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EVALUATION OF HUMAN THERMAL COMFORT AND HEAT STRESS IN AN OUTDOOR URBAN SETTING IN SUMMER UNDER ARID CLIMATIC CONDITIONS

Thermal sensation and heat stress potential were evaluated in summer in an outdoor arid environment. Such evaluation had never been made in arid regions. Various scales: the temperature-humidity index (THI), physiological effective temperature (PET), universal thermal climatic index (UTCI) and standard effective temperature (SET*) were used for the evaluation. RayMan software model was used to estimate the PET and SET* and the UTCI-calculator was used for UTCI. The required air dry and wet bulb temperatures (T_d, T_w), solar radiation flux (S_0) and wind speed (V) were measured in summer (April 29–July 15). The results showed that: Persons are exposed to strong heat stress and would feel very hot most of the day time; and they are safe from heat stress risk and would feel comfortable most of the night time. Heat stress levels can be determined using the PET or UTCI scales; both are valid for arid environment and their results are almost similar; however, the THI cannot be used. SET* index specifically describes the thermal sensations and discomfort conditions along with summer days at any activity under arid conditions.

1. INTRODUCTION

Human thermal comfort is defined as a condition of mind which expresses satisfaction with the surrounding environment. High temperatures and humidity provide discomfort sensations and sometimes heat stress (i.e. reducing the body's ability to cool itself). Moreover, discomfort and heat stress reduce productivity of workers and may lead to more serious health problems, especially for aged persons. In hot summer seasons of arid regions, high outdoor air temperatures due to intensive solar radiation and

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low relative humidity are present. Consequently, discomfort sensations and heat stress are strongly expected. Human thermal comfort may not be attainable most of time during the day in summer of arid environment Therefore; persons should take care when they go outside in hot summer to protect their health from heat and/or sunstroke.

Since the 1950s, human thermal comfort and heat stress under indoor (i.e., in residential, industrial, commercial and institutional buildings) and outdoor conditions have been discussed exhaustively in several studies [1–15]. They concerned the thermal comfort and/or heat stress for worldwide regions other than arid regions. Various scales for thermal comfort and heat stress have been established in the form of numerical relations or graphs. For a long time, the temperature-humidity index (THI), and the wet bulb-globe temperature (WBGT) were used for evaluating heat stress levels; and the predictive mean vote (PMV) was used for evaluating human thermal comfort. However, determining the WBGT requires specific measurements and it is quite difficult to perform such measurement for long time to get total evaluation for summer season. In addition, the range of PMV scale is limited (i.e., from –3 – very cold to +3 – very hot) [4]; and it cannot be applied for arid climate having extremely high air temperatures and low relative humidity in summer ($T_d > 40$ °C, $RH < 15\%$). Under such conditions, the high extremity of T_d as well as T_{mrt} need universal heat stress indices to be used for evaluating the human thermal sensation and heat stresses. The suitable heat stress indices could be summarized in the following:

- The physiological effective temperature (PET) and the universal thermal climatic index (UTCI) are used for evaluating thermal comfort and heat stress as well; both are in temperature scale. PET is a thermal index that gives an estimation of the thermal sensation and the corresponding heat stress level. PET is based on the Munich energy-balance model for individuals (MEMI) and a two node model, not being constrained by a steady state approach, PET is applicable for both the indoor and outdoor environment studies [14]. Several advantages of using PET as reported by [14] include: (i) it is a universal index; irrespective of clothing (clo values) and metabolic activity (met values), (ii) it gives the real effect of the sensation of climate by human beings, (iii) it is measured in °C and so can be easily related to common experience, and (iv) it is useful in both hot and cold climates thus it can be applied successfully in the arid environment (high temperature and low relative humidity). PET can be calculated simply using the RayMan software, which is made freely available by its authors. The RayMan model avoids all the complications of the two node model and takes simple inputs, i.e., the air dry bulb temperature (T_d), relative humidity (RH), wind velocity (V) and mean radiant temperature (T_{mrt}) or global solar radiation flux (S_0) [16]. The RayMan model is valid for hot and sunny climate in which, values of T_{mrt} exceed 60 °C at around noon. Ranges of PET in °C for different grades of thermal perception by human beings are reported in [17].
- The universal thermal climatic index (UTCI) was developed for characterizing thermal stress. It is an equivalent temperature for a given combination of wind, radia-

tion, humidity and air dry bulb temperature. The associated assessment scale for the UTCI was developed from the simulated physiological responses and comprises 10 categories: extreme cold stress – very strong cold stress – strong cold stress – moderate cold stress – slight cold stress – no thermal stress – moderate heat stress – strong heat stress – very strong heat stress – extreme heat stress [18]. The UTCI was designed for wide ranges of activity, clothing resistance, and climatic conditions. UTCI can be calculated simply by using the UTCI calculator, which is made freely available by its authors at [19]. The input parameters to this calculator are the air dry bulb temperature (T_d), relative humidity (RH) and the temperature difference ΔT ($\Delta T = T_{mrt} - T_d$).

- The standard effective temperature (SET*) index describes the relationship between thermal sensation (TSENS) and discomfort (DISC). SET* is the most appropriate way for comparing thermal sensation, discomfort and physiological effect of a wide range of environmental situations, clothing and activity levels including outdoor extreme weather conditions [20]. The SET* and T_{mrt} can be calculated using the RayMan software model if the global solar radiation flux (S_0) is available as an input parameter.

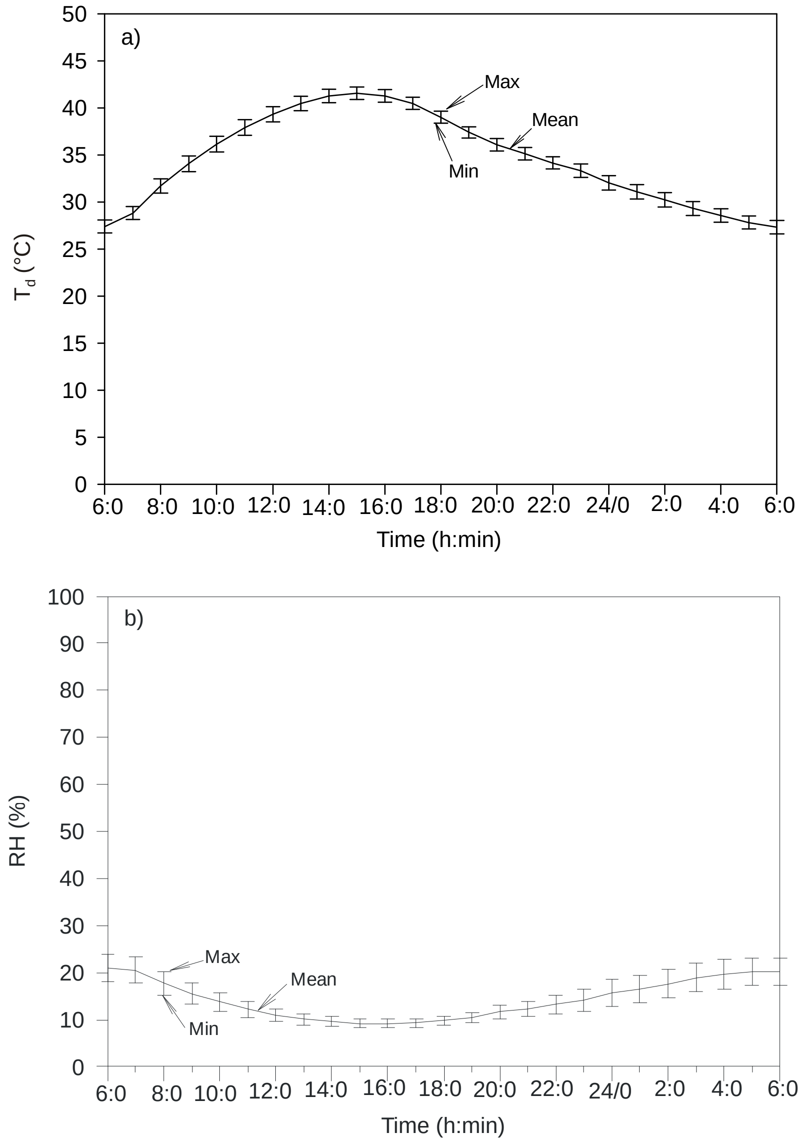
Survey of previous studies revealed that most of these studies focused on the environmental conditions for human occupancy either indoor or outdoor to evaluate the human thermal comfort and heat stress potential in various areas worldwide. However, the comfort conditions under arid climate (e.g. in the Arabian Peninsula) had never been evaluated. Accordingly, evaluation of heat stress and human thermal comfort in an urban setting under arid environment such as in the Arabian Peninsula, is urgently needed. This study aims to evaluate human sensations and heat stress levels in hot summer by: (i) describing the mean sensations of persons in the outdoor arid environment and (ii) evaluating the level of risks due to heat stress potential. The mean values of T_d, RH and S_0 was estimated for an entire day (day and night time) representing the period from April 29 to July 15, 2010. These data for an assumed day represents the weather conditions in summer season. Several indices (i.e., THI, PET, UTCI and SET*) were used to examine the applicability of using these scales for arid environment in summer.

2. THEORTICAL BACKGROUND

Factors affecting human thermal comfort and heat stress level can be classified as follows:

- Environmental factors such as the dry bulb temperature of air and its relative humidity (T_d and RH), air current speed (V) and the mean radiant temperature of the surrounding (T_{mrt}). The latter is defined as that uniform temperature of an imaginary black enclosure in which a person would have the same radiation exchange with the actual environment.

• Physiological factors such as the body metabolic heat generation rate (M in met, 1 met = 58.15 $W \cdot m^{-2}$) which depends on different factors such as personal activity, sex, age, nationality and type of clothing. Therefore, these factors vary between individuals. Accordingly, many statistical studies have been performed on large numbers of persons of all ages, gender, nationalities and activities to examine the human body responses to environmental conditions and to arrive at a quantitative description of human thermal comfort.



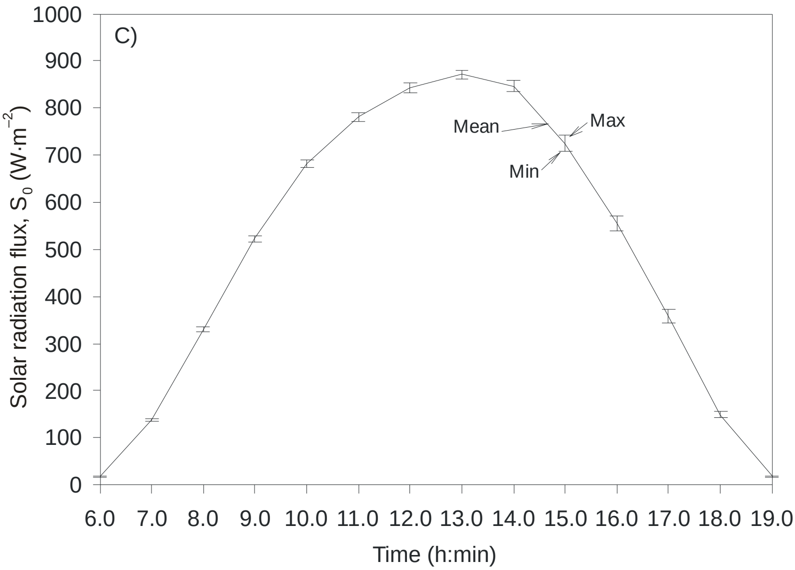


Fig. 1. Time courses of the maximum, minimum and mean values of the environmental parameters measured in the outdoor, in summer (from April 29 to July 15, 2010) in the central region of Riyadh for: a) air dry bulb temperature (T_d), b) relative humidity (*RH*) and c) global solar radiation flux (S_0)

Thermal scales for human mean sensation to the environment were developed based on human body energy balance under comfort conditions (e.g. PET, UTCI and SET*). In which, the rate of energy generated by a human's body (*M*) should equal the rate of energy needed for the external mechanical work (*W*) plus the rate of energy release from the body through respiration, evaporation, convection and radiation. The thermal efficiency (η) of individual human bodies, as an engine, ($\eta = W/M$), was estimated to be ≤20% on average [8]. Therefore, a person should lose heat at the rate of ($M - W$) in order to be comfortable. In the present study, values of T_{mrt}, *PE* and SET* in °C were calculated by the RayMan software model. The input parameters were the mean values of T_d, *RH* and S_0 (Fig. 1). In addition, the body input parameters: human activity (*M* value), clothing factor (0.6 clo), sex (male), height (175 cm) and weight (80 kg) were used in the analysis.

Heat exchange between the clothing surface of the body and surrounding is by radiation, convection, evaporation due to sweating, skin diffusion, respiratory evaporative heat, and respiratory convective heat loss. Human in the outdoor or indoor exposed to a heating load that depends mainly on the difference between the surface temperature of clothing (T_{cl}) and the mean radiant temperature (T_{mrt}). T_{cl} is affected by the body and the surrounding conditions and it is impossible to be measured directly. Therefore, T_{cl} is usually computed iteratively according to [4, 9] using the following equation:

$$T_{cl} = 35.7 - 0.028(M - W) - 3.69 \times 10^{-8} I_{cl} F_{cl} \times \left[(T_{cl} + 273)^4 - (T_{mrt} + 273)^4 \right] - I_{cl} F_{cl} h_c (T_{cl} - T_d) \tag{1}$$

where I_{cl} is the insulation resistance of the entire clothing (e.g., I_{cl} = 0.093 °C·m^2·W^{-1} for outdoor clothes). F_{cl} is the ratio of the clothed to the naked body area (F_{cl} = 1.2 on average) and h_c is the convective coefficient between the clothing surface and the surrounding air (W·m^{-2}·°C^{-1}) and is given as [4, 7, 8]:

$$h_c = \text{max\_of} \begin{cases} 2.38\left(T_{cl} - T_d\right)^{0.25} & \text{for free convection} \\ 12.1\sqrt{V} & \text{for forced convection} \end{cases} \tag{2}$$

3. EXPERIMENTAL MEASUREMENTS

The experiments were conducted in the outdoor on the Agricultural Research and Experiment Station, Agriculture Engineering Department, King Saud University (the central region of Riyadh, Saudi Arabia, 46°47′ E, longitude and 24°39′ N, latitude). The measurements of environmental parameters were carried out from April 29 to July 15, 2010 (i.e., air dry bulb temperature, T_d, relative humidity, RH and global solar radiation flux, S_0). The measured data were taken every 10 s, averaged and recorded at every 10 min in a data logger (CR-23X Micrologger), and then averaged at every one hour. The time courses of the maximum, minimum and mean values of T_d, RH and S_0 during a day in the period of measurements are shown in Fig. 1a–c. In these figures, the deviations between the mean and the maximum and minimum values of each T_d, RH and S_0 were small, and then choosing the mean values for a day is acceptable to represent the environmental conditions in summer season. Dry and wet bulb temperatures (T_d, T_w) were measured using an aspirated psychrometer. The psychrometer had two type-T thermocouples (copper–constantan of 0.3 mm in diameter). The psychrometer was calibrated and the error was ≤ 1.2% for a dry bulb temperature up to 100 °C. RH was calculated by substituting the measured values of T_d and T_w in psychrometric relations reported in [21]. The daily average of air speed (V) was estimated based on the available metrological data to be around 0.5 m·s^{-1}, on average, during summer (from April 29 to July 15, 2010). The global solar radiation flux was measured by using CMP3-Pyranometer (Kipp & Zonen B.V., Inc., USA), having a maximum error of ±2%, a working temperature range from –40 °C to 80 °C, and the wavelength range of 310–2800 nm.

4. RESULTS AND DISCUSSION

In summer of arid regions, existing high air temperature (Fig. 1a), low relative humidity (Fig. 1b) and intensive solar radiation flux (Fig. 1c) make the levels of heat stress risks and the uncomforted sensation are expected in the outdoor. During 24 h in a summer season (from April 29 to July 15, 2010), the maximum, minimum and mean values of T_d, *RH* and S_0 were estimated.

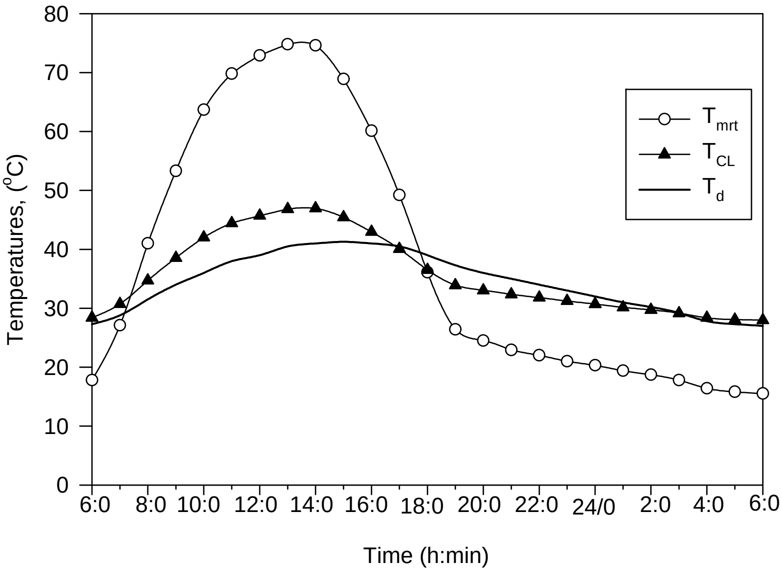


Fig. 2. Time dependence of the mean dry bulb temperature of air (T_d) and the corresponding mean radiant temperature (T_{mrt}), and clothing temperature (T_{cl}) estimated in the outdoor under hot sunny summer conditions (April 29–July 15, 2010), in the central region of Riyadh

The main source of discomfort and heat stress is the heat load exchange between the persons and their surroundings through radiation and convection modes. Radiation exchange depends on the difference, to the power four, between the mean radiant temperature (T_{mrt}) and clothing surface temperature (T_{cl}); and the convection exchange depends on the difference between T_{cl} and the dry bulb temperature (T_d) of air. The time dependences of the T_{mrt} and T_{cl} (predicted using Eq. (1)) and the T_d are shown in Fig. 2. During the day time, T_{mrt} was much higher than T_{cl} except for short periods around sunrise and sunset. Therefore, human's body always experiences a positive heat radiation load (i.e., heat gain). During the night time, T_{mrt} was lower than T_{cl} causing a negative radiation heat load (released from the body). On the other hand, T_{cl} was relatively higher than T_d during the day time, causing a negative convective heat released from the body. However, the convection exchange is minor during the night time. Radiation heat load has the dominant effect because the temperature difference ($T_{mrt} - T_{cl}$) is much higher than ($T_d - T_{cl}$).

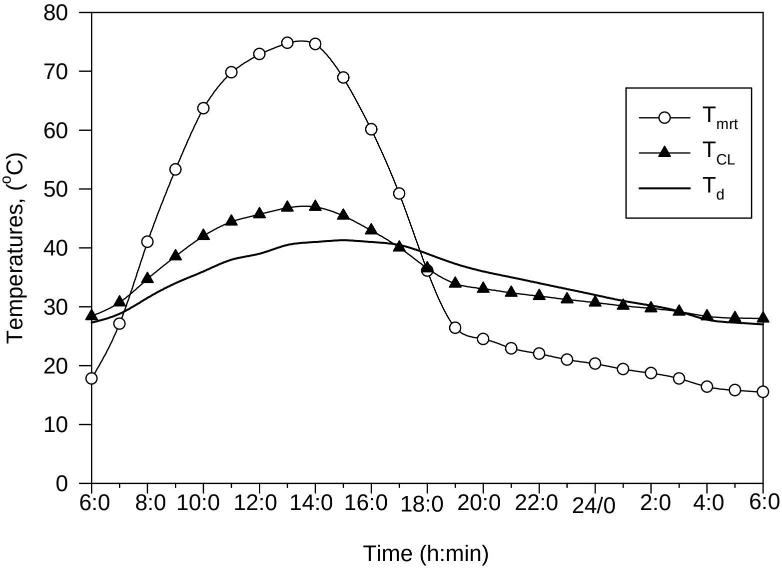


Fig. 3. Time dependence of the physiological effective temperature (PET) estimated in the outdoor in hot summer conditions (April 29–July 15, 2010) in the central region of Riyadh

Figure 3 shows the time dependence of the PET (°C) indicating the mean sensations of persons and the corresponding level of heat stress along with a day in summer. A person would feel very hot during most of the day (9:30 am–5:00 pm). In the morning and during the night times, the mean sensations are distributed on the figure as slightly warm, warm and hot. Accordingly, under such weather conditions, persons would never feel comfortable even during most of the night time. Although, the PET is a universal scale, irrespective of the clothing and level of activity. However, a slight increase in the level of activity (up to about met = 3) can improve thermal comfort sensation due to the increase of sweating and respiration rates. For more specific details, the SET* index was calculated by the RayMan software model, as the PET, based on the mean values of T_d, RH and S_0 in a summer day. Unlike PET and UTCI indices, the SET* depends of the level of activity (met value). The time course of the SET* in a summer day was illustrated in Fig. 4 for various levels of activities (M = 1, 2 and 3 met). The thermal sensation (TSENS) and the discomfort conditions (DISC) were also illustrated. In general, increasing the level of activity slightly reduces the heat stress level and did not improve the comfort conditions. At low activity (m = 1 met), persons would feel comfort in the morning and most of the night times. Increasing the activity reduces the time of comfort sensation. Under arid conditions, persons in the outdoor would feel hot, very hot and unacceptable hot during most of the day time according to Fig. 4.

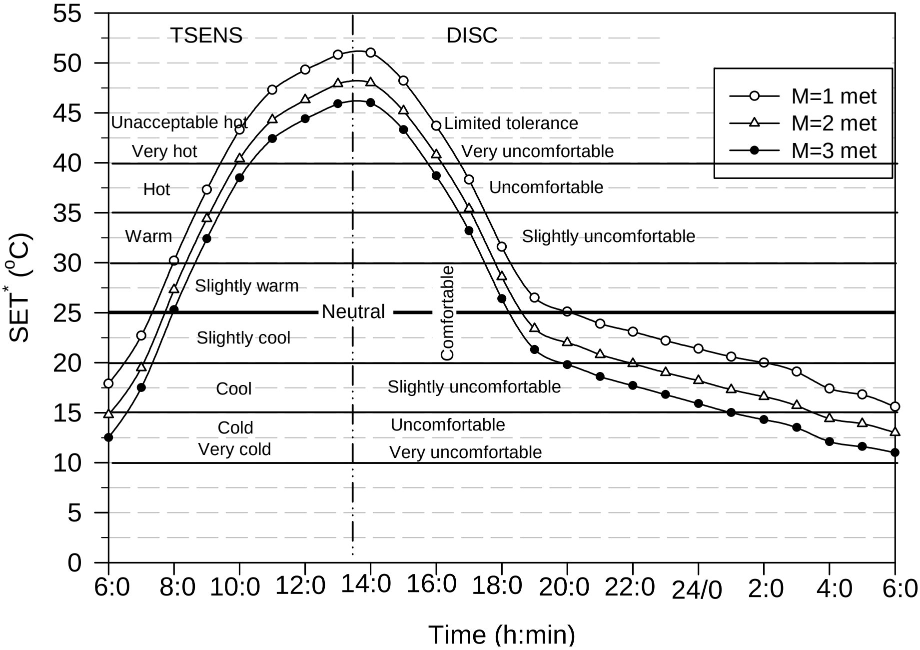


Fig. 4. Time dependence of the standard effective temperature (SET*) estimated in the outdoor in hot summer conditions (April 29–July 15, 2010) in the central region of Riyadh

The time course of the universal thermal climatic index (UTCI) is shown in Fig. 5. This index was estimated using the UTCI-calculator based on the mean values of T_d and RH during a summer day (Fig. 1a, b) and the temperature difference, ($T_{mrt} - T_d$). Based on the UTCI values in Fig. 5, the distribution of the heat stress levels is almost similar to those in Fig. 3. Accordingly, either PET or UTCI index can be used to describe heat stress under arid environment. However, the SET* index provides more specific distribution of thermal sensation (TSENS) and comfort conditions (DISC) along with the day and night times.

A simple combination of temperature and relative humidity, (i.e., the temperature-humidity index, THI), had been proposed for long time to measure heat stress. The THI in °C in function of the dry bulb temperature (T_d in °C) and the relative humidity (RH%) was calculated [7] by:

$$\mathrm{THI} = T_d - 0.55\left(1 - \frac{RH}{100}\right)\left(T_d - 14.44\right) \quad (3)$$

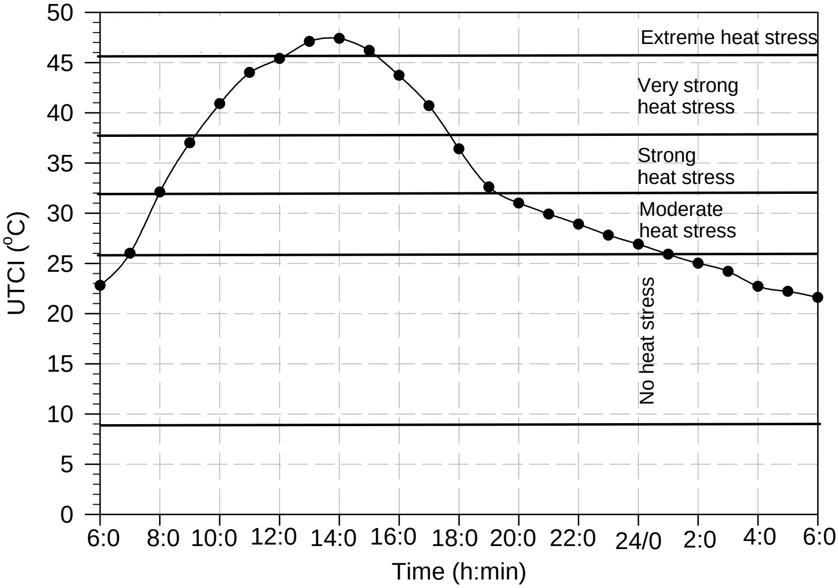


Fig. 5. Time dependence of the universal thermal climatic index (UTCI) estimated in the outdoor in hot summer conditions (April 29–July 15, 2010) in the central region of Riyadh

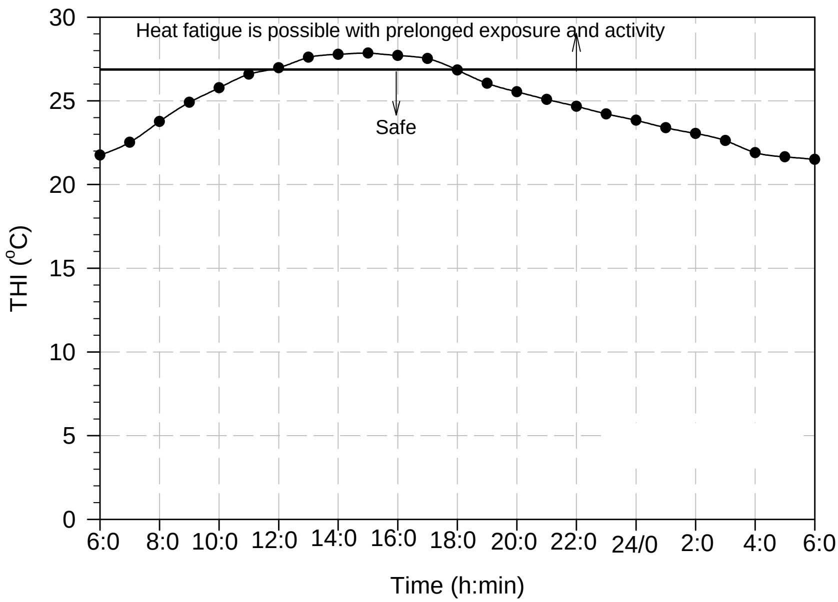


Fig. 6. Time dependence of the temperature-humidity index (THI) estimated in the outdoor in hot summer conditions (April 29–July 15, 2010) in the central region of Riyadh

The time course of the THI based on the mean values of T_d and *RH* (Fig. 1a, b) is shown in Fig. 6. Persons are safe most of the day and all tight times, and are exposed to moderate heat stress at around noon. Comparing the THI to the PET, SET* and UTCI values in Figs. (3)–(5), the conclusion based on THI is impossible. Accordingly, the THI failed to clearly describe the heat stress levels along with a hot summer day and cannot be applied for arid environment.

5. CONCLUSION

Evaluation of human thermal comfort and heat stress in summer under arid climatic conditions has been presented. Outdoor urban environment was selected for the study. The main conclusions from this study could be summarized as follows:

On hot sunny summer, individuals in the outdoor environment would feel very hot and uncomfortable most of the day time, especially at around noon; and the heat stress risk is expected during most of the day time. However, individuals are safe (no heat stress) and would fell comfort most of the night time.

At around solar noon, the extremity of heat stress risks and unacceptable hot sensation provide very uncomfortable conditions. Under such conditions, persons should take care in the outdoor with and without activities.

The PET or the UTCI scale can be used for the arid environment to evaluate heat stress potential and their results are almost similar. The SET* index is an optimum index to specifically describe the thermal sensations and discomfort conditions along with summer days with any activity. However, the THI cannot be used, at all, to describe heat stress levels under arid environment.

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