exp(5)	6.53	0.745	<0.01
PET	2.93	-1.41•Exp(9)	3.50	0.726	<0.01
T_{mrt}	2.9	-2.31•Exp(7)	4.01	0.684	<0.01
UTCI	2.93	-4.73•Exp(6)	2.21	0.721	<0.01

Table 7 Thermal sensation scale used in surveys

Place	Climate characters	Thermal sensation scale	Range of T_a (°C)	Rang or T_{mrt} /T_g (°C)	Authors and year
Sydney	Humid subtropical, mild and cool in winter to warm and hot in the summer	ASHRAE 7- point	20.4-43.3	20.9-67.9	Spagnolo and de Dear (2003)
Taichung	Warm humid subtropical climate	ASHRAE 7-point	14- 39	/	Lin et al. (2009)
Guangzhou	Typical subtropical climate, hot summer and warm winter	ASHRAE 7-point	32-39	32-51	Xi et al. (2012)
Szeged	Transitional climate between oceanic (Marine West Coast Climate/Oceanic climate) and continental climate	ASHRAE 9- point	12.5 -28.5	10-60	Kántor et al. (2012)
Damascus	Cool desert climate	ASHRAE 9- point	17.3- 39.6	27.4-71.4	Yahia and Joiansson (2013)
Tel Aviv	Mediterranean climate, hot, humid yet rainless summers	ASHRAE 9- point	21.4-33.7	/	Cohena et al. (2013)
Nagoya	Humid subtropical climate, hot summer and cold winter	ASHRAE 7- point	31.9-32.9	31.9- 48.4	Watanabe et al. (2014)
Tianjing	Temperate, continental-type monsoon climate, cool zone	ASHRAE 7- point	25.6-30.7	/	Lai et al. (2014)
Rio de Janeiro	Tropical savanna climate	ASHRAE 7- point	24.8 -37.0	/	Kruger et al. (2015)

Wuhan	Humid subtropical climate, hot summer and cold winter	ASHRAE 7-point	31-38	/	Huang et al. (2016)
Rome	Mediterranean climate, with mild winters and hot, dry summers	ASHRAE 7- point	3.2- 35.9	/	Salata et al. (2016)
Changsha	Humid subtropical climate, hot summer and cold winter	ASHRAE 9- point	18.7-39.8	18.8-57.8	Liu et al. (2016)
Guangzhou	Subtropical climate zone	ASHRAE 7-point	24.7- 34.6	25.6-65.93	Zhao et al. (2016)
Brazil	Tropical climate zone	ASHRAE 7-point	/	/	Hirashima et al. (2016)
Campo Grande	Highland tropical climate	ASHRAE 7-point	15.3-32.3	17.5-33.6	Lucchese J.R. et al. (2016)
Italy	Typical Mediterranean climate	ASHRAE 7-point	3.2-35.9	7.6-48.1	Salata et al. (2017)
HongKong	Subtropical climate zone	ASHRAE 7-point	/	/	Huang et al. (2017)
Dar es Salaam	Hot-humid climate	ASHRAE 7-point	20.0-33.2	27.0-52.4	Ndetto and Matzarakis (2017)
Rio de Janeiro	Tropical savanna climate	ASHRAE 7-point	24.9-36.8	13.1- 76.4	Kruger et al. (2017)
Brazil	Highland tropical climate	ASHRAE 7-point	15.3-34.4	/	Lucchese and Andreasi (2017)
Groningen	Cool temperate climate, Summers are somewhat warm and humid	ASHRAE 7- point	21.3- 33.5	22.3- 40.4	Wang et al. (2017)
Mediterran ean	Climate of Mediterranean	ASHRAE 7-point	10.47-35.86	9.98-48.07	Golasi et al. (2018)
Cuenca	typical continental Mediterranean	ASHRAE 7-point	/	/	Galindo and Hermida (2018)

Tehran	Cold semi-arid climate	ASHRAE 7-point	2.8-37.5	0.1-49.1	Hadianpour et al. (2018)

Table 8 Heat stress categories

UTCI(Brode et al., 2012)			WBGT(ISO 7243, 1989)			PET(Marianna et al., 2014; Matzarakis and Mayer, 1996)					SET*(Mcintyre, 1980)			Present study
Thermal sensation	EU	T_{op}	Thermal sensation	USA	T_{op}	Thermal sensation	EU	Taiwan	T_{op}(EU)	T_{op}(Taiwan)	Thermal sensation	USA	T_{op}	T_{op}
Extreme heat stress	> 46	>48.5	Black(all training should be stopped)	> 32.2	>43.21	Extreme heat stress	> 41	> 42	> 37.8	> 38.6	Very hot	> 37.5	> 39.26	
Very strong heat stress	38 - 46	36.6 - 48.5	Red(active exercises for all but the well-acclimated should be curtailed)	31.1 - 32.2	39.9 - 43.21									
Strong heat stress	32 - 38	27.7 - 36.6	Yellow(Active exercise for un-acclimated persons should be curtailed)	29.4 - 31.0	34.7 - 39.5	Strong heat stress	35 - 41	38 - 42	32.7 - 37.8	**35.2 - 38.6**	Hot	34.5 - 37.5	39.3 - 34.5	**> 34.0**
Moderate heat stress	26 - 32	18.7 - 27.7	Green(keep alert for possible increases in the index and for symptoms of heat stress)	27.8 - 29.3	29.8-34.3	Moderate heat stress	29 - 35	34 - 38	27.6 - 32.7	**31.8 - 35.2**	Warm	30.0 - 34.5	27.5 - 34.5	**30.0 - 34.0**
						Slight heat stress	23 - 29	30 - 34	22.6 - 27.6	**28.5 - 31.8**	Slightly warm	25.6 - 30.0	20.5 - 27.4	**28 - 30**
No thermal stress	9 - 26	-6.6 - 18.7	No Flag(Unlimited)	25.6 - 27.7	23.0-29.5	No thermal stress	18 - 23	26 - 30	18.4 - 22.6	25.1 - 28.5	Neutral	22.2 - 25.6	15.2 - 20.5	/
Slight cold stress	0 - 9	-20.0 – (-6.6)	/	/	/	Slight cold stress	13 - 18	22 - 26	14.1 - 18.3	21.7 - 25.1	Slight cool	17.5 - 22.2	7.8 - 15.2	/

Moderate cold stress	-13 - 0	-39.1 – (-20.0)	/	/	/	Moderate cold stress	8 - 13	18 - 22	9.9 - 14.1	18.3 - 21.7	Cool	14.5 - 17.5	3.0 - 7.8	/
Strong cold stress	-27 – (-13)	-60.1 - (-39.3)	/	/	/	Strong cold stress	4 - 8	14 - 18	6.5 - 9.9	15.0 - 18.3	Cold	10.0 - 14.5	-4.1 - 3.0	/
Very strong cold stress	-27 – (-40)	-79.5 – (-60.1)	/	/	/	Extreme cold stress	< 4	< 14	< 6.5	< 15.0	very hot	< 10.0	< -4.05	/
Extreme cold stress	< -40	< -79.5	/	/	/									

Table 9 Linear models in some previous investigations

Reference	Linear models	R^2
Lin et al.(2011)	MTSV=0.1302SET*- 3.8142 (hot season) MTSV=0.0739SET* - 2.0657 (cool season)	0.919 0.945
Hwang and Lin.(2007)	MTSV= 0.087SET* - 2.248 (semi-outdoor environments) MTSV=0.116SET* - 3.156 (For outdoor environments)	0.970 0.980
Lin et al.(2009)	MTSV=0.199PET - 4.722 (Cool season) MTSV=0.118PET - 3.025 (Hot season)	0.890 0.960
Hassaan and Mahmoud (2011)	MTSV=0.206PET - 6.680 (Peak hot season) MTSV=0.099PET - 3.009 (Peak cool season) MTSV=0.145PET - 3.625 (Enrance hot season) MTSV=0.071PET - 2.479 (Enrance cool season) MTSV=0.52PET - 4.222 (Spine hot season) MTSV=0.139PET - 3.009 (Spine cool season) MTSV=0.106PET - 2.117 (Fountain hot season) MTSV=0.074PET - 2.253 (Fountain cool season) MTSV=0.12PET - 2.156 (Lake hot season) MTSV=0.087PET - 2.698 (Lake cool season) MTSV=0.129PET - 2.845 (Pavement hot season) MTSV=0.087PET - 2.363 (Pavement cool season) MTSV=0.118PET - 2.399 (Canopy hot season) MTSV=0.127PET - 3.236 (Canopy cool winter) MTSV=0.146PET - 3.869 (Seating hot season) MTSV=0.093PET - 2.603 (Seating cool season) MTSV=0.211PET - 6.346 (Cascade hot season) MTSV=0.073PET - 1.889 (Cascade cool winter)	0.953 0.348 0.944 0.768 0.719 0.768 0.606 0.768 0.651 0.654 0.863 0.447 0.784 0.727 0.876 0.703 0.985 0.663
Xi et al. (2012)	TSV=0.1382SET* - 3.3469	0.305
Cohena et al. (2013)	MTSV=0.3292PET-5.9692 (UPK hot season) MTSV=0.0.2146PET - 3.5737 (UPK cool season) MTSV=0.2078PET - 3.6741 (UST hot season) MTSV=0.2363PET - 3.9149 (UST cool season) MTSV=0.2198PET - 3.9077 (USQ hot season) MTSV=0.2111PET - 3.6226 (USQ cool season)	0.885 0.963 0.965 0.965 0.966 0.966
Yahia and Johansson (1957)	MTSV=0.060PET - 0.941 (Hot season) MTSV =0.114PET -2.755 (Cool season)	0.420 0.600
Lai et al. (2014)	MTSV=0.101PET -1.571 (Hot season) MTSV=0.188PET -1.73 (Cool season) MTSV=0.13UTCI -2.273 (Hot season) MTSV=0.183UTCI -0.392 (Cool season)	0.893 0.752 0.876 0.946
Watanabe et al. (2014)	MTSV=0.271 UTCI -9.237	0.665
Kriuger et al. (2015)	MTSV=0.1404 UTCI -3.2933	0.940
Elnabawi et al. (2016)	MTSV = 0.0998 (PET) - 2.947 (Hot season) MTSV = 0.0881(PET) - 2.1411 (Cool season)	0.830 0.811
Huang et al. (2016)	MTSV=0.123UTCI - 2.362	0.401
Liu et al.(2016)	MTSV = 0.131PET - 2.296 (Spring)	0.585

	MTSV = 0.188PET - 4.386 (Summer) MTSV = 0.112PET - 2.232 (Autumn) MTSV = 0.163PET - 2.431 (Winter)	0.778 0.521 0.663
Salata et al. (2016)	MTSV =0.17PET- 4.575 (Hot season) MTSV=0.118PET- 4.575 (Cool season)	0.847 0.949
Wang et al. (2017)	MTSV =0.058PET - 0.696	0.680
Hadianpour et al. (2018)	TSV = 0.11PET – 2.42 (Whole year) TSV = 0.11PET – 2.36 (Spring) TSV = 0.17PET – 4.26 (Summer) TSV = 0.11PET – 2.41 (Autumn) TSV = 0.15PET – 2.58 (Winter) TSV = 0.64 PMV – 0.16 (Whole year) TSV = 0.61 PMV – 0.14 (Spring) TSV = 0.63 PMV – 0.15 (Summer) TSV = 0.55 PMV – 0.04 (Autumn) TSV = 0.62 PMV – 0.34 (Winter) TSV = 0.13UTCI –2.70 (Whole year) TSV = 0.12 UTCI – 2.50 (Spring) TSV = 0.22 UTCI – 5.68 (Summer) TSV = 0.13 UTCI – 2.80 (Autumn) TSV = 0.17 UTCI – 2.92 (Winter)	0.846 0.814 0.648 0.658 0.562 0.841 0.809 0.624 0.736 0.495 0.845 0.804 0.653 0.657 0.588