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Investigation into sensitivities of factors in outdoor thermal comfort indices

Zhaosong Fang[a,b], Zhang Lin[b,*], Cheuk Ming Mak[c], Jianlei Niu[c,d], Kam-Tim Tse[e]

[a] School of Civil Engineering, Guangzhou University, Guangzhou, China
[b] Division of Building Science and Technology, City University of Hong Kong, Kowloon, Hong Kong
[c] Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong
[d] School of Architecture, Design and Planning and School of Civil Engineering, The University of Sydney, Australia
[e] Department of Civil & Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong

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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.

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 (T_a), 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], the Universal Thermal Climate Index (UTCI) [14], and Berkeley Comfort Model [15,16]. One of the most popular thermal indexes, Physiological Equivalent Temperature (PET) was developed based on the Munich Energy-balance Model for Individuals (MEMI) [17]. Some research works were completed based on the application of PET in outdoor thermal environment and their outcomes have been conducted in different places [18–20], the PET value can be calculated using available software packages- RayMan [21] to evaluate the outdoor thermal environment. Ruiz and Correa

* Corresponding author.
E-mail address: bsjzl@cityu.edu.hk (Z. Lin).

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[22] carried out a study in Mendoza (Argentina) and tested six different indexes (PMV and PET included) revealing predictive abilities lower than 25%. Kantor et al. [23] found that the neutral PET (NPET) in Taiwan differed by 9 K, from that in Szeged, Hungry. In addition, the effects of various seasons on thermal comfort could not been ignored. Some investigations [24–26] indicated that the NPET in hot climate was higher than that in cold climate. Liu et al. [27] found that in Changsha, the NPET reached the highest value (23.3 °C) in summer and the lowest valued (14.9 °C) in winter, with a temperature difference of 8.4 °C. Salata et al. [25] used the regression lines to decide the NPET value of 26.9 °C for the hot season and 24.9 °C for the cold one. Nikolopoulou and Lykoudis [28] also determined the neutral PET in 7 different European cities in hot season and cold season. On the other hand, some studies [29,30] modified the outdoor thermal comfort ranges of PET with considering the impacts of psychological adaptation and behavioral adjustments, which indicated that the PET has been further developed for application.

Another notable outdoor thermal index, Universal Thermal Climate Index (UTCI) as a lasted outdoor thermal index was reported [31]. It was developed based on a multi-node model of human thermoregulation [32]. It is appropriate for assessments in all climatic zones and seasons [33,34]. 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). To apply the UTCI, Havenith et al. [35] extended the UTCI-Fiala model with the adaptive clothing model. Lai et al. [36] carried out the field survey to studies of outdoor thermal comfort in northern China. The results showed significant differences between the Mediterranean Climate [37] and the climate of northern China. Thus, UTCI still needs to be developed for application in different climate zones.

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 [21]. Therefore, for outdoor environments, the PET (Physiological Equivalent Temperature) and UTCI (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 [21] 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 in the PET and UTCI models. Based on the RayMan software of PET, the factors, including T_a, RH, V_a, mean radiation temperature (T_{mrt}), clothing insulation (I_{clo}), and metabolic rate, needed to be input. For UTCI, based on the input webpage of the online version, only the effects of T_a, RH, V_a, and T_{mrt} were considered. Firstly, the equivalent temperatures (PET and UTCI) 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 UTCI 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 [38]. Thirdly, several studies reported that PET facilitates application, make thermal stress understandable and comprehensible for the users not familiar with modern human biometeorological terminology, including urban designers, landscape architects, policy makers and the lay people [24,39]. Fourthly, PET could be calculated using available software packages (e.g., RayMan) [21]. 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 [21]. It was an appropriate tool for calculating T_{mrt} and PET [21] to evaluate the outdoor thermal environment with the thermal stress categories (shown in Table 1) in some previous studies [21,24,39]. 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.

Table 1
UTCI and PET equivalent temperature categories in terms of thermal stress [39,43,44].

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

2.2. UTCI

Within COST Action 730 [40], 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 [41,42].

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 [41,42] 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 [43]:

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

The stress categories of the UTCI was obtained in previous investigations [43,44] 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 (2) [43]:

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

2.3. Simulated cases

International thermal comfort standard [45,46] and previous investigations [47,48] 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