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A review of researches about human thermal comfort in semi-outdoor spaces

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Abstract

The role of human thermal comfort on sustainable architecture and urban design is substantial. To concentrate on outdoor thermal comfort subject as well as indoor thermal comfort is a key to solve the global warming and wasting energy problems for future years. Semi-opened spaces as favorable and frequent spaces for people in urban areas affect strongly the quality of life and well-being of persons. Although the assessments of outdoor thermal comfort have been increased in recent years, the number of researches that primarily focused on human thermal comfort in semi-outdoor spaces is few. This article reviews the studies about semi-opened spaces have been executed in various climate conditions since late years. Furthermore, it explained the general assessment methods of the semi-outdoor thermal comfort.

Keywords: semi-outdoor spaces, thermal comfort, sustainable architecture.

Introduction

By population growth and global warming, it is needed to design the spaces which can enhance the quality of life, general health condition and social-economic points of view. Paying more attention to human's satisfaction in outdoor and semi- outdoor spaces is a momentous duty for architectures as well as urban planner experts. Thermal comfort is regarded as one of the most important contexts for sustainability which plays great role in urban zones in addition to noise level, air contamination, esthetic and approachability (Mayer, 2008). The thermally satisfaction of human being in outdoor and semi-open spaces is extremely influenced by local microclimate parameters. Subsequently, the usage of these locations can be fluctuated by the level of human's thermal comfort (Chen and Ng, 2012).

Semi-outdoor spaces can be defined as the spaces which are partly open in the direction of the outdoor circumstance(Nikolopoulou and Steemers, 2003). Foundation upon the classification by Chun *et al.* (2008), three categorizations is introduced. The first type is located inside the buildings such as entry atrium. The second type is covered spaces which are connected to structure like balcony. The last type is shaded spaces situated in outdoor environment entirely. Station, covered street and pavilions are regarded in this category. Thermal comfort in semi-enclosed spaces is the result of interaction of human subjective factors with four main thermal elements, i.e. air temperature, wind speed, solar radiation and humidity. There are several researches on assessment human thermal comfort in outdoor areas(e.g. Cheng *et al.*, 2007; Ali-Toudert and Mayer, 2006; Nikolopoulou and Lykoudis, 2006; Tseliou *et al.*, 2010),but the number of studies which entirely focused on analyzing human thermal comfort in semi-opened spaces is few. However, the attention of scientists about investigation of thermal comfort conditions of semi-outdoor spaces has

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been increased in late years. Heretofore, the sport stadia (Bouyer *et al.*, 2007), repose spaces (He and Hoyano, 2010), urban area (Pagliarini G, Rainieri, 2011), large roof structures (Turrin *et al.*, 2012), bus stations (Lin *et al.*, 2006), rail way station (Hwang and Lin, 2007) and university campus (Makaremi *et al.*, 2012; Metje *et al.*, 2008) are some instances for performed investigation on thermal comfort in semi-opened spaces.

Methods of evaluation the thermal comfort in semi-outdoor spaces

Steady-state method

There are two principal methods for assessment thermal comfort in semi-outdoor spaces: the steady-state method and non-steady-state method. The supposition of steady-state method is the exposure of humans to an atmosphere climatic circumstance capable them to obtain thermal balance. Afterwards, the numerical solutions to the energy balance equations controlling thermoregulation are supplied in this method. This method has problem to describe dynamic facets of human thermal adaptation (Chen and Ng, 2012).

There are many indices which are established upon this method. Predicted Mean Vote (PMV) was introduced by Fanger (Fanger, 1982) anticipates the mean thermal response of individuals in large groups based on the seven-point scale (i.e +3 = hot; +2 = warm; +1 = slightly warm; 0 = neutral; -1 = slightly cool; -2 = cool; -3 = cold). This index is interpreted along with Predicted Percentage Dissatisfied (PPD) which expresses the percentage of persons who are not satisfied at individuals PMV values in thermal point of view. However, PMV and PPD primarily proposed to evaluate thermal comfort condition on indoor environment and not appropriate index for semi-outdoor and outdoor zones due to overvaluation the thermal sensation in the warmer climate and contrariwise in cold condition (Cheng *et al.*, 2011; Thorsson *et al.,* 2004).

Physiological Equivalent Temperature (PET) (Mayer and Höppe, 1987) is the common index for representing the steady-state method in outdoor and semi-outdoor spaces. Due to contemplate the impacts of short-wave and long-wave radiation fluxes on the human energy balance, PET is regarded as one of the most dominant and reliable index in semi-enclosed spaces. By definition, PET is defined as "the air temperature at which, in a typical indoor setting (air temperature = mean radiant temperature, relative humidity = 50 %, wind speed = 0.1 m/s), the heat budget of the human body is balanced with the same core and skin temperature as those under complex outdoor conditions" (Höppe, 1999). There are numerous benefits for carrying out the PET to appraise the thermal condition of outdoor and semi-outdoor spaces. First, it helps laymen to compare their own experiences with the entire impacts of composite thermal condition (Höppe, 1999). Secondly, because of the PET has a usually known unit (°C); it is an approved bioclimatic index to measure of thermal stress (Gulyas *et al.*, 2006). Third, it makes the modern human-bio meteorological terminology easy and apprehensible for the users who are not acquainted with (Lin *et al.*, 2010). Forth, it is included in guideline 3787 of the German Association of Engineers (VDI, 1998). Fifth, it can be computed by accessible software packages such as Rayman (Matzarakis *et al.*, 2007).

None-steady-state method

By contrast, the Pierce Two-Node model is the cornerstone of dynamic human thermal comfort's evaluation (Gagge, 1986). The conception of non-steady-state method is for passive state based on division the body as two main parts, skin and core. Divergence from the set points leads to deduce the core, skin and mean body temperature. Consequently, extrapolation of sweating rate and skin blood flow is simple in non-steady-state method. Höppe, (2002), proposed to utilize non-steady-state method in outdoor spaces due to the traveler characteristic of outdoor environment and likewise the tendency of steady-state model to over appraisal the level of dissatisfaction for presented people in outdoors for time intervals less than one hour.

Despite the interoperation of human thermal adaption's dynamic part is feasible by this method, difficulties of governing indicators, like mean body temperature, in semi-opened and opened spaces regarded as the first challenging aspect of applying this method. In the second place, the urban planners have to aware of biometeorological and psychological cognition which is not related to their proficiency.

Classification of approaches for assessment thermal comfort in semi-outdoor spaces

Questionnaire along with field measurement

The evaluation of human thermal comfort in semi-enclosed spaces can be divided into three categories. The first type is conducting the transverse questionnaire among a large group of presented people at study area during the time of data collection along with to measure the four main microclimate parameters, i.e. wind speed, air temperature, humidity and mean radiant temperature (e.g. Chun *et al.*, 2004; Pitts and Bin Saleh, 2007). The final results are deduced by statistical analysis of subjective assessment together with the findings of recorded values. This approach is practical since many prior scholars performed (such as Deb andRamachandraiah, 2011; Makaremi *et al.*, 2011; Metje *et al.*, 2008; Walton *et al.*, 2007). The subjective parameters play significant role in this approach and many previous investigations proved that psychological factors can affect the thermal satisfaction of people in non-indoor locations (e.g. Cheng *et al.*, 2011; Liu *et al.*, 2012a,Nikolopoulou and Lykoudis, 2006; Thorsson *et al.*, 2004). Nikolopouloua and Steemers (2003) demonstrated the dependence of approximately 50% of human thermal comfort on adaption.

The prominent problem of this procedure is the asthenia of transverse approach to indicate the impacts of changing climatic environment on thermal sensation (Cheng *et al.*, 2011) Besides, it is required more time as well as more precious instruments to perform (Arnfield, 2003). Eventually, the lack of control microclimatic parameters and random selection of volunteers are the last problem (Krüger and Rossi, 2011). Nevertheless, preparation of more precise consequence and advantageous subjective findings are the distinctive preponderance of this approach (Deb, & Ramachandraiah, 2011).

The longitude

The second approach called "longitude" which is similar to the former approach in recording microclimatic factors point of view, but, there is a difference on subjective assessment. In this procedure, selection of interviewers is not fortuitously and the respondents were chosen antecedently. However, there are a few numbers of researchers on the basis of longitude method to date. In the investigation by Cheng *et al.* (2011), they examined thermal comfort of people using longitude method in Hong Kong. Furthermore, Givoni *et al.* (2003), carried out study performing longitude method in outdoor and semi-outdoor location in apark in Israel. It was compared the differences between thermal satisfaction of selected respondents under shaded locations and unshaded areas.

The problem of this approach is choosing answerers in nonrandom manner. Since the respondents in this approach are acquaintance about the question of inquiry after the first time of replying, their answers accuracy about thermal sensation in various condition is decreased time by time. Moreover, the determined respondents groups (based on age, sex, nationality etc.) do not reflect the thermal condition of specific location justly.

The computational simulation

The last approach is on the basis of computational simulation using software. The general procedure is to input the environmental parameters as well as trees, building, cloud cover etc. Consequently, the software will approximate the thermal condition of study area introducing in preferred thermal index. In addition, some tools can estimate the Mean Radiant Temperature (Tmrt) in acceptable values based on other microclimatic variables(e.g. Rayman presented by Matzarakis *et al.* (2007). Eventually, the calculation of Sky View Factor (SVF) is conceivable by parts of software.

There are a few numbers of assessment thermal comforts in semi-outdoor spaces using modeling simulation. In the work by Bouyer *et al.* (2007), they analyzed thermal comfort condition in to sport stadia in difference countries (i.e. Turkey and France) based on the computational simulation. Additionally, ParaGen is the tool was performed by Turrin *et al.* (2012) in order to analysis the passive thermal control of covered spaces in semi-outdoor location. Moreover, He and Hoyano, (2010), investigated the thermal comfort condition under membrane structure in Japan using field measurement together with numerical simulation. The performed software in this study was computation fluid dynamics (CFD) and 3D-CAD-based thermal simulation tool. They claimed this couple software are capable to assess thermal comfort condition.

Up to present time, several tools have been introduced to help experts for modeling the environmental condition such as Rayman (Matzarakis et al., 2007); ENVI-met (Bruse and Fleer, 1998); SOLWEIG (Lindberg *et al.*, 2008) and Town Scope (Teller *et al.*, 2001). Despite this approach prepares useful data; the process of gathering initial input information consumes more time and more costly price.

The Adaptive Thermal Comfort

Thermal comfort comprises several aspects which can influence significantly on final personal judgment about ambient environment. Human adoption is one of the most effective matters affects the thermal comfort. By definition, the term 'adaptation' is "the gradual decrease of the organism's response to repeated exposure to a stimulus, involving all the actions that make them better suited to survive in such an environment" (Nikolopoulou and Steemers, 2003). On the word of the adaptive thermal comfort theory, the thermal comfort accomplished by individuals in a non-air-conditioned condition is considered as the outcome of the integrated influences of ambient physical environmental stimuli and non-physical subjects. Indeed, people implement assorted adaptive approaches without limits in agreement with their own thermal predilection to obtain thermal comfort. It is frequently consented that physiological, psychological and behavioral as three classifications of adaptation affect enabling people to regenerate their thermal comfort state under numerous thermal situations (Liu *et al.*, 2012a). Considering each types of thermal adaption is critical for investigation the subjective parameters in assessing human thermal comfort conditions in outdoor and semi-outdoor locations. The definition of physiological, behavioral (or physical) and psychological adaption based of previous studies (Liu *et al.*, 2012a; Nikolopoulou and Steemers, 2003) is represented briefly in the following:

Physiological Adaptation

Physiological adaption which is defined as any physiological alteration in reaction to circumfused thermal environmental changes is divided into two sub-divisions namely genetic adaption and acclimatization (Brager and de Dear, 1998). The concentration on the genetic adaption is troublesome and unpractical due to populations' movability. In contrast, many studies assess the acclimatization by conducting field measurement together with subjective survey in various climates. The mean skin temperature, vascular events, sweating and shivering are regarded as some of the body modification in order to intensification or diminishing the heat exchange between the human body and the surroundings to help maintain the constant core temperature of the physical structure (Liu *et al.*, 2012a).

Behavioral (Physical) Adaptation

Physical adaptation is most common adaption since it includes all the modifications of human in order to adaptation with the circumstance or alteration the environment based on the preferences (Nikolopoulou, & Steemers, 2003). On the foundation of study by Brager and de Dear, (1998), physical adaption separated into three sub-group which are: personal (e.g. modifying the clothing), technological (e.g. turn air condition on or off) and cultural responses (e.g. napping during heat time of day). Human adaptive behavior is a dynamic procedure and the regularity of physical adaptation is affected by compound elements like climate, culture and finances, level of obtainability/accessibility of control and regulatory actions, personal characteristics and the individual' thermal contextual (Liu *et al.*, 2012a). Moreover, on the basis of categorization by Nikolopouloua and Steemers, (Nikolopoulou, & Steemers, 2003), physical adaption can be classified as reactive and interactive adaption where reactive adaption only involves personal adjustment such as revision the clothing levels, posture and position or drinking, while, interactive adaption means altering the circumstance in order to enhance thermal condition.

Psychological Adaptation

Since the perception of persons about circumstance is various, the reaction of people about physical stimulation significantly depends on their background about specific situation and not their magnitude. Hence, the thermal perception of particular location is affected by psychological parameters (Nikolopoulou and Steemers, 2003). There is a positive association between sensed environmental control rank and thermal comfort and satisfaction (Liu *et al.*, 2012b). Even though psychological adaptation cannot be monitored clearly, definitely depicted and investigated, a number of scholars make attempt to describe it thoroughly. For instance, naturalness, time of exposure, expectations, perceived control, experience and environmental stimulation are considered as some effective factors for psychological adaptation (Nikolopoulou and Steemers, 2003).

Although the effects of psychological adaption on thermal sensation of people, both short-term and long-term periods, are fundamental, to date the number of study on how long the psychological adaptation would take is scarce. This may be because of the variance in race, living conditions, etc., which result differences in thermal perception criteria and cognitive procedures (Liu *et al.*, 2012a).

The last researches on human thermal comfort in semi-outdoor spaces

Basically, the attention of scientists about investigation of thermal comfort conditions of semi-outdoor spaces has been increased in late years. To date, there are some studies on assessment thermal comfort condition of semi-outdoor areas such as sport stadia (Bouyer *et al.*, 2007), repose spaces (He and Hoyano, 2010), urban area (Pagliarini and Rainieri, 2011), large roof structures (Turrin *et al.*, 2012) and bus stations (Lin *et al.*, 2006). However, it is needed to further investigation about assessing thermal comfort conditions of semi-open spaces.

Spagnolo and de Dear, (2003), clarify semi-outdoor areas as locations that, "while still being exposed to the outdoor environment in most respects, include man-made structures that moderate the effects of the outdoor conditions". This study which can be regarded as one of the most prior studies on assessing thermal comfort in semi-closed spaces in recent decade was performed in several semi-outdoor locations in Australia utilizing micrometeorological measurements and subjective survey simultaneously. In addition to recommend OUT_SET* as the appropriate thermal index for assessing the thermal sensation of outdoor subjects for the entire seasons, they stated inhabitants of semi-outdoor and outdoor circumstance can bear a wider temperature variety than the one anticipated for indoor thermal comfort.

In the research by Chun *et al.* (2004) they categorized transitional spaces as specific kinds of semi-closed spaces in three separated groups and conducted field measurement to evaluate thermal comfort conditions of people underneath mentioned locations. They concluded that due to physical activities of occupants and MET value; PMV index is not appropriate index to assess human thermal condition of semi-open spaces. In contrast, Lin *et al.* (2006) expressed that because of thermal indices like PMV, ET* and SET* fundamentally designed for indoor condition, they are not capable to explain thermal condition of outdoor and semi-outdoor spaces. Hence, they selected PET in order to assess the role of passive design strategies on thermal comfort in bus stops of Taiwan. They resulted better sheltered bus stops (or low value of sky view factor) due to ability for blocking more amount of solar radiation fluxes are more influential to prepare thermal comfort condition for pedestrians. They strongly emphasize to design bus stops with more sheltered spaces with respect to the climate condition of each region.

In the study by Hwang and Lin (2007) they examined thermal comfort of people on some public spaces such as railway station, cultural center, museum,art center and university campus. They foundpresented persons of semi-opened and outdoor environments have higherthermal endurance levels than people in naturally ventilatedindoor circumstance. Also it was demonstrated solar radiation has the most influential effect on subjective thermal comfort.

Pagliarini and Rainieri (2011) explored the thermal comfort condition of people under glass covered of semi-outdoor space in Italy. It was figured out that the seated persons felt thermal condition as similar as standing persons. However, the effect of solar radiation is higher on seated individuals. By contrast, seated persons sensed the impacts of wind in lower level compared with standing people. Also, Lin *et al.* (2006), assessed the effects of passive thermal strategies on bus stations by field of measurement in Taiwan. It was founded the Sky View Factor (SVF) has the significance influence on human thermal comfort, hence, it was strongly emphasized taking into account the better shaded spaces at semi-outdoor spaced in sub-equatorial climate.

Even though assessing thermal comfort using modeling instead of experimental method is a challengeable project due to it includes numerous basic research concepts, some studies endeavored to evaluate thermal comfort condition in semi-open spaces by implementation modeling (e.g. Ghaddar et al, 2011; Turrin et al, 2012). Furthermore, He and Hoyano, (2010) conducted field measurement of principal microclimate factors together with numerical simulation using SET* index in order to understand the role of membrane structure in semi-outdoor spaces on thermal comfort of people. The found out air temperature under membrane structure was 2-4° lower than outside air temperature in sunny day with low wind-ventilation situation. Moreover, in the work by Bouyeret al. (2007), they compared two distinctive sport stadia in different regions using simulation and PET index to investigate thermal condition of people. They deduced the appreciation of comfort in indoor condition is varied in comparison with outdoor and semi-outdoor environment. Consequently, aforementioned studies revealed the direct solar radiation can be regarded as the primary cause of thermal discomfort in semi-open areas and perception of thermal comfort in semi-enclosed locations is diverse to indoor due to several reasons such as psychological parameters and complicated quality of outdoor and semi-outdoor environments.

Likewise, in the study by Metje *et al.* (2008), the pedestrians' comfort level in outdoor and semi-closed spaces at the university campus was evaluated conducting a field measurement and questionnaire survey concurrently. They found the wind speed and the air temperature affect the human thermal comfort, while, it is difficult for respondents to distinguish the role of solar radiation and humidity on thermal comfort. In addition to microclimate parameters, they confirmed subjective adaption extremely influences on human thermal comfort. Similarly, in the research by Hwang and Lin, (2007) six distinctive semi-open locations were investigated in order to discover the thermal comfort demands for inhabitants in semi-closed areas using SET* thermal index. Their significance result is that in contrast to dwellers of easily restrained environments, inhabitants of difficult conditions are more comfortable at higher temperature. Furthermore, they expressed the potency of global radiation to modify the human thermal sensation is more powerful in comparison with air movement. Finally, they concluded in hot and humid climate, enhancing the wind speed and diminishing the amount of direct sun light in design concepts, can impressively improve the comfort level of individuals in semi-outdoor spaces.

Also, Walton *et al.* (2007) carried out an investigation in New Zealand in order to assess the effects of wind, air temperature and sun light on human thermal comfort by implementing measurements of the weather parameters together with contribution questionnaire among individuals as several scientists carried out the similar method. Based on their study, it reveals persons adapt themselves with outdoor circumstances constantly. Moreover, they concluded the wind gust effectively affect predicting versatility, while, the air temperature has the lowest level to influence on the ability of people to adapt.

The study by Makaremi *et al.* (2012) is investigated the semi-outdoor spaces at a university campus in Malaysia. In this work, on the basis of PET comfort range of Taiwan introduced by Lin and Matzarakis (2008) two various study area selected in order to evaluate thermal comfort condition of shaded spaces. The method of examination consisted of measuring the main weather factors together with contribution of subjective questionnaire by implementation of Rayman software. It was observed that PET values at the study area with low level of shading was exceeded the comfort zone in most of the daytime. In the other hands, the PET acceptable range presented in the most of the sunny hours, so, it shows the significance of shading to improve outdoor thermal comfort in tropical regions. Besides, it was resulted the tolerance of local people is more than non-local persons in such climate

Conclusions

The enthusiasm of scientists to study on thermal comfort condition of semi-outdoor and outdoor spaces has been raised since recent decade but it is needed to focus on more details and locations. Through representing a review on the prior studies, it is understood that although the evaluation of thermal comfort in semi-outdoor spaces of various climates has been done up to now, the number of researches which specifically concentrate on to assess the human thermal comfort in semi-open areas are few. Particularly, there is a lack of researches on assessing thermal conditions of semi-outdoor areas in hot-humid regions. Moreover, it is needed to find a proper universal thermal index for various climate conditions. This index can help urban planner to evaluate thermal condition of districts in the world in understandable range. Finally, to propose the practical software for simulation the thermal comfort of semi-outdoor spaces in easy and user-friendly manner.

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