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OUTDOOR THERMAL COMFORT

A review on the concepts, parameters and methods to evaluate Thermal Comfort in outdoor spaces

The outdoor thermal environment is greatly influenced by the built environment, e.g. anthropogenic heat, evaporation and evapo-transpiration of plants, shading by trees and man-made objects, and ground surface cover such as natural grass and artificial paving, etc. Outdoor spaces provide a pleasurable thermal comfort experience for people and effectively improve the quality of urban living. People experience different thermal sensation while carrying out the outdoor activities in streets, plazas, playgrounds, urban parks, etc.

Thermal Comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55, 2004). In the past decade, valuable researches were carried out for outdoor conditions (Ahmed, 2003; Ali-Toudert & Mayer, 2006; Cheng & Ng, 2006; Cheng, Ng, Chan, & Givoni, 2010; Givoni et al., 2003; Gulyas, Unger, & Matzarakis, 2006; Hoppe, 2002; Nikolopoulou & Lykoudis, 2006; Spagnolo & De Dear, 2003; Stathopoulos, Wu, & Zacharias, 2004; Tseliou, Tsiros, Lykoudis, & Nikolopoulou, 2009). The parameters of Outdoor Thermal Comfort as derived from these studies are as shown in Fig.1.

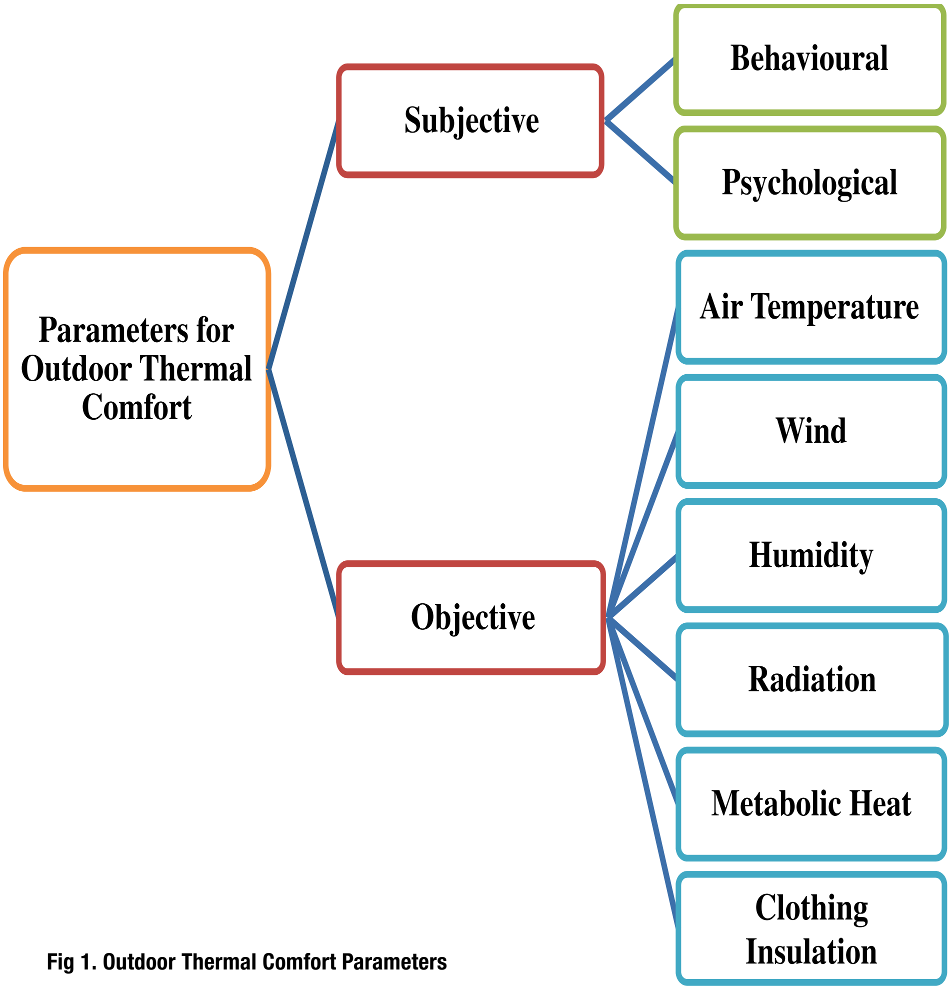

Fig 1. Outdoor Thermal Comfort Parameters

The Outdoor Thermal Comfort Evaluation is carried out following two methods in combination:

1. Micro-Meteorological Measurement: This includes physical measurement of the microclimatic conditions at the immediate surroundings of the subjects. The four main physical parameters those characterize thermal environment and thermal comfort sensation are Air temperature, Relative humidity, Wind and Solar Radiation.
2. Guided User Questionnaire Survey: It consists of questionnaire survey addressing the subjects' thermal comfort condition (e.g. thermal sensation and comfort) and also record of subjects' demographic background (gender and age) during the survey. The thermal comfort sensation can be recorded in any one of the thermal comfort scale as shown below in Table 1.

Table.1. Thermal Comfort Scale

ASHRAE SCALE		BEDFORD SCALE		SEVEN POINT		NINE POINT	
Hot	3	Much Too Warm	3	Very Cold	1	Very Cold	1
Warm	2	Too Warm	2	Quite Cold	2	Cold	2
Slightly Warm	1	Comfortably Warm	1	Cold	3	Cool	3
Neutral	0	Comfortable	0	Comfort	4	Slightly Cool	4
Slightly Cool	-1	Comfortably Cool	-1	Hot	5	Neutral	5
Cool	-2	Too Cool	-2	Quite Hot	6	Slightly Warm	6
Cold	-3	Much Too Cool	-3	Very Hot	7	Warm	7
						Hot	8
						Very Hot	9

Source: Nasir et al.,2012

Table 2. Metabolic Rate of Various Outdoor Activities

Activity	Metabolic rate (W/ m^2)
Sitting	1
Eating	3
Walking	2.6
Playing/exercise	4
Standing	1.2
Studying and sitting	1
Serving	1.6

Source: ASHRAE Handbook of Fundamentals, 1989

External parameters (e.g. activity level, Clo value etc.) required for the thermal comfort conditions calculation can be obtained from this questionnaire survey.

Activity level: The body converts a part of food into energy according to type of activity. Amount of energy produced per unit of time is called metabolic rate and it is expressed in Watt/ m2 of body surface. Table 2 presents metabolic rate for different activities.

Clothing: It is an interface between body and environment. Different clothing type has its own efficiency which is expressed by Clo value as shown in Table 3.

Subject's thermal sensation and comfort vote are obtained by face to face interview while subject's demographic background, clothing and activities are observed and recorded by the interviewer while conducting the survey. The results of the questionnaire survey are correlated with the micro-meteorological data to analyse the general thermal comfort conditions in the outdoor spaces of that place and the comfort requirement of the local people.

Outdoor Thermal Comfort Indices

According to outdoor thermal conditions, several indices exist to

Table 3. Clo Value Chart for Male

Types	Clo Values of various clothes					
Under Garments & Inners	0.05	Briefs				
	0.15	Vest (light)	0.29	Vest (heavy)		
Clothing above waist	0.14	Shirt short sleeve	0.22	Shirt long sleeve		
	0.25	T-Shirt short sleeve	0.29	T-Shirt long sleeve		
Clothing below waist	0.15	Shorts/Half pant				
	0.2	Capris				
	0.3	Jeans				
	0.26	Trouser light material	0.32	Trouser heavy material		
Winter Wears	0.3	Inner above waist	0.3	Inner below waist		
	0.2	Sweater light	0.37	Sweater heavy		
	0.22	Jacket light	0.49	Jacket heavy		
	1.5	Overcoat				
Others	0.5	Hat/Cap				
	0.1	Scarf/shawl				
	0.05	Tie				
	0.1	Socks till knee	0.5	Socks till ankle		
	0.04	Shoes	0.02	Sandal / Slippers	0.08	Boots

Based on ASHRAE Handbook of Fundamentals, 1989 and ANSI/ASHRAE Standard 55-2010 evaluate outdoor thermal condition. These indices can be classified in a number of ways.

a) According to capability for evaluating hot and cold conditions, they are classified as:-
   1. **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 provided for hot conditions. Cold stress indices such as Wind chill Index (WCI) and Wind Chill Equivalent Temperature (WCET) are provided for cold conditions
   2. **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).

b) Based on their guiding development principles, thermal indices can be classified as follows **(Scudo 2002):**
   1. **Empirical Thermal Indices:** Wind Chill Index (Siple and Passel 1945) and Discomfort Index (Thom and Bosen 1959)
   2. **Psycho-sociological-climatic indexes:** Actual Sensation Vote, Satisfaction Indexes
   3. **Energy balance equation indexes based on**
      a) Two-node model of the human body {Pierce Two-Node model (Gagge, Fobelets, & Berglund, 1986; Gagge, Stolwijk, & Nishi, 1971) treats the human body as two isothermal parts, skin and core} eg., OUTSET and on the assessment of all relevant thermal climatic parameters, including the heat balance equation (Hoppe 1999); e.g., PET (Hoppe's MEMI model)
      b) One-node model of the human body :- Perceived Temperature (PT) model based on Fanger's (1972) equation and also an outdoor radiant evaluation model (Jendritzki et al. 1990): PMV index

The general **Energy Balance Equation** of the human body is as follows (ANSI/ASHRAE Standard 55, 2004):

M - W = C + R +E+ C res + E res+ S

Where, **M** is metabolic rate (W/m2),
W is mechanical power (W/m2),
C is convective heat loss from skin (W/m2),
R is radiation heat loss from skin (W/m2),
E is evaporative heat loss from skin (W/m2),
E res is evaporative heat loss from respiration (W/m2),
C res is convective heat loss from respiration (W/m2) and
S is the rate of body heat storage (W/m

c) According to assessment methods involved in them, thermal Indices can be classified as follows (Nagano and Horikoshi, 2011):-
   1. **Steady State Assessment Methods:** These models are based on the assumption that people's exposure to an ambient climatic environment has, over time, enabled them to reach thermal equilibrium, and they provide numerical solutions to the energy balance equations governing thermo-regulation. E.g. Predicted Mean Vote Index (PMV) (Fanger, 1982), Physiological Equivalent Temperature (PET) (Mayer & Hoppe, 1987), The Index of Thermal Stress (ITS) (Givoni, 1976), OUT-SET (Pickup & De Dear,1999), COMFA Outdoor Thermal Comfort Model (Kenny, Warland, Brown, & Gillespie, 2009)
   2. **Non-Steady Assessment Methods:** The current studies related to non steady assessment methods are restricted mainly to indoor cases (Foda & Siren, 2010; Zhang, Huizenga, Arens, & Wang, 2004) or simulation cases in the virtual world (Bruse, 2005; Havenith, 2001; Huizenga, Zhang, & Arens, 2001). The assessment of unsteady outdoor thermal comfort conditions remains an active area of thermal comfort research, and constant efforts are being made for model development and field study (Fiala, Lomas, & Stohrer, 2001; Jendritzky, Maarouf, & Staiger, 2001; Shimazaki et al., 2011; Tokunaga & Shukuya, 2011).

Important Outdoor Thermal Comfort Indices

a) **Physiological Equivalent Temperature (PET):** PET was developed as an index which takes into account all basic thermoregulatory processes (Hoppe, 1993) and is based on a thermo-physiological heat balance model called Munich energy balance model for individuals (MEMI) (Hoppe, 1984; 1999). According to Mayer and Hoppe (1987) and Hoppe (1999), PET is defined as the equivalent air temperature at which, in a typical indoor condition heat balance of the human body exists (work metabolism 80 W of light activity, and clothing of 0.9 clo). The following assumptions are made for the indoor reference climate:

Mean radiant temperature equals air temperature (Tmrt =Ta). Air velocity is set to 0.1 m/s. Water vapour pressure is set to 12 hPa (approximately equivalent to a relative humidity of 50% at Ta=20°C).

The advantage of PET over other indices is that it is calculated in °C. PT (Perceived Temperature) and PET are closely correlated. Although PET is the equivalent temperature under a virtual indoor condition, it is applicable to a wide range of real outdoor conditions. PET is one of the recommended indices in new German guidelines for urban and regional planners (VDI, 1998) and is used for the prediction of changes in the thermal component of urban or regional climates. By using the Software RayMan developed by Matzarakis et al. (2007), PET can be calculated easily. PET results can be presented graphically or as bioclimatic maps. PET can be used as a single thermal index for analyzing various microclimates of large built environments like Airports and Railway Terminals.

b) **Predicted Mean Vote (PMV):** Fanger (1972) developed PMV (Predicted Mean Vote) for indoor climates with the aim to provide an index for ratings of thermal discomfort at various states of activity and clothing insulation. To apply PMV to outdoor conditions, Jendritzky and Nubler (1981) added complex outdoor radiation and the model is known as Klima-Michel Model (KMM). As an application of KMM model, Jendritzky and Nubler (1981) showed the distribution map of PMV in Freiburg from which effects of buildings and heat islands are obvious. Matzarakis and Mayer (1997) calculated PMV to develop a high-resolution map that presents the average annual number of days with strong heat stress (PMV>3.0), using Greece as an example. They selected PMV as the index because PMV with KMM is a well-suited measure for assessing the thermal environment of different outdoor-climates.

c) **Outdoor Standard Effective Temperature (OUTSET):** The new effective temperature (ET) is based on human energy balance and two-node model (Gagge et al., 1971) as discussed earlier. With ET the thermal conditions can be compared to the conditions in a standardized room with a mean radiant temperature equal to air temperature and a constant relative humidity of 50%. Gagge et al. (1986) improved ET and proposed the new standard effective temperature (SET) which is used frequently both as indoor and outdoor comfort index. Ishii et al. (1988) compared several thermal comfort indices and concluded that SET is better suited in evaluating outdoor comfort. Kinouchi (2001) also found that SET can be used as an index for the outdoor environment. Pickup and Dear (1999) improved the SET and developed thermal indices especially for outdoor conditions OUT-SET. In recent studies, distribution of SET is used as an output of CFD model (Lin et al., 2008).

d) **Universal Thermal Climate Index (UTCI):** The Universal Thermal Climate Index (UTCI) developed by Hoppe in 2002 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. 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). As the UTCI should represent the average conditions of a human within a given climate, a reference person shall need to be defined. 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< 29o C), Pa = 2KPa (Ta>29o C)

where Tr is globe temperature

Table 4. Comparative analysis between the thermal comfort indices, (PMV, PET and OUTSET)

INDICES/FACTORS	PMV	PET	OUTSET
Introduced	Fanger in 1972	Mayer and Hoppe in 1987,1999	Pickup and De Dear in 1999
Parameters Considered	Clothing and Activity levels as variables.	Earlier, it did not consider Clothing and Activity levels as variables. But in the Rayman Model, these variables are added.	Clothing and Activity levels as variables
Range	Limitations in the range of its upper and lower limits. (Temperature only from 10^0 C to 30^0C) Not suitable for tropical climate (extreme temperature).	Assumes RH=50% in the reference indoor situation which actually changes with T_a in outdoor situations. Hence less accurate.	Assumes Vapour Pressure of 12hPa which is constant water content in the air independent from T_a. Hence more accurate.
Applicability	It does not take into account the thermo-regulations of a human body. Hence not very accurate for extreme conditions (typically outdoors).Thus mainly used for indoor areas.	It takes into account the thermo-regulations of a human body. Hence more accurate for extreme conditions (typically outdoors). Hence better than PMV.	It takes into account the thermo-regulations of a human body. Hence more accurate for extreme conditions (typically outdoors). Hence better than PMV.

Based on Fazia Ali Toudert.,(2005), Givoni, B., Noguchi, M., Saaroni, H., Pochter, O., Yaacov, Y., Feller, N., & Becker, S. (2003),

(°C), Ta is air temperature (°C), Va is wind speed (m/s), RH is relative humidity (%), and Pa is air pressure (KPa).

UTCI can be calculated online. It takes into account all climatic factors: air temperature, mean radiant temperature, relative humidity, air pressure and the wind speed. A comparative analysis has been done for the three important and useful indices (PET, PMV, OUTSET) in Table 4 below.

Simulation Software for Outdoor Thermal Comfort

For the outdoor thermal comfort assessment, different software can be used for the calculation of the indices as well to carry out simulation in the outdoor spaces. Amongst them, Rayman and Envimet have been very successful and accurate and hence been discussed below briefly.

RayMan Model - RayMan stands for "radiation on the human body". Developed in 2007 (Matzarakis et al.), it is used for the calculation of the Tmrt (Mean Radiant Temperature). The three thermal indices PET, SET* and PMV are part of the RayMan model, as are energy fluxes and body parameters by MEMI. They all require mean radiant temperature T mrt as input. The output is given in the form of graphs. It is very useful software by which we can calculate PET, PMV and SET *. It is also easily available online.

Envi-Met - Envi-met is a grid-based three-dimensional model for the simulation of air flow, heat and vapour exchange, turbulence and particle dispersion in urban areas. The program is designed for micro-scale simulation with a typical resolution from 0.5 to 10 m in the horizontal land surface, and 10 s in time. It takes into account the key modelling inputs, including site location, initial climatic parameters, soil and plant type, building structure, and thermal properties. It can generate three-dimensional distributions of radiation, temperature, heat flux, humidity and wind flow. Recently, the ENVI-met has been adapted mainly to simulate surface-plant-air interactions in urban canyons, and to predict climatic consequences of different urban design options.

Conclusion

Outdoor Thermal Comfort is important and significant aspect of quality of living, especially in urban areas. Its assessment can be carried out through different thermal comfort indices and/or using software. Review on basic concepts, parameters and assessment methods to evaluate outdoor thermal comfort through thermal indices throw light on important research initiatives on the same. Also review on scope of software like Envimet and Rayman for evaluating outdoor thermal comfort highlights extension of analytical ability of researchers.

For the evaluation of the outdoor thermal comfort, PET is a more suitable index compared to PMV, OUTSET because of its advantages as discussed. UTCI is a recent index which is also similar to PET but further study is required for its proper appreciation and applicability in Indian scenario. In a tropical climate like India, with diverse climatic conditions, it will be interesting to evaluate PET variations across different climates. PET can be calculated from software like Rayman which is very easily available online. Simulation software like Envimet can also assist in outdoor thermal comfort assessment.

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