Psychrometric chart as a basis for outdoor thermal analysis

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Abstract

 Preparing thermal comfort conditions in outdoor public spaces is one of the considerations of architectural design. If the constructed area does not support comfortable conditions in outdoor spaces, it will cause microclimatic problems for pedestrians and adjacent buildings. Regarding the different thermal comfort conditions in outdoor spaces in comparison with indoor, several indices have been produced for outdoor thermal analysis during recent decades. The different methodology and approach to these indices have provided a diverse set of responses to thermal prediction of outdoor spaces. This diversity has made it difficult for architects to decide how to use these indices in outdoor design strategies. To provide a same basis to compare these results, this article will introduce each index with its definition, its basic calculation method, and its thermal condition categories. Following these information a psychometric chart that is provided by the author, shows its thermal categories as a graphic method. Using this psychometrics for thermal analysis will make it easy to compare different indices and their outdoor thermal predictions. Those architects, who are familiar with Building Bioclimatic Chart of Givoni for analyzing indoor thermal conditions, will find this method easy and practical for analyzing outdoor thermal condition by choosing an appropriate index.

Keywords: Outdoor thermal indices, Thermal zone, Psychrometric chart, Building bioclimatic chart, Microclimate, Heat stress, Cold stress

1. Introduction

 Inside the building -where the architectural design is incapable of achieving human thermal comfort - it is possible to provide comfort by using HVAC systems; despite the fact thatit is based on using fossil energy and leads to environmental impact. However, if the outdoor design does not support thermal situations, it will cause great problem, because there is not any HVAC solution. Howcan an architect find an appropriate prediction for outdoor thermal situation, is the main goal of this article.

 One of the pioneers who prepared a graph to predict pedestrians' outdoor comfort zone is Penwarden. In 1975, he introduced his graph (Fig 1) according to his comprehensive field studies in UK [1]. This graph that had been used for several years shows the needed periods for sunshine, shade and wind according to metabolic rate of pedestrian with suitable seasonal clothes. It was, basically, prepared for UK and is appropriate for semi-humid to moderate climates. Therefore, it does not give any recommendation for very hot or very cold

conditions. Moreover, Penwarden's graph does not consider humidity effect on thermal condition for arid zones – where evaporative cooling plays a great role. That is why it needs to be modified according to its shortcuts on the one hand and the new knowledge of outdoor thermal conditions on the other hand. Going toward an appropriate outdoor thermal index that will be used for all climatic situations such as hot/arid, hot/humid, cold/arid, cold/humid and moderate climate is the aim of all the researches that have been done in recent decades.

 Some main questions that can help target this aim are as follows:

 1. What are the most important parameters affecting human thermal sensation in outdoor spaces?

 2.What are the main thresholds of different thermal conditions in outdoor spaces?

 3. What are the most important parameters that will help modify the tolerable and dangerous thermal conditions for a longer exposure time?

 4. How is it possible to help architects use all these knowledge in making design decisions?

1.1. Effective Elements on Outdoor Thermal Condition

 According to definition of thermal comfort as a "condition of mind" or "objective sensation" [3], expectation and

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"Penwarden standard"
considers human
thermal comfort by
paying attention to:

- **Climatic elements:**
  - **temperature, wind**
    speed and solar
    radiation;
- **human factors:**
  - **Metabolic rates and**
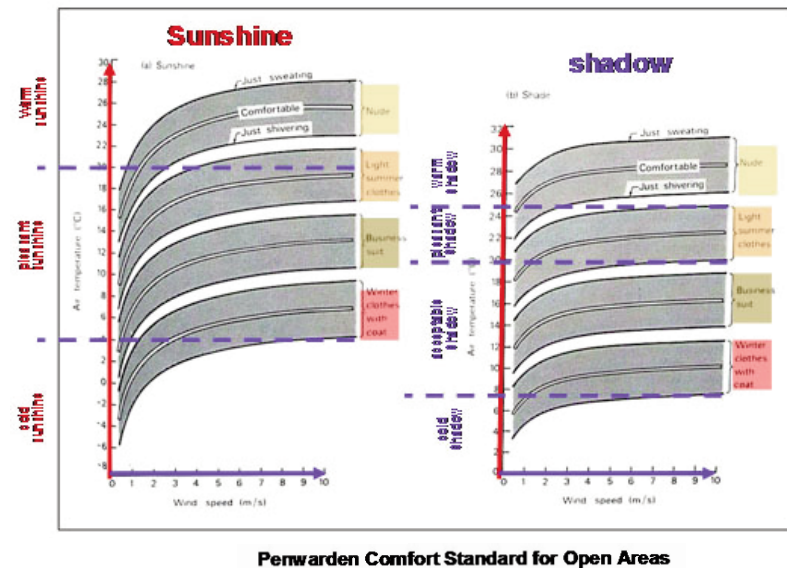   **clothing insulation**

Fig. 1. Penwarden Comfort Graph [1, 2]

acceptability of thermal sensation would not be the same in outdoor and indoor spaces. For example, a sedentary person with light clothing and light activity (with low metabolic rate) inside the building expect ideal comfort condition, while when he/she is wearing a suitable seasonal clothing and is walking outdoor (with higher metabolic rate), tolerable weather condition seems acceptable to him/her. That is why the thermal comfort investigations for indoor and outdoor is divided in two different branches and introduces different indices.

The aim of indoor thermal control is to provide a perfect comfort condition by the help of passive, hybrid or HVAC systems (design and technology). In outdoor spaces, it is impossible to provide an ideal thermal comfort. Therefore, the aim is to provide a tolerable thermal condition, increase the exposure time to longer period and decrease thermal risk.

Several investigators have stated that human comfort level depends on different elements which could be divided into two main objective and subjective parameters [4, 5 and 6]. Objective parameters are environmental and physiological parameters. Environmental elements are parameters such as land characteristics (Topography, altitude, latitude, longitude and surfaces coverage) and Meteorological parameters (Temperature, wind, humidity and solar radiation). physiological parameters are related to body condition such as age, gender and health that are quantified by body temperature, skin temperature (forehead, hand), heart rate, sweat production and shivering rate.

Subjective parameters are behavioral and psychological parameters. Behavioral elements are parameters as Personal parameters (human activity rate and cloths' clo) and cultural parameters(costumes and habits like feeding pattern, rest and work timetable and so on). Psychological parameters are related to adaptation and acclimatization that are defined as preference, expectation, acceptability and habitation.

According to Fanger's model, [7] that is known as steady state, only some of the effective elements are calculated for thermal comfort evaluation: Four meteorological parameters (including air temperature, humidity, wind speed and solar radiation) and two human parameters (including activity rate and clo value of clothing). In this model, comfort condition is defined by theoreticalcal culations and laboratory tests. It is claimed that this model is universal, because it eliminates the acclimatization and all its related parameters. It considers human thermal balance as a steady state condition and human as a passive receiver.

Fountain & Huizenga (1997) reported that, nowadays, to improve this model, some other human parameters such as forehead and hand temperature, sweating and shivering rate are taken into consideration for evaluating human thermal sensation. [5]

1.2. Outdoor Thermal Indices

Many of the research studies on thermal comfort have two objectives:

a. To find a way of describing the thermal environment which correlates well with human response, thus enabling reliable predictions to be made, and

b. To define the range of conditions found to be pleasant or tolerable by the population concerned.[9]

Therefore, in outdoor spaces, three thermal zones could be defined:

1. Comfort zone is the condition referring to when the weather is fine. This kind of weather does not need any changes to become pleasant.

2. Tolerable zone is the condition referring to when the weather is not pleasant, but physiologically is tolerable by human body. It is possible to bring it into comfort zone by some changes in outdoor microclimate (such as providing sunshine or shade, preparing cooling draught or shelter of wind chill, preparing evaporative cooling of water and green surfaces) and/or changing human condition (such as clothing, metabolic rate, drinking cold or warm drinks, limiting the outdoor exposure time). (Fig 2 and 3)

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Fig. 2. different solutions to make tolerable warm zone more comfortable
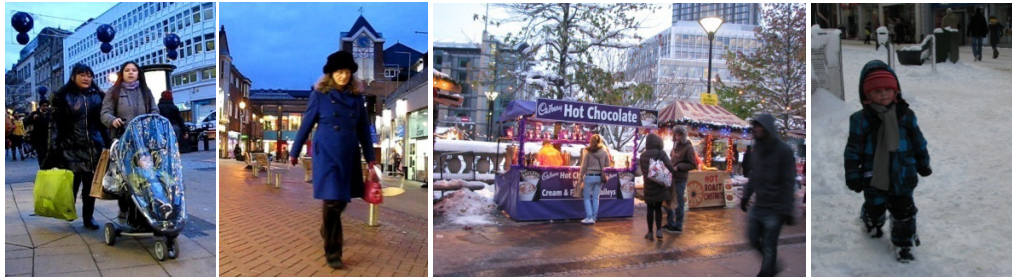

Fig. 3. different solutions to make tolerable cold zone more comfortable

3. Dangerous zone is the condition referring to when the body will go through the physiological heat or cold stress. The humidity may turn to the intolerable dryness or sultry condition. Presence in outdoor area is limited to a short exposure time.Longer exposure time will be dangerous and may cause exhaustion or heat stroke in hot weather and frostbite or hypothermia in cold weather. (Fig. 4)

According to outdoor thermal conditions, laboratory researches have proposed several indices for outdoor thermal condition analysis. The first group of indices is based on thermal stress model. Heat stress indicessuch as heat index (HI), Humidex, Tropical Summer Index (TSI), Discomfort Index (DI) and Wet Bulb GlobeTemperature (WBGT) are provided for hot conditions. Cold stress indices such as Wind chill Index (WCI) and Wind Chill Equivalent Temperature (WCET) are provided for cold conditions. Some of outdoor indices are prepared base on heat budget model. They are capable to evaluate both cold and hot conditions such as Perceived Temperature (PT), Temperature Humidity Index (THI), and Physiological Equivalent Temperature (PET). The latest index is based on comprehensive heat budget model of human biometeorology, called Universal Thermal Climate Index (UTCI). It has been provided by a group of specialists [8]. It is supposed to cover all the shortcomings of the other indices.

1.3. Research method

Introducing outdoor thermal indices and comparing them in the basis of a drawing method - for all outdoor thermal conditions (comfortable, tolerable and dangerous) - is the aim of this research. In this way all accessible thermal indices that are prepared for analyzing thermal conditions in open areas will be considered.

At first step, the indices are categorized according to the fundamental model that is thermal stress model and heat budget model. For each index, the way of preparation and the basic assumptions, considering climatic elements, calculation method and the main thermal zones are introduced.

At second step, thermal zones of several outdoor indices are converted on a psychometric chart. Converting all the indices on psychometric chart will have several advantages. Firstly: a Psychometric chart covers the important climatic elements

Fig. 4. Dangerous zone with short time exposure

except the wind and the sunshine. Therefore, it is a good base for comparing all the outdoor indices to find out their similarity and differences in the same conspectus. Secondly: It will become similar to Givoni's "Building Bioclimatic Chart" [10, 11] that shows thermal conditions inside the building and proposes passive, active or HVAC solutions on psychometric chart (Fig 5). Thirdly: It is easy for architects to show temperature and humidity data of a place on psychometric chart and find out the climatic needs in a period of a pattern year in both outdoor (open areas) and indoor (inside buildings) simultaneously. Consequently, in a short time, without being involved with professional studies of "Thermal Comfort", it is possible to achieve the main climatic design requirements.

2. Thermal Stress Models

2.1. Heat Stress Models

  Some of outdoor thermal indices are those which evaluate heat stress. Heat stress is the effect of excessive heat on the body, and the inability of the body to get rid of the excess heat fast enough to maintain an internal temperature balance. Sweating is a sign that the body is functioning normally to maintain its heat level [12]. There are two types of heat stress: heat exhaustion and heat stroke. The signs and symptoms of heat exhaustion are headache, nausea, vertigo, weakness, thirst, and giddiness. Fortunately, these conditions respond readily to prompt treatment. Heat stroke occurs when the body's system of temperature regulation fails and body temperature rises to critical levels. This condition is caused by a combination of highly varying factors, and its occurrence is difficult to predict. Heat stroke is a medical emergency [13]. The factors that may contribute to heat stroke are some environmental factors, workload, heavy clothing and physical condition,dehydration, infection, weak cardiovascular condition, age and prescription drugs [4]. The aim of heat stress indices is to evaluate the level of heat stress and give guidance for a safe presence in outdoor places according to the exposure time.

2.1.1. Heat Stress Index
  A heat stress index is a single value that integrates the effects of the basic parameters in any human thermal environment such that its value will vary with the thermal strain experienced by the individual [14]. This non-dimensional index was defined as the ratio of the net heat load on the body
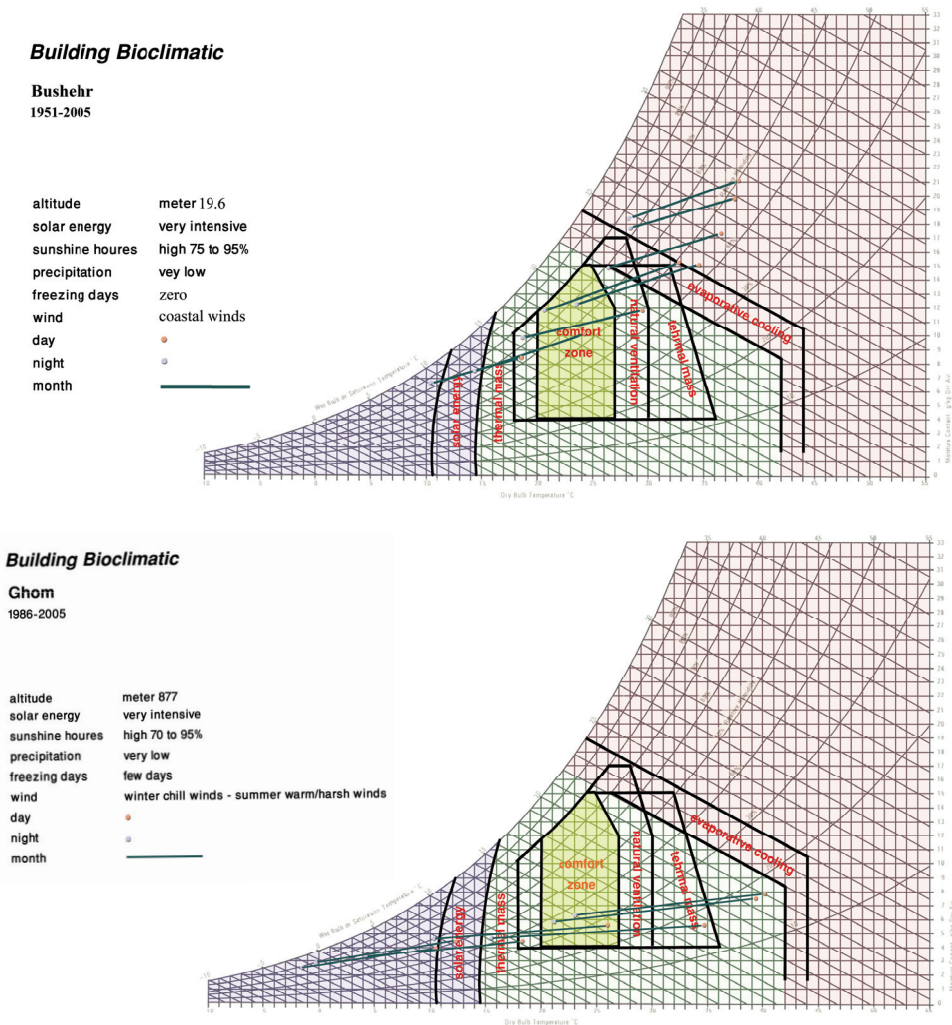

Fig. 5. Givoni's building bioclimatic chart for Bushehr (left) and Ghom (right) [2]

to the maximum evaporative heat loss possible from the skin surface to the environment. Heat stress index (HSI) was introduced by Blending and Hatch in 1956 as an index of environmental thermal strain [15]. It was completed as General heat stress index in recent years and is used in National Weather Service public forecasts of USA as apparent temperature. The General Heat Stress Index (GHSI), also referred to as the apparent temperature, is a measure of how the hot air "feels" to an average person based on the temperature and the humidity. It does not take into account direct sunshine, wind, or the type of clothing a person is wearing. [12]

NOAA's National Weather Service Weather Forecast Office has generated an online calculator for Heat Index and dew-point. For using this calculator valid entries are: air temperatures greater than 27°C, dew point temperatures greater than 16°C, and relative humidity higher than 40%. [16]

The General Heat Stress Index uses four categories related to "apparent temperature" to the probable occurrence of heat-stress-related injury (shadow condition) as shown in table 1.

Exposure to full sunshine can increase heat index values by up to 8°C. The time of exposure is an important factor in that situation. Some organizations have recommended heat stress exposure limits such as "Heat stress card" [17]. The thermal zones of Heat Stress Index are shown on psychometric chart Fig 6.

2.1.2. Humidex

The humidex, devised by Canadian meteorologists, was first used in 1965. The purpose was to create an easily understood method of describing how very hot and humid weather feels to an average person. The humidex combines the temperature and humidity into one number to reflect the perceived temperature. The humidex remains a useful, and very popular due to the

simplicity of the, means of determining how hot it actually feels outside. The humidex is similar to the heat index but is widely used in Canada (where the heat index is mostly used in USA). An online Canadian Humidex Calculator is available [18]. Humidex does not account for solar radiation. Degree of comfort and discomfort of Humidex is introduced in table 2.

An extremely high humidex is over 40. In such conditions, all unnecessary activities should be curtailed. If the reading is in the mid to high 30s, then, certain types of outdoor exercises should be toned down or modified. If working outdoors is an absolute necessity, drink plenty of liquids and taking frequent rest breaks is required. In hot, humid conditions, there is a considerable risk of heat stroke and sun stroke [18]. Fig 7 shows Humidex thermal zones on psychometric chart.

2-1-3- Wet Bulb Globe Temperature (WBGT)

The wet-bulb globe temperature (WBGT) is by far the most widely used heat stress index throughout the world. It was developed in the US Navy as part of a study on heat related injuries during military training. This index is recommended by many international organizations for setting criteria for exposing workers to a hot environment and was adopted as an

Table. 2. Degree of comfort and discomfort of Humidex [18]

Humidex (°C)	Degree of comfort and discomfort
Less than 29	Little or no discomfort
30 to 34	Noticeable discomfort
35 to 39	Evident discomfort
40 to 45	Intense discomfort; avoid exertion
45 to 54	Dangerous discomfort
Above 54	Heat stroke probable

Table 1. Four categories heat stress related injury [12]

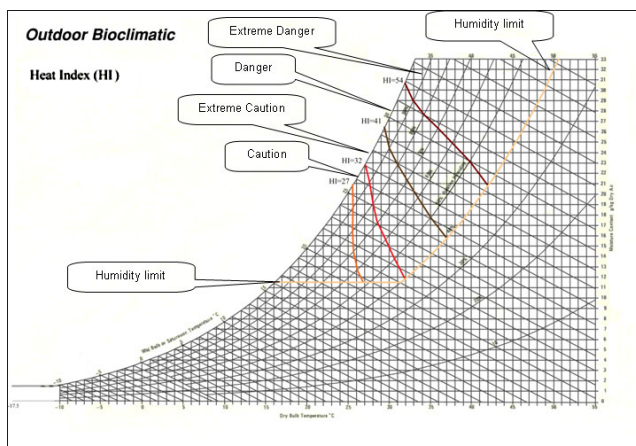| HI (°C)	Heat stress level
27–32	Caution (fatigue is possible with prolonged exposure and activity)
32–41	Extreme caution (sunstroke, heat cramps, and heat exhaustion are possible)
41–54	Danger (sunstroke, heat cramps, and heat exhaustion are likely; heat stroke is possible)
Over 54	Extreme danger (heat stroke or sunstroke are likely with continued exposure)

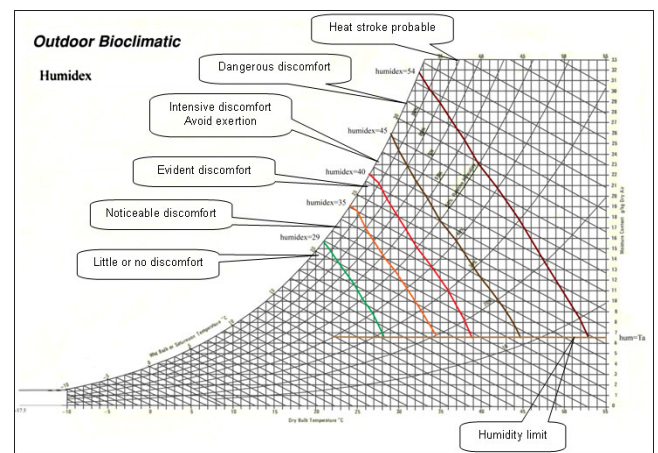**Fig. 6.** Heat index (HI) - thermal zones on psychrometric chart [2]

Fig. 7. Humidex - thermal zones on psychrometric chart [2]

ISO standard[19]. WBGT is a function of all four environmental factors (air temperature, air movement, radiant temperature and air humidity) affecting human environmental heat stress [20]. WGBT is developed for traditional work uniform of long sleeved shirt and pants with and without solar load. An adjustment factor is provided for some other clothing ensembles [4].

The Wet Globe Kit [21] utilizes the WBGT index to measure the potential heat stress risk. The WBGT Index accounts for the impact that direct sunlight has on the subject. The Wet Globe Kits include three thermometers to measure three different environmental factors as dry bulb DB), wet bulb (WB) and black globe (BG) temperature. WBGT is calculated using the following formula:

WBGT Index = 0.7 WB + 0.2 BG + 0.1 DB

A conversion table is provided to determine WGBT according the temperature and humidity [22]. WGBT thermal zones are introduced in table 3.

In hot areas, some US military installations display a flag to indicate the heat category based on the WGBT.if the WBGT reference value of 25°C is not exceeded, it could be concluded that heat stress was not a risk in that environment [23]. Fig 8

shows the thermal zones of Wet-Bulb Globe Temperature (WBGT) on psychometric chart.

2.1.4. Discomfort Index (DI)

The discomfort index (DI), is the only index beside the WBGT that is in daily use for more than 4 decades. The DI was originally proposed by Thom (1959) and was slightly modified by Sohar et al (1963) as follows: [24, 25]

DI=0.5T_w+0.5T_a

Where: T_w refers to wet temperature and Ta refers to air temperature (dry bulb temperature). Although DI does not account directly for radiation, is easy to use and is in use in Israel very satisfactorily. In its present form, the DI correlated to sweat rate, both, at rest and under exercise, reflecting its physiological significance. [14]

The following criteria shown in table 4 were established to characterize the environmental heat stress and correlate thermal sensation.

Calculation of DI for different wet and dry bulb temperatures help find the important zones of DI on psychometric chart. Fig 9 shows the thermal zones of Discomfort Index (DI) on psychometric chart.

2.1.5. Tropical Summer Index (TSI)

The Tropical Summer Index (TSI) is prepared by Sharma & Sharafat (1986) and it is appropriate for hot-dry and warm humid conditions [27]. It is produced by simultaneous observations of thermal sensations. the prevailing environmental conditions were taken by 18 young male adults fully acclimatized, over a period of three consecutive summer seasons in India from the months of May to July. Through the

Table 3. WGBT thermal zones [23]

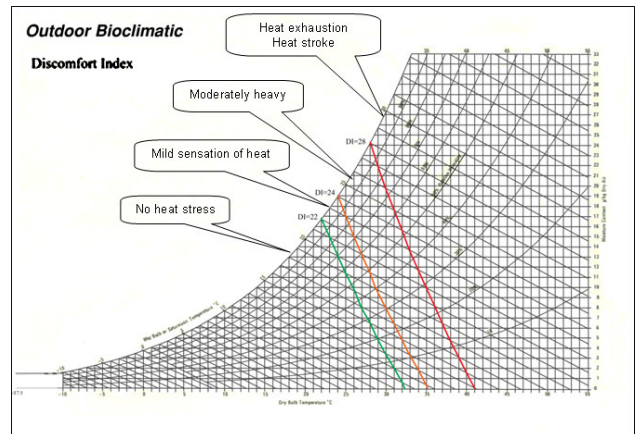| WBGT	Thermal zones
20-25	caution
25-32	extreme caution
32-39	danger
above 40	extreme danger
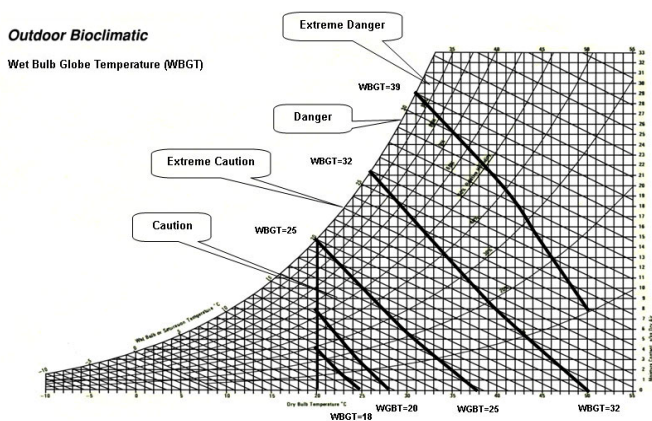
Fig. 8. Wet Bulb Globe Temperature (WBGT) - thermal zones on psychrometric chart [2]

Fig. 9. Discomfort Index (DI) - thermal zones on psychrometric chart [2]

Table 4. DI thermal zones [25, 26]

DI values	Thermal sensation
under 22	no heat stress is encountered
22–24	most people feel a mild sensation of heat
24–28	the heat load is moderately heavy, people feel very hot, and physical work may be performed with some difficulties
above 28	the heat load is considered severe, and people engaged in physical work are at increased risk for heat illness (heat exhaustion and heat stroke)

observations and multiple regression analysis, an equation has been found expressing the thermal sensation in terms of the environmental variables. From the equation, an index of thermal comfort, called "Tropical Summer Index" has been developed which compares very well with several existing indices.

"Tropical Summer Index" (TSI) is defined as the air/globe temperature of the still air at 50% RH which produces the same overall thermal sensation as the environment under investigation. This index takes into account all four environmental variables (air temperature, globe temperature, humidity, air velocity) in proportion to their influence on the thermal sensation. Use of the TSI is justified in the prevailing hot-dry and warm-humid conditions in India when radiant flux is not excessively high and the subjects have sufficient air motion for any visible perspiration to evaporate off.

Determining the thermal comfort conditions in this index is according to observations of four effective environmental variables and Bradford's five scales thermal sensation. A simple and approximate equation for the rapid determination of TSI values for any combination of environmental variables is as follows:

$$TSI = 1/3\ t_w + 3/4\ t_g - 2\ V^{1/2}$$

Where: TSI = Tropical Summer Index, t_w= Wet-bulb Temperature (°C), t_g = Globe temperature (°C), $V^{1/2}$ = Square root of air velocity (m/s)$^{1/2}$.

It is seen that the values of TSI almost agree for all practical purposes, over the wide range(24-40 °C). Ranges and optimum values of TSI for the middle three thermal sensations are shown in Fig 10[27]. For the sake of diagrammatic presentation, the lines of equal TSI are drawn on the psychometric chart. For this presentation the globe temperature is assumed to be synonymous with the dry-bulb temperature. The reduction in TSI for some selected wind speeds is shown as an inset in the diagram. The extended area of comfort condition is shown in the chart below according to the ranges and optimum values of TSI for the middle three thermal sensations.
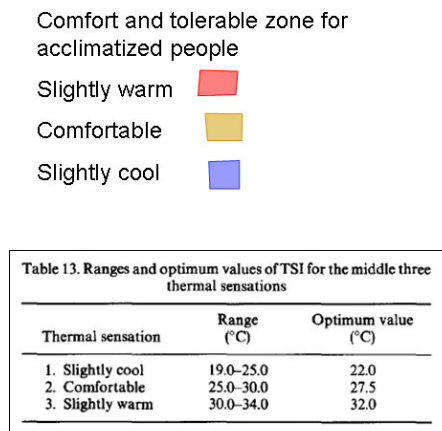
2.1.6. Summer Outdoor Comfort Zone

Another graph prepared for outdoor tropical locations is produced by Ahmed (2003). The comfort zone inthe shade is derived from the field study conducted in summer conditions in the city of Dhaka, a city in wet-Tropics. Hence, the lower threshold for comfort may vary in the winter season due to seasonal adaptation. The zone is derived for people involved in activity of 1 Met wearing 0.35-0.5 Clo under shaded conditions. The shaded area outlines the comfort zone under still conditions. The comfort zone indicates the influence of the airflow in increasing the tolerance to higher relative humidity. [28]

A dynamic outdoor comfort model is developed, which includes all the environmental factors identified in this work. The model includes, among others, conventionally accepted factors, thermodynamic effect of the airflow and issues of radiation. Fig 11 shows the summer outdoor comfort zone in a graph of temperature and relative humidity. As usual, thermal zones of this graph are shown on psychometric chart. (Fig 12)

2.2. Cold Stress Models

Generally, coldness is related to the actual lowering of the internal body temperature by loss of heat from the exposed flesh. Just as the temperature alone is not a reliable indicator of how hot a person feels the temperature of the air is not
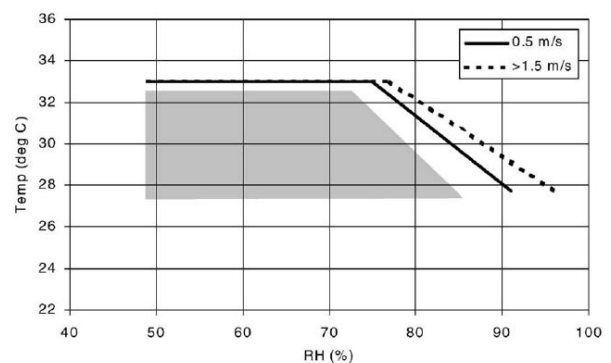

Fig. 11. Summer outdoor comfort zone for tropical locations [28]

Comfort and tolerable zone for acclimatized people

Slightly warm ▮

Comfortable ▮

Slightly cool ▮

Table 13. Ranges and optimum values of TSI for the middle three thermal sensations		
Thermal sensation	Range (°C)	Optimum value (°C)
1. Slightly cool	19.0–25.0	22.0
2. Comfortable	25.0–30.0	27.5
3. Slightly warm	30.0–34.0	32.0

Fig. 10. Tropical Summer Index (TSI) - thermal zones on psychometric chart [27]
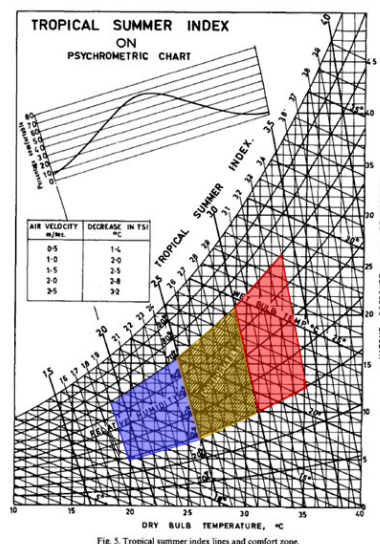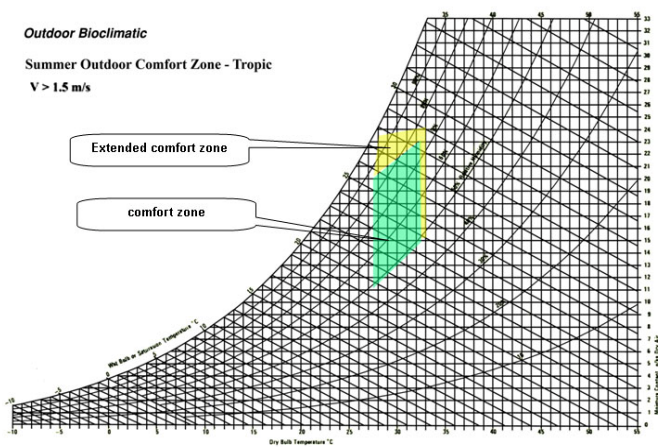
Fig. 12. Tropical summer outdoor comfort zone on psychrometric chart [2]

always a reliable indicator of how cold a person feels. Increased wind speeds may increase the rate of evaporation of moisture from exposed skin areas.

This not only will make a person "feel" cooler, but will actually lower the skin temperature, and consequently, the body temperature.

The two primary dangers to people exposed to the cold are frostbite and hypothermia. Frostbite is freezing of the skin, which damages the skin and the underlying flesh. Hypothermia is lowered internal body temperature due to prolonged exposure to cold air or immersion in cold water. Frostbite may cause only localized tissue death; but hypothermia, if not reversed, will kill people. [12]

2.2.1. Wind Chill Indices

Wind chill is the apparent temperature felt on exposed skin due to the combination of air temperature and wind speed. The wind chill temperature (often popularly called the "wind chill factor") is always lower than the air temperature. When the apparent temperature is higher than the air temperature, the Heat index (HI) is used instead. Nowadays, in daily weather news, wind chill factor and heat index are pronounced as feeling temperature. [29, 30]

Wind Chill Index (WCI) was introduced by Siple and Passelin 1945. In mid 1970s, the Wind Chill Equivalent Temperature was introduced as a revision of the wind chill index. New wind chill equivalent temperature (WCET) is the latest version of the wind chill that was introduced in 2007 [31, 48].

The wind chill equivalent temperature (also called the wind

chill index, the wind chill factor, or just plain wind chill), is the temperature required under no-wind conditions that will equal the cooling effect of the air (the actual air temperature) and the wind on an average size, nude person in the shade. Moisture content of the air, visible moisture on the skin or clothing, presence of sunshine, clothing, and physical activity are not considered [12]. The Wind Chill Equivalent Temperature was originally the air temperature at which the Wind-chill Index would be the same if the wind was calm, which for practical purposes was set to be 4 m/h [mile/hour] (1.8 m/s) in 1964. Wind chill equivalent temperatures could only be calculated for wind speeds higher than this limit [20].

In new resources for the reference still-air condition, the calculation assumes a minimum air speed of 1.34 m/s, which is the average walking speed of American pedestrians, young and old, crossing intersections in studies of traffic light timing [31].

Environment Canada's World Wide Web Site has provided an online calculation for the wind chill. Temperature more than 5°C and wind speed less than 5 km/h is not accepted by this calculator [32]. According to the new Wind Chill Equivalent Temperature (WCET), these conditions can be defined. [31]:

- The wind chill index does not happen (calculated) when the temperature is more than 5°C and the wind speed less than 5 km/h (1.4 m/s)
- The average person's skin begins to freeze at a wind chill of -25°C, and freezes in minutes at -35°C [51].
- In most of southern Canada, wind chill is included in the forecast when it reaches -25°C, the point where frostbite becomes a risk. A wind chill warning is issued when conditions become hazardous.

The wind chill index does not take into account the effect of sunshine. Bright sunshine may reduce the effect of wind chill (make it feel warmer) by 6 to 10 units. Bright sunshine can make you feel as much as ten degrees warmer. Here, online calculation for WCET is done according to different wind speeds. The hazardous WCET (-25 and -35°C) is calculated for important limits of wind speed such as 1.4 m/s and 5 m/s (10 m/s gust), that are the lowest and the highest acceptable wind speed in urban spaces respectively (Table 5). Fig 13 shows the thermal zones of WCET on the psychrometric chart.

3. Heat Budget Model Indices

None of the old, and still partly popular, indices mentioned take into account all the mechanisms of the heat exchange. Thus, they are not universally valid and cannot be applied to all climates, all regions, every seasons and every scale. Only

Table 5. Air temperature calculation for WCET thermal zones [2]

WCET	Thermal sensation
-10 to 0	low cold stress
-25 to -10	moderate cold stress
-35 to -25	heavy cold stress
Less than -35	extreme cold stress

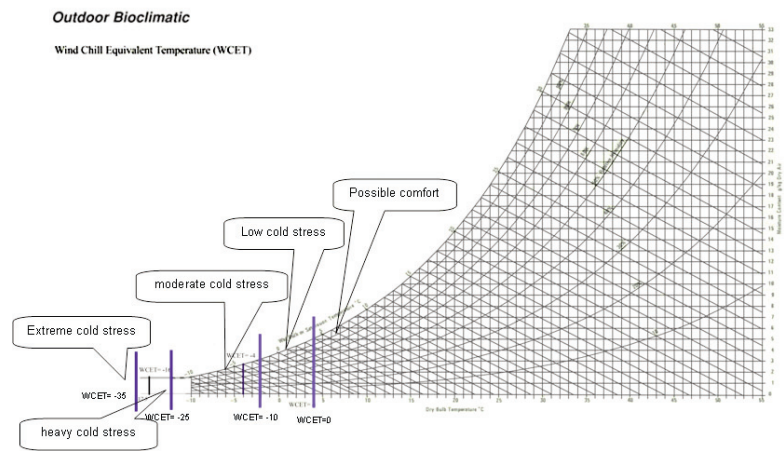| air temp C	wind speed (km/h)		
	15	18	38
WCET	wind speed (m/s)		
	1.4	5	10
0	1	4	5
-10	-7	-4	-2
-25	-21	-16	-13.5
-35	-29.5	-24	-21

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Fig. 13. Wind Chill Equivalent Temperature (WCET) - thermal zones on psychrometric chart [2]

complete heat budget models are sufficiently powerful to assess the thermal environment in thermo physiologically significant way [33].

Therefore, some of the thermal stress indices are capable to evaluate cold and hot conditions simultaneously base on the heat budget model.

3.1. Perceived Temperature (PT)

The perceived temperature, PT, in the dimension °C is the air temperature of a reference environment in which the perception of heat and/or cold would be the same as under the actual conditions[34]. Fig 14 shows the application of the perceived temperature. In the reference environment, the wind velocity is reduced to a slight draught, and the mean radiant temperature is equal to the air temperature (for example, an extensive forest). The water vapor pressure is identical to the actual environment as far as it is not reduced by condensation. [35]

Perceived heat and cold is computed by means of the comfort equation by Fanger (1970) which is based on a complete heat budget model of the human body [36]. The thermo-physiological assessment is made for a male, the "Klima Michel", aged 35 years, 1.75 m tall, weighing 75 kg. His work performance is 172.5 W which corresponds to a metabolic rate of 2.3 Met, and to walking ca. of 4 km/h on the flat ground. The assessment procedure is designed for staying outdoors. Accordingly, the standard male may choose his clothing between summer and winter clothes, in

order to gain thermal comfort as far as possible. Summer clothes (0.50 clo) correspond to a pair of light long trousers, a short-sleeved shirt and a pair of sandals, winter clothes (1.75 clo) in this approach to a suit of woolen material, a tie, a winter coat and warm, solid shoes are added. [33]

Perceived temperature will be calculated online [37]. It takes into account all climatic factors: air temperature, mean radiant temperature, relative humidity, and wind speed and air pressure.

The main thermal categories of perceived temperature are shown in table 6.

Fig 15 shows the main thermal zones of perceived temperature on psychometric chart in the condition that the mean radiant temperature is equal to the air temperature and the wind speed is assumed to be the most acceptable in urban areas (v=5 m/s).

3.2. Temperature Humidity Index (THI)

The effective temperature takes into account the wet and the drybulb temperature. It can be applied to locations that are both shaded and protected from the wind. One of the best indices estimating the effective temperature was developed by Thom (1959) called the thermo hygrometric index or Temperature Humidity Inex (THI). [38]

Although the THI was used originally to determine the discomfort due to heat stress, it has been extendedover a much wider range of conditions that refers to cold stress also. The optimum of THI occurs between 15°C and 20°C, and that is
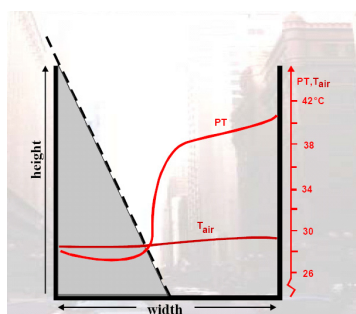

Fig. 14. Application of the PT [35]

Table 6. Perceived Temperature and thermal stress [33]

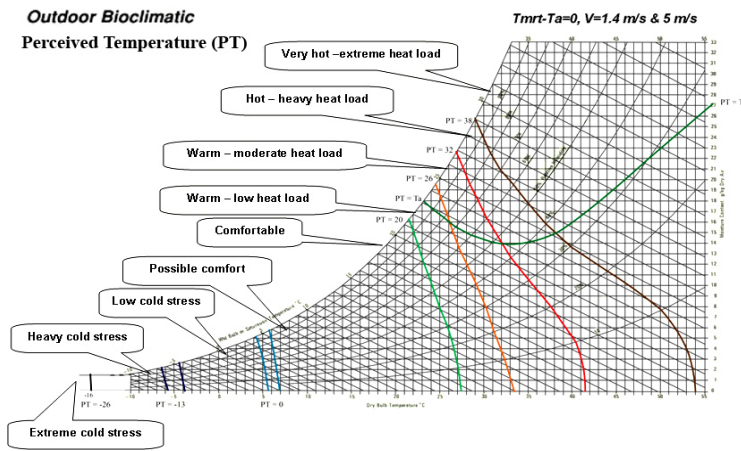| Perceived temperature (°C)	Thermal perception	Physiological stress
< -39	Very cold	Extremely cold stress
-39 to -26	Cold	Heavy cold stress
-26 to -13	Cool	Moderate cold stress
-13 to 0	Slightly cool	Low cold stress
0 to -20	Comfortable	Comfort possible
+20 to +26	Warm	Low heat load
+26 to +32	Warm	Moderate heat load
+32 to +38	Hot	Heavy heat load
> +38	Very hot	Extreme heat load

Fig. 15. Perceived Temperature (PT) - thermal zones on psychrometric chart [2]

the basis for defining comfortable conditions. Below, a THI of 15°C, evaporation takes away heat from the body thus requiring defense against cooling and increasing thermo genic mechanisms are required to combat increasing cold stress. The opposite condition occurs above a THI of 20°C, because the perspiration system becomes effective as a cooling mechanism to prevent overheating. The higher the THI the more ineffective this mechanism becomes.

The THI is secured by a simple linear adjustment applied to the average simultaneous dry-bulb and wet-bulb temperature [39]. The equation for THI using air temperature (t) and humidity is: [39]

THI (°C) = t-(0.55-0.0055f) (t-14.5)

Where t = air temperature measured in degrees Celsius and f = the relative humidity. The thermal categories of the THI are defined shown in table 7.

Using the formula of THI and above categories, the main thermal zones for outdoor spaces is drawn on psychometric chart. (Fig 16)

3.3. Universal Thermal Climate Index (UTCI)

The Universal Thermal Climate Index UTCI provides an assessment of the outdoor thermal environment in bio-meteorological applications based on the equivalence of the dynamic physiological response predicted by a model of human thermoregulation, which was coupled with a state-of-the-art clothing model [41]. The purpose of the Universal Thermal Climate Index (UTCI) is to inform the public of how

the weather feels, taking into account factors such as wind, radiation and humidity. In order to help the general public to relate directly to the UCTI, it is proposed that this index should be on the temperature scale (e.g. in degrees Celsius). [42]

As the UTCI should represent the average conditions of a human within a given climate, a reference person shall need to be defined. The reference person proposed has a metabolic rate of 135 W/m^2 while walking at 4 km/h. The wind speed should account for this walking speed in accordance with ISO 9920.

Wind direction is assumed to be undefined in relation to walking direction. The Klima-Michel model, which is presently used by the German Weather Service to predict a perceived temperature, PT (in °C) as a function of weather conditions, assumes the continuous variation of clothing insulation ranging from 1.75 clo (winter) to 0.5 clo (summer) according to the ambient temperature to achieve comfort (i.e. Predicted Mean Vote, PMV = 0) under reference conditions. If the given range of insulation does not allow for comfort, there will be a cold stress or heat load respectively. It is proposed that the UTCI model should use a larger range of insulations (2.6 to 0.5 clo) and should also consider the types of clothing that people tend to wear in particular cultures and sessions, with special attention for cold exposure based on ENV342 and results from the EU Sub zero project [42]. The operational procedure, which is available as software from the UTCI website [43], showed plausible responses to the influence of humidity and heat radiation in the heat, as well as to wind

Table 7. THI thermal categories [40]

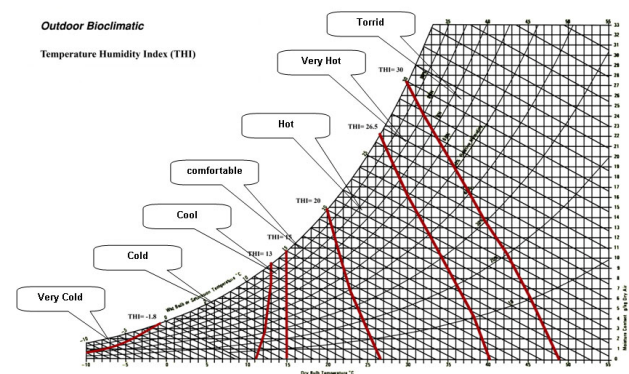| THI C°	Thermal category
bellow – 40	Hyperglacial
– 39.9 to – 20	Glacial
– 19.9 to –10	Extremely cold
– 9.9 to – 1.8	Very cold
– 1.7 to + 12.9	Cold
+ 13 to +14.9	Cool
+ 15 to + 19.9	Comfortable
+ 20 to + 26.4	Hot
+ 26.5 to + 29.9	Very hot
above + 30	Torrid

Fig. 16. Temperature Humidity Index (THI) - thermal zones on psychrometric chart [2]

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Table 8. UTCI thermal categories [41]

UTCI C°	Thermal category
bellow – 40	Extreme cold stress
– 40 to – 27	Very strong cold stress
– 27 to –13	Strong cold stress
– 13 to 0	Moderate cold stress
0 to + 9	Slight cold stress
+ 9 to +26	No thermal stress
+ 26 to + 32	Moderate heat stress
+ 32 to + 38	Strong heat stress
+ 38 to + 46	Very strong heat stress
above + 46	Extreme heat stress

speed in the cold and was in good agreement with the assessment of ergonomics standards concerned with the thermal environment. Concept for calculating UTCI of an actual condition is defined as air temperature of the reference condition yielding the same dynamic physiological response. Activity is assumed as walking 4 km/h (135 W/m2), clothing 0.5 Clo for summer, climate is assumed as:

$Tr = Ta$, $Va_{(10m)} = 0.5$ m/s
$RH = 50\%$ ($Ta < 29°$ C)
$Pa = 2$ KPa ($Ta > 29°C$)

Where Tr is globe temperature (°C), Ta is air temperature (°C), Va is wind speed (m/s), RH is relative humidity (%), Pa is air pressure (KPa). [41]

UTCI will be calculated online [44]. It takes into account all climatic factors: air temperature, mean radiant temperature, relative humidity, air pressure and the wind speed. All UTCI documents that show the proposed amounts are available at [45]. All other references are available in its website. Fig 8 shows the main thermal categories of UTCI.

Using the formula of UTCI and above categories the main thermal zones for outdoor spaces is drawn on psychrometric chart. (Fig 17)

There are some other indices introduced for analyzing outdoor thermal sensation that are not considered in this article. These are Physiological Equivalent Temperature (PET) and Outdoor Standard Effective Temperature (SET* OUT).

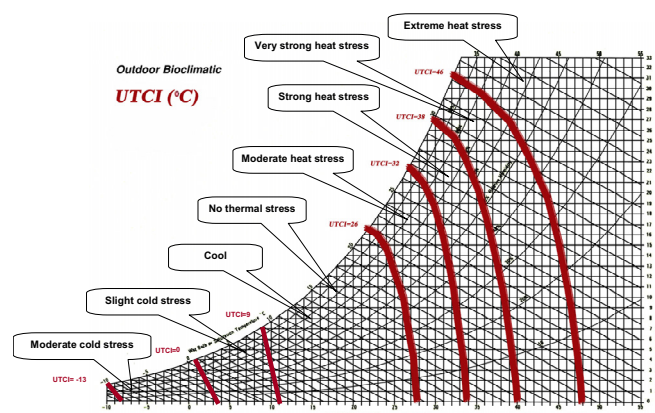PET (°C) produced in Germany, is based on a complete heat budget model of the human being, describing the physiological processes in detail. It provides the air temperature of are ference environment in which heat fluxes would be the same as in the actual environment. PET is calculated by Ray Man Program that was not accessible to author during this research. PT and PET are closely correlated. [33]

The Outdoor Apparent Temperature AT°C is the air temperature of a calm environment with tmrt = ta in which a standardized person achieves the same heat transfer as under the actual environmental conditions. In general it is correlated with the PT and PET. [33]

4. Other Important Considerations in Outdoor Thermal Analysis

There are some important issues that must be discussed related to outdoor thermal indices. At first it is necessary to find out the main roll of humidity and air movement in different climatic conditions. It will help to find the answers to these questions: When is dryness harassment? When is evaporation less effective? When is sultry harassment? When the cold wet condition is dangerous? When the air movement does not have a cooling effect? When will the air movement increase cold stress? Sunshine is another important factor that will change the thermal sensation. The level of its effect depends on the degree of coldness or hotness.

4.1. Humidity and Air Movement Effect in Hot Conditions

Humidity of the atmosphere has little effect on thermal comfort sensation at or near comfortable temperatures, unless it is extremely low or extremely high. It does, however, play an important role in the evaporative regulation [46]. In compliance with discomfort observations ASHRAE Standard 55 recommends that the dew point temperature of the occupied spaces should not be less than 2°C. At high humidity, too much skin moisture tends to increase discomfort, particularly skin moisture of physiological origin (water diffusion and perspiration). [20]

Air movement accelerates evaporation providing a physiological cooling. In low humidity (below 30%), this effect is significant as there is an unrestricted evaporation even
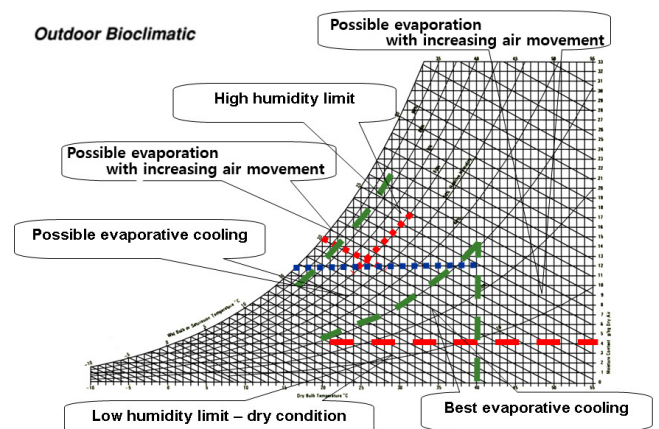

Fig. 17. Universal Temperature Climate Index (UTCI) - thermal zones on psychrometric chart [2]

Fig. 18. Humidity zones on psychrometric chat in high temperatures [2]

with still air. In high humidity (about 85%), the evaporation is restricted; thus, even the air movement cannot adequately increase the cooling effect. Evaporation is most significantly accelerated in medium (40-50%) humidity. [46]

Drawing important humidity zones on psychometric chart will modify upper and lower boundaries of accepted humidity in outdoor spaces. It shows that in hot arid conditions evaporative cooling has more effect than wind speed. Whereas, in hot humid conditions wind speed has more effect and evaporative cooling is impossible.

4.2. Humidity and Air Movement Effect in Cold Conditions

In cold conditions air movement has a great effect on thermal sensation. By increasing the air speed in temperatures less than 5°C the wind chill effect happens and lowers the feeling temperature. If clothing were to get wet, the cooling effect would be greater than what is predicted by WCET model and the chance of hypothermia would be greater. Fig 19 shows that by increasing the air speed from 1.4m/s to 5 m/s (10 m/s gust), the thermal zone will drop one level lower.

In cold temperatures, humidity levels will reach the saturation condition by low amounts of mixing ratio (g/kg). Temperature humidity index (THI) shows that there is a significant difference between arid cold and humid cold conditions. For example, in the mountainous area where the height is 2250 meter above the sea level, temperature -15°C

with humidity less than 20% feels cold, whereas, with humidity between 20-80%, it feels very cold and with humidity of more than 80% it feels extremely cold (Fig 20). In wet, windy conditions, someone wearing inadequate clothing can become hypothermic in quite mild temperatures [22,]. Activity is an important factor in such conditions.

This can be very important, because when there is a high clothing insulation, the range of metabolic rates which are within the band between sweating and shivering is reduced, so there is a danger of sweating and creating thermal bridges in the clothing. Wool and polyester fabrics retain Some protective value when wet; cotton and goose down do not. Areas of the body that lose large amounts of heat (head, neck, legs, and hands) should be covered [47]. Unfortunately, none of the indices related to cold conditions, did study the relation between high activity levels and clothing.

4.2. Sunshine Effect

Sunshine, even in the cold winter days, can make a difference in the thermal sensation. Bright sunshine can make a person feel 6-10ºC warmer as advised in the "new" wind chill chart [49, 50]. The effect of sunshine is much more pronounced at low wind speeds and gradually diminishes as the wind speed intensifies and its effects become dominant. [48]

In warm conditions solar radiation will increase the thermal stress danger.
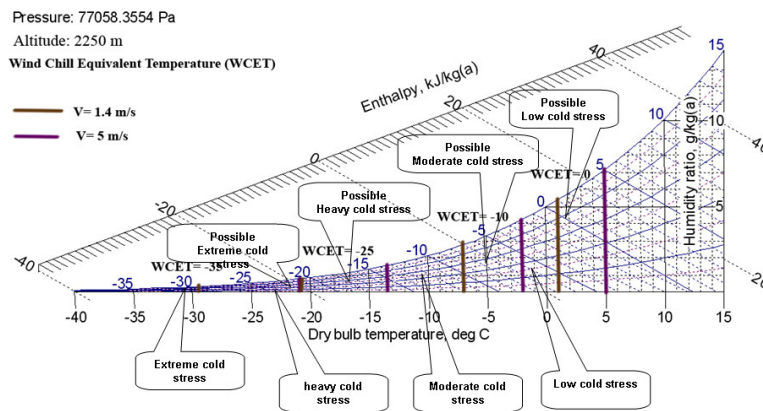

Fig. 19. WCET Index - effect of wind speed on thermal zones on psychrometric chat in low temperatures [2]
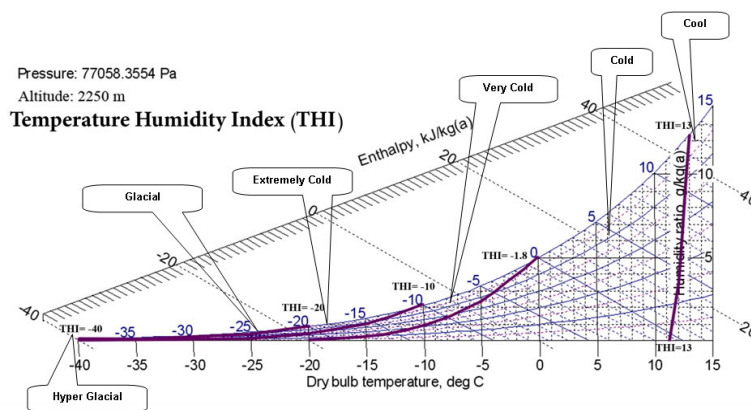

Fig. 20. THI Index - effect of humidity on thermal zones on psychrometric chat in low temperatures [2]

4.3. The Main Thermal Zones

4.3.1. Hot Conditions

To analyze the hot conditions the indices appropriate for hot periods which are used are, are Heat Index (HI), Humidex, Wet Bulb Globe Temperature (WBGT), Discomfort Index (DI), Tropical Summer Index (TSI), Perceived Temperature (PT), Universal Temperature Climate Index (UTCI), Temperature Humidity Index (THI) and Tropic THI, Tropical Summer Outdoor Comfort Zone.

To find out the main thermal zones in hot condition, table 9 is produced. It shows that some of the indices such as DI, PT and THI do not introduce extremely hot conditions that are defined by other indices such as humidex, HI and WBGT. Also, some of them such as THI and WBGT do not introduce median zones between comfort and hot conditions (such as low heat load and moderate heat load).

This table shows that the hot conditions can be divided into non-tropical and tropical places. Among the indices TSI, tropic THI and Summer Outdoor Comfort Zone are appropriate for tropics. This table shows that the thermal conditions in tropical places are one level lower than non tropical places. It means that low heat load conditions in non tropical places are felt comfortable in tropics and moderate heat load conditions are felt as low heat load. The reason should be acclimatized adaptation of local people to tropical climate.

The main thermal zones that are determined in these indices are as below:

1. Extreme heat load means that the situation is extremely dangerous because of heat stroke.

2. Dangerous discomfort or heat load means that there is dangerous condition of heat exhaustion.

3. Heavy heat load means that there is intensive discomfort and heat exhaustion is probable.

4. Moderate heat load means that there is a milled sensation of heat and evident of discomfort. There is a caution of heat stress. For these three conditions comfort will be achievable by using microclimate treatment such as preparing appropriate shadow, air movement and evaporative cooling.

5. Low heat load means that there is noticeable discomfort.

6. No heat load or Comfort condition means that there is no discomfort or little discomfort.

4.3.2. Cold Conditions

Analyzing the cold conditions is done by using four indices appropriate for cold periods. These are: Wind chill equivalent temperature (WCET), Perceived temperature (PC) temperature humidity index (THI) and Universal Temperature Humidity Index (UTHI).

To find out the main thermal zones in cold condition, table 10 is produced. It shows that some of the indices such as PT and WCET do not introduce capable thermal zones between cool

Table 9. thermal condition comparison between outdoor indices in hot condition [2]

Thermal sensation	Slightly cool		comfortable		Slightly warm		warm		hot				Very strong heat stress			
Physiological stress level	Slight cold stress		No thermal stress		Slight heat stress		Moderate heat stress		Strong heat stress				Very strong heat stress			
PET	Slightly cool	13	comfortable 18		Slightly warm	23	warm 29		hot 35		41		> +41			
PT	Low cold stress	-13	Comfort possible	0	Low heat stress	+20	Moderate heat stress	+26	Heavy heat stress	+32	+38				> 38	
UTCI	Slight cold stress	0	no thermal stress	+9			Moderate heat stress	+26	Strong heat stress	+32	+38	Very strong heat stress	+46		> +46	
THI			comfortable	+15		+20			Hot		+26.5	Very hot	+30		>30	
DI			No heat stress	< 22	Low heat stress	22	Moderate heat stress	24	Strong heat stress	28	> 28					
WBGT							Caution	20	Extreme caution	25	32	danger	39		> 40	
Humidex					Little discomfort	29	Noticeable discomfort	30	Evident discomfort 35	Intense discomfort 40	45	Dangerous discomfort	54		> 54	
HI					Caution	27	Extreme caution	32		41	Danger	54			> 54	
TSI tropic			Slightly cool	19	comfortable	25	Slightly warm	30	34							
TSCZ tropic					comfortable	27	Extended comfort zone	32.5	33							
THI tropic					comfortable	21	Low heat load	24	26							

Table 10. thermal condition comparison between outdoor indices in cold condition [2]

Thermal sensation		Very cold				Cold		Cool		Slightly cool		Comfortable	
Physiological stress level	Hyper glacial	Extreme cold stress		Very strong cold stress		Strong cold stress		Moderate cold stress		Slight cold stress		No thermal stress	
PET		Very cold	< 4			cold	4	cool	8	Slightly cool	13	comfortable	18	23
PT		Very cold	< - 39	Heavy cold stress	39	moderate cold stress	-26	Low cold stress	-13	Possible comfort	0		+20
UTCI		Extreme cold stress	<-40	Very strong cold stress	-40	Strong cold stress	-27	Moderate cold stress	-13	Slight cold stress	0	No thermal stress	+9	
THI	< -40	Hyper glacial	glacial	-40	Extremely cold	-20	Very cold	-10	cold	-1.8	cool	+13	comfortable	+15	+20
WCET		Extreme cold stress	< -35	Heavy cold stress	-35	Moderate cold stress	-25	Low cold stress	-10	No thermal stress	0	No thermal stress	

and comfort condition. THI and UTCI introduce temperature less than 10C as cool while other indices recognize it as possible comfort or no thermal stress. It needs more study to make clear which prediction is more reliable. Adaptation of local people to cold weather will be an intervening factor for this analysis.

The main zones determined by these indices can be categorized as follows:

7. Possible comfort condition means cold stress is not serious and comfort condition will be possible by using microclimate treatment such as preparing appropriate sunshine, thermal mass and preventing of local cold breeze.

8. Slightly cool condition means that low cold stress and wind chill may happen.

9. Cold condition means that moderate cold stress may happen.

10. Very cold condition means that heavy cold stress may happen.

11. Glacial and hyper glacial means that extreme cold stress may happen and being exposed to outdoor for a long period is seriously dangerous.

Here, this question arises: How similar thermal zones of different indices are in coincidence? To find out the answer, some new field study researches are required.

5. Conclusion

According to the outdoor thermal conditions, laboratory researches have proposed several indices for outdoor thermal condition analysis. The first group of indices is based on thermal stress model. Heat stress indices such as heat index (HI), Humidex, Tropical Summer Index (TSI), Discomfort Index (DI) and Wet Bulb Globe Temperature (WBGT) are prepared for hot conditions. Wind Chill Equivalent Temperature (WCET) is prepared according to wind chill effect in cold stress conditions. Some of outdoor indices are prepared base on the heat budget model. They are capable to evaluate both cold and hot conditions such as Perceived Temperature (PT), Temperature Humidity Index (THI), and Physiological Equivalent Temperature (PET). The latest index is based on the comprehensive heat budget model of human biometeorology, called Universal Thermal Climate Index (UTCI). It has been prepared by a group of specialists [8]. In this article, all these indices where studied and compared with one an other in the psychometric chart base. It became clear that these indices are not in a good coincidence together. Doing some field study is required to find out which index should be capable for a specific climate. Using an index for a specific project in a city needs to be clarified by local observations to find out which index will be more suitable for predicting the thermal condition of the study site. An example of this method is a field study which has been done in Ahvaz, Iran as a pilot research to show the method and reliability of this research. [52]

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