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Research Article

Human Thermal Comfort and Heat Stress in an Outdoor Urban Arid Environment: A Case Study

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To protect humans from heat stress risks, thermal comfort and heat stress potential were evaluated under arid environment, which had never been made for such climate. The thermal indices THI, WBGT, PET, and UTCI were used to evaluate thermal comfort and heat stress. RayMan software model was used to estimate the PET, and the UTCI calculator was used for UTCI. Dry and wet bulb temperatures (T_{d}, T_{w}), natural wet bulb temperature (T_{nw}), and globe temperature (T_{g}) were measured in a summer day to be used in the calculation. The results showed the following. (i) The thermal sensation and heat stress levels can be evaluated by either the PET or UTCI scales, and both are valid for extremely high temperature in the arid environment. (ii) In the comfort zone, around 75% of individuals would be satisfied with the surrounding environment and feel comfortable during the whole day. (iii) Persons are exposed to strong heat stress and would feel uncomfortable most of the daytime in summer. (iv) Heat fatigue is expected with prolonged exposure to sun light and activity. (v) During the daytime, humans should schedule their activities according to the highest permissible values of the WBGT to avoid thermal shock.

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 low relative humidity are present. Consequently, discomfort sensations and heat stress are expected. 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 under indoor conditions (i.e., in residential, industrial, commercial, and institutional buildings) and outdoor conditions have been discussed exhaustively in several reports, for example, [1–15]. These studies concerned the thermal comfort and/or heat stress for worldwide regions other than arid regions. Different scales for thermal comfort and heat stress have been established in the form of numerical relations or graphs. Among these scales, the temperature-humidity index (THI) and the wet bulb-globe temperature index (WBGT) are used for heat stress for long time ago. Recently, the physiological effective temperature (PET) and the universal thermal climatic index (UTCI) are used for 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 the following (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 so it can be applied successfully in arid environment (high temperature and low relative humidity). PET can be calculated simply by RayMan software, which is made freely available by its authors. RayMan model avoids all the complications of the two-node model and takes simple inputs, that is, 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_o) [16]. 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].

Another scale was developed (i.e., the universal thermal climatic index (UTCI)) as an equivalent temperature for a given combination of wind, radiation, humidity, and air dry bulb temperature. The associated assessment scale for the UTCI was developed from the simulated physiological responses and comprises 10 categories that range from extreme cold stress to 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, and extreme heat stress [18]. The UTCI can be calculated simply by using the UTCI calculator, which is made freely available by its authors in [19]. The input parameters to this calculator are the air dry bulb temperature (T_d), relative humidity (RH), and the temperature difference ΔT, ($\Delta T = T_{mrt} - T_d$).

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 different 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. One entire day (daytime and nighttime) was considered (May 8-9, 2012); that day represents, to some extent, the weather conditions in summer season. Several indices (i.e., THI, WBGT, PET, and UTCI) were evaluated to examine the applicability of using these scales in the arid environment.

2. Theoretical Background

Factors affecting human thermal comfort can be classified as follows.

(i) 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 surroundings (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. Value of T_{mrt} (°C) can be calculated by measuring T_d (°C) and the globe temperature T_g (°C) and using the relation reported in [6, 7] as

$$T_{mrt} = \sqrt[4]{\left(T_g + 273\right)^4 + \frac{h_{cg}}{\varepsilon_g \sigma}\left(T_g - T_d\right)} - 273, \quad (1)$$

where ε_g is the emissivity of the black globe (i.e., $\varepsilon_g = 0.95$), σ is the Stefan-Boltzmann constant, and h_{cg} ($\mathrm{Wm^{-2}\,{}^\circ C^{-1}}$) is the convective heat transfer coefficient between the black globe surface and the surrounding air. This coefficient can be estimated as in [6, 15] by

$$h_{cg} = \max\_\text{of} \begin{cases} 6.3\dfrac{(V)^{0.6}}{D^{0.4}}, & \text{forced convection,} \\ 1.4\left(\dfrac{T_g - T_d}{D}\right)^{0.25}, & \text{free convection,} \end{cases} \quad (2)$$

where D is the diameter of the black globe sensor (0.15 m). In the present study the free convection was considered because the wind speed was low ($<0.5\,\mathrm{m\,s^{-1}}$) during the experiment.

(ii) Physiological factors such as the body metabolic heat generation rate (M in met, $1\,\text{met} = 58.15\,\mathrm{Wm^{-2}}$) which depends on different factors such as personal activity, gender, 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. Thermal scales for human mean sensation to the environment were developed based on human body energy balance under comfort conditions, 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 a rate of ($M - W$) in order to be comfortable.

Thermal loss from the clothing surface of the body to the surroundings is by radiation, convection, evaporation due to sweating, skin diffusion, respiratory evaporative heat, and respiratory convective heat loss. Humans in the outdoor or indoor are exposed to a heating load that depends mainly on the difference between the surface temperature of clothing (T_{cl}) in °C and the mean radiant temperature (T_{mrt}) in (1). Value of the T_{cl} is affected by the body and the surrounding conditions, and it is impossible to be measured directly.

Therefore, value of T_{cl} is usually computed iteratively using the following equation [4, 9]:

$$\begin{aligned} T_{cl} = {} & 35.7 - 0.028\,(M - W) \\ & - 3.69 \times 10^{-8} I_{cl} F_{cl} \left[(T_{cl} + 273)^4 - (T_{mrt} + 273)^4 \right] \\ & - I_{cl} F_{cl} h_c \,(T_{cl} - T_d), \end{aligned} \quad (3)$$

where I_{cl} is the insulation resistance of the entire clothing (e.g., $I_{cl} = 0.093^\circ\mathrm{C\,m^2\,W^{-1}}$ for outdoor clothes). F_{cl} is the ratio of the clothed body area 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 ($\mathrm{Wm^{-2}\,{}^\circ C^{-1}}$) and is given by [4, 7, 8] as

$$h_c = \max\_\mathrm{of} \begin{cases} 2.38 (T_{cl} - T_d)^{0.25}, & \text{free convection} \\ 12.1 \sqrt{V}, & \text{forced convection.} \end{cases} \quad (4)$$

In summer of arid regions, human thermal comfort may not be attainable most of the time during the day. Under such conditions, the high extremity of T_d as well as T_{mrt} requries universal heat stress indices to be used for evaluating the human thermal sensation and the levels of heat stress. The suitable heat stress indices are the PET and UTCI. These scales can be calculated by using RayMan software and UTCI calculator (free available by their authors).

However, apart from the availability of software there are two heat stress indexes that can be calculated simply by using two simple relations (i.e., the temperature-humidity index, (THI) and wet bulb-globe temperature (WBGT)). These scales have been used successfully for long time ago. The THI in degree °C is given by [20, 21] as

$$\mathrm{THI} = T_d - 0.55 \left(1 - \left[\frac{\mathrm{RH}}{100} \right] \right) (T_d - 14.44), \quad (5)$$

in which T_d is in °C and RH in %.

The levels of risks corresponding to given heat stress were classified according to the THI values and are reported in [21] as follows: THI $<$ 27°C (safe); 27°C $<$ THI $<$ 32°C (heat fatigue is possible with prolonged exposure and activity); 32°C $<$ THI $<$ 41°C (sunstroke and heat exhaustion are possible with prolonged exposure and activity); 41°C $<$ THI $<$ 54°C (sunstroke and heat cramps are possible), and THI $>$ 54°C (sunstroke, heat stroke and heat confusion, or delirium is possible).

The WBGT (°C) is an index of heat stress imposed on the human body by the thermal environment. It is a combination of dry bulb temperature, air current speed and relative humidity of air and radiation [20]. The WBGT can be calculated using a correlation proposed by ISO-7234 standard for the outdoor conditions (in the presence of solar radiation) and is given by [20] as

$$\mathrm{WBGT} = 0.7 \left(T_{nw} \right) + 0.2 \left(T_g \right) + 0.1 \left(T_d \right), \quad (6)$$

where T_{nw} (°C) is the natural wet bulb temperature (i.e., commonly measured with a thermometer that is covered with a moist, white muslin wick and exposed to the atmosphere without ventilation or shading) and T_g (°C) is the globe temperature (i.e., commonly measured with a temperature probe placed in the center of a blackened, hollow copper sphere). Both T_{nw} and T_g are passively exposed to the ambient environment, whereas dry bulb temperature (T_d) is usually measured by an aspirated psychrometer.

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). An experiment was conducted on the same location to measure the environmental parameters to be used for other purposes; it was from April 29 to July 15, 2010. The maximum, minimum, and mean values of air dry bulb temperature (T_d) were depicted in Figure 1. In this figure, the deviation between the mean and the maximum and minimum values of T_d was small, and then choosing one day in the present experiment is acceptable to represent the conditions of summer season. Accordingly, the current experiment was carried out during a complete day (day and nighttime) in a summer season (May 8-9, 2012) to measure the required environmental parameters to be used in the calculation of T_{mrt}, T_{cl}, THI, WBGT, PET, and UTCI. The measured data were taken every 10 seconds, averaged and recorded at every one minute in a data logger (CR-23X Micrologger), and then averaged at every one hour. The measured parameters were as follows. (i) Dry and wet bulb temperatures (T_d and T_w) using aspirated psychrometer. The psychrometer had two type-T thermocouples (copper constantan of 0.3 mm in diameter). The psychrometers were calibrated, and the error was ≤1.2%°C for a dry bulb temperature up to 100°C. (ii) Globe temperature (T_g) using black globe thermometric probe (BST131) having a globe diameter of 0.15 m, a time response of 20 min, surface reflectance ≤2%, a working temperature range of −50°C–80°C and a measuring error of ±0.5%°C for a dry bulb temperature up to 80°C. (iii) Natural wet bulb temperature (T_{nw}) using a type-T copper constantan thermocouple of 0.3 mm in diameter, whose junction was covered with a moist, white muslin wick and kept exposed to the ambient. RH in (5) was calculated by substituting the measured values of T_d and T_w in psychrometric relations reported in [22]. The daily average of air speed (V) was estimated based on the available metrological data to be around 0.5 m s^{-1}.

4. Results and Discussion

In summer it is important to evaluate heat stress and human thermal comfort to avoid risks that may occur to persons in the outdoor in arid regions. Figure 2 illustrates the time course of the measured meteorological parameters (i.e., T_d, T_g, RH, and S_o). In this figure, because of the intensive solar radiation flux (S_o), the dry bulb temperature of air (T_d) reaches 40°C, the globe temperature (T_g) exceeds 50°C at around noon, and the relative humidity (RH) drops below

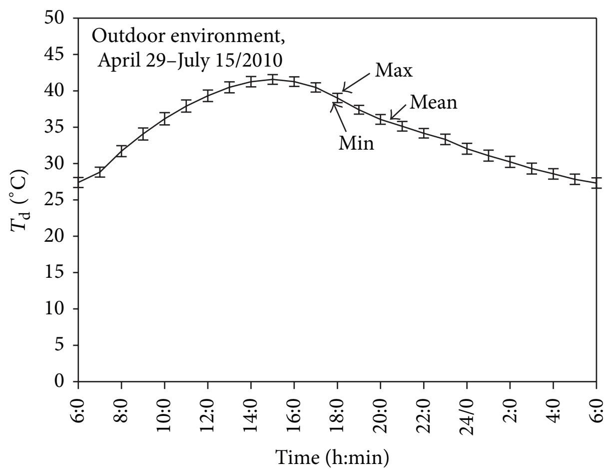

FIGURE 1: Time course of the minimum, maximum, and mean values for the dry bulb temperature (T_d) of air measured, in the outdoor, from April 29 to July 15, 2010, in the central region of Riyadh.

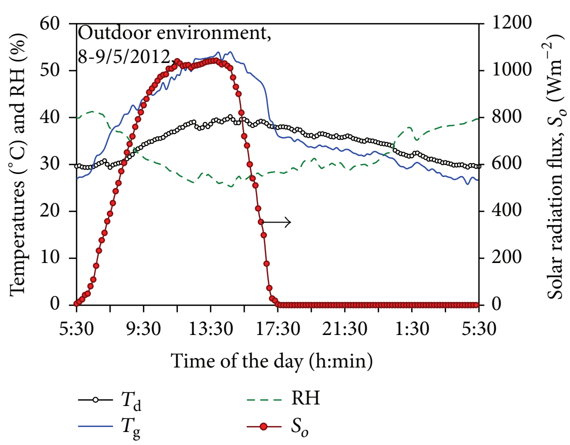

FIGURE 2: Time course of the environmental parameters measured, in the outdoor, in a hot sunny summer day (May 8-9, 2012), in the central region of Riyadh.

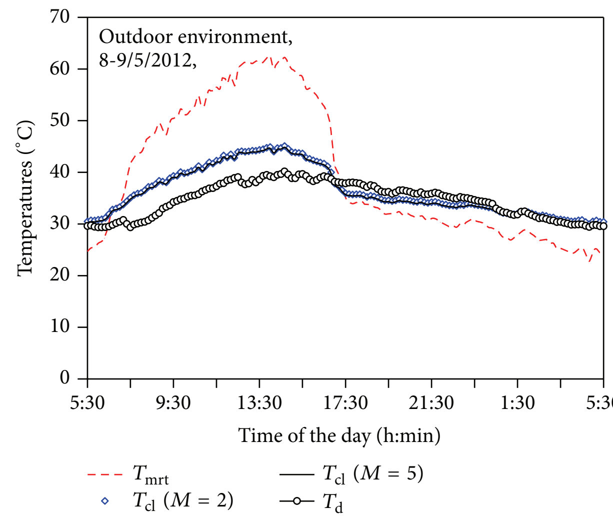

FIGURE 3: Time course of the mean radiant temperature (T_{mrt}), clothing temperature (T_{cl}) estimated at different activities and dry bulb temperature of air (T_d) in the outdoor in a hot sunny summer day, in the central region of Riyadh.

30%. During the nighttime, values of T_g drop below T_d due to the effect of the night cooling of the globe surface (i.e., emission to sky).

The main source of discomfort and heat stress is the heat load exchanges between the persons and their surroundings through radiation and convection modes. Radiation exchanges depend 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 courses of the T_{mrt} and T_{cl} predicted using (1) and (3) and the T_d are illustrated in Figure 3. This figure shows that during the daytime, T_{mrt} was much higher than T_{cl} except for short periods around sunrise and sunset. Therefore, the human body always experiences a positive heat radiation load (i.e., they have a net heat gain). During the nighttime, T_{mrt} was relatively 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 daytime, causing a negative convective heat released from the body. However, the convection exchange is minor during the nighttime. Radiation heat load has the dominant effect because the temperature difference ($T_{mrt} - T_{cl}$) is much higher than ($T_d - T_{cl}$). In addition, variation of person's activities showed no significant effects on the clothing surface temperature.

Figure 4 illustrates the time course of the simply calculated index (THI) and T_d in that day (May 8-9, 2012). Even though the air temperature level (T_d) is high and could reach about 40°C around noon, this index indicated that persons are safe from heat stress risks before noon (up to 11:30) and during the nighttime. This is because the relative humidity (RH) is low (see Figure 2) and the combination between T_d and RH (1) produces the safe conditions to humans. From 11:30 up to sunset, heat stress is expected with activities. However, this index gives only an expectation of heat stress as a whole without details that show the different levels of risk during this time (from 11:30 to sunset).

Figure 5 illustrates the time course of the WBGT index during the whole day in the outdoor. According to the predicted values of the WBGT in this figure, several types of activities can be done safely during summer because the high temperature in this region is allocated with low relative humidity. However, the level of activity (light, medium, or heavy) and the work-rest time should be distributed along with the daytime according to the permissible value of the WBGT to avoid risks of thermal stresses and discomfort sensation. A classification of different levels of activity that can be done and the corresponding highest permissible value of the WBGT was reported in [7, 23, 24]. A person who follows these instructions will be safe in the outdoor in summer.

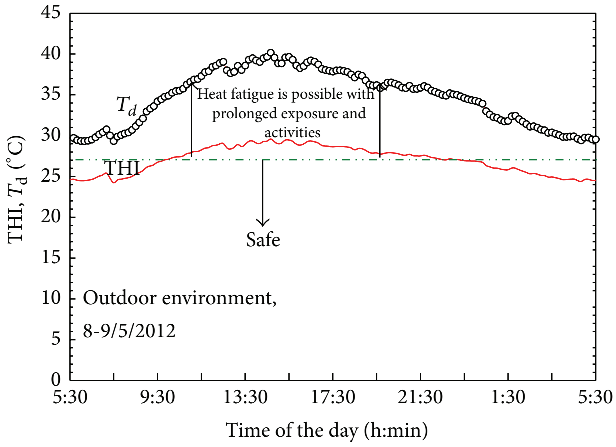

Figure 4: Time course of the temperature-humidity index (THI) estimated in the outdoor in a hot sunny summer day, in the central region of Riyadh.

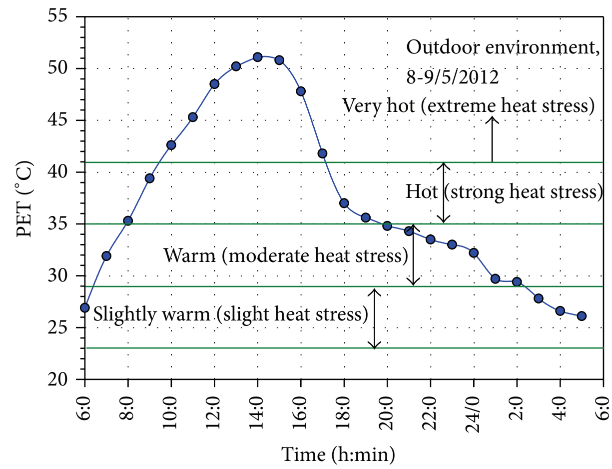

Figure 6: Time course of the physiological effective temperature (PET) estimated in the outdoor in a hot summer day in the central region of Riyadh.

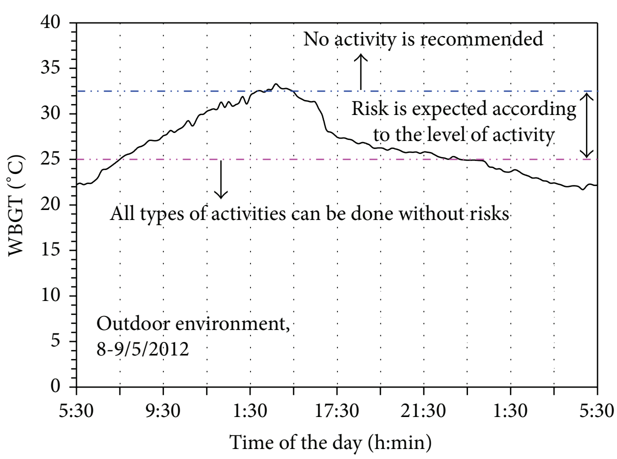

Figure 5: Time course of the wet bulb-globe temperature index (WBGT) estimated in the outdoor in a hot sunny summer day, in the central region of Riyadh.

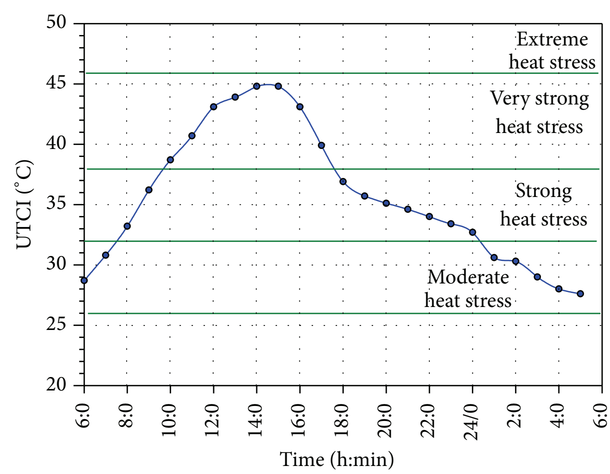

Figure 7: Time course of the universal temperature climatic index (UTCI) estimated in the outdoor in a hot summer day in the central region of Riyadh.

Figure 6 shows the time course of PET indicating the mean sensations of persons and the corresponding level of heat stress along with the day of measurement. A person would feel very hot during most of the day (9:30 am–5:00 pm). In the morning and during the nighttime, the mean sensations are distributed on the figure as slightly warm, warm, and hot. The PET is a universal index, irrespective of the clothing and level of activity. However, increasing the level of activity will provide more comfort sensation due to the increase of sweating and respiration rates.

The time course of the universal thermal climatic index (UTCI) is illustrated in Figure 7; this index was estimated by using the UTCI calculator. Based on the UTCI values in Figure 7, the distribution of the thermal sensation and the corresponding heat stress is almost similar to that in Figure 6. Accordingly, both PET and UTCI indices can be used successfully for the arid environment.

In addition to the PET, the outputs of RayMan software also include the predicted mean vote scale (PMV). Thus, the corresponding value of the predicted percentage of dissatisfied (PPD) can be calculated using the well-known exponential relation reported in [4]. In general, for different levels of activities ($M = 1-5$), values of the PMV were plotted against the values of the PPD in Figure 8. This figure showed that even within the comfort zone that was illustrated in the figure, about 25% of the individuals would be dissatisfied and dislike the environment and about 75% of them would feel comfortable and satisfied with the surrounding environment.

5. Conclusion

Evaluation of human thermal comfort and heat stress in a summer day (May 2012) under arid climatic conditions was presented. Outdoor urban environment was selected for

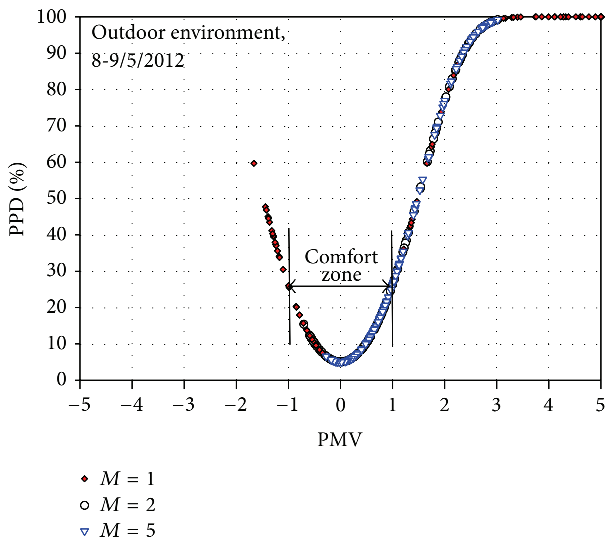

Figure 8: The predicted mean vote (PMV) against the predicted percentage of dissatisfied (PPD) estimated at different levels of activities under the outdoor conditions in a hot sunny summer day in the central region of Riyadh.

the study. The main conclusions from this study could be summarized as follows.

(i) On hot sunny summer days, individuals in the outdoor environment would feel very hot and uncomfortable most of the daytime, especially around noon. Heat stress is expected during most of the daytime; however, activities can be done without risks, and persons are safe from heat stress if they scheduled their activities according to the permissible values of the WBGT index.

(ii) During most of the day, heat fatigue is expected with prolonged exposure to solar radiation and activities.

(iii) Both the PET and UTCI scales can be used successfully for the arid environment to evaluate the thermal sensation, and heat stress and their results are almost similar.

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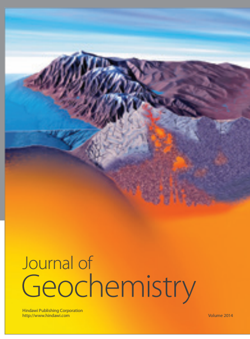

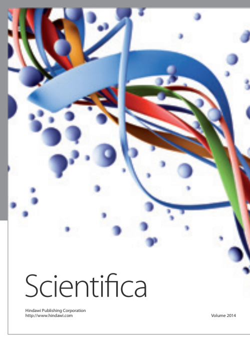

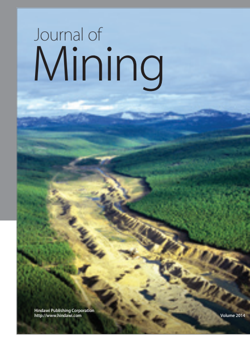

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