Evaluation of thermal comfort and heat stress indices in different countries and regions – A Review

Sadia Yasmeen1,2 and Hong Liu 1,2

1 Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing 400045, China.
2 National Center for International Research of Low-carbon and Green Buildings (Ministry of Science and Technology), Chongqing University, Chongqing 400045, China.
* sadia.esrm@hotmail.com

Abstract: Energy efficiency, sustainability, productivity, thermal comfort, occupational health issues are emanating from rising global temperature associated with climate change. The prime purpose of this review is to focus on the present models to evaluate thermal comfort and heat stress level in various parts of the world in order to, identify the significant limitations in the development appropriate model. To assessed thermal comfort and heat stress a considerable number of models are already existing where about 40 models exist for only to determine heat stress itself. Existing comfort models are criticized for less metabolic rate, cloth insulation, not suitable for the outdoor diverse climate or for over or underestimation of the thermal concessions. On the other hand, to assessed heat stress WBGT-index is most widely used because of its simplicity. Several studies raised its limitations, whereas the PHS model is more appropriate but hard to understand for general people. For Thai people, HSI (Heat Stress Index) is best rather than others claimed by the authors. Thermal Work Limit (TWL) is suitable for both indoor and outdoor environments. Authors adopt the approaches to determine the region-based comfort and stress level through exploiting different models. For better evaluation models were improved through including or excluding new variables since the first development of thermal comfort indices. However, no unique model has developed afterward. Perfection and utilities of models depend on regional climatic behavior, which is apart from other relevant aspects. Therefore, further study should be necessary to establish a unique model or if not reasonable then focus on to obtain the accurate model for each climatic region.

Keywords: Climate change, Global temperature, Thermal comfort, heat stress, WBGT-indices, PHS model and Thermal Work Limit (TWL).

1. Introduction

It is firm to precisely calculate the accurate figure of increased temperatures, but researchers undoubtedly agree about rising global temperature (Novak et al., 2019). Growing temperature is adequately representing the term ‘comfort’ more strongly as a significant concern along with other occupational health hazards such as heat stress, skin cancer, heat stroke, heat exhaustion and so on. The pleasant and uncomfortable temperature for the occupational workers is evaluated by body responses and their personal feelings (Xiong et al., 2017). On the other hand, an unequal heat balance between human and external environment causes heat stress (Parsons, 2003). Heat stress exhibits some visible symptoms like fatigue, a headache, tiredness, dizziness, muscle cramp, vomiting, hypertension, hyperventilation and some more (Nerbass et al., 2017).

To evaluate the thermal comfort and heat stress for occupational well-being there are several indices at present been existing precisely. These are inappropriate for all climatic conditions to properly monitor thermal comfort or heat stress (Epstein & Moran, 2006). Researchers utilized the combination of theories and compute the connectivity between the environment and human physiology in the specific context of appraisal the thermal comfort and heat stress in a laboratory rather than on-site research which...
carefully made them less valid (Li et al., 2016). The specific purpose of this review to summarize the existing widely used indices regarding human comfort and heat stress along with properly identifies the suitable one in diverse climatic conditions.

2. Methods
To conduct this review information’s regarding thermal comfort and heat stress indices published journal papers and conference proceedings were obtained through searching (web of science, Scopus, springer and science direct). Furthermore, international reports and standards were counted here. Searched keywords are; ‘thermal comfort’, ‘high ambient temperature’, ‘thermal index’, ‘climate change’, ‘global warming’, ‘thermal environment’, ‘occupational health’, ‘heat stress’, ‘climatic zone’, ‘WBGT’, ‘outdoor workers’, ‘health effects’ and so on. Relevant keywords were used to acquire the published papers without any year limits of official publications till 2019. In addition, published papers in the English language were only considered for the review.

3. Results
Approximate 33 number of published journal papers have selected in a different year of publication until 2019. In the selection of journals, mainly preferred outdoor studies rather than indoor. The different location-based study was selected such as Thailand, Iran, China, Australia including European countries. The countries which are most affected by the hot climate was easy to find studies in that region rather than the cold zone.

3.1 Thermal comfort indexes
Thermal comfort has been defined by ISO 7730 (2005) is, that condition of mind which expresses satisfaction with the thermal environment. Furthermore, ASHRAE 55 (2013) point out six environmental and non-environmental factors (metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity, humidity) that properly define thermal comfortability.

The first thermal comfort indication model was developed by P.O. Fanger in the 1960s and several years later he coined the modern term PMV (Predicted Mean Vote). PMV calculated based on Fanger’s equation and at the same time using the PMV equation Predicted Percentage of Dissatisfied (PPD) can be calculated (Equation 1). This model was developed for the indoor environment and also applied for the outdoor condition. Both ISO 7730 and ASHRAE.55 has been accepted Fanger’s model for a person’s comfort or discomfort on the rating scale (Van Hoof, 2008).

\[
PPD = 100 - 95 \times e^{(-0.03353 \times PMV^4 - 0.2179 \times PMV^2)}
\]  

Standard Effective Temperature (SET) is another efficient model to estimate indoor and outdoor thermal sensation. In this model, the individual thermal situation compared with constant relative humidity (50%) and means radiant temperature equal to air temperature (Gagge et al., 1986).

The last two decades of the 19th-century Physiological Equivalent Temperature (PET) was developed. The thermal balance between the human body to the surrounding environment with a low metabolic rate and 0.9 clothing insulation was under deliberation. PET is based on Munich Energy-balance Model for Individuals (MEMI) (Peter, 1999). Effective temperature (ET) is another index considering three environmental parameters air temperature (dry bulb), humidity (wet bulb temperature) and air velocity. ET represents a standard environment that comprises constant, wet air and the output thermal sensitivity is as like exists environment.

Universal Thermal Climate Index (UTCI) was declared in 2011 by the International Society of Biometeorology (ISB) as an alternative model to assess outdoor thermal sensation (Park et al., 2014). UTCI was basically developed to assess outdoor environmental thermal sensation where, ambient temperature, wind velocity, humidity and radiant heat including cloth insulation is taking into account. Equation 2 is the mathematical representation of UTCI index (Blazejczyk, 2011).

\[
UTCI = 3.21 + 0.872 \times t + 0.2459 \times Mrt - 2.5078 \times v - 0.0176 \times RH
\]

Here; \( t \) = air temperature (°C), \( Mrt \) = mean radiant temperature (°C), \( v \) = wind speed (m/s), \( RH \) = relative humidity (%). The UTCI-Fiala is the advanced physiological model forms on the fundamental basis of the new UTCI (Fiala et al., 2012).
3.2 Thermal sensational differences in a different climatic zone:

Different parts of the world, countries have different climatic characteristics (Mary & Eslam, 2017). Moreover, within the country climate varies with the dissimilar climatic zone (Li et al., 2018; Roshan et al., 2019) which influence the human thermal condition and physiology (Queiroz et al., 2018). Spagnolo & de Dear (2003) found that OUT.SET was the most numerically suitable rather than PET and ET for subtropical climate Sydney, Australia. On the contrary view, Honjo (2009) has mentioned, PET was much satisfactory to evaluate the outdoor thermal comfort in Greece, Hungry and Japan, in addition, PET is a better substitute for the microclimate to assess the human heat balance mechanism accurately (Cheng et al., 2012). In terms of PMV, overestimate and underestimate the real sensation of Swedish people and also exceeded the limits of the model (Honjo, 2009). Cheng et al., (2012) report similar results, PMV overrated summertime sensation and underestimated in winter. UTCI thermal model is much suitable in contrast with PET in the semi-humid, hot summer and cold winter region (Xi’an, Southern part of China)(Xu et al., 2018) and the northern part of China (severe cold and cold climatic zone) (Lai et al., 2014). On the other hand, recent study claims, WBGT, SET, PET and UTCI is not suitable for high temperature though following indices had a strong linear relationship with mean thermal sensation vote (Fang et al., 2019). Table 1 shows the index and zone-wise variation of the thermal sensation.

Table 1. Differences in comfortable temperature in diverse region and index.

| Zone             | Seasons   | Index | Study          |
|------------------|-----------|-------|----------------|
| Taiwan           | 28.5 (Summer) | 26.7 (Winter) | SET (Lin et al., 2011) |
| Microclimate, Hong Kong | 25 (Summer) | 21 (Winter) | PET (Cheng et al., 2012) |
| Xi’an            | 23.2 (summer) | 14.9 (Winter) | UTCI (Xu et al., 2018) |
| Harbin           | 20 (summer) | 18 (Winter) | PET (Chen et al., 2018) |
| Shanghai         | 13-30 (Autumn) | 9-25 (Winter) | PET (Chen et al., 2015) |

3.3 Heat stress indexes

The increase of body internal temperature and asymmetric heat evaporative system cause of heat stress (Nerbass et al., 2017). Epstein & Moran (2006) mentioned almost 40 indices are already existing to estimate heat stress though, it is impossible to develop a worldwide model for measuring heat stress levels. Among all the indices the Wet Bulb Globe Temperature (WBGT) and Predicted Heat Strain (PHS) are internationally used index. International Organization for Standardization (ISO) and American Conference on Governmental Industrial Hygienists (ACGIH) approved the WBGT index.

In the year 1957 WBGT was developed by Yaglou and Minard (D’Ambrosio Alfano et al., 2014). According to Parsons (2006), WBGT was the improvement of the effective Temperature (ET) index (1920). The Index is calculated for both indoor and outdoor by following equations (Equation 3 & 4). The equation made up by natural wet-bulb temperature (tnw), air temperature (ta) and black globe temperature (tg). Based on the WBGT index occupational exposure heat exposure limit TLV (Threshold limit value) proposed in 1971 by Henschel (Malchaire, 1979).

\[
WBGT = 0.7tnw + 0.3tg \]  (3)

\[
WBGT = 0.7tnw + 0.2tg + 0.1ta \]  (4)

The Discomfort Index (DI) was proposed (Equation 5; td=Dry-bulb temp. and tw=Wet-bulb temp.) to evaluate the discomfort level of occupants. After the establishment of ET and insufficiency to assist the uncomfortable conditions DI was formulated to overcome the problem (Thom, 1959).

\[
DI = 0.4(t_d + t_w) + 15 \]  (5)

In 1989, on the basis of the required sweat rate calculation, ISO 7933 was established for the first time and well known as the Predicted Heat Strain (PHS) model. Equation 6 characterizes body heat transfer (ISO, 7933). Thermal Work Limit (TWL) is developed following ISO 7933 to evaluate their heat stress.
TWL calculated based on five environmental parameters (dry bulb, wet bulb, globe temperature, air velocity and atmospheric pressure).

\[ M - W = C_{\text{res}} + E_{\text{res}} + K + C + R + E + S \]  

(6)

Here, \( M \) = metabolic rate, \( W \) = effective mechanical power, \( C_{\text{res}} \) = heat exchanges in the respiratory tract, \( E_{\text{res}} \) = heat exchange by evaporation, heat exchange by, \( K \) = conduction, \( C \) = convection, \( R \) = radiation, \( E \) = evaporation and \( S \) = acclimated heat storage in the body.

Heat Stress Index (HSI) was introduced by Belding & Hatch (1955), mainly focused on body heat balance. This index was not applicable for high and low workloads. Humidex is the simpler edition of HIS, that considered the combined effects of air temperature and humidity (Rowlinson et al., 2014). Physiological strain index (PSI) is the index to assess heat strain from physiological parameters, heart rate and core temperature (Miller & Bates, 2007).

3.4 Geography and indexes

The WBGT index is mostly used in research, nationally (UK, China, USA etc.) and internationally (ISO, ACGIH) recognized as a heat stress indicator. Recently, Chindapol et al., (2017) evaluated the differences between the indexes in the hot and humid climate (Thailand). Authors claimed that HSI is the best heat stress index in terms of elderly people because of the sensibility of temperature, humidity and evaporation. Where WBGT, TSI and DI overestimated the actual sensation in addition, exhibited a more significant response to air temperature. In a arid and semi-arid condition WBGT index also overrated the heat stress level (Heidari et al., 2018). Taking the contrary view, Farshad et al., (2014) have argued that climate like Iran WBGT index is suitable to measure heat stress of the construction worker and experimental results closely matched with ISO 7243 standard. Miller & Bates (2007) claimed that TWL is better in both artificial chamber and outdoor working sites than the WBGT index. TWL considered air velocity very intensively and there is no boundary to predict work intensity, which WBGT can’t. Brake & Bates (2002) also agree on the validity (up to 380Wm-2) and applicability of TWL, that is focused on personal sensibility. Table 2 represents the value of TWL and WBGT in diverse climatic areas and groups of people. Chan et al. (2013) study also supports the previously mentioned statement on the TWL index used in Hong Kong. Due to some limitations of the WBGT index, TWL is a logically better one, which is simple and clear to understand. The validity of the TWL heat stress model was found to be satisfactory (90% accuracy).

| Samples                     | Heat stress indices |
|-----------------------------|---------------------|
|                             | WBGT (°C)          | TWL (Wm⁻²) |
| Random samples (Australia)  | 31.7               | 154        |
| Construction worker (Iran)  | 26.5               | 161.5      |
| Index                       | WBGT (°C)          | TWL (Wm⁻²) |
|                             | 24                 | 175        |

3.5 Existing models and limitations

Present models have been criticized for various reasons like less metabolic rate, cloth insulation, not suitable for the outdoor diverse climate or for over or underestimation of the thermal concessions. WBGT-index is most widely used to assess heat stress level but in high humidity and low airflow index cannot evaluate the heat stress level accurately, and don’t consider occupants physiological aspects. PHS model is more appropriate but hard to understand for general people. PMV is criticized because of the over and underestimation of sensation and it considers the inadequate metabolic rate to assess the thermal sensation.

4. Conclusion

This review demonstrates an evidence base addressing the appropriateness of models varies on the various climatic zone. To progressively reduce occupational injuries proper evaluation of heat stress and
precisely define thermal comfort is an important issue and ineluctable matter. Existing indices are not suitable for all climatic zones and sometimes it’s a matter of debate. Indices are focused on varied aspects like environmental variables or physiological or psychological and some are concerned any two of them together. Results from studies in this review sufficiently indicate a strong relationship between thermal comfort and heat stress indexes with climatic areas, which could be varying with participants. There is a probability to cause errors if we pay attention to all aspects at a time. Researchers need to pay attention to assess the possible fittest (valid and easy to apply) index at least based on each climatic area.

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