OUTDOOR THERMAL COMFORT INDEX IN MALAYSIAN URBAN AREAS

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PREFACE

In the name of Allah, the Supremely Merciful and Most Kind.

To my beloved family, who give me support and pray for my success.

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ABSTRACT

Rapid urbanisation and industrialisation have adversely impacted the urban environmental heat stress due to urban heat island phenomenon. These thermal environmental problems can be even more challenging to people living in urban areas with tropical hot and humid climatic conditions throughout the year. Buildings in urban area is one of the major elements that contributes to the heat stress problem. The objectives of the study are threefolds. First, to evaluate outdoor thermal comfort by using Universal Thermal Climate Index (UTCI) associated with regression equation during the hottest daily temperature based on 3 years of hourly climatic data at principal meteorological stations of five selected cities in Malaysia. Second, to simulate the current urban layout of the five cities with different types of area (i.e., residential, commercial and industrial areas) based on the analysed climatic input data of the worst case scenario by using Computational Fluid Dynamic (CFD) modelling to investigate its impact on UTCI. Third, to establish the most influential building arrangement parameter towards the outdoor thermal comfort. It was revealed that the UTCI values at five principal meteorological stations for the worst case scenario of heat stress were in the range of 35 ˚C to 37 ˚C. Meanwhile, the predicted UTCI levels due to the impact of buildings within the current urban layouts of the five cities were generally higher in the range of 39 ˚C to 47 ˚C. Alor Setar's residential area was found to have the lowest UTCI while Alor Setar's industrial area demonstrated the highest UTCI value. The predicted results from the Pearson coefficient correlation analysis revealed that packing density and H/W ratio are the two parameters that show significant impact toward UTCI with the correlation coefficient (R^2) of 0.746 and 0.689 respectively. However, the result from MLR analysis showed that packing density is the one and only BAP that has strong positive influence towards UTCI with the correlation coefficient (R^2) of 0.557.

ABSTRAK

Pembangunan dan perindustrian yang pesat telah memberi kesan buruk terhadap stres haba di persekitaran bandar akibat daripada fenomena pulau haba bandar. Masalah ini lebih kritikal bagi mereka yang tinggal di kawasan bandar yang beriklim tropika panas dan lembab sepanjang tahun. Bangunan merupakan elemen utama yang menyumbang kepada masalah stres haba ini. Terdapat tiga objektif di dalam kajian ini. Pertama, menilai tahap keselesaan termal luaran menggunakan Indeks Keselesaan Termal Universal (UTCI) berasaskan persamaan regresi pada data suhu tertinggi berdasarkan purata data cuaca untuk tempoh 3 tahun yang direkodkan setiap jam di stesen meteorologi utama bagi lima bandar terpilih di Malaysia. Kedua, mensimulasikan susun atur bandar semasa bagi lima bandar dengan berlainan jenis bangunan (kediaman, komersial & perindustrian) berdasarkan data input cuaca teranalisis bagi senario kes terburuk menggunakan pemodelan CFD bagi menyelidik kesannya terhadap UTCI. Akhirnya, menentukan Parameter Penyusunan Bangunan (BAP) yang paling mempengaruhi UTCI. Didapati bahawa tahap UTCI di lima stesen meteorologi utama adalah dalam lingkungan 35 °C hingga 37 °C. Sementara itu, tahap UTCI ramalan yang disebabkan oleh kesan bangunan-bangunan di dalam susun atur bandar semasa umumnya adalah lebih tinggi dalam lingkungan 39 °C hingga 47 °C. Kawasan jenis bangunan perumahan di Alor Setar didapati mempunyai nilai UTCI terendah manakala kawasan jenis bangunan industri di Alor Setar menunjukkan nilai UTCI tertinggi. Keputusan dari analisis korelasi *Pearson* menunjukkan ketumpatan pemadatan dan nisbah tinggi-lebar adalah dua BAPs yang memberi kesan signifikan terhadap UTCI dengan nilai pekali korelasi (R^2) masing-masing adalah 0.746 dan 0.689. Namun begitu, keputusan dari analisis MLR menunjukkan bahawa ketumpatan pemadatan adalah satu-satunya BAP yang mempunyai pengaruh positif sederhana terhadap UTCI dengan nilai pekali korelasi (R^2) 0.557.

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LIST OF SYMBOLS AND ABBREVIATIONS

UHI	-	Urban Heat Island
BAP	-	Building Arrangement Parameter
BAPs	-	Building Arrangement Parameters
UTCI	-	Universal Thermal Climate Index
$UTCI_{BAP}$	-	Universal Thermal Climate Index due to BAP
PET	-	Physiologically Equivalent Temperature
SET	-	Standard Effective Temperature
PMV	-	Predicted Mean Vote
MRT	-	Mean Radiant Temperature
TEP	-	Temperature of Equivalent Perception
PTCI	-	Perceptual Thermal Comfort Index
FAR	-	Floor Area Ratio
OSR	-	Open Space Ratio
TSV	-	Thermal Sensation Vote
S/V	-	Surface to Volume Ratio
RH	-	Relative Humidity
UDF	-	User Defined Function
CFD	-	Computational Fluid Dynamic
RANS	-	Reynolds Averaged Navier Stokes
UTHM	-	Universiti Tun Hussein Onn Malaysia
ppa	-	People per acre
v_i	-	Velocity input
v_i	-	Simulated velocity
λ_f	-	Frontal Area Density Ratio
λ_p	-	Packing density Ratio
H/W	-	Height to Width Ratio

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CHAPTER 1

INTRODUCTION

1.1 Background of study

The impact of urban heat stress on the society and environment, especially in the urban regions, prompted this study to explore such problem. Accordingly, global warming and climate change occur in different parts of the world, which primarily contribute to the phenomenon of urban heat island (UHI). The UHI, an anthropogenically generated phenomenon, occurs when an urban region, compared to rural region, becomes warmer than its surrounding environment. The region can be up to 10°C warmer, depending on the local environment and atmospheric conditions. Urban heat island is the ultimate phenomenon that causes urban heat stress. The subsequent chapter discusses factors that contribute to UHI and the strategies to mitigate urban heat stress in detail. Specifically, this study focused on the factor of building arrangement parameters (BAPs) with respect to the urban design purposes, especially in the early stage of urban planning. The outdoor thermal comfort index using the Universal Thermal Climate Index (UTCI) was used in this study to quantify the level of heat stress. Proper planning is highly imperative in the effort to minimise the impact of global warming in the urban canopy layer. In this case, the level of outdoor thermal comfort in these future urban areas can be improved. This study focused on the pedestrian level given the public preference to participate in the outdoor activities, such as cycling, walking, and other activities without experiencing unfavourable climatic conditions, especially in the worst-case scenario of heat stress.

1.2 Problem statement

An urban area can be described as a combination of place and occupants in a massive population that includes various natural elements, social activities, and human activities. Usually, the occupants prefer to participate in outdoor activities, such as cycling, walking, and other activities at the pedestrian level without experiencing unfavourable climatic conditions. However, rapid urbanisation and industrialisation have adversely impacted the urban environmental heat stress due to urban heat island phenomenon. Recently, the problem of heat stress becomes a major concern among people living in urban areas. Numerous studies highlighted the critical problem of heat stress across different countries all over the world. Additionally, the relationship between urbanisation and the formation of heat stress problem was also extensively demonstrated. For instance, Shenzhen in China was reported to encounter critical case of heat stress and thermal aggravation impact that affect urban sustainability (Chen *et al.*, 2004) . The phenomenon of heat stress in Japan has also recently worsened during the summer, which prompted Ooka, Chen & Kato (2008) and other Japanese researchers to explore the impact of future plants and building layout for the development of optimum urban design guidelines. Besides that, van Hove *et al.* (2015) reported that Netherlands also recently experienced the highest increase of temperature (from a difference of 4.3 °C to about 8 °C) due to the rapid urbanisation, which reflects the critical case of urban heat stress.

The impact of urban heat stress on the public health have also gained growing interest among researchers. For instance, Tam, Gough & Mohsin (2015) assessed the level of urban heat stress at five selected urban areas (i.e., Buffalo, Chicago, Oshawa, Montreal, and Edmonton), which assisted the public health officials in their effort to reduce health-related risks due to heat stress problem. After all, extreme heat events (EHEs) in the urban regions were revealed to contribute to the high rates of both mortality and morbidity (Norton *et al.*, 2015). Similarly, Toparlar *et al.*, (2015) asserted that urban heat stress affects the urban microclimate and negatively affects the death and illness of society. Another study also revealed that the outdoor thermal comfort primarily affects the health of pedestrians in the urban areas (Taleghani *et al.*, 2014). Therefore, the unwanted impact of heat stress towards occupants in urban areas should be reduced.

In general, several factors contribute to the phenomenon of UHI that can lead to urban heat stress problem. The factors that contribute to heat stress in urban areas include: (1) the production of anthropogenic heat from various industrial activities; (2) the emission of light from the buildings and ground, resulting in the formation of infrared radiation; (3) the shrinkage of green areas; (4) sunlight and climatic conditions; and (5) poor urban design that contributes to heat stress problems, such as the increase in temperature and heat from solar radiation (Memon, Leung, & Chunho, 2008; You, Kim, & You, 2013). For instance, Papamanolis (2015) acknowledged the characteristics of the built environment as a factor that contribute to heat stress problem. Thus, building arrangement in terms of building height serves as an important factor that contributes to urban heat stress. Urban morphology and urban properties were identified as some of the major factors that influence the urban microclimate of urban areas (Latini, Cocci Grifoni, & Tascini, 2010). On a similar note, van Hove *et al*. (2015) highlighted the significant relationship of building arrangement, urban furniture, and green landscaping with the formation of urban heat stress. The BAPs, such as height to width ratio (H/W ratio), packing density, and building shape, also influence the wind flow and dispersion (Ahmad, Khare, & Chaudhry, 2005). Niu *et al*. (2015) also identified the density of tall buildings in the urban areas as a major factor that reduces the average wind speed and contributes to urban heat stress. According to Rajagopalan *et al.* (2014), narrow streets with the growing number of tall buildings entrap heat and greatly reduce the wind flow, which contribute to the increase of temperature. This highlights the significance of building arrangement in terms of building height as a factor that contributes to urban heat stress. Building arrangement, especially of those densely built-up urban zones, increases the temperature, resulting in the formation of urban heat stress zones (Abd Razak *et al*., 2013; Gago *et al*., 2013; Yuan, Ng & Norford, 2014). Notably, the relationship between building arrangement and urban heat stress within the Malaysian context was also assessed. Rajagopalan *et al.* (2014) demonstrated the existence of urban heat stress in Muar, Johor, which reaffirmed the occurrence of urban heat stress in Malaysia. The study revealed that urban heat stress intensifies around 4 °C during the day and around 3.2 °C at night.

Despite the significance of building arrangement strategies as one of effective measures to minimise the impact of urban heat stress which subsequently reduces the heat stress problem, the study did not highlight systematic means to mitigate urban heat stress in detail. Meanwhile, Jamei *et al*., (2015) also demonstrated the existence of urban heat stress in Melaka, Malaysia. Evidently, urban heat stress is a critical thermal environmental problem that occurs in the urban areas globally (Ã & Lun, 2008), including Malaysia which subsequently reduce the outdoor thermal comfort at pedestrian level. Hence, BAPs clearly would contribute to urban heat stress, which propelled this study to investigate the significant BAPs that influence the heat stress particularly in Malaysian urban areas. In this thesis, an attempt has been made to evaluate the most influential building arrangement parameter towards the pedestrian's outdoor thermal comfort.

1.3 Research questions

Based on the research problem highlighted earlier, the following questions have been formulated for this study:

i. What is the level of outdoor thermal comfort at the worst case scenario at urban areas in Malaysia?
ii. What is the impact of the current complex building layouts on the outdoor thermal comfort at urban areas in Malaysia?
iii. What are the most influential of BAPs towards outdoor thermal comfort in hot and humid tropical climate especially in Malaysia urban areas?

1.4 Research aims and objectives

The aim of this research is to establish the outdoor thermal comfort index due to BAPs in hot and humid tropical climatic region, particularly in the urban areas (complex building) of Malaysia. In order to achieve this aim, specific objectives are set as the following;

i. To evaluate the outdoor thermal comfort at the hottest daily temperature based on the climatic data of 3 years at selected urban areas in Malaysia.
ii. To investigate the impact of the current complex building layouts on the outdoor thermal comfort at selected urban areas in Malaysia based on the analysed climatic input data of the worst case scenario using CFD modelling.
iii. To establish the most influential building arrangement parameter towards the outdoor thermal comfort.

1.5 Scope of study

This study specifically evaluated the outdoor thermal comfort adopting UTCI with respect to the urban design purposes. Hence, the development of a new assessment method to quantify the outdoor thermal comfort level was not part of this study. Instead, this study served to assist in the planning and design of building with respect to the BAPs, which addressed the urban heat stress and outdoor thermal comfort in hot and humid tropical climate, particularly in the urban areas of Malaysia. In addition, this study employed 3D urban simplified models of actual case studies of five selected cities namely Alor Setar (represents northern region), Shah Alam (represents Central Region), Kuantan (represents East Coast Region), Kuching, and Kota Kinabalu (both represent East Malaysia) to characterise the urban areas in Malaysia (Burian, Brown, & Linger, 2002). Johor Bahru city (represents Southern Region) was not considered since the nearest weather station located in Senai is quite far, which is more than 25 km away. In particular, a flat surface for all cases was assumed for the topographic map in this study. A static condition (i.e., stationary objects, such as buildings) without green areas, human beings, or any factors that produce water vapour or condensation (that may have contributed to the relative humidity changes) was assumed. It may have contradicted to the actual situation with dynamic conditions due to non-stationary objects, such as automobiles, green areas, and human beings. Nevertheless, this dynamic approach was clearly not possible for this study to explore the urban areas at macro-scale that typically requires a super computer to run the simulation (extremely high computational cost). Apart from that, this study explored the outdoor thermal comfort level in only three different types of urban area, namely commercial, residential, and industrial areas within the five selected cities, using the Computational

REFERENCES

Mochida, A., & Lun, I. Y. (2008). Prediction of wind environment and thermal comfort at pedestrian level in urban area. *Journal of wind engineering and industrial aerodynamics*, *96*(10-11), 1498-1527.

Razak, A. A., Hagishima, A., Ikegaya, N., & Tanimoto, J. (2013). Analysis of airflow over building arrays for assessment of urban wind environment. *Building and Environment*, *59*, 56-65.

Abdallah, A. S. H. (2015). The influence of urban geometry on thermal comfort and energy consumption in residential building of hot arid climate, Assiut, Egypt. *Procedia Engineering*, *121*, 158-166.

Achour-Younsi, S., & Kharrat, F. (2016). Outdoor thermal comfort: impact of the geometry of an urban street canyon in a Mediterranean subtropical climate–case study Tunis, Tunisia. *Procedia-Social and Behavioral Sciences*, *216*, 689-700.

Adunola, A. O. (2014). Evaluation of urban residential thermal comfort in relation to indoor and outdoor air temperatures in Ibadan, Nigeria. *Building and Environment*, *75*, 190-205.

Ahmad, K., Khare, M., & Chaudhry, K. K. (2005). Wind tunnel simulation studies on dispersion at urban street canyons and intersections—a review. *Journal of Wind Engineering and Industrial Aerodynamics*, *93*(9), 697-717.

Andreou, E. (2013). Thermal comfort in outdoor spaces and urban canyon microclimate. *Renewable Energy*, *55*, 182-188.

Bajšanski, I. V., Milošević, D. D., & Savić, S. M. (2015). Evaluation and improvement of outdoor thermal comfort in urban areas on extreme temperature days: Applications of automatic algorithms. *Building and Environment*, *94*, 632-643.

Gadi, M. (2016, July). Urban outdoor thermal comfort of the hot-humid region. In *MATEC Web of Conferences* (Vol. 66, p. 00084). EDP Sciences..

Barakat, A., Ayad, H., & El-Sayed, Z. (2017). Urban design in favor of human thermal comfort for hot arid climate using advanced simulation methods. *Alexandria*

Engineering Journal, *56*(4), 533-543.

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., & Tinz, B. (2012). Comparison of UTCI to selected thermal indices. *International journal of biometeorology*, *56*(3), 515-535.

Blocken, B., & Persoon, J. (2009). Pedestrian wind comfort around a large football stadium in an urban environment: CFD simulation, validation and application of the new Dutch wind nuisance standard. *Journal of wind engineering and industrial aerodynamics*, *97*(5-6), 255-270.

Bröde, P., Fiala, D., Błażejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., ... & Havenith, G. (2012). Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *International journal of biometeorology*, *56*(3), 481-494.

Bröde, P., Krüger, E. L., Rossi, F. A., & Fiala, D. (2012). Predicting urban outdoor thermal comfort by the Universal Thermal Climate Index UTCI—a case study in Southern Brazil. *International journal of biometeorology*, *56*(3), 471-480.

Burian, S. J., Brown, M. J., & Linger, S. P. (2002). Morphological analyses using 3D building databases: Los Angeles, California. *Los Alamos National Laboratory*, *74*.

Charabi, Y., & Bakhit, A. (2011). Assessment of the canopy urban heat island of a coastal arid tropical city: The case of Muscat, Oman. *Atmospheric Research*, *101*(1-2), 215-227.

Chatzidimitriou, A., & Yannas, S. (2016). Microclimate design for open spaces: Ranking urban design effects on pedestrian thermal comfort in summer. *Sustainable Cities and Society*, *26*, 27-47.

Chen, H., Ooka, R., Harayama, K., Kato, S., & Li, X. (2004). Study on outdoor thermal environment of apartment block in Shenzhen, China with coupled simulation of convection, radiation and conduction. *Energy and Buildings*, *36*(12), 1247-1258.

Monteiro, L. M. (2005, September). Review of numerical modelling of outdoor thermal comfort. In *Proceedings of the World Sustainable Building Conference, Tokyo, Japan* (pp. 27-29).

Dalman, M., Salleh, E., Sapian, A. R., Tahir, O. M., Dola, K., & Saadatian, O. (2011). Microclimate and thermal comfort of urban forms and canyons in traditional and modern residential fabrics in Bandar Abbas, Iran. *Modern Applied Science*, *5*(2), 43.

Department of Statistic Malaysia. (2013). Population by age, sex and ethnic group, MALAYSIA.Retrievedfrom.http://pqi.stats.gov.my/result.php?token=4931ab32 afdc9b779306ea57fc3c0c43

Department of Statistics Malaysia. (2018). Current population estimates, Malaysia, 2017- 2018.

Djamila, H., Chu, C. M., & Kumaresan, S. (2013). Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia. *Building and Environment*, *62*, 133-142.

Efthimiou, G. C., Kumar, P., Giannissi, S. G., Feiz, A. A., & Andronopoulos, S. (2019). Prediction of the wind speed probabilities in the atmospheric surface layer. *Renewable energy*, *132*, 921-930.

Morakinyo, T. E., & Lam, Y. F. (2016). Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort. *Building and Environment*, *103*, 262-275.

Erell, E., Pearlmutter, D., Boneh, D., & Kutiel, P. B. (2014). Effect of high-albedo materials on pedestrian heat stress in urban street canyons. *Urban Climate*, *10*, 367-386.

Federal Department of Town and Country Planning Peninsular Malaysia. (2006). *National Urbanisation Policy*. Kuala Lumpur.

Federal Department of Town and Country Planning Peninsular Malaysia. (2011). *Garis Panduan Perancangan Perumahan*.

Fiala, D., Havenith, G., Bröde, P., Kampmann, B., & Jendritzky, G. (2012). UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *International journal of biometeorology*, *56*(3), 429-441.

Franke, J., Hellsten, A., Schlunzen, H., & Carissimo, B. (2007). The COST Action 732: Best Practice Guideline for the CFD Simulation of Flows in the Urban Environment. *University of Hamburg, Hamburg, Germany*.

Gagliano, A., Detommaso, M., Nocera, F., & Evola, G. (2015). A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs. *Building and Environment*, *90*, 71-81.

Gago, E. J., Roldan, J., Pacheco-Torres, R., & Ordóñez, J. (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews*, *25*, 749-758.

Garg, V., Kotharkar, R., Sathaye, J., Rallapalli, H., Kulkarni, N., Reddy, N., ... &

Sarkar, A. (2016). Assessment of the impact of cool roofs in rural buildings in India. *Energy and Buildings*, *114*, 156-163.

Ghaffarianhoseini, A., Berardi, U., & Ghaffarianhoseini, A. (2015). Thermal performance characteristics of unshaded courtyards in hot and humid climates. *Building and Environment*, *87*, 154-168.

Grimmond, C. S. B., & Oke, T. R. (1999). Aerodynamic properties of urban areas derived from analysis of surface form. *Journal of applied meteorology*, *38*(9), 1262-1292.

Sidawi, B., Hamza, N., & Setaih, K. (2014). CFD modeling as a tool for assessing outdoor thermal comfort conditions in urban settings in hot arid climates.

Havenith, G., Fiala, D., Błazejczyk, K., Richards, M., Bröde, P., Holmér, I., ... & Jendritzky, G. (2012). The UTCI-clothing model. *International journal of biometeorology*, *56*(3), 461-470.

Hayama, H. (2016). *AIJ Benchmarks for Validation of CFD Simulations Applied to Pedestrian Wind Environment around Buildings Architectural Institute of Japan*.

Holmes, M. J., & Davies, G. M. J. (2003). Data exchange for thermal modelling and ventilation simulation. *International Journal of Ventilation*, *2*(1), 55-63.

Hong, B., & Lin, B. (2015). Numerical studies of the outdoor wind environment and thermal comfort at pedestrian level in housing blocks with different building layout patterns and trees arrangement. *Renewable Energy*, *73*, 18-27.

Höppe, P. (2002). Different aspects of assessing indoor and outdoor thermal comfort. *Energy and buildings*, *34*(6), 661-665.

Hosseini, S. H., Ghobadi, P., Ahmadi, T., & Calautit, J. K. (2017). Numerical investigation of roof heating impacts on thermal comfort and air quality in urban canyons. *Applied Thermal Engineering*, *123*, 310-326.

Ignatius, M., Wong, N. H., & Jusuf, S. K. (2015). Urban microclimate analysis with consideration of local ambient temperature, external heat gain, urban ventilation, and outdoor thermal comfort in the tropics. *Sustainable Cities and Society*, *19*, 121-135.

Irwin, J. S. (1979). A theoretical variation of the wind profile power-law exponent as a function of surface roughness and stability. *Atmospheric Environment (1967)*, *13*(1), 191-194.

Ishida, Y., Endo, Y., Mochida, A., Shirasawa, T., Yoshie, R., & Tanaka, H. (2009). Large eddy simulation of flow and pressure fields around buildings in high dense cities-Effects of nonuniformity of building heights on drag force and momentum transport. In *Proceedings of the 7th International Conference on Urban Climate, 4pp*.

Fanger, P. O. (1984). Moderate thermal environments determination of the PMV and PPD indices and specification of the conditions for thermal comfort. *ISO 7730*.

Jabarudin, W. M. T. W., & Harith, Z. Y. H. (2012). Harnessing Wind Comfort in Coastal Resort Malaysia. *Procedia-Social and Behavioral Sciences*, *50*, 537-548.

Jamei, E., Jamei, Y., Rajagopalan, P., Ossen, D. R., & Roushenas, S. (2015). Effect of built-up ratio on the variation of air temperature in a heritage city. *Sustainable Cities and Society*, *14*, 280-292.

Jamei, E., & Rajagopalan, P. (2017). Urban development and pedestrian thermal comfort in Melbourne. *Solar Energy*, *144*, 681-698.

Jamei, E., Rajagopalan, P., Seyedmahmoudian, M., & Jamei, Y. (2016). Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. *Renewable and Sustainable Energy Reviews*, *54*, 1002-1017.

Jendritzky, G., de Dear, R., & Havenith, G. (2012). UTCI—why another thermal index?. *International journal of biometeorology*, *56*(3), 421-428.

Jendritzky, G., Maarouf, A., Fiala, D., & Staiger, H. (2002, October). An update on the development of a Universal Thermal Climate Index. In *15th Conf. biomet. aerobiol. and 16th ICB02* (Vol. 27, pp. 129-133).

Jeong, M. A., Park, S., & Song, G. S. (2016). Comparison of human thermal responses between the urban forest area and the central building district in Seoul, Korea. *Urban forestry & urban greening*, *15*, 133-148.

Jiang, Y., Song, D., Shi, T., & Han, X. (2018). Adaptive Analysis of Green Space Network Planning for the Cooling Effect of Residential Blocks in Summer: A Case Study in Shanghai. *Sustainability*, *10*(9), 3189.

Jihad, A. S., & Tahiri, M. (2016). Modeling the urban geometry influence on outdoor thermal comfort in the case of Moroccan microclimate. *Urban Climate*, *16*, 25-42.

Franke, J. (2006, July). Recommendations of the COST action C14 on the use of CFD in predicting pedestrian wind environment. In *The fourth international symposium on computational wind engineering, Yokohama, Japan* (pp. 529-532).

Johansson, E., Spangenberg, J., Gouvêa, M. L., & Freitas, E. D. (2013). Scale-integrated atmospheric simulations to assess thermal comfort in different urban tissues in the warm humid summer of São Paulo, Brazil. *Urban Climate*, *6*, 24-43.

Kampmann, B., Bröde, P., & Fiala, D. (2012). Physiological responses to temperature and humidity compared to the assessment by UTCI, WGBT and PHS. *International journal of biometeorology*, *56*(3), 505-513.

Karakounos, I., Dimoudi, A., & Zoras, S. (2018). The influence of bioclimatic urban redevelopment on outdoor thermal comfort. *Energy and Buildings*, *158*, 1266-1274.

Ketterer, C., & Matzarakis, A. (2016). Mapping the Physiologically Equivalent Temperature in urban areas using artificial neural network. *Landscape and Urban Planning*, *150*, 1-9.

Kozlowski, M., Ahmad, G., Mohamad, Z., Khairuddin, K. Z., & Rahman, A. A. (2014). *Urban Design Guidelines Kuala Lumpur*. *IZM consult* (Vol. 1).

Krüger, E. L., Minella, F. O., & Rasia, F. (2011). Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil. *Building and Environment*, *46*(3), 621-634.

Kubota, M. T., & Ahmad, S. (2004). Measurement of the wind flow in residential areas of Johor Bahru Metropolitan City toward planning guidelines for energy saving city in Malaysia. *Simposium Kebangsaan Masyarakat Bandar*, 1-12.

Kubota, T., & Ahmad, S. (2005). Analysis of wind flow in residential areas of Johor Bahru City. *Journal of Asian Architecture and Building Engineering*, *4*(1), 209-216.

Kubota, T., & Ahmad, S. (2006). Wind environment evaluation of neighborhood areas in major towns of Malaysia. *Journal of Asian Architecture and Building Engineering*, *5*(1), 199-206.

Kubota, T., Miura, M., Tominaga, Y., & Mochida, A. (2008). Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: Development of guidelines for realizing acceptable wind environment in residential neighborhoods. *Building and Environment*, *43*(10), 1699-1708.

Lamarca, C., Qüense, J., & Henríquez, C. (2018). Thermal comfort and urban canyons morphology in coastal temperate climate, Concepción, Chile. *Urban Climate*, *23*, 159-172.

Latini, G., Grifoni, R. C., & Tascini, S. (2010, December). Thermal comfort and microclimates in open spaces. In *Proceedings Building XI Conference,* *Paper* (Vol. 79, pp. 5-9).

Lau, K. K. L., Ren, C., Ho, J., & Ng, E. (2016). Numerical modelling of mean radiant temperature in high-density sub-tropical urban environment. *Energy and buildings*, *114*, 80-86.

Lee, H., Holst, J., & Mayer, H. (2013). Modification of human-biometeorologically significant radiant flux densities by shading as local method to mitigate heat stress in summer within urban street canyons. *Advances in Meteorology*, *2013*.

Li, C., Li, X., Su, Y., & Zhu, Y. (2012). A new zero-equation turbulence model for micro-scale climate simulation. *Building and Environment*, *47*, 243-255.

Li, J., Niu, J., Mak, C. M., Huang, T., & Xie, Y. (2018). Assessment of outdoor thermal comfort in Hong Kong based on the individual desirability and acceptability of sun and wind conditions. *Building and Environment*, *145*, 50-61.

Lin, T. P., & Matzarakis, A. (2008). Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. *International Journal of Biometeorology*, *52*(4), 281-290.

Liu, J., & Niu, J. (2016). CFD simulation of the wind environment around an isolated high-rise building: An evaluation of SRANS, LES and DES models. *Building and Environment*, *96*, 91-106.

Liu, J., Niu, J., & Xia, Q. (2016). Combining measured thermal parameters and simulated wind velocity to predict outdoor thermal comfort. *Building and Environment*, *105*, 185-197.

Liu, L., Lin, Y., Xiao, Y., Xue, P., Shi, L., Chen, X., & Liu, J. (2018). Quantitative effects of urban spatial characteristics on outdoor thermal comfort based on the LCZ scheme. *Building and Environment*, *143*, 443-460.

Lu, S., Chen, Y., Liu, S., & Kong, X. (2016). Experimental research on a novel energy efficiency roof coupled with PCM and cool materials. *Energy and Buildings*, *127*, 159-169.

Makaremi, N., Salleh, E., Jaafar, M. Z., & GhaffarianHoseini, A. (2012). Thermal comfort conditions of shaded outdoor spaces in hot and humid climate of Malaysia. *Building and environment*, *48*, 7-14.

Malaysia, M. D. (2009). Climate change scenarios for Malaysia 2001–2099. *Malaysia Meteorological Department*.

Marcus, M. G., & Detwyler, T. R. (1985). Urbanization and Environment. *Duxbury Press, California*.

Martilli, A. (2014). An idealized study of city structure, urban climate, energy consumption, and air quality. *Urban Climate*, *10*, 430-446.

Martins, T. A., Adolphe, L., Bastos, L. E. G., & de Lemos Martins, M. A. (2016). Sensitivity analysis of urban morphology factors regarding solar energy potential of buildings in a Brazilian tropical context. *Solar Energy*, *137*, 11-24.

Martins, T. A., Adolphe, L., Bonhomme, M., Bonneaud, F., Faraut, S., Ginestet, S., ... & Guyard, W. (2016). Impact of Urban Cool Island measures on outdoor climate and pedestrian comfort: simulations for a new district of Toulouse, France. *Sustainable Cities and Society*, *26*, 9-26.

Matzarakis, A., Muthers, S., & Rutz, F. (2014). Application and comparison of UTCI and PET in temperate climate conditions. *Finisterra*, *49*(98).

McDermott, R., McGrattan, K., & Hostikka, S. (2008). Fire dynamics simulator (version 5) technical reference guide. *NIST Special Publication*, *1018*, 5.

Md Din, M. F. (2012). Investigation of Heat Impact Behavior on Exterior Wall Surface of Building Material at Urban City Area. *Journal of Civil & Environmental Engineering*, *02*(02).

Memon, R. A., Dennis, L. Y., & Chunho, L. I. U. (2008). A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences*, *20*(1), 120-128.

Mirzaee, S., Özgun, O., Ruth, M., & Binita, K. C. (2018). Neighborhood-scale sky view factor variations with building density and height: A simulation approach and case study of Boston. *Urban climate*, *26*, 95-108.

Morakinyo, T. E., Balogun, A. A., & Adegun, O. B. (2013). Comparing the effect of trees on thermal conditions of two typical urban buildings. *Urban Climate*, *3*, 76-93.

Nasir, R. A., Ahmad, S. S., & Ahmed, A. Z. (2012). Psychological adaptation of outdoor thermal comfort in shaded green spaces in Malaysia. *Procedia-Social and Behavioral Sciences*, *68*, 865-878.

Nasir, R. A., Ahmad, S. S., & Zain-Ahmed, A. (2013). Adaptive outdoor thermal comfort at an urban park in Malaysia. *Journal of Asian Behavioral Studies*, *3*, 1-16.

Nazarian, N., Fan, J., Sin, T., Norford, L., & Kleissl, J. (2017). Predicting outdoor thermal comfort in urban environments: A 3D numerical model for standard effective temperature. *Urban climate*, *20*, 251-267.

Nazarian, N., Sin, T., & Norford, L. (2018). Numerical modeling of outdoor thermal comfort in 3D. *Urban climate*, *26*, 212-230.

Niu, J., Liu, J., Lee, T. C., Lin, Z. J., Mak, C., Tse, K. T., ... & Kwok, K. C. (2015). A new method to assess spatial variations of outdoor thermal comfort: Onsite monitoring results and implications for precinct planning. *Building and Environment*, *91*, 263-270.

Norton, B. A., Coutts, A. M., Livesley, S. J., Harris, R. J., Hunter, A. M., & Williams, N. S. (2015). Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landscape and urban planning*, *134*, 127-138.

Nutkiewicz, A., Jain, R. K., & Bardhan, R. (2018). Energy modeling of urban informal settlement redevelopment: Exploring design parameters for optimal thermal comfort in Dharavi, Mumbai, India. *Applied energy*, *231*, 433-445.

Oke, T. R. (1988). Street design and urban canopy layer climate. *Energy and buildings*, *11*(1-3), 103-113.

Onjo, T. H. (2009). Thermal comfort in outdoor environment. *Global environmental research*, *13*(2009), 43-47.

Ooka, R., Chen, H., & Kato, S. (2008). Study on optimum arrangement of trees for design of pleasant outdoor environment using multi-objective genetic algorithm and coupled simulation of convection, radiation and conduction. *Journal of Wind Engineering and Industrial Aerodynamics*, *96*(10-11), 1733-1748.

Papamanolis, N. (2015). The main characteristics of the urban climate and the air quality in Greek cities. *Urban Climate*, *12*, 49-64.

Paramita, B., Fukuda, H., Perdana Khidmat, R., & Matzarakis, A. (2018). Building Configuration of Low-Cost Apartments in Bandung—Its Contribution to the Microclimate and Outdoor Thermal Comfort. *Buildings*, *8*(9), 123.

Park, S., Tuller, S. E., & Jo, M. (2014). Application of Universal Thermal Climate Index (UTCI) for microclimatic analysis in urban thermal environments. *Landscape and Urban Planning*, *125*, 146-155.

Qaid, A., Lamit, H. B., Ossen, D. R., & Shahminan, R. N. R. (2016). Urban heat island and thermal comfort conditions at micro-climate scale in a tropical planned city. *Energy and Buildings*, *133*, 577-595.

Zhao, Q., Sailor, D. J., & Wentz, E. A. (2018). Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment. *Urban Forestry & Urban Greening*, *32*, 81-91.

Ragheb, A. A., El-Darwish, I. I., & Ahmed, S. (2016). Microclimate and human comfort considerations in planning a historic urban quarter. *International Journal of Sustainable Built Environment*, *5*(1), 156-167.

Rajagopalan, P., Lim, K. C., & Jamei, E. (2014). Urban heat island and wind flow characteristics of a tropical city. *Solar Energy*, *107*, 159-170.

Reiter, S. (2008). Validation process for CFD simulations of wind around buildings. In *Proceedings of the European Built Environment CAE Conference* (p. 18). Londres.

Rodríguez, A., Consuegra, L. G., & Matzarakis, A. (2016). Spatial-temporal study on the effects of urban street configurations on human thermal comfort in the world heritage city of Camagüey-Cuba. *Building and Environment*, *101*, 85-101.

Rosso, F., Golasi, I., Castaldo, V. L., Piselli, C., Pisello, A. L., Salata, F., ... & de Lieto Vollaro, A. (2018). On the impact of innovative materials on outdoor thermal comfort of pedestrians in historical urban canyons. *Renewable energy*, *118*, 825-839.

Ruiz, M. A., Sosa, M. B., Cantaloube, E. N. C., & Cantón, M. A. (2015). Suitable configurations for forested urban canyons to mitigate the UHI in the city of Mendoza, Argentina. *Urban Climate*, *14*, 197-212.

Sajad, Z., Hasheminejad, N., Shirvan, H. E., Hemmatjo, R., Sarebanzadeh, K., & Ahmadi, S. (2018). Comparing Universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year. *Weather and climate extremes*, *19*, 49-57.

Saleh, H., Yoong, C. P., Sulaiman, L. H., Sinnadurai, J., Murad, S., Muttalib, K., … Baba, N. (2014). Annual report 2014. *Kementerian Kesihatan Malaysia*, *16*.

Salleh, S. A., Latif, Z. A., Mohd, W. M. N. W., & Chan, A. (2013). Factors contributing to the formation of an urban heat island in Putrajaya, Malaysia. *Procedia-Social and Behavioral Sciences*, *105*, 840-850.

Sapian, A. R. (2009). Validation of the computational fluid dynamics (CFD) method for predicting wind flow around a high-rise building (HRB) in an urban boundary layer condition. *Journal of Construction in Developing Countries*, *14*(2), 1-20.

Sharmin, T., Steemers, K., & Matzarakis, A. (2015). Analysis of microclimatic diversity and outdoor thermal comfort perceptions in the tropical megacity Dhaka, Bangladesh. *Building and Environment*, *94*, 734-750.

Shen, T., Chow, D. H. C., & Darkwa, J. (2013). Simulating the influence of microclimatic design on mitigating the Urban Heat Island effect in the Hangzhou Metropolitan Area of China. *International Journal of Low-Carbon Technologies*, *11*(1), 130-139.

Soltani, A., & Sharifi, E. (2017). Daily variation of urban heat island effect and its correlations to urban greenery: A case study of Adelaide. *Frontiers of Architectural Research*, *6*(4), 529-538.

Song, J., & Wang, Z. H. (2015). Supplementary data of "Impacts of mesic and xeric urban vegetation on outdoor thermal comfort and microclimate in Phoenix, AZ". *Data in brief*, *5*, 918-920.

Stathopoulos, T. (2006). Pedestrian level winds and outdoor human comfort. *Journal of wind engineering and industrial aerodynamics*, *94*(11), 769-780.

Stavrakakis, G. M., Zervas, P. L., Sarimveis, H., & Markatos, N. C. (2010). Development of a computational tool to quantify architectural-design effects on thermal comfort in naturally ventilated rural houses. *Building and Environment*, *45*(1), 65-80.

Sun, S., Xu, X., Lao, Z., Liu, W., Li, Z., García, E. H., ... & Zhu, J. (2017). Evaluating the impact of urban green space and landscape design parameters on thermal comfort in hot summer by numerical simulation. *Building and Environment*, *123*, 277-288.

Syed O. T., Mohamad, N. N., & Jamaludin, S. N. (2013). Outdoor thermal comfort: the effects of urban landscape morphology on microclimatic conditions in a hot-humid city. *WIT Transactions on Ecology and the Environment*, *179*, 651-662.

Szűcs, Á. (2013). Wind comfort in a public urban space—Case study within Dublin Docklands. *Frontiers of architectural Research*, *2*(1), 50-66.

Taleghani, M. (2018). Outdoor thermal comfort by different heat mitigation strategies- A review. *Renewable and Sustainable Energy Reviews*, *81*, 2011-2018.

Taleghani, M., Kleerekoper, L., Tenpierik, M., & van den Dobbelsteen, A. (2015). Outdoor thermal comfort within five different urban forms in the Netherlands. *Building and environment*, *83*, 65-78.

Taleghani, M., Tenpierik, M., van den Dobbelsteen, A., & de Dear, R. (2013). Energy use impact of and thermal comfort in different urban block types in the Netherlands. *Energy and Buildings*, *67*, 166-175.

Tam, B. Y., Gough, W. A., & Mohsin, T. (2015). Urban Climate The impact of urbanization and the urban heat island effect on day to day temperature variation.

Urban Climate, *12*, 1–10.

Tan, C. L., Wong, N. H., & Jusuf, S. K. (2013). Outdoor mean radiant temperature estimation in the tropical urban environment. *Building and Environment*, *64*, 118-129.

Targhi, M. Z., & Van Dessel, S. (2015). Potential contribution of urban developments to outdoor thermal comfort conditions: The influence of urban geometry and form in Worcester, Massachusetts, USA. *Procedia engineering*, *118*, 1153-1161.

Tominaga, Y., Mochida, A., Shirasawa, T., Yoshie, R., Kataoka, H., Harimoto, K., & Nozu, T. (2004). Cross comparisons of CFD results of wind environment at pedestrian level around a high-rise building and within a building complex. *Journal of Asian architecture and building engineering*, *3*(1), 63-70.

Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M., & Shirasawa, T. (2008). AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of wind engineering and industrial aerodynamics*, *96*(10-11), 1749-1761.

Tong, S., Wong, N. H., Tan, C. L., Jusuf, S. K., Ignatius, M., & Tan, E. (2017). Impact of urban morphology on microclimate and thermal comfort in northern China. *Solar Energy*, *155*, 212-223.

Toparlar, Y., Blocken, B., Vos, P. V., Van Heijst, G. J. F., Janssen, W. D., van Hooff, T., ... & Timmermans, H. J. P. (2015). CFD simulation and validation of urban microclimate: A case study for Bergpolder Zuid, Rotterdam. *Building and Environment*, *83*, 79-90.

United Nations. (2014). *Department of Economic and Social Affairs, Population Division*. World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352).

Van Hooff, T., & Blocken, B. (2010). Coupled urban wind flow and indoor natural ventilation modelling on a high-resolution grid: a case study for the Amsterdam ArenA stadium. *Environmental Modelling & Software*, *25*(1), 51-65.

Van Hove, L. W. A., Jacobs, C. M. J., Heusinkveld, B. G., Elbers, J. A., Van Driel, B. L., & Holtslag, A. A. M. (2015). Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Building and Environment*, *83*, 91-103.

Versteeg, H. K., & Malalasekera, W. (1995). *Introduction to Computational Fluid Dynamics: The Finite Volume Method*. Harlow: Longman Scientific and

Technical.

Vinchurkar, S., & Longest, P. W. (2008). Evaluation of hexahedral, prismatic and hybrid mesh styles for simulating respiratory aerosol dynamics. *Computers & Fluids*, *37*(3), 317-331.

Wang, Y., Bakker, F., de Groot, R., Wörtche, H., & Leemans, R. (2015). Effects of urban green infrastructure (UGI) on local outdoor microclimate during the growing season. *Environmental monitoring and assessment*, *187*(12), 732.

Wang, Y., Berardi, U., & Akbari, H. (2016). Comparing the effects of urban heat island mitigation strategies for Toronto, Canada. *Energy and Buildings*, *114*, 2-19.

Wilkinson, S., Hanna, S., Hesselgren, L., & Mueller, V. (2012). Inductive Aerodynamics. *Cumincad.Architexturez.Net*, *2*, 39–48.

Yang, F., & Chen, L. (2016). Developing a thermal atlas for climate-responsive urban design based on empirical modeling and urban morphological analysis. *Energy and buildings*, *111*, 120-130.

Yang, W., Lin, Y., & Li, C. Q. (2018). Effects of landscape design on urban microclimate and thermal comfort in tropical climate. *Advances in Meteorology*, *2018*.

Yang, W., Wong, N. H., & Lin, Y. (2015). Thermal comfort in high-rise urban environments in Singapore. *Procedia Engineering*, *121*, 2125-2131.

Yoshie, R., Mochida, A., Tominaga, Y., Kataoka, H., Harimoto, K., Nozu, T., & Shirasawa, T. (2007). Cooperative project for CFD prediction of pedestrian wind environment in the Architectural Institute of Japan. *Journal of wind engineering and industrial aerodynamics*, *95*(9-11), 1551-1578.

Yoshie, R., Mochida, A., & Tominaga, Y. (2005). Cross Comparison of CFD Prediction for Wind Environment at Pedestrian Level around Buildings. *Proceedings of The Sixth Asia-Pacific Conference on Wind Engineering*, 2648–2660.

You, K. P., Kim, Y. M., & You, J. Y. (2013). Change of Wind Velocity Caused by the Development of Downtown Areas: A Case Study in Jeonju Korea. In *Applied Mechanics and Materials* (Vol. 421, pp. 792-797). Trans Tech Publications.

Yuan, C., Ng, E., & Norford, L. K. (2014). Improving air quality in high-density cities by understanding the relationship between air pollutant dispersion and urban morphologies. *Building and Environment*, *71*, 245-258.

Zahid, I. Q. M., & Chan, A. L. S. (2016). Pedestrian level wind environment assessment around group of high-rise cross-shaped buildings: effect of building shape, separation and orientation. *Building and environment*, *101*, 45-63.

Zinzi, M., & Agnoli, S. (2012). Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region. *Energy and Buildings*, *55*, 66-76.