ASSESSMENT OF OUTDOOR THERMAL COMFORT IN URBAN MICROCLIMATE IN HOT ARID AREAS

Khalid Setaih, Neveen Hamza, and Tim Townshend
School of Architecture, Planning and Landscape, Newcastle University,
Newcastle upon Tyne, NE1 7RU, United Kingdom
Email: k.m.setaih@ncl.ac.uk; neveen.hamza@ncl.ac.uk; tim.townshend@ncl.ac.uk

ABSTRACT

Due to rapid and intensified urbanisation in cities, the characteristics of outdoor urban microclimates have been detrimentally influenced, altering the perception and satisfaction of pedestrians, especially in hot and dry climates. This poses challenges to many researchers and urban space designers in finding appropriate methods to reduce the urban heat stress and thus to enhance the thermal comfort level of outdoor pedestrian spaces, to prolong the period of their use of space and viability as urban retreats. However, there is limited research conducted on outdoor urban spaces in hot arid climate. Therefore, the purpose of this current research is to review the outdoor thermal comfort interaction factors, as well as to contribute to the knowledge of the literature by conducting a case study of a pedestrian street in the hot dry city of Madinah, Saudi Arabia. It also aims to find out the available methods to increase the outdoor pedestrian thermal comfort level in hot and dry urban microclimates, in addition to understand how CFD simulation method can influence the urban space design and planning processes.

This review covers the effect of the moderation of the built environment's components on the microclimatic parameters on pedestrians' scale, with the aim for optimising the thermal comfort level in outdoor urban spaces. The literature also covers the use of simulation tools used to simulate environmental conditions outdoors with specific focus on CFD simulation for outdoor thermal comfort applications. Finally, this paper expects to highlight the limitations of both the microclimatic enhancement approach and the CFD simulation as a tool in the field of urban design.

INTRODUCTION

The external environment has a significant effect on the way people live, which is determined by natural conditions, anthropogenic factors, the density of urban constructions, and the size of vegetation areas, etc. (Klemm, 2007). The increasing number of buildings in a city, reduction of vegetation areas and the use of warm building and ground surface materials affect the conditions of microclimate in urban spaces, which can influence the use of outdoor space. People expectations, when staying outdoors, are different from indoors, as they expect variability in the exposure circumstances, such as variant in sun and shade, modifications in wind speed and direction, and changes in humidity rate, etc. (Givoni et al., 2003). Pedestrian satisfaction level with the thermal environment is one of the important subjective indications that determine the amount of time to spend in outdoor public spaces. However, it is difficult to judge one's satisfaction level with the thermal environment as it can vary from a person to another.

Researchers have attempted to design models that can estimate the comfort conditions people find acceptable outdoors (e.g. PET by Hoppe, 1999; OUT_SET* by Pickup and de Dear, 2000; Extended PMV by Fanger and Toftum, 2002, etc.). PET index, for example, is defined as "the physiological equivalent temperature at any given place (outdoor or indoor) and is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body (work metabolism 80 W of light activity, added to basic metabolism; heat resistance of clothing 0.9 clo) is maintained with core and skin temperatures equal to those under the conditions being assessed" (Hoppe, 1999:73). For the calculation of PET index, this research has employed RayMan program (Matzarakis et al., 2007). It requires the inputs of human activity level, clothing insulation ratio, air temperature, mean radiant temperature, relative humidity and air speed. The distribution of human thermal comfort index with the aid of simulation models, it can be possible to estimate the human thermal comfort condition for a proposed 3D urban design (Murakami, 2006).

Computational fluid dynamics (CFD) is increasingly recognised as a significant and useful simulation tool for the prediction of the four classical thermal environment parameters and the assessment of pedestrian thermal microenvironment (Ullah, 2003; Lin et al., 2008; Chen et al., 2008; Chung and Choo, 2011; Stavrakakis et al., 2012; Zhang et al., 2012; Blocken et al., 2012).

However, to understand the contribution of CFD in the approach of urban design, this paper will start by reviewing the thermal comfort interaction factors and present the data collected from the field measurement in Madinah, Saudi Arabia. Then it will look into the methods used to moderate urban microclimates to mitigate urban heat stress in outdoor public spaces. The theories of adaptive thermal comfort proposed by researchers, such as Nicol et al., 2012, Stavrakakis et al., 2012, Akbari et al., 1992, Lin et al., 2010, are applied as measure to understand the possibility of utilizing outdoor spaces and for the extension of its use. This paper will then review the use of CFD in urban design studies for the simulation and analysis of thermal environment, and will highlight its limitations as a tool in this field.

OUTDOOR THERMAL COMFORT

According to Brown (2010), many of outdoor urban environments, especially in hot dry countries, tend to be poorly regulated and not thermally comfortable. However, pedestrian thermal comfort levels can be improved once the design of microclimate is considered with the use of appropriate urban interventions that have cooling effects. It is crucial to understand the concept of thermal comfort for the outdoor space design and the relationship between the effects of the environmental parameters, the objectives of urban physical configuration, social behavioural factors, as well as approaches of human thermal physiological and psychological factors (Chen and Ng, 2012:122; Aihua et al., 2011:1855).

there are six key factors to human thermal comfort that should be considered for the design with microclimate, which are the environmental factors (i.e. air temperature, relative humidity, air movement, mean radiant temperature) and personal factors (i.e. clothing insulation ratio and activity or metabolic heat rate) (Figure 1).

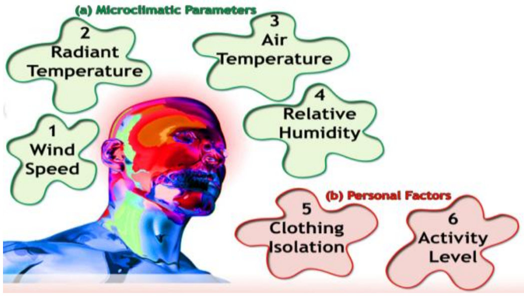

Fig.1: Thermal comfort interaction factors.

A CASE STUDY OF A HOT DRY URBAN MICROCLIMATE

One of the major microclimate issues facing urban space designers is the presence of the thermal discomfort in many outdoor pedestrian spaces in the Middle East, especially during day-time in hot and dry seasons, such as in Madinah city in Saudi Arabia. The current research has conducted an in-situ measurement approach on a segment along Quba road, a street of three kilometres long in Madinah, for the duration of 24 hours a day per week. This segment or location is characterised by its intensity of built-up area ratio. A digital weather meter (Kestrel 4400 Heat Stress Tracker) was used to monitor the urban microclimatic parameters. The research has used the measured parameters as an input in RayMan program for the calculation of PET index (i.e. Physiological Equivalent Temperature) to predict the human thermal comfort in the area of interest. The following microclimatic parameters were taken into account in the PET index:

- Air Temperature (Ta)
- Relative Humidity (RH)
- Wind Velocity (V)
- Mean Radiant Temperature (MRT)

The MRT in the commercial urban space was calculated from the measurements of the globe temperature, wind speed and air temperature based on the following equation (Thorsson et al., 2007):

$$MRT = \left[\left(T_g + 273.15\right)^4 + \frac{1.335 \times 10^8\, V^{0.71}}{\varepsilon D^{0.4}} \times \left(T_g - T_a\right) \right]^{\frac{1}{4}} - 273.15$$

where T_g is globe temperature (°C), T_a is air temperature (°C), V is air velocity (ms^{-1}), D is globe diameter (= 25mm) and ε is globe emissivity (=0.95).

The figures below (Fig.2 a & b) show that the number of pedestrians increases significantly when the sun sets. This is because of the absence of the solar radiation. Therefore, this outdoor area of Quba road, which is characterised by residential over retail buildings, gets very busy at night between 17:00-23:00 hours in all seasons. The MRT in winter is slightly lower than the air temperature during the day times. However, in spring the MRT increases when the sun rises and reaches 10°C above the air temperature in the afternoon, and drops in the evening when the sun sets.

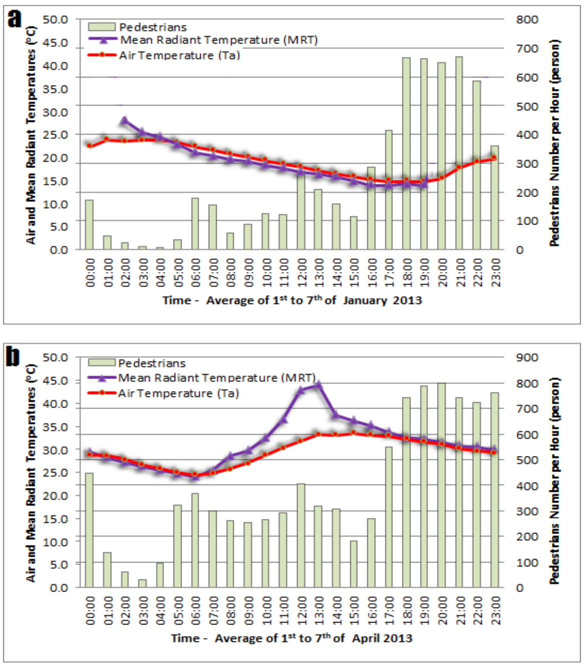

Fig.2: MRT in winter (a) and spring (b) in 2013. * There was an anomaly in measurements in Chart)a(between 20:00 to 1:00 these values are removed from readings.

Time	Oct-12						Jan-13						Apr-13					
HH:MM	V m/s	Ta °C	RH %	Tg °C	MRT °C	PET °C	V m/s	Ta °C	RH %	Tg °C	MRT °C	PET °C	V m/s	Ta °C	RH %	Tg °C	MRT °C	PET °C
00:00	0.5	32.5	21.2	33.1	33.2	**32.3**	1.8	22.4	33.1	33.6	39.0	**23.3**	0.6	28.8	18.6	29.4	29.5	**27.6**
01:00	0.5	31.4	23.3	31.2	31.2	**30.5**	1.9	23.9	29.6	38.1	45.0	**27.3**	0.5	28.7	24.2	28.4	28.3	**27.3**
02:00	0.4	30.3	25.1	29.9	29.8	**29.3**	2.0	23.6	29.9	26.3	27.9	**19.5**	0.6	27.8	23.7	27.4	27.3	**25.9**
03:00	0.4	29.7	26.3	29.5	29.5	**28.8**	1.6	23.8	28.7	25.0	25.6	**19.5**	0.5	26.7	22.2	26.4	26.4	**24.9**
04:00	0.3	29.1	27.3	28.8	28.8	**28.3**	1.9	23.8	27.8	24.3	24.6	**18.6**	0.5	25.9	24.6	25.6	25.6	**23.9**
05:00	0.3	28.6	28.0	28.5	28.5	**27.8**	1.9	23.3	28.0	23.1	23.0	**17.6**	0.7	25.0	28.0	24.9	24.9	**22.4**
06:00	0.3	28.0	28.4	27.7	27.7	**27.1**	1.3	22.4	30.0	21.7	21.4	**17.2**	0.5	24.6	31.0	24.3	24.2	**22.5**
07:00	0.4	28.2	28.2	28.8	28.9	**27.5**	1.6	21.7	33.4	21.0	20.6	**15.6**	0.4	24.8	31.5	25.4	25.5	**23.6**
08:00	0.5	28.3	27.5	30.6	31.1	**28.4**	1.4	20.9	36.0	20.2	19.8	**15.1**	0.7	25.8	29.4	28.0	28.7	**24.8**
09:00	0.6	30.3	24.4	32.7	33.2	**30.6**	1.1	20.2	37.6	19.6	19.3	**15.0**	0.4	27.0	21.8	29.4	29.8	**27.0**
10:00	0.5	32.3	20.8	35.2	35.8	**33.4**	1.2	19.5	38.7	18.8	18.5	**13.7**	0.6	28.8	18.4	31.7	32.4	**29.0**
11:00	0.5	33.9	18.6	38.5	39.4	**36.3**	0.9	18.7	40.5	18.1	17.8	**13.7**	1.1	30.4	15.3	34.9	36.5	**31.2**
12:00	0.5	35.5	16.0	44.6	46.3	**40.9**	1.3	18.1	41.5	17.4	17.1	**11.6**	0.6	31.8	11.9	41.0	42.9	**36.3**
13:00	0.5	35.8	15.3	44.2	45.8	**40.8**	1.1	17.3	45.9	16.7	16.5	**11.3**	0.9	33.3	10.6	41.7	44.1	**37.5**
14:00	0.5	36.0	14.2	39.4	40.0	**38.0**	1.0	16.7	46.8	16.2	16.0	**10.9**	0.9	33.2	9.7	36.6	37.6	**34.2**
15:00	0.5	35.7	14.7	37.7	38.1	**36.8**	0.9	16.0	49.3	15.3	15.0	**10.4**	0.6	33.7	8.2	35.8	36.2	**34.2**
16:00	0.5	35.3	14.8	36.8	37.1	**36.0**	0.9	15.5	50.4	14.6	14.3	**9.8**	1.0	33.3	8.6	34.8	35.2	**33.2**
17:00	0.5	36.0	14.4	36.6	36.7	**36.3**	1.0	15.1	51.8	14.4	14.1	**9.1**	0.8	33.0	9.3	33.6	33.8	**32.4**
18:00	0.4	36.6	13.7	36.8	36.8	**36.7**	1.2	15.2	51.6	14.7	14.4	**8.8**	0.6	32.3	10.8	32.6	32.6	**31.5**
19:00	0.4	36.1	15.6	36.5	36.6	**36.3**	1.5	15.0	52.9	14.6	14.4	**7.9**	0.5	31.8	12.9	32.2	32.3	**31.1**
20:00	0.3	35.6	16.9	35.9	35.9	**35.7**	1.8	15.7	52.0	20.4	23.2	**10.4**	0.6	31.2	15.0	31.5	31.6	**30.3**
21:00	0.4	35.0	17.9	35.5	35.6	**35.1**	1.3	17.8	46.6	30.1	35.1	**18.6**	0.7	30.3	17.0	30.7	30.9	**29.2**
22:00	0.4	34.3	18.9	35.1	35.2	**34.5**	1.6	19.2	41.6	32.7	39.0	**20.6**	0.7	29.7	17.8	30.5	30.7	**28.6**
23:00	0.4	33.4	21.3	34.0	34.1	**33.4**	1.8	19.9	38.1	30.3	35.5	**19.1**	0.5	29.3	18.4	29.9	30.0	**28.4**
AVERAGE	**0.4**	**32.8**	**20.5**	**34.5**	**34.8**	**33.4**	**1.4**	**19.4**	**40.1**	**22.0**	**23.2**	**15.2**	**0.6**	**29.5**	**18.3**	**31.1**	**31.5**	**29.0**

Table 1: PET Index for Outdoor Thermal Comfort and the measurements of Urban Microclimatic Parameters during the season of autumn (October), winter (January) and spring (April).

In addition to the microclimatic factors, the personal parameters used in PET index are, (Nicol et al., 2012):

- Activity Level (W): as walking a fixed number of 192.5W (=1.8met) was used in this case study as an input in RayMan.
- Clothing Insulation (Clo): 0.84 clo in winter and 0.59 in all other seasons were used.

The results of PET and the microclimatic measurements in the case study are shown in Table.1 for Autumn (October 2012), Winter and Spring (January and April 2013, respectively), which was calculated using RayMan software. These data will be used in the future studies for the comparison and validation of CFD outcomes, thus to investigate in the urban interventions that may enhance the hot dry microclimate of the study area and the outdoor pedestrian thermal comfort condition.

MICROCLIMATIC ENHANCEMENT METHODS FOR THERMAL COMFORT

This section reviews the available methods of urban microclimatic moderation approach in the urban canopy layer. The urban micro-environmental parameters, i.e. air temperature, mean radiant temperature, relative humidity and wind velocity, are the most influential factors on pedestrian thermal comfort level, as urban designers and planners at least should consider these factors when designing public spaces within built environment (Arens and Bosselmann, 1989; Gaitani et al., 2007).

These parameters can be modified by the effect of the use of urban interventions, which thus may enhance the outdoor thermal comfort conditions (Fig. 3). For example, the use of high emissivity and reflectivity materials (Lin et al., 2007), trees and vegetation in urban areas, use of water features (Robitu et al., 2006), and the shading devices (e.g. trees, buildings, pergolas) (Lin et al., 2010; Hwang et al., 2011), all of

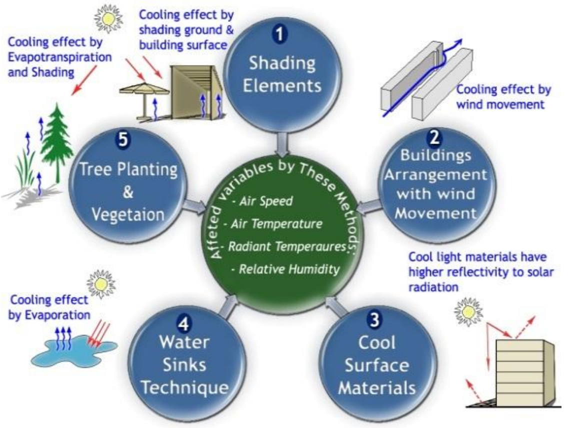

Fig. 3. Cooling Effects of the Use of Urban Interventions

these have great impacts on the reduction of urban heat stress.

Gaitani et al. (2007) argued that these urban interventions should be highly considered in urban planning process in order to enhance the urban microclimate in hot dry areas and especially to increase the outdoor thermal comfort conditions. Active regulation of cooling effects requires investigative simulation of the interaction of the aforementioned variables within the spatially influenced microclimate distribution (Mochida et al., 2006). Computational Fluid Dynamics (CFD) model, for example, is a powerful simulation tool for assessing outdoor environment issues, such as thermal and wind discomfort, using required data inputs of solar radiation, geometry of boundary condition, boundary conditions of ground and building wall surfaces, etc. (Murakami et al., 1999).

The following sections look at urban interventions that are used to decrease pedestrian heat stress in urban microclimates.

Cool Reflective Materials

The use of high albedo materials, which are characterised by the ability of their surfaces to reflect incoming solar radiation in urban environments, is an effective technique that considered as a promising method to reduce the effects of the thermal environment on pedestrian comfort (Akbari et al., 1992; Fintikakis et al., 2011). Research evidence indicated that increasing the solar reflectance of materials by 0.25 leads to significant reduction of the material temperature by 10^{o}C, as it keeps the structure surfaces cooler under the sun, thus reduces the convection of heat from the material to ambient air (Synnefa et al., 2011; Akbari et al., 2001). Research on white and light coloured surfaces has demonstrated significant improvements on thermal comfort as a result of a high ability in reducing the ambient temperature (Levinson et al., 2007; Synnefa et al., 2008, 2010).

Water Surfaces

Use of water features is a good heat sinks technique that also helps in improving the pedestrian thermal comfort level in hot dry urban built environments. The water bodies might not be a suitable heat sink for climates with high humidity conditions. In hot dry climates, water features such as fountains, water ponds, water streams, and shallow water in public spaces can dissipate part of the extreme urban heat through evaporative cooling system (Stavrakakis et al., 2012). “Evaporation and evapotranspiration are always associated to the heat transfer between water, vegetation and air”, as their presence improve the urban thermal environment in hot seasons by cooling the air (Robitu et al., 2006:440). Researchers in Japan such as Nishimura et al. (1998) proposed a concept of artificial waterfall and spray fountain and urban canal facility in hot and humid urban spaces to alter the temperature and humidity and create better microclimate for pedestrian comfort. The results have confirmed the usefulness of water facilities in easing the uncomfortable thermal environment, with a reduction in the microclimatic air temperature reaching 11^{o}C.

Green Spaces and Vegetation

One of the most common and effective methods used to improve the outdoor pedestrian thermal comfort condition in hot and dry urban spaces is by planting vegetation and trees in public spaces. Such method can allow for the moderation of the heat gain from the sun to the urban environment (Dimoudi and Nikolopoulou, 2003). Picot (2004) and Mahmoud (2011) assert that vegetation plays a strong role in modifying urban microclimates and enhancing outdoor thermal comfort. However, the common drawback of the influence of tree cover on microclimate is that it may stand as an obstacle against the desired wind speed in hot urban street canyons, which is due to the friction of plant canopies (Mahmoud, 2011). Despite of this, one of the great advantages of the tree cover is the cooling affect that results from the joint impact of evapotranspiration and canopy shading (Shashua-Bar and Hoffman, 2000). According to Fintikakis et al. (2011) beyond its aesthetic role and pleasant nature perception, increasing green spaces in urban areas represents a significant mitigation technique as it participates in heat-stress relaxation, blocking noise, air quality improvement and wind protection.

The Use of Shading Elements

Shading by physical elements (i.e. trees, buildings, artificial shading devices) is a preferred urban intervention in hot climates, as it provides shading by blocking the incident solar radiation, which influences outdoor thermal atmospheres and, therefore, affects the thermal sensitivities of pedestrian in outdoor areas (Lin et al., 2010). Results have shown that there are significant differences between a human thermal comfort sensation values in sunny areas than it is in the shaded areas as a result of the main contribution of the solar radiation (Murakami, 2006). Our body sensation depends more on the temperature of the surroundings and the degree of insolation rather than the convection, thus we feel cooler in shaded areas than those in sun (Monteih and Unsworth, 1990; Matzarakis et al., 2007; Armson et al., 2012). Experimental studies on people’s behaviour in Taiwan revealed that a great percentage of a public square users in summer prefer to stay in building shade or under the shade of trees (Lin, 2009). Moreover, experiments in Malaysia observed that although the temperature is higher than the acceptable range of comfort, people gather in areas that are shaded by buildings and other shading structures in outdoor spaces (Makaremi et al., 2012). However, results have shown that highly shaded locations in winter tend to have uncomfortable cool surface temperature, but more comfortable in summer, spring and autumn (Hwang et al., 2011).

Building Arrangements with Wind Movement

Montazeri and Blocken (2013) stated that wind-induced pressure distributions depend on many factors in urban environment such as the conditions of approach-flow, wind direction, urban geometry of structures and the urban surroundings. High-rise buildings, for example, can introduce high wind velocity at pedestrian level; however, this may be controlled by architectural design and other windbreak features, such as tree-plantings (Blocken et al, 2009). Research has shown that in urban areas where there is no wind, the value of a human thermal comfort condition index, can increase between 9-12°C, thus air movement in hot areas is necessary (Murakami et al., 1999). This indicates that air temperature is not the only parameter that determines the assessment of thermal comfort condition, but also the wind speed. Good design of urban fabric with air movement can reduce the effect of thermal environment, as this can control the wind direction and speed.

The use of the above-mentioned urban interventions to mitigate heat stress in hot dry microclimates seems useful in hot seasons; however, in the cold season the use of these features can decrease the temperatures in urban spaces and increase the discomfort of cold condition in winter. Therefore, a careful balance needs to consider when choosing urban interventions for outdoor thermal comfort in summer and winter conditions.

SIMULATION EFFECTS IN URBAN SPACE DESIGN

Chung and Choo (2011) suggest that Computational Fluid Dynamics (CFD) analysis should be accomplished at the urban design stage, instead of using it just for architectural design, to achieve better outdoor environments at the urban level and thus at human scale. CFD as a predictive tool maybe more effective in mitigating certain performances of urban interventions than actual build and test process. However, knowledge of a good modelling effort can be of value to city planners and designers (ASHRAE, 2009). CFD simulation is a valuable technique that allows the urban designers and other researchers to visualise and evaluate the intangible urban environmental factors, such as airflow, air and radiant temperatures, pollutant concentration level, etc., throughout CFD codes. The intangible environment in urban areas is formed as an outcome of the transport phenomena of heat, momentum, moisture and contaminant by convection, diffusion and radiative heat transfer (Murakami, 2006). CFD codes are numerical procedures of solving governing equations, which can be used to solve fluid flow, heat transfer, chemical reactions as well as thermal stresses (ASHRAE, 2009). Planning a CFD model is based on whether to conduct a steady-state or transient simulation, and to determine the physics that should be examined, such as turbulence, heat transfer coefficient, radiation phenomena, etc. In order to conduct a CFD analysis, there are three main steps must be accomplished (Kaushal and Sharma, 2012), which are:

- Generation of grid, i.e. pre-processing;
- The actual computational processing (i.e. solving relevant equations); and
- Post-processing, i.e. visualisation of the results.

SIMULATION OF THERMAL COMFORT

The flowchart (Fig.4) represents a framework for the assessment of outdoor human thermal comfort. To predict the microclimatic parameters by using CFD coupled simulation, this requires data inputs of solar radiation data, geometry of boundary condition and boundary conditions of ground and building surfaces. The predicted microclimatic parameters by the CFD simulation, i.e. wind velocity, air temperature, mean radiant temperature and relative humidity, coupled with the external inputs of personal factors, such as clothing ratio and activity level, are the human thermal comfort six main interaction factors. These factors can indicate the thermal comfort condition with the help of human thermal comfort indices, such as the Physiological Equivalent Temperature (PET).

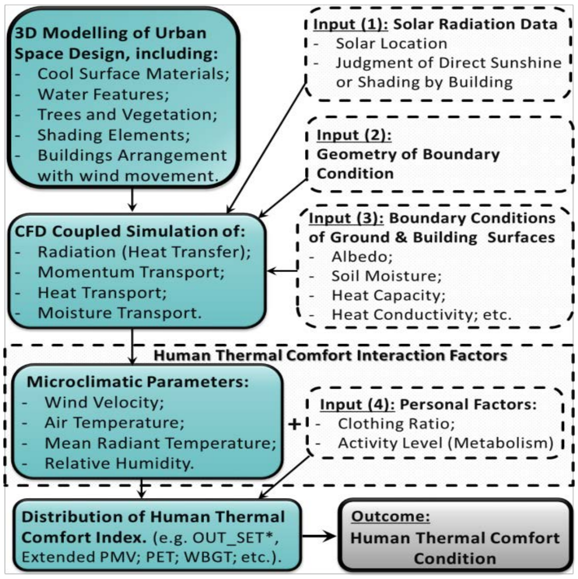

Fig. 4. A Framework for the Assessment of Outdoor Human Thermal Comfort. Source: Adapted from Murakami et al., (1999).

It is considered that using appropriate architectural interventions (i.e. buildings and ground surface materials, water and plantation surfaces, building arrangement with wind conditions) have effects on urban microclimatic parameters and people's behaviour towards outdoor thermal environments, as these interventions may give promising results in terms of thermal comfort enhancement approach in hot dry climates (Stavrakakis et al., 2012).

Simulation of the Urban Interventions

With the aid of the numerical results of CFD, variables such as air velocity ratio, frontal area index (i.e. the total areas of building walls facing the wind flow, divided by plane area in the computational domain) and thermal sensation index (e.g. PET) can utilise to evaluate the thermal comfort and air circulation performance outdoors (Zhang et al., 2012). It has been proven that the frontal area index of buildings, as a proposed urban design parameter, has a significant effect on the level of change in the thermal comfort when it reaches under 12% of area (Zhang et al., 2012). In addition, CFD can be used to determine mean wind-induced pressure distributions on building wall surfaces (Montazeri and Blocken, 2013).

Robitu et al. (2006) proposed a coupled CFD radiation model to examine the effects of natural green elements as well as water features on urban microclimate spaces, by the means of numerical study to simulate evaporation and evapotranspiration as a concept of heat and mass transfer mechanisms. Murakami (2006) modelled the plant canopy considering the effects of drag force of the planted trees, shading effects on short-wave radiation and the long-wave, and the production of latent heat from the canopy. This can obtain using the modified kinetic energy model for the aerodynamics effect of vegetation by applying extra terms in flow, momentum and energy equations (Lin et al., 2008).

To mitigate the urban heat Fintikakis et al. (2011) used a coupled CFD test tool and an experimental method with the use of the imposing measurements of surface temperature as boundary conditions in the CFD model. This involved the use of materials with high albedo value, increased green area ratio and the use of cool sinks (Akbari et al., 1992; Gaitani et al., 2007). The results have shown a significant reduction in the air temperature. Takahashi et al. (2004) developed a CFD simulation code for the prediction of solid-surfaces temperatures via integrating CFD computations with the calculations of surface radiation exchange and unsteady heat conduction equation. Researchers such as Mochida and Lun (2008) have used the Monte-Carlo simulation based method to compute the radiative heat transport (Omori et al., 1990; Howell, 1998).

ISSUES OF CFD IN URBAN DESIGN

CFD is useful for predicting wind flow patterns and the assessment of outdoor pedestrian thermal comfort. However, one of the difficulties of CFD is the required accuracy for solving problems of turbulence and the heat transfer in outdoor urban environments. Each boundary layer should be modelled in high detail to achieve accurate results. This requires high-resolution grids, which makes the computation system complicated (Blocken et al., 2009). According to Erell et al. (2011), modelling the boundary conditions of an urban area rather than a single building becomes difficult when high accuracy results from CFD are sought. Mirzaei and Haghighat (2010) argue that the complex urban atmospheric interactions require a vast number of nodes analyses in CFD to simulate an urban environment.

Another issue of CFD is the difficulty of simulating different scales of turbulence in an urban environment (e.g. atmospheric and canopy scale turbulences). For such simulation, it requires separate and simplified modelling, which may give inaccurate results. Challenges faced in practice also include the availability of the software and the compatibility with different operating systems (Chung and Choo, 2011). This incompatibility can make it difficult to incorporate work and generate continuity in the design progression.

CONCLUSION

Computational Fluid Dynamics (CFD) simulation is increasingly recognised as a significant and useful tool for the prediction and assessment of thermal comfort in outdoor urban microclimates as well as indoors. This paper has emphasised the importance of the use of outdoor spaces. It has mentioned that the external thermal environment regulated by the atmospheric natural conditions, man-made anthropogenic factors, the density of urban constructions and the size of vegetation. Pedestrian satisfaction with the thermal environment controls their behaviour and the duration of use of outdoor spaces. The most effective urban enhancement interventions to urban microclimates and specifically the thermal comfort level were also highlighted. The use of cool surface materials, vegetation and tree canopy cover, water features and shading elements have cooling effects, which can enhance the thermal environment conditions in hot dry seasons. CFD simulation is a useful tool to simulate the intangible microclimatic parameters, i.e. air temperature, air velocity, solar radiation and relative humidity, which are influenced by the above mentioned urban interventions. CFD can predict these required parameters for the assessment of pedestrian thermal comfort in urban areas with the distribution of human thermal comfort index, such as OUT_SET*, PET and extended PMV.

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