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Investigation into sensitivities of factors in outdoor thermal comfort indices against the field survey data

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Abstract: With the development of the urban city, increasing attention has been paid to outdoor thermal comfort. In this paper, an analysis of the sensitivities of different factors, including the personal factors and physical parameters of the thermal environment was conducted. The results showed that there was a strong linear relationship between the Physiological Equivalent Temperature (PET) and operation temperature. When the operation temperature was lower than 32 °C, the effect of air velocity on the PET was positive. However, the effects of other factors, including relative humidity, clothing insulation, and metabolic rate, on the PET were insignificant. An exponential relationship was found between the UTCI and the operation temperature. The effect of air velocity change on the UTCI became weaker and weaker with the increase of operation temperature. Compared with the PET, the linear relationship between the UTCI and relative humidity was clearer. A field survey of thermal comfort carried out in Guangzhou University was used for the validation of the thermal comfort models. It was observed that the clothing insulation requirement increased with the decrease of air temperature in autumn. The variations in metabolic rate were also obvious, from 1met to 3.8 met. More than 70% of the people had been walking before they arrived at the survey locations. In addition, there were some differences in the neutral PET and UTCI temperature between the metabolic rates of 1.0-2.0 met and of 2.6 met. Meanwhile, models of MTSV against the PET and UTCI under different metabolic rates were established.

Keywords: Outdoor thermal environment; PET and UTCI; thermal sensation; clothing insulation; metabolic rate

1. Introduction

On average, people spend more than 90% of their time indoors [1, 2], which caused the dramatically increase in energy consumption for creating comfort indoor thermal environment. At present, people are encouraged to spend more time outdoors. However, people directly expose to the integral environment with the interaction of air temperature (*Ta*), air velocity (V_a), relative humidity (*RH*) and radiation fluxes that impact the human thermos-physiological state, therefore greatly influence human thermal comfort. In order to create a comfortable and healthy microclimate conditions, urban planning, as one of the challenges, needs to be conducted considering the physical, environmental, economic and social aspects [3, 4]. Optimized design of outdoor environment can not only improve city livability but also save heating and air conditioning energy consumption of the buildings by shorten time spend indoors. Therefore, it is necessary to use appropriate outdoor thermal comfort models to evaluate the outdoor thermal environment properly.

In recent years, various thermo-physiological models, which can be divided into two major categories [6], have been developed to improve the prediction accuracy of thermal comfort [5]. In 1957, Yaglou and Minard [7] developed the wet-bulb globe temperature (WBGT) index, which gained popularity mainly due to its simplicity and convenience of use. It was applied in field by the US Army, and also adopted by the World Health Organization (WHO) and the American College of Sports Medicine (ACSM) (1996)[8,9]. And then, Gagge et al. [10] introduced the correction of the "equivalent temperature" (SET*) in 1971. After that, other thermal indices were gradually reported, including the predicted mean vote (PMV) [11], the OUT_SET*[12], the Physiologically equivalent temperature (PET) [13], and the Universal Thermal Climate Index (UTCI)[14]. One of the most popular thermal indexes, Physiological Equivalent Temperature (PET) was developed based on the Munich Energy- balance Model for Individuals (MEMI) [19]. Some research works were completed based on the application of PET in outdoor thermal environment and their outcomes have been conducted in different places [20-22], the PET value can be calculated using available software packages- RayMan [23].

Another notable outdoor thermal index, Universal Thermal Climate Index (UTCI) as a lasted outdoor thermal index was reported [24]. It was developed based on a multi-node model of human thermoregulation [25]. It is appropriate for assessments in all climatic zones and seasons [26, 27]. 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).

Based on the reviews of previous investigations, theoretical thermoregulatory models developed for the indoor environment was not adequate for describing the thermal comfort conditions of outdoors, due to the great complexity of the outdoor environment and the variability of outdoor parameters temporally and spatially [23]. Therefore, for outdoor environments, the PET (Physiological Equivalent Temperature) and UCTI (Universal Thermal Climate Index) have been extensively applied to evaluate the thermal comfort levels. However, both the PET and UTCI models are related to many factors, including thermal environment and human factors. The effects of these factors were very complicated. Thus, based on the available software package RayMan [23] and the project's website, the investigation of sensitivities of several primary factors in the PET and UTCI was essential to assess the outdoor thermal indices. Few such reports were found in previous investigations.

The aim of this study is to demonstrate the importance of different factors (T_a, RH, V_a, mean radiation temperature (T_{mrt}), clothing insulation (I_{clo}) and metabolic rate) in different outdoor thermal indices. Firstly, the equivalent temperatures (PET and UCTI) of different thermal environments were calculated and analyzed. Secondly, considering the impact of human factors, the field thermal comfort survey was carried out in Guangzhou and the results were also used for model validation. Thirdly, the PET and UCTI were developed for the evaluation of different outdoor activity levels.

2. Thermal comfort indices

2.1 PET

PET was selected as the main thermal index in this research with several advantages. Firstly, PET enables a layperson to compare the integral effect of the complex outdoor thermal conditions with their own indoor experiences [28]. Secondly, PET was an accepted bioclimatic index because it had a commonly known unit (°C) as the measurement of thermal stress [29]. Thirdly, several studies reported that PET facilitates application, make them understandable and comprehensible for the users not familiar with modern human biometeorological terminology, including urban designers, landscape architects, policy makers and the lay people [30, 31]. Fourthly, PET could be calculated using available software packages (e.g., RayMan) [23]. The estimation of PET using the RayMan model, which was developed in the Meteorological Institute, University of Freiburg, Germany and was considered as one of the recently developed radiation and bioclimatic models, was very flexible and practical [23]. It was an appropriate tool for calculating T_{mrt} and PET [23] to evaluate the outdoor thermal environment with the thermal stress categories (shown in Table 1) in some previous studies [23, 30, 31]. Therefore, in this investigation, based on this software and the field survey data, the PET would be one of the famous outdoor thermal indices to be analyzed.

2.2 UTCI

Within COST Action 730 [32], the development of UTCI was conducted to assess the human reaction to the outdoor thermal environment with respect to heat and cold stress. The index permits the comparison and assessment of the impact of T_a, RH, V_a and thermal radiation on physiological strain with respect to reference conditions [33, 34].

It involves the definition of a reference environment with 50% relative humidity (but vapor pressure not exceeding 2 kPa), clam air and radiant temperature equals air temperature. To facilitate the widespread use of the UTCI, the operational procedure [33, 34] provided simplified algorithms with which the UTCI values can be computed taking T_a, V_a, T_{mrt} and water vapor pressure (P_a) as input by a table - lookup approach or by regression equations. It is written in mathematical terms as [36]:

$$\text{UTCI}\ (T_a, T_r, V_a, P_a) = T_a + offset\ (T_a, T_r, V_a, P_a) \quad (1)$$

The stress categories of the UTCI was obtained in previous investigations [35, 36] and given in Table 1. Following Meteorological conventions, V_a was taken as the value 10 m above the ground level. If V_a measurement was only available at a height x (m) different from 10 m, the measured air velocity (V_{axm}) should be converted to the required input V_a according to Equation 3 [36]:

$$V_a = V_{axm}.Log(10/0.01)/Log(x/0.01) \quad (2)$$

Table 1 UTCI and PET equivalent temperature categories in terms of thermal stress [35-37]

Stress category	PET(°C)	UTCI (°C)
Extreme heat stress	> 41	Above +46
Very strong heat stress		+38 to +46
Strong heat stress	+35 to +41	+32 to +38
Moderate heat stress	+29 to +35	+26 to +32
Slight heat stress	+23 to +29	
No thermal stress	+18 to +23	+9 to +26
Slight cold stress	+13 to +18	+9 to 0
Moderate cold stress	+8 to +13	0 to -13
Strong cold stress	+4 to +8	-13 to -27
Very strong cold stress	< 4	-27 to -40
Extreme cold stress		Below -40

2.3 Simulated cases

International thermal comfort standard [15, 38] and previous investigations [39, 40] have pointed out that the dominant factors affecting thermal comfort includes four thermal parameters (T_a, V_a, RH, and T_{mrt}), and two occupants' parameters (M and I_{cl}). These six factors are normally applied to evaluate the indoor and outdoor thermal comfort. Meanwhile, the operation temperature (T_{op}) as one of the most important thermal comfort indices was used in place of T_a and T_{mrt} in some standards [15, 38]. It took the major impacts of T_a, T_{mrt} on thermal comfort into consideration, and was calculated by the following equation [15, 38]:

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

Therefore, in this investigation, five factors, including T_{op}, V_a, *RH*, I_{clo}, and *M*, affect the thermal comfort level were considered to analyze the sensitivities in the thermal comfort indices. Based on the climate characteristics of Guangzhou, the monthly average air temperature is always in the range of 15 °C to 30 °C in summer and autumn. The maximum T_a may exceed 40 °C in outdoor thermal environment. Thus, 26 levels of T_a were considered in the simulation cases, as shown in Table 2. The mean *RH* is always very high with a range of 70% to 90%. In order to extend the limit of *RH* on outdoor thermal environment, the *RH* from 30 % to 90% was considered in this study. The variation of I_{clo} was very obvious. Based on the survey, I_{clo} of pedestrian was in the range from 0.3 clo to 1.2 clo. Thus 10 different levels of I_{clo} were adopted totally. For the high V_a in the outdoor thermal environment in Guangzhou, the maximal V_a was 3.2 m/s in this study. *M* of the pedestrian was different from that of occupant in indoor environment. They activity level is walking or slightly walking. Thus, *M* was set from 80 W to 260 W. The detail information of simulation cases was shown in Table 2 with total simulation cases of 198198.

Table 2 Detail information of simulation cases

Levels	Operative temperature (°C)	Velocity (m/s)	Relative humidity (%)	Clothing insulation (clo)	Metabolic rate (W)
1	15	0.1	30	0.3	80
2	16	0.4	40	0.4	100
3	17	0.8	50	0.5	120
4	18	1.2	60	0.6	140
5	19	1.6	70	0.7	160
6	20	2	80	0.8	180
7	21	2.4	90	0.9	200
8	22	2.8	--	1	220
9	23	3.2	--	1.1	240
10	24	--	--	1.2	260
11	25	--	--	--	--
12	26	--	--	--	--
13	27	--	--	--	--
14	28	--	--	--	--

15	29	--	--	--	--
16	30	--	--	--	--
17	31	--	--	--	--
18	32	--	--	--	--
19	33	--	--	--	--
20	34	--	--	--	--
21	35	--	--	--	--
22	36	--	--	--	--
23	37	--	--	--	--
24	38	--	--	--	--
25	39	--	--	--	--
26	40	--	--	--	--

3. Methodology

3.1 Location of study

This investigation was carried out at Guangzhou University in Guangzhou, 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 [41], T_{mrt} was 28.4 °C in July, *RH* was around 83% in summer and 70% in winter [42]. Climatically Guangzhou was a typical subtropical city with uniformly high temperatures, high humidity and abundant summer rainfall.

The sites taken into account for the research were the outdoor areas of the campus of Guangzhou University (Figure 1). They were chosen in order to cover a wide variety of environment conditions in terms of local climate. Within these sites, locations with different microclimatic conditions (i.e., shaded, unshaded, meadow, concrete-paved areas, *etc*.) were identified and used in this study, as shown in Figure 1.

Fig. 1. Sites of survey (A) outside building blocks, (B) lawn, (C) square, (D) open area with cement paving

3.2 Protocol of field data

To analyze thermal comfort and evaluate the effects of the microclimate conditions, the field survey was carried out simultaneously with micrometeorological measurements and thermal comfort questionnaire. The measured thermal parameters include T_a, T_g, RH, and V_a. The study started from July to mid-August, and October through mid-November in 2016, thus covering both summer and autumn. In every day, the survey lasted for 10 hours from 8:30 to 18:30. Three thermal parameters, including T_a, RH, and T_g were continuously measured and automatically recorded at one-minute intervals. 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. An introduction of the questions was given to every subject, then the subject finished the questionnaire based on their understanding of all question.

3.3 Micrometeorological measurements

Micrometeorological instruments were positioned on a tripod for easy fix and transportation to different positions. The heights of the measurement positions were 0.6 m and 1.1m according to the Standards [43]. T_a and RH were measured with ZDR-20 sensors. T_g was measured using a thermometer (JTR10). And an anemometer (Kanomax Model KA22) was adopted to measure V_a. All the detailed information of micrometeorological measurements, including the ranges and accuracies, were summarized in Table 3.

Table 3 Instruments for micrometeorological measurements

Name	Parameters	Measurement 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	± 2 %

T_{mrt}, influenced by both short-wave radiation and long-wave radiation, has a strong effect on human thermal comfort [44]. It was calculated according to ISO 7726 [43] for forced convection from the measured T_g, V_a, T_a and globe emissivity (ε_g, assumed to be 0.95) and diameter (D, approximately 150 mm):

$$T_{mrt} = \{(T_g + 273)^4 + \left[\frac{(1.1\times10^8\times V_a^{0.6})}{(\varepsilon_g\times D^{0.4})}\right] \times (T_g - T_a)\}^{1/4} - 273 \qquad (2)$$

3.4 Survey questionnaire

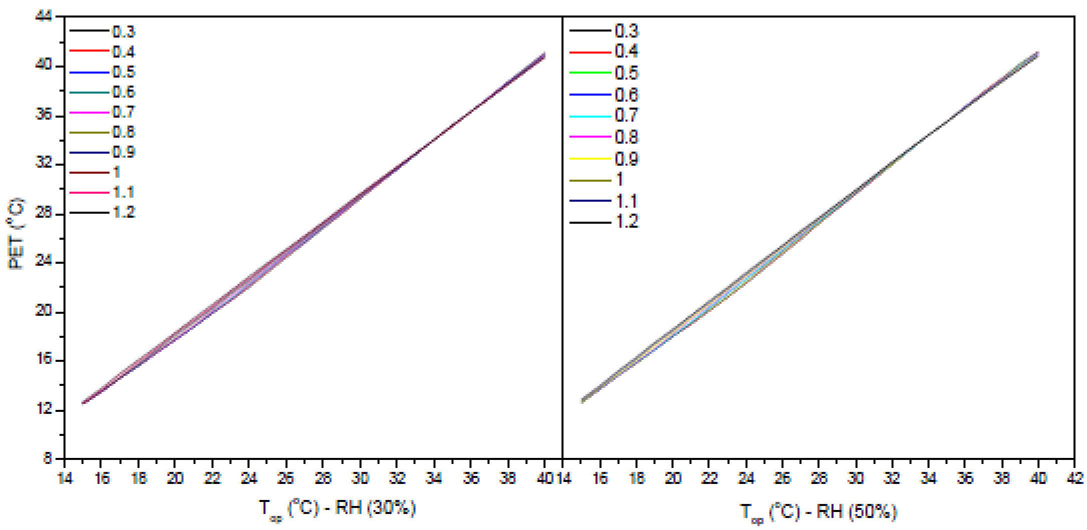
In this study, a survey questionnaire campaign was conducted during the field measurements. The questionnaire is consisted of three parts. The first part was about the personal information (i.e., age, gender, height and weights). The second part recorded the respondents' thermal adaptation, including their thermal experience, activity type, and clothing condition. The third part requested the participants to record their instantaneous thermal comfort status. The thermal comfort was judged on the 9-point thermal sensation vote scale [45] (i.e., -4: very cold, -3: cold, -2: cool, -1: slightly cool, 0: neutral, 1: slightly warm, 2: warm, 3: hot and 4: very hot). The study collected a total of 2007 questionnaires.

4. Results

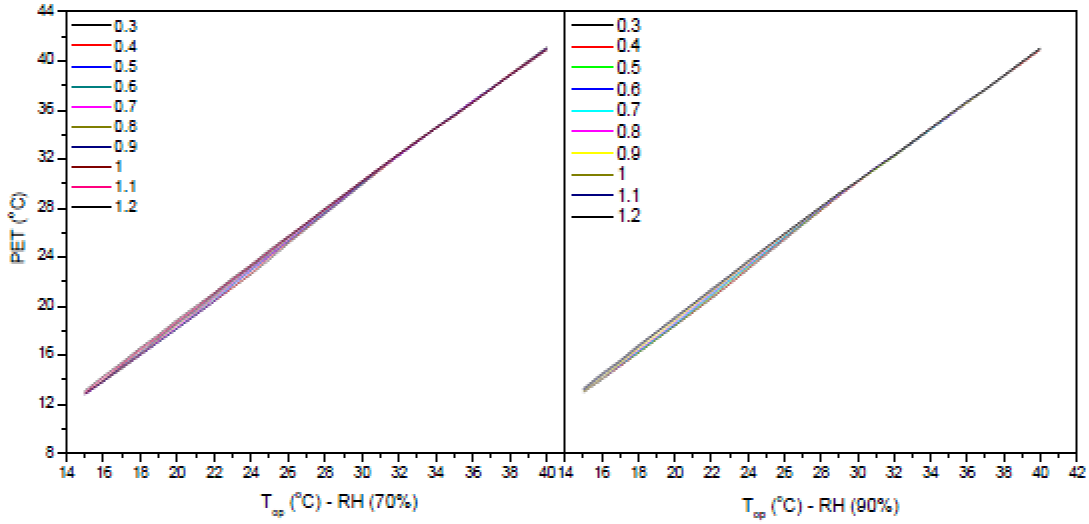
4.1 PET simulation results

4.1.1 PET against T_{op} under different clothing insulation levels

The cloth insulation, I_{clo}, as one of the most important factors affecting thermal comfort, has been improved in some previous investigations [46, 47]. To assess the correlation between I_{clo} and PET, the variations of PET at four different *RH* levels were analyzed. Figure 2 showed the variation of PET against T_{op} and I_{clo} levels. There was a strong correlation between the T_{op} and PET. The PET increased dramatically with the raising of the T_{op}. However, the effects of I_{clo} on PET were not significant. From Figure 2, all the lines of different I_{clo} levels concentrated almost together. The differences between them could be ignored, especially under the higher T_{op} conditions. Meanwhile, the effects of relative humidity (*RH*) levels (30 %, 50 %, 70%, and 90%) on PET were also considered. The differences in PET, caused by *RH*, were not significant. Thus, PET is not sensitive to both I_{clo} and *RH*. The effect of T_{op} on the PET was more significant than those of the other factors. The use of linear regression analysis in these researches highlighted that T_a has, in principle, the greatest influence on human thermal sensation. The research of Nikolopoulou and Lykoudis [46,47] showed that there was a strong relationship between microclimatic and comfort conditions, with T_a and solar radiation as important determinants of comfort in five examined European countries.



(a) (b)



(c) (d)

Fig. 2 PET against T_{op} under conditions of different clothing insulation levels at air velocity of 0.4 m/s and (a) RH 30%; (b) RH 50%; (c) RH 70%; and (d) RH 90%

4.1.2 PET against T_{op} under different air velocity

For outdoor thermal environment, V_a is more fluctuant and has a larger range of variation than that of the indoor thermal environment. For instance, the results of the field survey conducted at the University of Birmingham by Metje et al. [48], even though supported the dominant role of T_a in thermal comfort, showed that V_a was a more important factor than the other factors. Therefore, nine different V_a levels were analyzed in the current study. Figure 3 shows how PET varied with V_a. When T_{op} was lower than about 36 °C, PET descended with the increase of V_a. When T_{op} was lower than 26 °C, the decrease of PET with V_a was more obvious. However, when T_{op} exceeded 36 °C, the trend of PET versus V_a changed suddenly. The PET increased with the rise of V_a in the *RH* range between 30% and 70%. It was well known that the rise of V_a could enhance the heat exchange between the human body and the surrounding air to cool the human body, even in draught [49]. Therefore, the human thermal sensation would descend with the rise of V_a. Nevertheless, from Figure 3, the variation of PET against V_a was unreasonable, i.e., the PET deceased while the air velocity rised when T_{op} exceeding 36 °C. Tseliou et al. [50] reported that V_a caused small scale differentiations in cooler mean thermal sensation vote (MTSV) zone. More specifically, under the influence of wind, individual's thermal sensation scale changes with a transit to cooler MTSV zones at higher air temperature. Unlike the cool MTSV sensation zones, no changes were observed in warmer zones. Nicolopoulou and Lykoudis [46, 47] showed that the low wind regime did not appear to significantly affect the thermal comfort levels in various urban open areas in Europe.

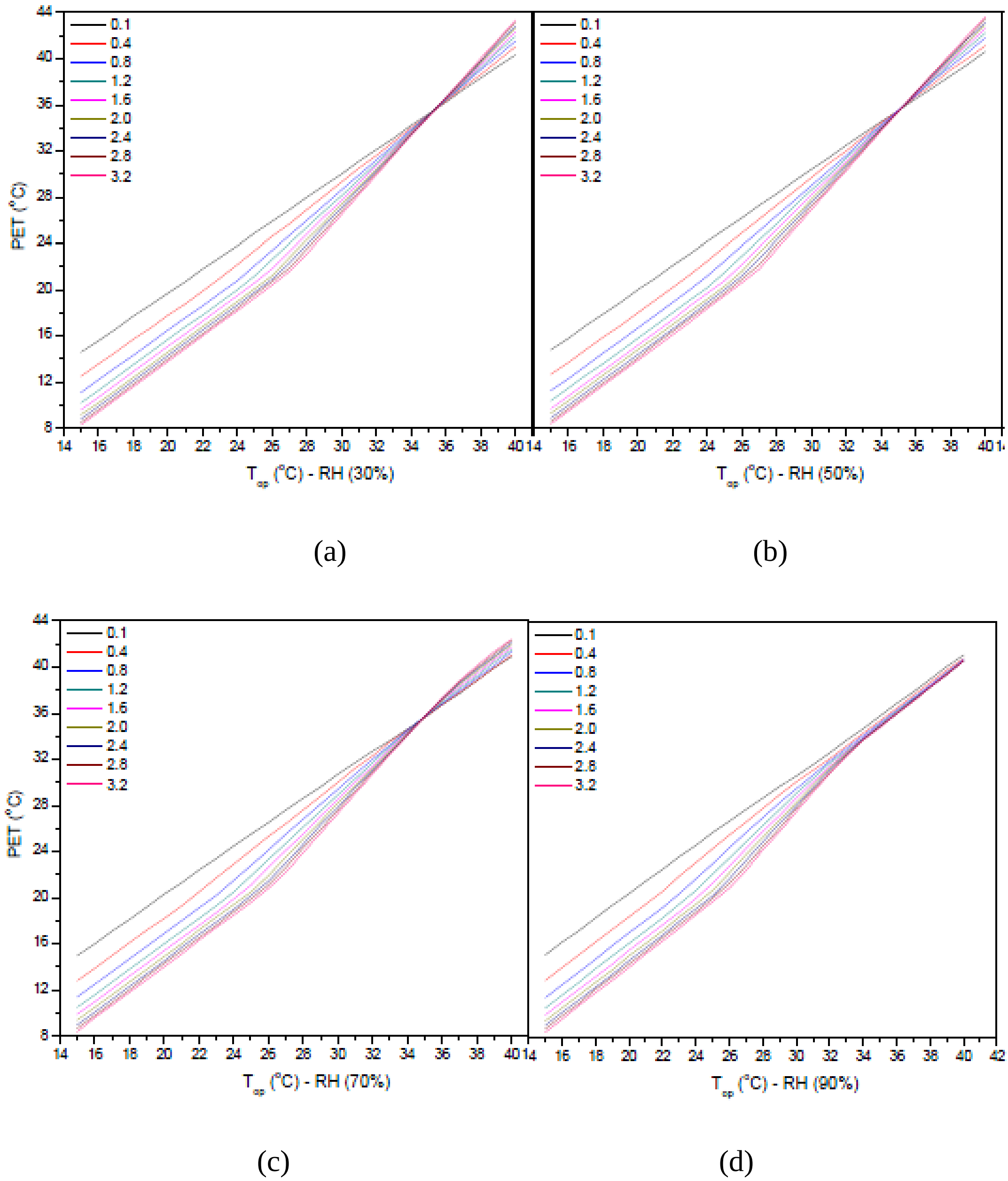
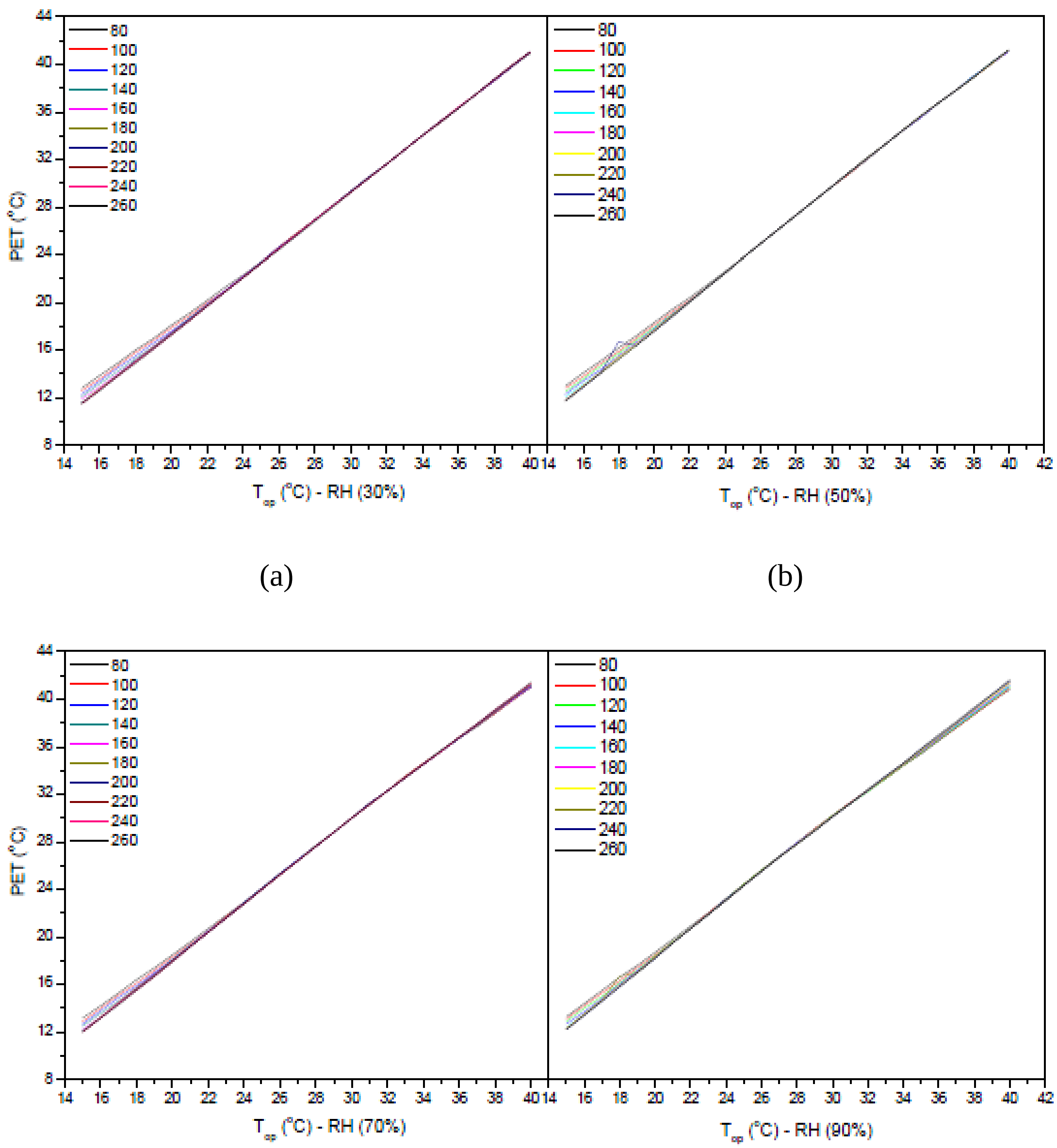


Fig. 3 PET against T_{op} under different air velocity (0.5 clo, 80 W); (a) RH 30%; (b) RH 50%; (c) RH 70%; (d) RH 90%

4.1.3 PET against T_{op} under different metabolic rate

Humans require energy to perform work and to maintain a core temperature of around 37 °C. The higher their activity level was, the larger amount of heat was produced. If too much heat was produced then the body would sweat, and causing discomfort. If too little heat was produced, blood would be withdrawn from the hands and feet, skin temperature would fall and people would feel cold and uncomfortable [51]. This indicated that the effect of metabolism on thermal comfort is prominent. Figure 4 shows that PET changed with metabolic rates. This shows that the effects of metabolic rate on PET could be ignored, especially when T_{op} exceeds 22°C. When T_{op} is lower than 22°C, the PET varies slightly with different metabolic rates.



(c) (d)

Fig. 4 PET against T_{op} under different metabolic rate (velocity 0.4 m/s, 0.5 clo): (a) RH 30%; (b) RH 50%; (c) RH 70%; (d) RH 90%

4.2 UTCI simulation results

4.2.1 UTCI against air velocity

To offset the risen temperature, an increased Va improved the thermal comfort condition, which has been improved according to some previous investigations. An interaction of V_a and T_a was evident as the effect of rising air velocity depended on air temperature [49]. Figure 5 shows how the UTCI varied with V_a. When T_{op} was lower than 28 °C, the UTCI decreased with the rise of air velocity. The lower the T_{op} was, the more obvious the decrease of UTCI. However, when T_{op} exceeded 28 °C, the change of UTCI with V_a was not evident. This result is similar to the results of Tseliou et al. [50]. They reported that V_a causes only small scale differentiations in cool thermal sensation zones. More specifically, under the influence of wind, individuals' thermal sensation scale changed with a transit to cool thermal sensation zone at higher T_a. Unlike the cool thermal sensation zone, no changes were observed in warmer zone. Tan [49] also reported that in the warmer thermal environment, the rise of air velocity could not only reduce the mean overall thermal sensation (MTSV), but also the mean skin temperature. However, when T_a exceeds 32 °C, the variation of skin temperature, caused by V_a, was insignificant. Therefore, the setoff effort of air velocity would weaken with the rise of T_{op}. In addition, Figure 5 also indicates that the change of UTCI with V_a under different *RH* levels were similar. Nevertheless, under the same V_a and T_{op} conditions, the UTCI of high *RH* was higher than that of low *RH*. Comparing the effects of V_a on UTCI and PET, the difference was very significant.

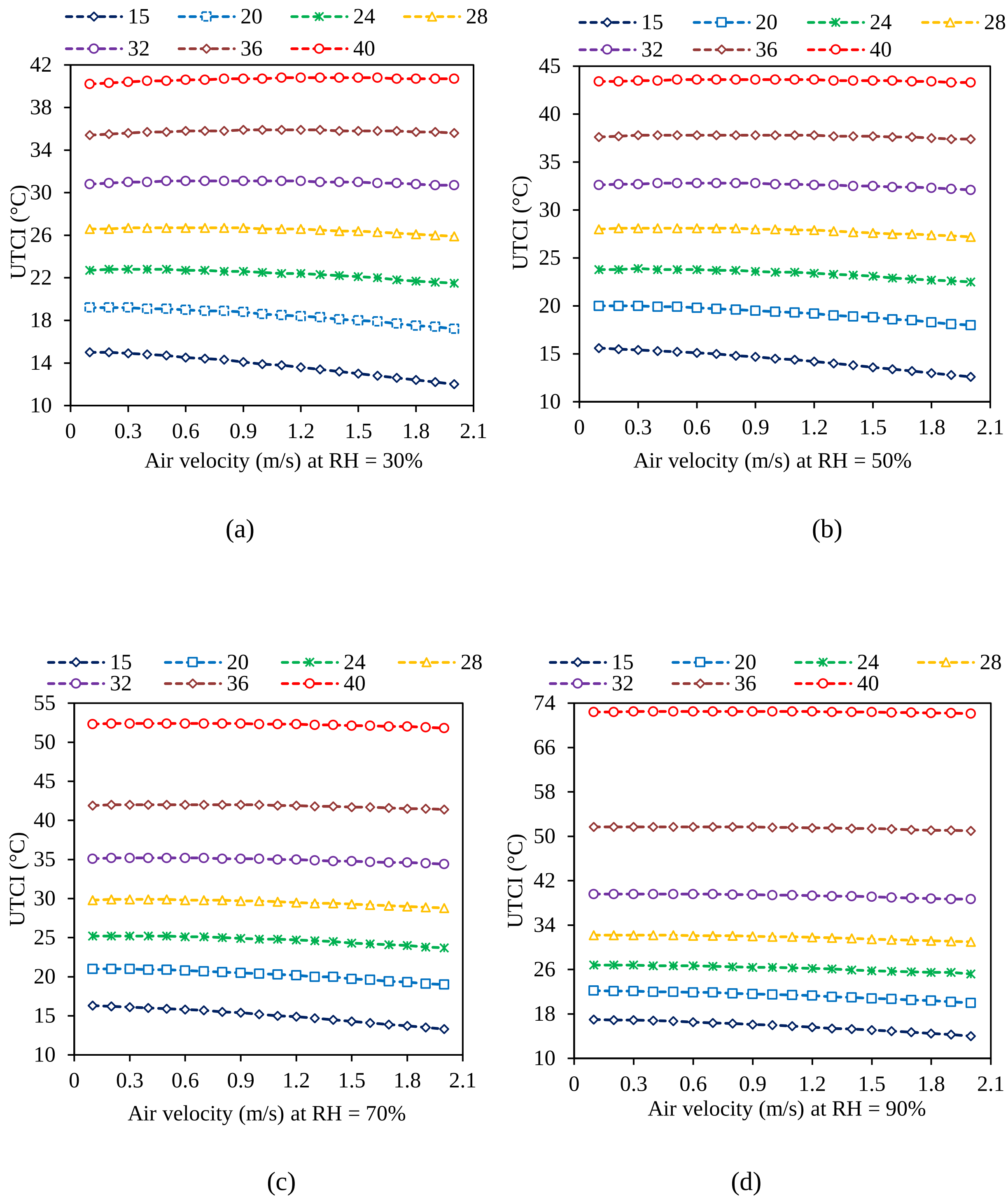
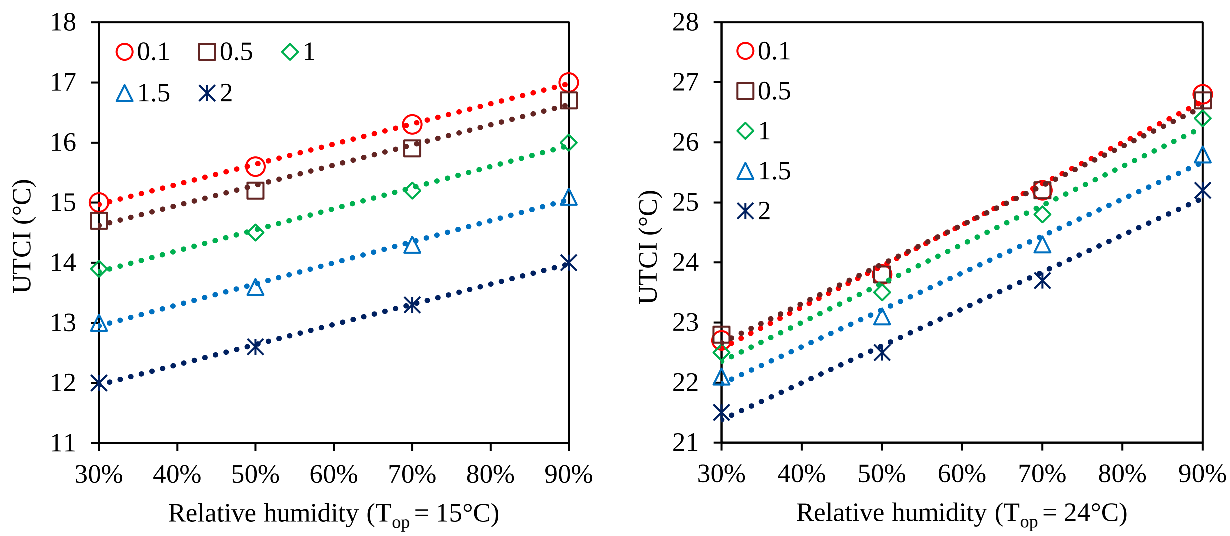


Fig. 5 UTCI against air velocity

4.2.2 UTCI against relative humidity

The effects of *RH* on UTCI are depicted in Figure 6. The change of *RH* caused a linear increased in UTCI. At moderate temperatures, the differences in UTCI, caused by different V_a levels, were more significant than that at warmer temperature, which was similar to the results shown in Figure 6. At the warm temperature, the effects of V_a on UTCI could be ignored. The scatters were concentrated together. It was easily found that the slopes of UTCI in moderate temperature were smaller than that in warm temperature. This indicated that the effects of *RH* on UTCI were much stronger in warm condition. However, in the warm temperature, the negative effects of *RH* on thermal comfort need to be considered. In an outdoor thermal environment, pedestrian should avoid staying in hot and humid conditions for thermal comfort. The primary reason is that at high air humidity and temperature, the cooling of the mucous membranes in the upper respiratory tract on inhalation is decreased, causing the air to be perceived as stuffy and unacceptable [51].



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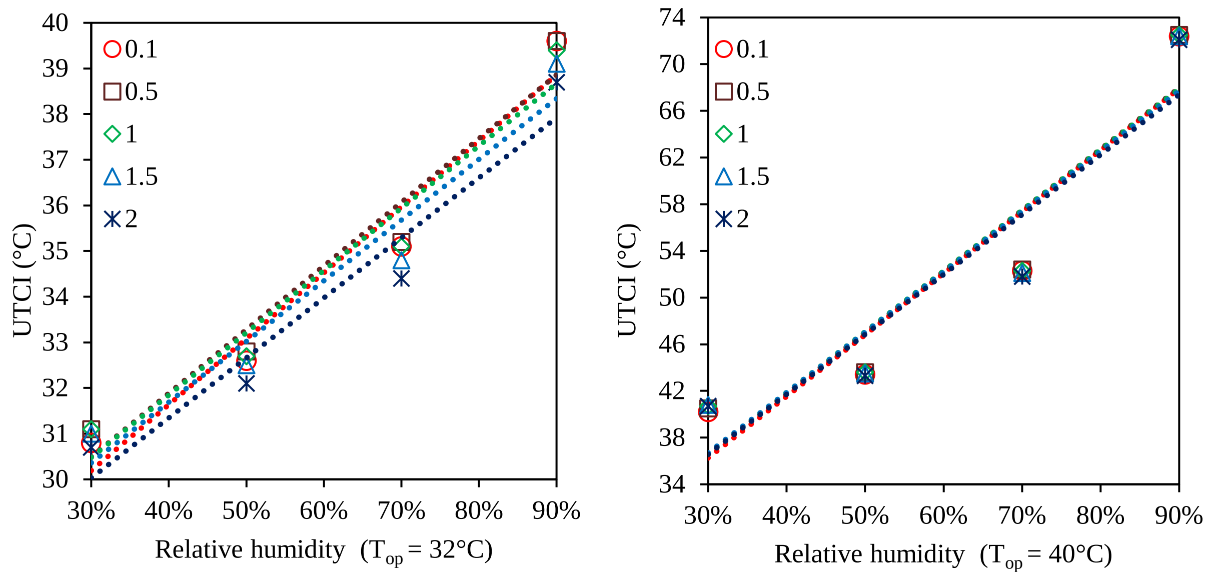


(c) (d)

Fig. 6. UTCI against air humidity

4.2.3 UTCI against the operative temperature

T_{op}, as one of the most popular thermal comfort indices for evaluation of indoor thermal environment, has been applied and defined in many standards [15, 38]. It was also proved that there were some strong correlations between the T_{op} and human thermal comfort in outdoor thermal environment. Therefore, the relationship between UTCI and T_{op} needed to be analyzed. Figure 7 shows the variation of UTCI with T_{op} under different *RH* conditions. The regression relationships between UTCI and T_{op} were shown in Figure 7. Under the different *RH* conditions, all of them fitted the regression models given below:

$$UTCI = a_i e^{bT_{op}} \quad (1)$$

Based on the simulation results, all the regression relationship models were as following:

$$UTCI = 7.667e^{0.0429T_{op}} \ (R^2\text{=0.978} \quad \text{RH=30\%)} \quad (3)$$

$$UTCI = 7.851e^{0.0438T_{op}} \ (R^2\text{=0.982} \quad \text{RH=50\%)} \quad (4)$$

$$UTCI = 7.505e^{0.0484T_{op}} \ (R^2\text{=0.99} \quad \text{RH=70\%)} \quad (5)$$

$$UTCI = 6.393e^{0.0587T_{op}} \ (R^2\text{=0.987} \quad \text{RH=90\%)} \quad (6)$$

All the R^2 values of the models were close to unity, which indicated that the correlations between UTCI and T_{op} were very strong. Comparing the models for different *RH* conditions, the slopes of the UCTI were very different. The higher the *RH* was, the steeper the slope was in a warm thermal environment. This indicates that the effects of *RH* would become more and more significant in a warm thermal environment. Therefore, people should reduce the activity intensity in a hot and humid outdoor thermal environment.

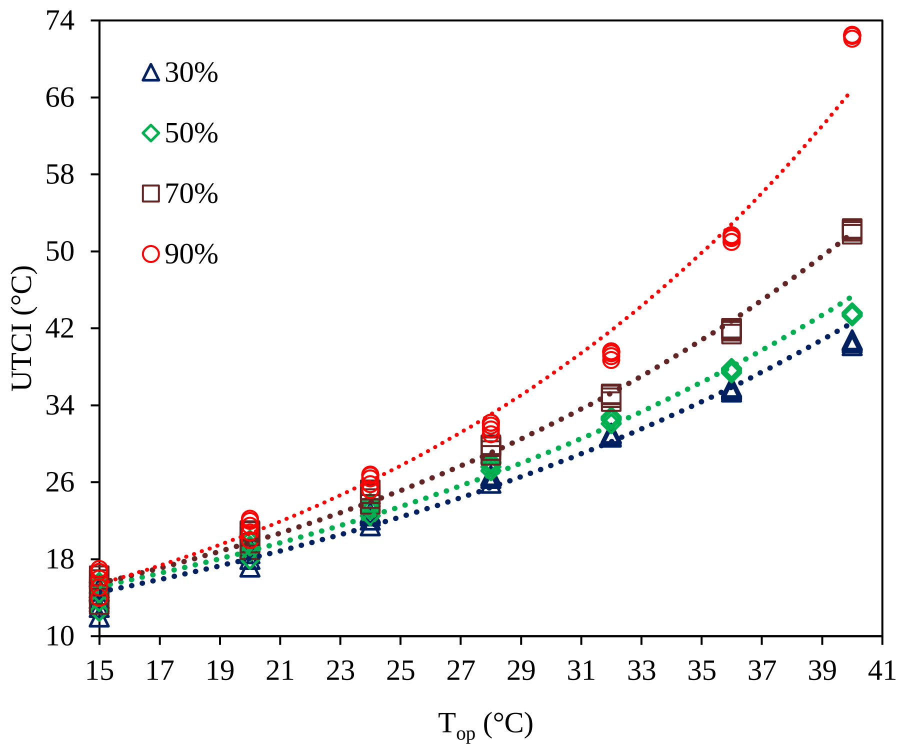


Fig. 7 UTCI against T_{op} under different RH levels

4.3 Field survey results

4.3.1 Variation of clothing insulation

Clothing has a primary impact on thermal comfort and human thermos-physiological responses. Likewise, it is influenced by sweating, movement and temperature distribution of the human body [52]. Figure 8 shows the variation of I_{clo} with T_a in summer and autumn. There was significant difference between the values I_{clo} in summer and autumn. In summer, people would wear light cloth to adapt to the hot outdoor thermal environment. Therefore, I_{clo} was kept relatively constant. The mean I_{clo} was near 0.42 clo in summer. However, in autumn, I_{clo} was higher than that in summer. The primary reason was that the outdoor T_a was lower than that of summer. In order to keep warm and comfortable, people would wear more cloth, which caused the higher I_{clo}. In addition, there was a strong linear relationship between I_{clo} and T_a (R^2=0.72). I_{clo} increased with the decrease of T_a. The maximum value was close to 0.85 clo, and the minimum value was near 0.42 clo. Thus, in an outdoor thermal environment, the effects of I_{clo} on thermal comfort need to be considered.

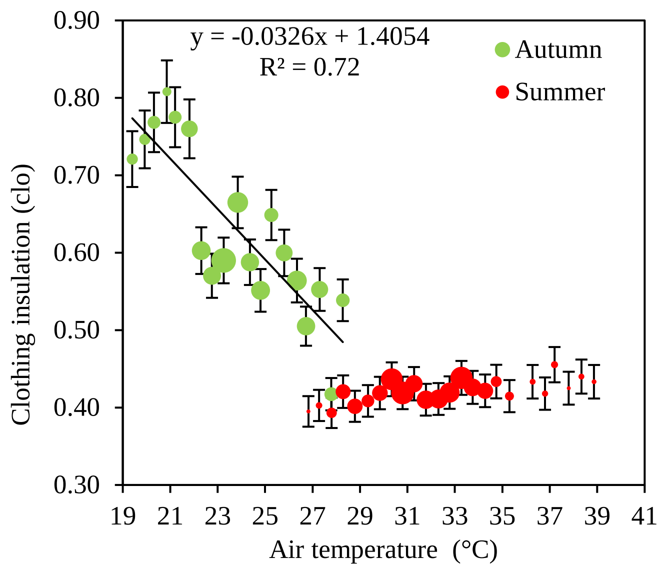


Fig.8 Variation of clothing insulation under different seasons

4.3.2 Variation of the metabolic rate

Human thermal comfort depends on the balance between the rate of metabolic heat production and losses due to the exchange with the surrounding environment [53]. Thus, M was one of the most important factors influencing the human thermal comfort. Both ISO [15] and ASHRAE [38] standards suggest an average steady state value of 1.2 met for typical office workers. However, the metabolic rates of people were variable in outdoor thermal environments (Figure 9). Shown in Figure 9, most of the people kept walking outdoors. This metabolic rate accounted for 70.54%, much larger than half of the outdoor occupants. The most minimal share of the activities was taken up by running, accounting for only 0.9%. The remaining metabolic rates accounted for nearly 30%, including 1 MET for 8.11%, 1.2 MET for 12.59%, and 2.6 MET for 7.87%. Therefore, for evaluation of outdoor thermal comfort, metabolic rate needs to be considered differently from that in an indoor thermal environment.

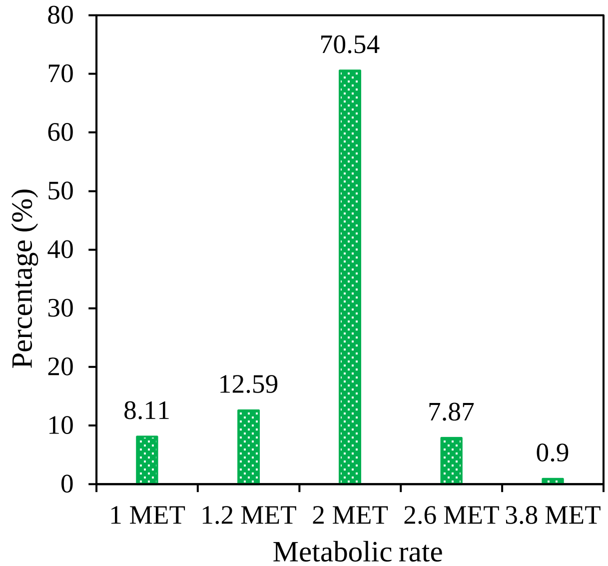


Fig. 9 Percentage of Metabolic rate

4.3.3 MTSV against PET

Based on the above analysis of the percentage of the metabolic rate, there was significant difference between the outdoor and indoor conditions. Considering the effects of different metabolic rates on thermal comfort, the relationships between MTSV and PET were analyzed. Based on the Bin method (1 °C PET) [54, 55], the field survey data were analyzed and shown in Figure 10 that MTSV increased with the rise of PET. Likewise, when PET was constant, *M* would influence the variation of MTSV. Shown in Figure10 (a), when *M* was kept in the range between1 and 2 met, the variation degree of MTSV was similar. The MTSV values were close to each other at metabolic rates of 1met, 1.2 met and 2 met. When people kept slight walking, the metabolic rate would increase. Likewise, the heat exchange between human body and the surrounding thermal environment would be enhanced. This would help to keep the heat balance of the human body. Thus, the variations of MTSV were insignificant. However, when *M* was 2.6 met, the variation in MTSV was more prominent. At the same PET, MTSV at 2.6met was higher than that at the other metabolic rates by nearly 0.5 unit scale. Therefore, the metabolic rates were divided into two groups. One group was 1-2 met, and the other group was 2.6 met as shown in Figure 10(b). Based on the data for these two groups, the fitted regression relationships were decided. The regression models of the two groups of metabolic rates were as following:

$$MTSV = 4.79\ ln(PET) - 14.247 \text{ for 2.6 met, } (R^2=0.86) \quad (2)$$

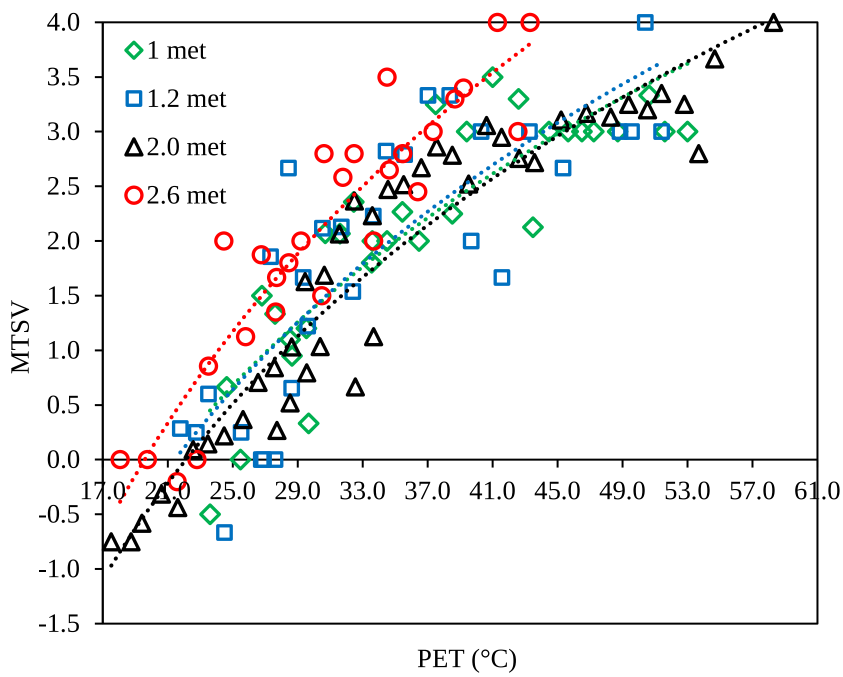
MTSV = 4.11 $ln(PET)$ - 12.65 for 1-2 met, (R^2=0.82)   (3)

According to the models, the thermal stress categories were decided and given in Table 4

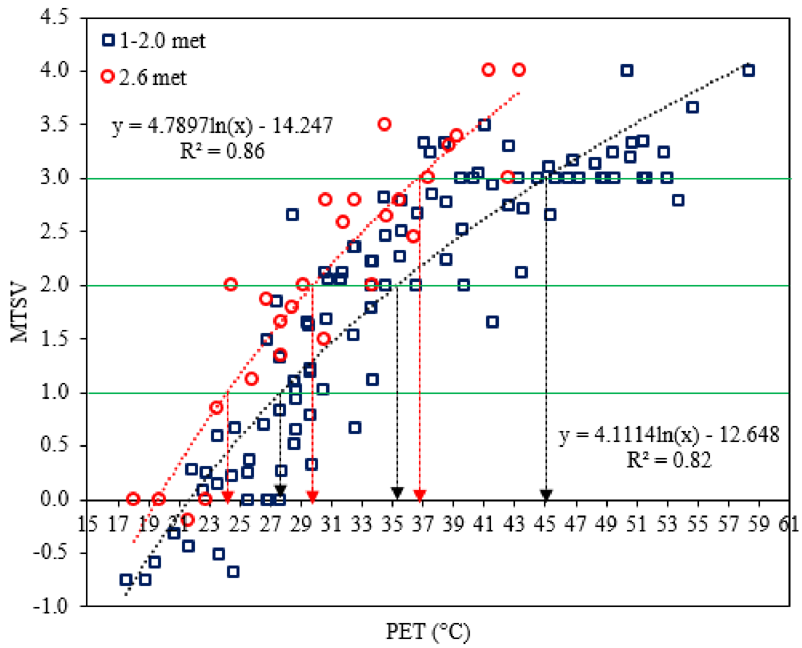
Table 4 Thermal stress categories of different metabolic rates

Thermal sensation vote scale / Metabolic rate/ PET (°C)	Neutrality (0)	Slightly warm (1)	Warm (2)	Hot (3)
1.0-2.0 met	21.9 °C	27.7 °C	35.4 °C	44.6 °C
2.6 met	19.4 °C	24.2 °C	29.8 °C	36.4 °C

Comparing the thermal stress categories of the different metabolic rates, the neutral PET at 1.0-2.0 met was lower than that at 2.0 met by 2.5 °C. Meanwhile, other thermal stress categories of PET were different in both of the two groups of metabolic rate. The differences in PET increased with MTSV. The maximal difference was 7.8 °C. Therefore, the thermal stress categories of PET should include the effect of metabolic rates.



(a)



(b)

Fig. 10 MTSV against the PET under different metabolic rates

4.3.4 MTSV against UTCI

Figure 11 shows the variation of MTSV against the UTCI under different metabolic rates. Shown in Figure 11(a), the variation of MTSV at different metabolic rates was similar to that of PET, shown in Figure10 (a). The MTSV increased with the rise of UTCI. Likewise, there were significant differences among different metabolic rates, especially at *M* of 2.6 met. The scatters of different metabolic rates, including 1 met, 1.2 met and 2.0 met, were close to each other. Therefore, the metabolic rates were also divided into two groups, similar to that of PET. Shown on Figure 11 (b), the regression relationships between MTSV and UTCI were analyzed and obtained. Both of the R^2 exceed 0.7. The formulae are given as follows:

MTSV= 4.382 *ln (UTCI)* – 13. 046 for 2.6 met, (R^2 = 0.74) (1)

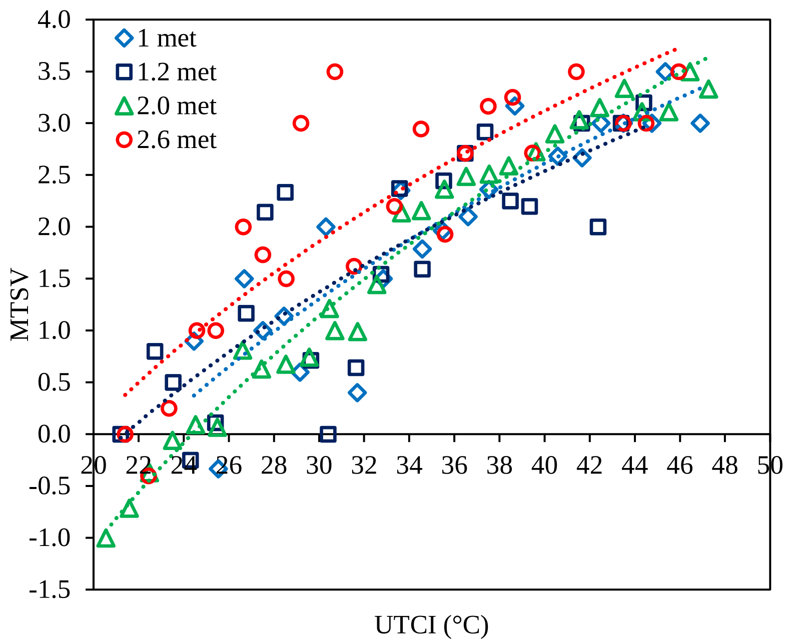
MTSV= 4.834 *ln (UTCI)* – 15.184 for 1.0-2.0 met, (R^2=0.83) (2)

According to the variation of MTSV, the thermal stress categories of UTCI were decided and summarized in Table 5.

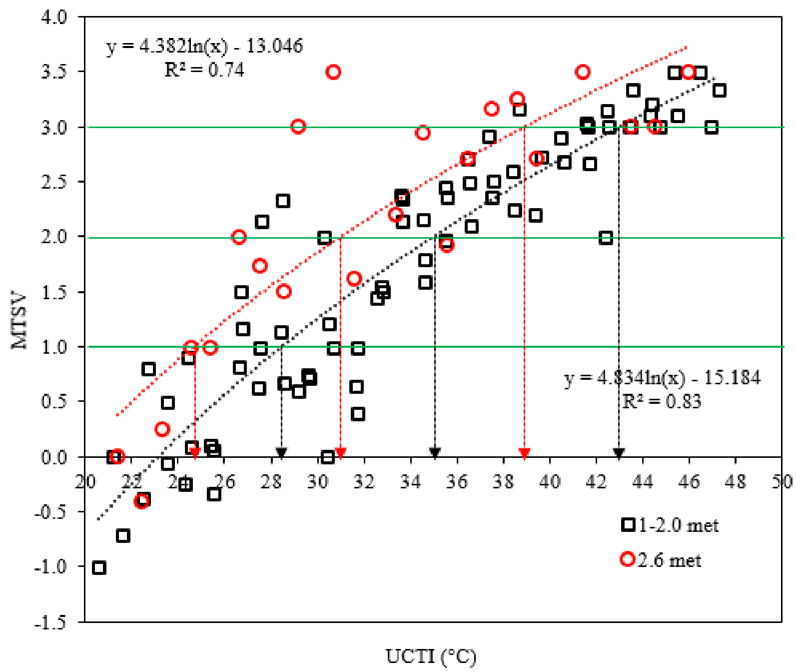
Table 5 Thermal stress categories of UTCI with different metabolic rates

Thermal sensation vote scale / Metabolic rate/UTCI (°c)	Neutrality (0)	Slightly warm (1)	Warm (2)	Hot (3)
1.0-2.0 met	23.2 °C	28.5 °C	35.1 °C	43.1 °C
2.6 met	19.7 °C	24.6 °C	30.7°C	39.0 °C

Shown on Table 5, the differences among thermal stress categories were significant. When the MTSV equals 0, the UTCI at 2.6 met was 19.7 °C, lower than that at 1.0-2.0 met by 3.5°C. In the environment of the same thermal sensation, the UTCI at 2.6 met was lower than that at 1.0-2.0 met by nearly average of 3.93°C due to the higher *M*. Thus, the thermal stress categories of UTCI need to be developed with the consideration of variation in *M*.



(a)



(b)

Fig. 11 MTSV against the UCTI under different metabolic rates

4.4 Building Models of MTSV

Based on the analysis of the survey data and regression models, the relationships between the MTSV and thermal comfort indices (TCI), including PET and UTCI, were developed. According to Equations (1) and (2), variation degree of MTSV was obtained as follows:

$$\frac{\Delta MTSV}{\Delta MET} = \frac{0.68\ln(TCI) - 1.6}{\Delta MET} \quad (5)$$

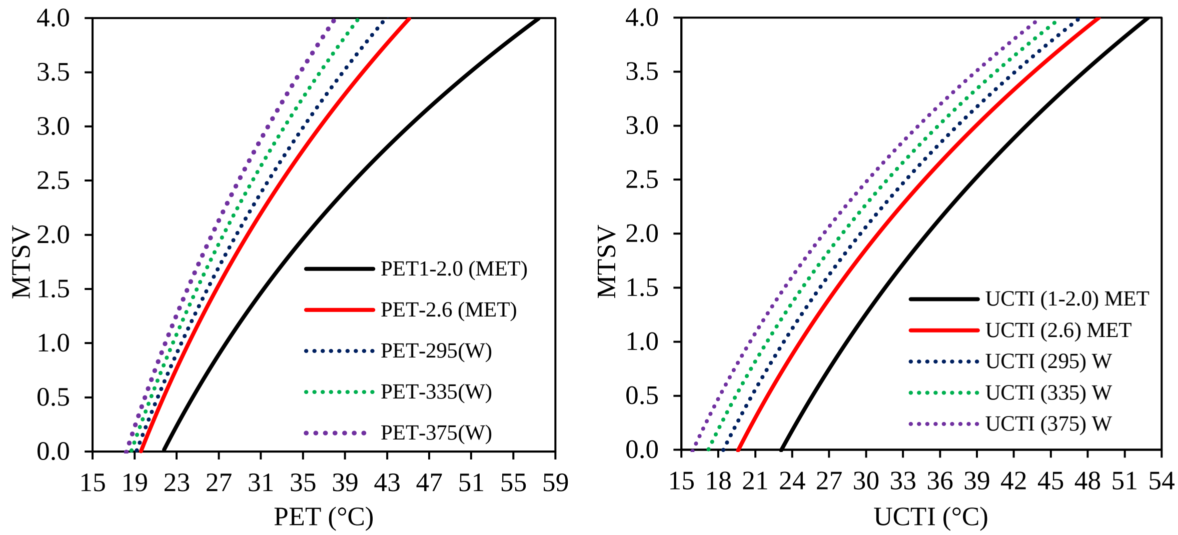
Based on the statistics of basic information of pedestrians, the average metabolic rate of 1-2.0 met was nearly 137 W. And M of 2.6 met was 255 W. Thus, ΔMET is equal to 118W. The increasing degree could be calculated by Equation (6)

$$\frac{\Delta MTSV}{\Delta MET} = 0.00576\,ln(TCI) - 0.0136 \quad (6)$$

Therefore, based on Equation (6), the prediction models of MTSV with TCI and different M were developed as follows:

$$MTSV = MTSV_{1-2.0\,MET} + (0.00576\,ln(TCI) - 0.0136) * (M - 138) \quad (7)$$

Figure12 shows the prediction of overall thermal comfort with thermal comfort indices PET and UTCI. The MTSV increased with the rise of PET or UTCI. And it also increased with the increase of *M*. According the models for different *M* values, the neutrality PET and UTCI were different. Shown on Figure 12 (a), the neutral PET temperatures for 1-2.0 met and 375 W are 21.9 °C and 18.2 °C respectively. Shown on Figure.12 (b), the neutrality UTCI temperatures for 1-2.0 met and 375 W are 23.2°C and 15.9 °C respectively. The differences between these different prediction indices for the metabolic rates were significant. Therefore, it is suggested that the metabolic rates should be considered in PET and UTCI predictions for outdoor thermal environments.



(1) PET (2) UTCI

Fig. 12 The model of MTSV for PET and UTCI

5. Discussion

5.1 The effects of variation in clothing insulation

For prediction or evaluation of the thermal environment, among the possible factors influencing the thermal sensation of the subjects, insulation due to clothing is certainly one of the most important factors. The thermal environment influences the skin temperature and wetness.

These two factors have a direct impact on the body's heat balance, which was also the main driver for thermal discomfort [56]. When a person kept a sitting position comfortably in a normally ventilated room (V_a at 0.1m/s, T_a at 21 °C and *RH* at less than 50%), 24% of the metabolic heat of the person was lost via evaporation from the skin. The remaining 44.2 W/m^2 was lost through the clothing by convection, conduction and radiation [56, 57]. Thus, there was a strong relationship between the heat loss and the clothing insulation. Therefore, the I_{clo} value affects occupants' thermal sensation votes [58]. Thus, determination of the I_{clo} value based on clothing status was very important for the evaluation of thermal comfort.

In order to calculate the clothing insulation, the method described in ISO 9920 was used [59], which defines whole body clothing heat resistant by adding up sectional clothing resistance over different body parts according to a parallel mode [60]. In some of the codes [15, 38], usually thermal comfort ranges were calculated based on the clothing insulation of 0.5 clo and/or 1 clo. If other information is not available, thermal comfort evaluations are performed with an I_{clo} value of 0.5 clo for the cooling season, and 1 clo for the heating season. However, in most of the previous investigations, participants were allowed to adjust their I_{clo} according to the air temperature variation, which would lead to a strong relationship between the clothing insulation and T_a, including indoor air temperature (T_i), outdoor air temperature (T_o), T_{op}, and ET*, as shown in Table 6.

Table 6 Relationships between clothing insulation and air temperature

Years	Authors	Relationship between clothing insulation and air temperature	Locations
2016	Ning et al. [61]	I_{clo}= - 0.0736×T_i +2.3818 (for cool exposure, R^2 = 0.7759) I_{clo}= -0.0567×T_i+2.0314 (for warm exposure, R^2 = 0.8892)	Residential thermal environment (Harbin)
2007	Goto et al. [62]	I_{clo}= 0.842 - 0.013×T_o (R^2 = 0.307) I_{clo} = 1.972 - 0.052×T_a (R^2 = 0.134)	Six office buildings (Sendai, Tsukuba and Yokohama)
2010	Zhang et al.	I_{clo}= - 0.036×ET* + 1.582 (R^2 = 0.861)	NV buildings

	[63]		(Design drawing studio building, teaching building and dormitory buildings in Guangzhou)
2013	de Carvalho et al. [57]	I_{clo} = 1.48 - 0.04272×$T_{day.x-1}$ - 0.009827.max $T_{day.x}$ (R^2 = 0.63)	Classrooms (Leiria)
2013	Pantavou et al. [64]	I_{clo} = 1.15(0.06) + 0.02(0.01) ×T_{air} -0.003(0.001) ×T_{air2} + 0.00005435(0.00) ×$T_{air\ 3}$ (R^2 = 0.72, $p < 0.01$) I_{clo}= 1.36(0.01) + 0.0243(0.0007) ×T_{air} - 0.00049(0.00004) ×T_{air2} + 0.00001(0.00) ×T_{air3} (R^2 = 0.99, $p < 0.01$) (by the average I_{clo} per 1°C)	Outdoor thermal environment (Athens)
2016	Mustapa et al. [58]	I_{clo} = -0.02×T_o + 0.89 (R^2 = 0.029) (this means that occupants wore less clothing when they noticed that the T_o was high, especially occupants in the CL mode offices	Office buildings (Fukuoka)
2014	Luo et al. [65]	I_{clo} = - 0.050×T_{op} + 1.913 (R^2 = 0.894) (District heating supply) I_{clo}= - 0.088×T_{op} + 2.646 (R^2 = 0.983) (Individual household gas boiler heating) I_{clo}= - 0.011×T_{op} + 1.678 (for air-source heat pump, R^2 = 0.856)	Office (shanghai, Beijing)
2015	Yang et al. [66]	I_{clo}= - 0.018×T_o + 1.035 (for severe cold, R^2 = 0.816) I_{clo}= - 0.033×T_o + 1.345 (for cold, R^2 = 0.921)(I_{clo}= - 0.035×T_o+1.458 (for hot summer and cold winter, R^2 = 0.964) I_{clo} = - 0.052×T_o+1.999 (for hot summer and	Different buildings (in several cities in China)

	warm winter, R^2 = 0.950)	
Present study	I_{clo} = - 0.0326× T_o + 1.4054 (R^2=0.72)	Outdoor thermal environment

Shown on Table 6, the slopes of all the regression models were negative. This indicated that the higher T_a was, the less I_{clo} was. In addition, most of corresponding R^2 values in Table 6, exceed 0.7. The maximal corresponding R^2 was higher than 0.99. In this investigation, the slope of regression model was -0.0326 with corresponding value R^2 of 0.72, similar to other previous investigations [61-66]. Goto et al. [62] found that I_{clo} decreased by approximately 0.05 clo with every 5 °C increase of T_o when I_{clo} was higher than 0.5 clo. Thus, the variation of I_{clo} in different seasons was very obvious. Ning et al. [61] reported that the mean clothing insulation was 0.97 clo and 0.74clo respectively in cool and warm exposure environments. I_{clo} decreased by 0.15clo and 0.11 clo respectively in cool and warm exposures with every 2 °C increase of T_i. Cena and de Dear [67] reported that I_{clo} levels were 0.5 clo in summer and 0.7 clo in winter, in a hot-arid region of Western Australia. Schiavon [68] reported that the median clothing insulation was 0.59 clo in summer and 0.69 clo in winter.

The clothing insulation is obviously greater in cool exposure than warm exposure environment. Therefore, people in moderate activities wear different clothing ensembles according to the variation of seasons, lighter in summer and heavier in winter. Therefore, in the thermal comfort models, the effects of different clothing insulation on thermal comfort are very significant. When the clothing thermal resistance increases, the human thermal sensation also increases. In the previous investigations [69-72], with clothing resistance varied from 0 to 1.39 clo, the MTSV increased less than 2 °C. And with the variation of clothing resistance from 0.1, 0.3 to 0.5 clo, the MTSV only varied slightly. Overall speaking, MTSV varied with altering of clothing thermal resistance. De Carli et al. concluded that in mechanically conditioned buildings, a variation of 0.1clo is sufficient to significantly affect the comfort evaluation based on the PMV-PPD model [73]. Buratti et al. also reported that Thermal comfort temperature (corresponding to PMV = -0.5 to +0.5) decreased when I_{clo} increased [74]. Thus, the effects of I_{clo} must be considered in the thermal comfort models for the evaluation of outdoor thermal environment. However, in PET model, the effects of the variation of I_{clo} were non-significant, as shown in Figure 2. For the UTCI model, the UTCI value was calculated by the webpage version without considering the variation of clothing insulation. Based on the above analysis, the effects of clothing insulation on PET and UTCI need to be considered further.

5.2 Effects of metabolic rate

The PMV model, based on the heat balance equation of the human body, has been widely adopted as the tool for thermal comfort evaluation [11]. It is determined by six factors. One of the most important factors is the metabolic rate. It was verified in ISO Standard 8996 (2004), which, according to the activity, varies between 40 and 410 W/m^2, matched well with the survey result in the current investigation (Figure 9). Thus, it is necessary to consider the effects of metabolic rate in the thermal comfort models. Hasan et al. studied the sensitivity of the PMV thermal comfort model relative to its environmental and personal parameters of a group of subjects in a space [75]. They found that metabolic rate had the highest impact on the PMV. This result was similar to that of Luo et al. [65]. They found that when the metabolic rate increased from 0.9 met to 1.5 met, the predicted neutral temperature varied more than 2 °C, or approximately 1.5 unit scale difference in PMV was found. Yang et al. also reported that when the metabolic rate raised by 0.2 met, the acceptable temperature decreased by 2.3 °C [66], which means that following the rise of M, the comfortable temperature range is narrowed. The upper limits of both temperature and relative humidity are much lower. Other thermal comfort models also take metabolic rate as an essential prerequisite for human body heat balance calculation. Therefore, based on the survey data, modification of the PET and the UCTI considering the effects of metabolic rate were obtained. Shown on Figure12, when the metabolic rate increased from 1.0 met to 2.6 met, more than 0.5 unit scale of thermal sensation increased in both PET and UTCI models. Especially for the PET model, the effects of metabolic rate became more significant with the rising of PET. In a thermal environment of the same MTSV, the PET for 2.6 met is higher than that for 1.0-2.0 met, by 2.5 to 7.8 °C. For the UTCI model, the UCTI value for 2.6 met is higher than that of 1.0-2.0 met by 3.9 UTCI, similar to the previous investigations [65, 66, 75]. All detailed information is shown in Tables 4 and 5. Based on the survey data, the modification models of PET and UCTI were analyzed.

Conclusion

This study aimed to analyze the sensitivity of different factors, including the personal factors and physical parameters of thermal environment, in outdoor thermal comfort models. The popular outdoor thermal comfort models of PET and UTCI were chosen for analyses. Meanwhile, a field survey investigation was carried out at Guangzhou University for validation. The following conclusions and suggestions are noteworthy:

(1) There was a linear relationship between PET and T_{op}. When T_{op} was lower than 32 °C, the effect of the variation of V_a on PET was positive. In other words, the higher the velocity was, the lower the PET was. However, the effects of the variations of other factors, including RH, I_{clo}, and M, on PET were non-significant and thus could be ignored.

(2) There was an exponential relationship between UTCI and T_{op} acquired via regression. Under different relative humidity, the exponential relationships were significantly different. The effects of the variation of velocity on UTCI become weaker and weaker with the increase of T_{op}. When T_{op} was lower than 26 °C, the effect of V_a was positive. However, when T_{op} exceeded 26 °C, the effect could be ignored. Compared with the PET, the linear relationship between the UTCI and RH was more evident and significant. Nevertheless, in the web version of UTCI, I_{clo} and M should not be ignored. This version does not consider the effects of the clothing insulation and metabolism.

(3) Based on the survey study, clothing insulation increased with the decrease of T_a in autumn, and there was linear relationship between I_{clo} and T_a. In summer, most of the people dress in light clothing for thermal comfort adjustment. In addition, the variations of metabolic rate were significant, from 1 met to 3.8 met. More than 70% of the people had been walking before they arrived at the survey locations. Less than 30% of the people had sat or stood in the survey location for more than 15 min. Therefore, the models should consider the metabolic rate for evaluation of outdoor thermal environment.

(4) According to the survey data, there were some differences in the neutral PET and UTCI between the conditions of 1.0-2.0 met and 2.6 met. The difference in neutral temperature was nearly 2.5 °C. Meanwhile, the models of MTSV against PET and UTCI under different metabolic rates have been established.

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