Use of CFD Simulation in Urban Design for Outdoor Thermal Comfort in Hot and Dry Climates: A Review

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Abstract:

Pedestrian thermal comfort in outdoor environments depends mainly on environmental parameters, urban physical configurations, and socio-behavioural factors. Due to rapid urbanisation and the density of urban construction, the characteristics of outdoor microclimate have been influenced, leading to pedestrian dissatisfaction with the thermal environment in many cities. This problem has posed many challenges to urban designers and other researchers in finding suitable ways to mitigate the heat stress of thermal environments in outdoor urban spaces. The purpose of this current research seeks to review the appropriate methods that may be used to increase the thermal comfort conditions in outdoor pedestrian spaces. This paper also reviews the use of computational fluid dynamics (CFD) to simulate outdoor wind flow conditions that affect pedestrian thermal comfort in urban design as a tool for the simulation of outdoor thermal comfort factors. Finally, it highlights a number of advantages and challenges in the application of CFD.

Keywords:

CFD; Outdoor Pedestrian Space; Thermal Comfort; Microclimate; Urban Design

Introduction

The outdoor pedestrian thermal sensation conditions depend mainly on environmental parameters (i.e. air and radiant temperatures, solar radiation, relative humidity and air velocity), urban physical configuration (i.e. urban fabric, buildings height and arrangement, vegetation, water features, ground surface treatment and building surface materials), and socio-behavioural factors (i.e. expectation, clothing rate and activity level). However, in the last few decades, due to the rapid urbanisation and the dense construction in urban areas, the characteristics of outdoor microclimate have been influenced, leading to pedestrian dissatisfaction with the thermal environment in many cities. This problem pose many challenges to urban designers and other researchers in finding suitable ways to mitigate the heat stress of thermal environments in outdoor urban spaces. Therefore, the purpose of this current research seeks to find out appropriate methods to increase the thermal comfort in the spaces between buildings; such as the use of water features, large areas of vegetation, and use of reflective materials. It highlights air temperature, radiant temperature, air velocity, humidity, activity level and clothing as the main interaction factors in human thermal comfort level. This paper also reviews the potential and limitations of using CFD in urban design as a tool for underpinning our understanding of outdoor thermal comfort parameters.

Thermal Comfort Interaction Factors

The quality of life within a city environment is strongly influenced by the quality of outdoor spaces and the level of human comfort offered by these spaces (Makaremi et al., 2012). Thermal comfort in outdoor areas can be affected by the individual buildings in that specific location, the urban morphology at a scale of neighbourhood, the urban heat island (UHI) effect at a scale of city, the effect of topography at a scale of regional area and the effects of climate and climate change at the global scale (Moonen et al., 2012). Gaitani et al. (2007) argue that the human thermal comfort condition is determined by six main interaction factors, where four are physical parameters and two are personals that should be considered for the thermal comfort condition calculations, which are:

1. Ambient air temperature: influences the convective mode of heat transfer as well as the exchange of dry and humid air;
2. Velocity of the air movement: significantly influences the heat convection and loss percentage of evaporation from our body;
3. Relative humidity: influences human thermal sensation when there is high a percentage of moisture in the air, especially when increased sweating occurs;
4. Mean radiant temperature: influences the radiation mode of heat transfer.
5. Activity level: influences the human metabolic rate that is the amount of energy produced per unit of time.
6. Clothing ratio: influences the thermal and hydric exchanges between the human body and environment by either resisting the exchange or assisting.

In order to measure human thermal comfort (i.e. the perception satisfaction with the thermal environment) it is necessary to establish at an early stage a comfort index, which basically demonstrates the comfort sensation of a person in a given condition (Moonen et al., 2012). Thermal comfort can be defined using a number of indices, including the Extended Predicted Mean Vote (PMV), Standard Effective Temperature (SET*), Physiological Equivalent Temperature (PET), Outdoor Wet-Bulb Globe Temperature ($WBGT_{out}$), etc. PMV was originally developed for indoor environments and has been extended to calculate the outdoor thermal comfort for a given level of activity and clothing ratio using air temperature and humidity, with air speed and mean radiant temperature. SET^* on the other hand, predicts the outdoor thermal comfort based on the air temperature of a reference environment in which a person has the same mean skin temperature and skin wetness as in a real situation. Whereas, PET is defined "as the air temperature of a reference environment in which the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed" (Moonen et al., 2012:6). Finally, the $WBGT_{out}$, which can be used to measure human heat stress in outdoor environments, is calculated by dry bulb temperature, wet bulb temperature, and black globe temperature (Auliciems and Szokolay, 2007).

The behaviour of outdoor urban environments is significantly different to natural environments, because the artificial materials used to create that environment affect the absorption of short and long wave radiation (Mirzaei and Haghighat, 2010). The urban environment also affects the transpiration, the release of anthropogenic heat, and blocks prevalent wind, all of which can affect the microclimate of the urban environment. According to Ahmed-Ouameur and Potvin (2007), the variation of texture in an urban space can modify micro-climatic parameters such as humidity, air temperature, solar radiation, wind direction and speed, which in turn affect pedestrian comfort. Thermal comfort can be affected by urban morphology such as the geographical location of the area and by the urban form, including the orientation, volume, dimensions, and proportions of the urban landscape (Lin et al., 2010). The types of materials used in the horizontal and vertical limits as well as the type and extent of vegetation, will significantly influence the thermal quality of the outdoor microclimate. Research proves that the air temperature in densely built areas is higher than in other areas (Moonen et al., 2012). This increase in heat is attributed to the fact that short and long-wave radiation is trapped within the building, heat is stored in the building fabric, and there is a release of anthropogenic heat from energy used in air-conditioning or heating the building.

Outdoor Adaptive Thermal Comfort Methods

The design of adaptive thermal comfort methods should take account of the local population, their physiological adaptation to thermal environments, and their expectations. Lin (2009) cites studies, which found that people living in hot and humid regions have greater tolerance for high temperatures than those residing in temperate regions. This implies that the design of outdoor urban space since occupant perceptions and preferences for thermal environments vary with an individual's physiological adaptation to a climate, as well as psychological expectations of environmental performance (Lin, 2009).

In designing for thermal comfort in an outdoor urban area, a designer must consider the trade-off between various physical interventions to buildings and urban space that the shelter provided and the disruption to wind patterns that may promote thermal comfort (Lin, 2009). The aim of these facilities is to give the urban user a degree of choice over their use of outdoor space. A study by Nikolopoulou and Steemers (2000) found that people want to have control of their space, for example people want to have the choice in deciding whether they sit in the sun or the shade.

Various methods can be used to improve the thermal comfort of the urban space users, including creating shelters using trees, vegetation and natural landscaping, or by constructing artificial shelters. These shelters can block direct short-wave radiation flux and reduce temperatures of the urban surfaces. The use of the space can be maximised in all thermal environments, if there are benches to avail of the warm sunshine in winter or spring (Lin, 2009). Moonen et al., (2012) suggest that other mitigation measures include ground-level ponds and roof ponds. Mirzaei and Haghighat (2010) add that the most effective mitigation measures to reduce thermal discomfort and UHI include using reflective materials in a city, increasing the level of soft landscaping, creating ponds within urban areas, and reducing released of anthropogenic heat by appropriate design of canopies and buildings. Attia and Duchhart (2011) points out that hard landscaping can be used to offer protection from the elements, providing shade from the sun and shelter from the wind.

Brown (2010) indicates that the materials and the colour of those materials used in an outdoor urban environment can promote thermal comfort. For example, light coloured materials reflect solar radiation, which means that the surface will remain cooler than dark surfaces. However, the reflected solar radiation will be absorbed by another surface within the landscape. In contrast, dark coloured materials will absorb radiated heat which means that a dark coloured surface will heat up faster than a light coloured surface, with minimal, if any reflected radiated heat. Konstantina (2011) suggests that the type of materials used in an urban environment can affect not only the thermal comfort of the urban dwellers but their perception of thermal comfort. Konstantina (2011) points out that if there is a high use of albedo (i.e. the fraction of solar radiation reflected from a surface) materials in the urban environment, then there will be small variations in relative temperature in that area. This can be avoided by creating urban space with different materials, for example using albedo materials mixed with areas of grass or water features. This mix creates variations in temperature and also creates a visual diversion for users of that space. Attia and Duchhart (2011) argue that the type of urban design will depend on the climatic conditions of the particular site. For example in hot and arid regions, where there is a great variation in diurnal temperatures, trees can be used in urban areas to retain warm air at night. The level of heat retained depends on the type of trees and the foliage density, the size and shape of the trees as well as their location. Deciduous trees have dense foliage and can therefore be used to provide solar protection and retention of heat. Water features can provide a natural cooling mechanism to reduce ambient temperatures in an urban area through evaporation. According to Attia and Duchhart (2011) the surface temperature of the water is affected by heat transfer and evaporation, such that water is normally warmer in winter and cooler in summer, with day time temperatures lower than night time temperatures. This means that bodies of water can moderate extreme temperature variations.

However, there are a number of ways in which the thermal comfort of outdoor space can be assessed in order to facilitate the design of suitable mitigation measures. Mirzaei and Haghighat (2010) imply that one of the difficulties in analysing specific urban microclimates and designing suitable mitigation measures is that this microclimate is the result of a multitude of micro-scale processes such as human metabolism and middle-scale interactions including wind, temperature, humidity and other atmospheric forces. In analysing this type of climate, it is not always possible to integrate all the contributing factors accurately and therefore a designer must make certain assumptions and simplifications in the analysis process. These simplifications can make the results less effective. There are different methods used to analyse the thermal environment and to enable the design of adaptive thermal comfort, including simulation methods, e.g. Computational Fluid Dynamics (CFD) (Mirzaei and Haghighat, 2010).

Use of CFD Simulation in Microclimate Studies

Computational fluid dynamics (CFD) is a simulation modelling technique that was developed as a mechanical engineering design tool. This technique has developed for analysis of air movement in and around buildings, investigating the pedestrian wind environment, the effects of wind driven rain and the impact of vegetation on urban microclimate (Erell et al., 2011). CFD can be used to analyse ventilation and heat concentration patterns at the urban design stage to facilitate the design and development of outdoor spaces that offer the urban occupant a comfortable usable environment (Chung and Choo, 2011). It is used for both the indoor and outdoor environmental studies. When designing an indoor environment, designers can use CFD to analyse and develop efficient ventilation and ventilation management systems (Somarathne et al., 2005). In outdoor urban design, CFD simulation can be applied to assess the effects of heat gain from the building geometry, building materials and other external heat sources such as air-conditioning units (Priyadarsini et al., 2008).

Thermal comfort is a complicated interaction of physical and physiological factors and these complex interactions are difficult to model and to analyse. Ahmed-Ouameur and Potvin (2007) carried out a study of the effects of different morphological conditions on pedestrian thermal comfort. The study divided the urban fabric scale into four indicators, i.e. building density, vegetal density, urban roughness, and porosity. The researchers concluded that these factors could affect the ambient temperature, radiant temperature and relative humidity, as well as the wind movement and light intensity in an urban area. Auliciems and Szokolay (2007) point out that thermal comfort is also influenced by thermal perception, personal preference, and satisfaction. According to Lin et al. (2010) the outdoor thermal environment is affected by anthropogenic heat, evaporation shading of landscaping and buildings, as well as the ground covering. Chung and Choo (2011) state that different urban typologies affect the wind flow through a city or urban environment. In essence, as the city becomes more compact with higher building height to width ratios, the UHI will increase. In addition wind patterns in and around an urban landscape can affect the thermal comfort of urban dwellers. A study by Cheng et al., (2007) established the importance of wind in response to thermal comfort and concluded that thermal discomfort increased when wind was suppressed. The study also concluded that an increase of between 0.3-1 m/s of wind speed could reduce ambient temperature by 2^{o}C, which could help ensure thermal comfort for outdoor space users (Cheng et al., 2007).

Given the complexity of these factors, Chung and Choo (2011:35) point out that CFD can be used to understand the airflow in an urban environment. CFD simulations used to analyse heat gain and to generate cross-ventilation and improve thermal comfort. According to Mirzaei and Haghighat (2010), the benefit of CFD is that it simultaneously solves all the governing equations of fluid inside the urban areas, including conservation of mass, potential temperature, momentum, and water vapour. This means that it is possible to obtain very accurate information regarding UHI distribution within and above building canopies with CFD than with other simulation techniques including energy-balancing models.

Advantages and Drawbacks of CFD Tool

As the world becomes increasingly populated, there will be an increasing need for dense urban developments, potentially increasing the number of high-rise buildings in the urban landscape. This type of development can trap radiated heat, air pollutants and create thermally uncomfortable outdoor environments for urban occupants and in doing so can adversely affect the identity of the microclimate of outdoor urban space (Chung and Choo, 2011). According to Mirzaei and Haghighat (2010) summertime UHI can decrease the outdoor air quality, increase the energy demand of a city. It can also intensify pollutants in urban atmospheres, alter local wind patterns, increase humidity with the ambient temperatures, and affect the rate of precipitation. The advantage of the CFD technique is that it can be used to analyse most of these factors, including heat radiation patterns, wind direction, and speed. Numerical modelling with CFD can investigate the convective heat transfer coefficient (CHTC) and convective mass transfer coefficient (CMTC) for exterior surfaces of buildings to evaluate its effect on the environment (Blocken, 2009). Recent studies show that CFD can also simulate air pollutant concentration distributions around buildings (e.g. Tominaga and Stathopoulos, 2009) and in urban street canyons (e.g. Neofytou et al., 2008). CFD is therefore useful in analysing the microclimate of dense urban space. The data developed in CFD simulation modelling can be used by designers to improve the comfort levels of the urban thermal microclimate (Chung and Choo, 2011).

By improving the design process, it could be argued that CFD also enables a designer to maximise the use of outdoor space, as urban dwellers are more likely to stay in air-conditioned buildings if the outdoor space is too hot, too humid, or polluted. The indirect advantage therefore of CFD is that in making outdoor space more attractive, there may be potentially less energy used on air conditioning, which is beneficial to the environment in terms of decreasing artificial heat sources. If the simulation model is implemented at the design stage of a project this can ensure that, the development of design can be optimised for thermal comfort (Chung and Choo, 2011).

Other advantages of CFD in urban design studies compared to observational techniques, field experiments or wind-tunnel experiments include the fact that in CFD there are virtually no restrictions on the geometry of the computational model, whereas in using alternative methods such as a wind tunnel, the geometry has to be scaled down. The CFD allows a large degree of freedom with respect to boundary conditions modelled. CFD enables the designer to obtain a very high spatial flow-field resolution in specific areas of interest by using spatial discretisation. This high resolution can be obtained at every location in the flow field, whereas when using field experiments or wind tunnels, there is limited spatial resolution and access for complex configurations. A further advantage of this technique is that fluid flow, active and passive scalars such as heat, moisture, and pollutants can be solved at the same time. This is possible to a degree in field experiments but not feasible in wind tunnels due to the small scale of the process. Technically building geometries and scalars such as pollutants and snow can be measured at their actual scale in CFD. The high spatial resolution in the CFD makes it relatively easy to obtain data such as heat flows from urban surfaces and flow rates through building openings (Moonen et al., 2012).

On the other hand, one of the CFD challenges is that it is difficult to solve problems of turbulence and the transfer of convective heat in the urban environment. CFD models are process-based tools, which therefore require high data inputs and a great level of complexity, as well as high computational costs that can make it difficult to quantitatively evaluate the uncertainty of the predictions (Robson et al., 2008). According to Blocken et al. (2009:489) “accurate CFD modelling of convective heat and mass transfer requires accurate and detailed modelling of each part of the boundary layer.” In order to obtain accurate results, each boundary layer must be modelled in detail, which requires complex high-resolution grids, and makes the process complicated and difficult (Blocken et al., 2009). This will cost time for both the analysts to create a model and for the computer to calculate the equations (ASHRAE, 2009). Erell et al. (2011) agree stating that it is difficult to model the boundary conditions in an urban area with a high degree of accuracy to obtain useful results from CFD. According to Mirzaei and Haghighat (2010), the main problem with CFD is that the atmospheric interactions of a city are complicated and their analysis requires a vast number of nodes to simulate a city. Another problem is that it is difficult to match the temporal and spatial resolution of the interactions within a city. For example, the different scales of atmospheric turbulence and canopy-scale turbulence. These factors must be simplified and modelled separately in the CFD process, which affects the accuracy of the results. Erell et al. (2011) add that the calculations obtained from CFD are limited to short periods of time and the methodology cannot be applied to problems requiring time scales longer than a few days. Another difficulty with CFD is that the package is not available in most professional practices. According to Chung and Choo (2011:36-37), even when the package is available there can be an operating system compatibility problem with some users running the system on Linux and UNIX platforms, while others use Windows or Macintosh platform, which is also typically used for Computer Aided Architectural Design systems. This incompatibility makes it difficult to integrate work and create continuity in the design process.

Conclusion

In conclusion, this paper has highlighted the six main interaction factors in thermal comfort on pedestrian level, which have been grouped into environmental factors, i.e. air temperature, radiant temperature, relative humidity and air velocity, and personal factors, i.e. activity level and clothing ratio. These interaction factors can be controlled by appropriate design using thermal comfort adaptive methods. The suggested methods in this paper were the use of water features, large vegetated areas, the use of high reflective surface materials on buildings and ground covers, and the use of shading elements. Furthermore, it has demonstrated the use of CFD simulation in this field of urban space design for the enhancement of outdoor pedestrian thermal comfort conditions. Although CFD technique has both advantages and disadvantages, it is suggested that it has huge potential in the assessment of thermal environment and wind comfort.

References:

Ahmed-Ouameur, F. and Potvin, A. (2007), *Microclimates and Thermal Comfort in Outdoor Pedestrian Spaces: A Dynamic Approach Assessing Thermal Transients and Adaptability of the Users*, Conference Proceedings of the American Solar Energy Society, ASES, Cleveland, Ohio, July.

ASHRAE (2009), *Handbook: Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, (ASHRAE) Inc., Atlanta, GA.

Attia, S. and Duchhart, I. (2011), *Bioclimatic Landscape Design in Extremely Hot and Arid Climates*, 27th Conference on Passive and Low Energy Architecture, PLEA 2011, Louvain-la-Neuve, Belgium, July.

Auliciems, A. and Szokolay, S.V. (2007), *Thermal Comfort*, Passive and Low Energy Architecture International - Design Tools and Techniques, Note 3 (2nd edition), PLEA, Brisbane.

Blocken, B., Stathopoulos, T., Carmeliet, J. and Hensen, J. (2009), *Application of CFD in Building Performance Simulation for the Outdoor Environment*, 11th International IBPSA Conference, Glasgow, Scotland, July.

Brown, R. (2010), *Design with Microclimate: The Secret to Comfortable Outdoor Space*, Washington DC: Island Press.

Cheng, V., Ng, E. and Givoni, B. (2007), *Outdoor Thermal Comfort for Hong Kong People: A Longitudinal Study*, Singapore, PLEA 2007: Proceedings of the 24th Passive and Low.

Chung, D.H.J. and Choo, M.L. (2011), *Computational Fluid Dynamics for Urban Design: the Prospects for Greater Integration*, International Journal of Architecture Computing, 09(01), pp. 33-55.

Erell, E., Pearlmutter, D. and Williamson, T.J. (2011), *Urban Microclimate: Designing the Spaces between Buildings*. London: Earthscan.

Gaitani, N., Mihalakakou, G. and Santamouris, M. (2007), *On the Use of Bioclimatic Architecture Principles in Order to Improve Thermal Comfort Conditions in Outdoor Spaces*, Building and Environment, 42(1), pp. 317-324.

Konstantina, S. (2011), *Microclimatic Interventions on an Urban Square in Patras, Greece (38^o 15'N, 21^o 45'E)*, PLEA2011: 27th Conference on Passive and Low Energy Architecture, Louvain-la-Neuve, Belgium, July.

Lin, T. (2009), *Thermal Perception, Adaptation and Attendance in a Public Square in Hot and Humid Regions*, Journal of Building and Environment, 44(10), pp. 2017-2026.

Lin, T., Matzarakis, A., Hwang, R. and Huang, Y. (2010), *Effect of Pavements Albedo on Long-Term Outdoor Thermal Comfort*, Proceedings of the 7th Conference on Biometeorology, Freiburg, Germany, April.

Makaremi, N., Salleh, E., Jaafar, M.Z. and GhaffarianHoseini, A. (2012), *Thermal Comfort Conditions of Shaded Outdoor Spaces in Hot and Humid Climate of Malaysia*, Journal of Building and Environment, 48(0), pp. 7-14.

Mirzaei, P.A. and Haghighat, F. (2010), *Approaches to Study Urban Heat Island – Abilities and limitations,* Building and Environment, 45(10), pp. 2192-2201.

Moonen, P., Defraeye, T., Dorer, V., Blocken, B. and Carmeliet, J. (2012), *Urban Physics: Effect of the Micro-Climate on Comfort, Health and Energy Demand*, Journal of Frontiers of Architectural Research, 1(3), pp. 197-228.

Neofytou, P., Haakana, M., Venetsanos, A., Kousa, A., Bartzis, J. and Kukkonen, J. (2008), *Computational Fluid Dynamics Modelling of the Pollution Dispersion and Comparison with Measurements in a Street Canyon in Helsinki*, Journal of Environmental Modeling & Assessment, 13(3), pp. 439-448.

Poreh, M. (1996), *Investigation of Heat Islands Using Small Scale Models*, Journal of Atmospheric Environment, 30(3), pp. 467-479.

Priyadarsini, R., Hien, W.N. and David, C.K.W. (2008), *Microclimatic Modeling of the Urban Thermal Environment of Singapore to Mitigate Urban Heat Island*, Journal of Solar Energy, 82(8), pp. 727-745.

Robson, B.J., Hamilton, D.P., Webster, I.T. and Chan, T. (2008), *Ten Steps Applied to Development and Evaluation of Process-Based Biogeochemical Models of Estuaries*, Environmental Modelling & Software, 23(4), pp. 369-384.

Somarathne, S., Seymour, M. and Kolokotroni, M. (2005), *Dynamic Thermal CFD Simulation of a Typical Office by Efficient Transient Solution Methods*, Journal of Building and Environment, 40(7), pp. 887-896.

Tominaga, Y. and Stathopoulos, T. (2009), *Numerical Simulation of Dispersion around an Isolated Cubic Building: Comparison of Various Types of k-e Models*, Journal of Atmospheric Environment, 43(20), pp. 3200-3210.

Voogt, J.A. and Oke, T.R. (2003), *Thermal Remote Sensing of Urban Climates*, Remote Sensing of Environment, 86(3), pp. 370-384.