Impact of Urban Canyon Direction on Solar Radiation and Airflow in Hot and Humid Regions

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Abstract

Urban configuration modification is an efficient approach to mitigating Urban Heat Island (UHI) effect. This study investigates the significant impact of urban canyon direction on solar radiation and airflow which influences microclimate and thermal comfort. The Envi-met (V3.1 beta) simulation indicates that East-West Canyon received the worst level of air temperature and meant radiant temperature compared to when the canyon was directed perpendiculars to the wind direction (South East – North West). The finding scientifically demonstrates that in Kuala Lumpur context, with the weak influences of urban wind, solar radiation plays the significant impact on the microclimate.

Keywords: Solar radiation; airflow; urban canyon, urban simulation

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1.0 Introduction

Urban Heat Island (UHI) is a current urban energy budget and other social-economic issues in a high-density urban area. As it is stressed to be an impact of urbanization, UHI raises significantly together with rapid new urban development (US Environmental Protection Agency, 2015 and Ng, 2009). The warmer air temperature within the dense urban area over the surrounding rural area was reported up to 5.6ºC and reaches the maximum intensity on three to five hour after sunset (Wang, Berardi, & Akbari, 2016; Oke, 1978). As hot, humid regions receive the high intensity of solar radiation throughout the year, UHI effects play a significant role in their urban energy budget. Arifwidodo & Chandrasiri (2015) reported that in 2012 UHI in Bangkok as up to 7ºC while Elsayed (2012) justified in his study that UHI of Kuala Lumpur was 1.5 ºC higher on 2004 compared to 1985. This phenomenon is a threat to the city area since the warmer urban environment demands energy consumption for space cooling.

Indoor and outdoor environment are interrelated; therefore, both cause adjustment of UHI intensity and urban thermal comfort. The interrelation of the related variables indicates a direct impact on climate change (Sachindra, Ng, Muthukumaran & Perera, 2015), thermal comfort, energy demand, air pollution, and social issues (Arifwidodo & Chandrasiri, 2015; Gartland, 2014; Santamouris et al., 2001; Oke, 1987). Human activities and modification of surface area determine the urban energy budget. US Environmental Protection Agency (2013) described that besides anthropogenic heat, urban heat circle significantly depends on the modification of the urban surface. In this context, the configuration of the built up area and the open spaces are the major roles. Earlier work (Yola and Siong, 2013) and Ng (2009) justified that due to lacking open space issue, urban development trend has no alternative but to extend vertically. The configuration of the dense urban area mainly influences the microclimate in between buildings. The issue is a shortwave radiation where it directly affects the daytime temperature and the indoor activities, especially in working places. Contrary, the ground surface emits the longwave radiation causes the UHI during the night time.

Yola and Siong (2015) pointed out in their earlier work that the configuration of spaces and buildings in the dense urban area plays a significant role in the modification of urban microclimate and thermal comfort. As high-density becomes a trend, the high-rise buildings shape the urban area into the giant wall that creates shaded spaces between buildings. Shaded spaces with good access to urban wind generate a better thermal comfort in the hot and humid region. Better thermal comfort offers livable outdoor activities and better indoor thermal comfort. Studies also reported that indoor thermal comfort is strongly related to mitigation of cooling load (Abdallah, 2015; Chen, Sung, Chang, Chi, 2013; Givoni, 1998). Lundgren & Kjellstrom (2013) justified that every 1ºC outdoor temperature increase requires an 180 MW base electricity load majorly required by air conditioning. It also reported that demand for the use of air conditioning which in buildings directly increases UHI in the urban area (Ohashi et al., 2007; Tremeac et al., 2012).

This framework illustrates the significance role of the urban configuration in corresponding to the best scenario of urban microclimate to achieve the maximum thermal comfort and energy conservation. Therefore, the aim of this study is to justify the significant impact of the urban canyon configuration on urban microclimate and thermal comfort.

Specifically, the objective is to investigate the impact of urban canyon direction on the modification of the solar radiation and airflow. The finding of this study assists urban planners and designers to strategies the urban configuration to work with the urban microclimate and generate the best scenario of thermal comfort.

2.0 Literature Review

There are ranges of design and planning strategies to mitigate the trend of temperature increase. The use of high albedo building materials and roof coating, involving green and water bodies and having more open surface instead of pavement and other cooling material are currently encouraged to reduce the heat and improve evaporation. However, urban planners and designers highlight that strategizing urban configuration is an efficient solution to the temperature increase issue. Studies reported that urban configuration plays a significant impact on microclimate and outdoor thermal comfort (Achour-Younsi, & Kharrat, 2015; Kariminia, Ahmad & Saberi, 2015; Almhafdy, Ibrahim, Ahmad, & Yahya, 2013). The urban canyon is the urban space configuration that is frequently investigated to measure urban microclimate and thermal comfort as the open space obstructed by vertical surface of building walls. However, as discussed earlier, based on the argument on the factors that affects both urban microclimate and thermal comfort, the factors that affect both measures for different types of urban configurations become fundamental. In this scenario, the urban configuration is always examined and described by several factors that contribute to microclimate modification. Blazejczyk, Epstein, Jendritzky, Staiger, & Tinz (2011) stressed that urban heat island, reduced wind speed, and maximum solar radiation penetration are the significant roles in urban canyon microclimate.

The urban surface energy system could clearly present from the heat cycle. Solar radiation (short wave) affects the daytime air temperature. Solar radiation partially converts into latent heat, while when it falls on the urban built-up surface, it absorbs and stores the heat day and night time (Givoni, 1998). This scenario will be worsening when the built up surface located within the enclosed spaces between buildings. This issue causes the air temperature increase in the night time in the urban area, which is the main contributor of UHI intensity. Oke (1981) formulated model (equation 1 & 2) that present the maximum level of UHI in canyon space formed by the relationship between height to width (H/W) aspect ratios and sky view factor (SVF). This result indicates that the configuration of building height and spaces between buildings determines the solar radiation penetration on the ground surface. The open country space would significantly generate lesser UHI compared to the deeper canyon (Givoni, 1998). Meanwhile, the configuration of the urban roughness also impacts on the urban ventilation. As the radiation is absorbed and stored as heat in the urban surface, airflow behaves to eases the heat (Erell, Pearlmutter & Wiliamson, 2010). As the high-density urban configuration creates the pattern of urban spaces, urban ventilation becomes a critical factor for creating the outdoor and indoor thermal comfort. In a hot and humid region, urban ventilation mainly reduces the heat stress over human body (Ng, 2009). Givoni & Noguchi (2004) formed the thermal sensation of human affected by air temperature, solar radiation, and airflow. Both solar radiation and airflow work differently on different urban configuration, as the blocks could shade the spaces from the direct radiation or blocking the airflow (Figure1).

$$dTmax = 7.45 + 3.97 * \ln (H/W) \quad (1)$$
$$dTmax = 15.27 – 13.88 * SVF \quad (2)$$

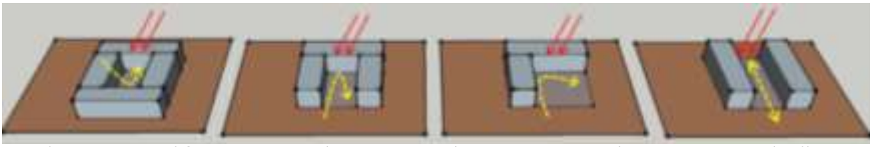


Figure 1: Illustration of Solar Radiation (marked as red) and Urban Wind (marked as yellow) Effect on Four Urban Configurations

Therefore, the configuration of the urban canyon in response to the exposure to the solar radiation and airflow is the concern of this paper. The apparent justification of the relationship of the urban microclimate or thermal comfort on the urban canyon with the key finding of aspect ratio and sky view factor scientifically justified by Oke (1981), Givoni (1998), Ng (2009) and Erell, Pearlmutter, & Williamson (2010). Recent studies describe further modifications of urban configuration that significantly affect urban microclimate and thermal comfort. One of them is canyon direction. Studies (Erell, Pearlmutter, & Williamson, 2010; Ng, 2009; Givoni, 1998) highlight that urban canyon direction determines the behavior of solar to conduct the heat and the airflow to ventilate the canyon spaces. Thus, as the direction of urban canyon takes major consideration in the planning and design process of urban configuration, strategizing urban canyon direction in response to the Kuala Lumpur microclimate context is the focus of this study.

3.0 Methodology

Hypothetical urban canyon configuration of symmetrical 40 meters height urban blocks chosen as the case of this study (illustrated by Figure 2). This consideration is to maintain the constant urban configuration and unobstructed space to observe the urban microclimate. The height to width ratio (H/W) of the hypothetical Canyon is 2:1 with 6:19 built up to open space ratio. The directions of the urban canyon were limited to four scenarios; canyon directed towards solar radiation exposures (East-West and North - South) and the urban wind (North East – South West and South East – North West (illustrated in Figure 3). ENVI-met V3.1, 3D microclimate simulation software was used to conduct the simulation as it reported that the ENVI-met is a suitable tool to perform the quantitative analysis of this study, as also highlighted in the previous study (Yola and Siong, 2014). The data simulated through the receptor that consistently positioned in the middle of the canyon at the 0-meter position. The microclimates data was taken every sixty minutes for 24 hours which were limited to the direct radiation, diffuse radiation, humidity, velocity, air temperature (Ta) and Meant Radiant Temperature (MRT). The urban canyon location was set in Kuala Lumpur city center (3º8'N

101°41'E) on 5th August 2014. The sun path of this date illustrated in Figure 4.

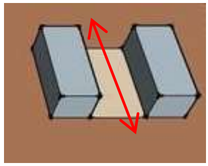
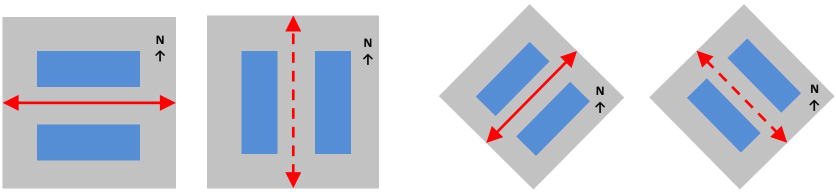


Figure 2: Hypothetical Urban Canyon Configuration



East-West (Canyon Direction Parallel with Solar Radiation)	**South-North** (Canyon Direction Perpendicular to Solar Radiation)	**North East – South West** Canyon Parallel with the Wind Direction	**South East – North West** Canyon Perpendicular to the Wind Direction

Figure 3: Urban Canyon Direction Towards Solar Radiation Exposure (left) and the Wind Direction (right)

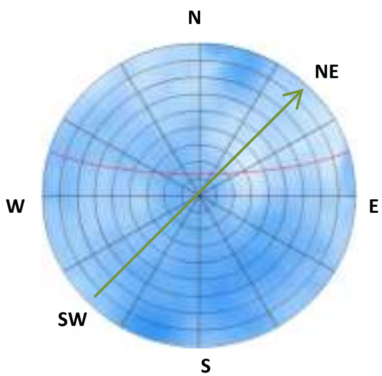


Figure 4: Sun Path Marked on Red, and Urban Wind Direction Marked on Green on 5 August 2015 at Study Area
Adapted from Photovoltaic Education Network, 2015

The input data in ENVI-met based on 2014 Kuala Lumpur weather data. The urban wind speed was 1.6 m/s with 225 South-West Direction. The relative humidity was at 83%, and the initial temperature was at 300K. The heat transmission of the wall was 1.94 W/m²K, and heat transmission of the roof was 6 W/m²K, and the albedo wall was 0.3 while albedo roof was 0.5. The data presented through comparison of day-time and night-time, as well as the mean of each variable to observe the effect of the four scenarios of canyon direction.

4.0 Results and Discussion

The microclimate results presented by comparing the impact of the solar radiation and the air flow. Thus, direct and diffuse solar radiations, whereby humidity and velocity are justified to examine the urban wind effects. Air temperature (Ta) is to show the urban micro-climate while Meant Radiant Temperature (MRT) represents the outdoor thermal comfort. Direct radiation (Table 1) recorded high reading when Canyon directed to East-West and North East – South West (591.76 W/m² and 244.37 W/m²). Contrary, diffuse radiation behaves differently (Table 2). Canyon directed to South East – North West and North - South direction (33.29 W/m²) was higher over East-West (33.25 W/m²) and North East – South West (33.12 W/m²). The similar trends also indicated on both relative humidity and airflow (Table 3 and Table 4). The relative humidity was high when the canyon directed to North - South (69.64 %) and South East – North West (69.54 %). Lastly, the highest airflow found when Canyon directed to South East – North West (1.97 m/s) followed by North - South direction (1.52 m/s).

Table 1: Direct radiation

Canyon direction	Direct radiation (W/m²)
South East – North West	164.21
North East – South West	244.37
East-West	591.76
North - South	164.92

Table 2: Diffuse radiation

Canyon direction	Direct radiation (W/m²)
South East – North West	33.29
North East – South West	33.12
East-West	33.25
North - South	33.29

Table 3: Relative Humidity

Canyon direction	Daytime (%)	Night time (%)	Mean (%)
South East – North West	71.39	67.69	69.54
North East – South West	74.00	79.07	76.53
East-West	69.37	67.78	68.58
North - South	70.52	68.75	69.64

Table 4: Airflow

Canyon direction	Daytime (m/s)	Night time (m/s)	Mean (m/s)
South East – North West	1.75	2.19	1.97
North East – South West	0.06	0.07	0.06
East-West	1.21	1.56	1.39
North - South	1.29	1.76	1.52

The air temperature (Ta) and Meant Radiant Temperature (MRT) of urban canyon directed to the four different scenarios were tested to identify how the four discussed components of urban microclimate influence the level of UHI and urban thermal comfort. The results (Table 5 and Table 6) show that the highest air temperature (Ta) identified when canyon as oriented to East-West (27.29ºC), follows by when the canyon directed to North East – South West (27.16ºC). The same trend also indicated on Meant Radiant Temperature (MRT). The highest Meant Radiant Temperature (MRT) indicated when the canyon directed to East-West (48.87ºC) and North East – South West (29.71ºC).

Table 5: Air Temperature (Ta)

Canyon direction	Daytime (ºC)	Night time (ºC)	Mean (ºC)
South East – North West	28.57	24.90	26.73
North East – South West	28.57	25.75	27.16
East-West	28.78	25.81	27.29
North - South	28.37	25.58	26.97

Table 6: Mean Radiant Temperature (MRT)

Canyon direction	Daytime (ºC)	Night time (ºC)	Mean (ºC)
South East – North West	37.25	17.58	27.42
North East – South West	40.35	19.07	29.71
East-West	58.96	38.78	48.87
North - South	36.17	18.03	27.10

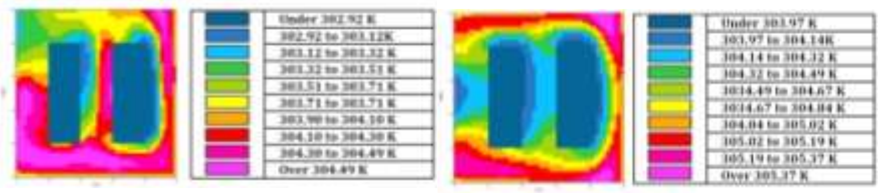


Figure 5: x-y Air Temperature (Ta) Image on East-West (left) and North East – South West (right) at 0 meters, 14.00 pm

The surface image of both air temperature (Ta) and Mean Radiant Temperature (MRT) illustrated in Figure 5 to Figure 6. The images generated for only the two scenarios with the highest readings to show the significant impact on the ground surface area. The images were the x-y section at 0-meter on 14.00 pm where the radiation was of the maximum intensity.

Besides showing the difference between East-West and North East – South West, the images are also presenting the patterns of both air temperature (Ta) and Mean Radiant Temperature (MRT).

Figure 6: x-y Mean Radiant Temperature (MRT) Image on East-West (left) and North East – South West (right) at 0 meters, 14.00 pm

The results show that East – West Canyon direction has the highest air temperature (Ta), as well as Mean Radiant Temperature (MRT) compared to North - South. This finding is because of the canyon was exposed to direct solar radiation along East-West sun path. When the canyon influenced by urban wind direction, both air temperature and (Ta) Mean Radiant Temperature (MRT) of the canyon direction parallel with the wind was higher over perpendicular to the urban wind. It is a questioned phenomenon as urban wind flow should reduce the heat frequently at urban canyon as this urban canyon configuration shape an urban wind tunnel between the buildings. This finding explains that the low wind speed at the ground surface of dense Kuala Lumpur fails to reduce thermal stress which generated by high intensity of solar radiation. Therefore, the whole scenario shows that with the urban wind effect, the air temperature (Ta) and Mean Radiant Temperature (MRT) could reach the maximum level when the canyon direction closed to East-West where the direct solar radiation is maximum.

5.0 Conclusion

Urban configuration emphasized as one of passive energy strategies to maximize UHI mitigation. This study brings up the need for spaces between the urban blocks in creating the outdoor thermal comfort for city dwellers. In achieving this purpose, this study by examining urban canyon as the chosen urban configuration to present both urban microclimate and thermal comfort. The results show that in Kuala Lumpur context, the exposure of urban canyon towards solar radiation indicates higher air temperature (Ta) and Meant Radiant Temperature (MRT). This finding is due to high intensity of solar radiation and slow airflow in Kuala Lumpur city context. This finding could be used to recommend urban planners and designers to strategize the urban space configuration to avoid sun path along the East-West direction instead of the concern on the urban ventilation. This strategy aims to minimize air temperature increase as well as to achieve maximum thermal comfort within the outdoor space between the urban blocks.

References

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. doi:10.1016/j.proeng.2015.08.1043.

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. doi:10.1016/j.sbspro.2015.12.062.

Almhafdy, A., Ibrahim, N., Ahmad, S. S., & Yahya, J. (2013). Analysis of the courtyard functions and its design variants in the Malaysian hospitals. Procedia - Social and Behavioral Sciences, 105, 171–182. doi:10.1016/j.sbspro.2013.11.018.

Arifwidodo, S., & Chandrasiri, O. (2015). Urban heat island and household energy consumption in Bangkok, Thailand. Energy Procedia, 79, 189–194. doi:10.1016/j.egypro.2015.11.461.

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., & Tinz, B. (2011). Comparison of UTCI to selected thermal indices. International Journal of Biometeorology, 56(3), 515–535. doi:10.1007/s00484-011-0453-2.

Chen, R., Sung, W.-P., Chang, H.-C., & Chi, Y.-R. (2013). Applying outdoor environment to develop health, comfort, and energy saving in the office in hot-humid climate. The Scientific World Journal, 2013, 1–8. doi:10.1155/2013/367283.

Elsayed, I. (2012). A study on the urban heat island of the city of Kuala Lumpur, Malaysia. Journal of King Abdulaziz University-Meteorology, Environment and Arid Land Agriculture Sciences, 23(2), 121–134. doi:10.4197/met.23-2-8.

Emmanuel, R., Rosenlund, H., & Johansson, E. (2007). Urban shading—a design option for the tropics? A study in Colombo, Sri Lanka. International Journal of Climatology, 27(14), 1995–2004. doi:10.1002/joc.1609.

Erell, E., Pearlmutter, D., & Williamson, T. (2010). Urban Microclimate: Designing the spaces between buildings. Washington, DC: Earthscan / James & James.

Gartland, L. (2014). Heat islands: Understanding and mitigating heat in urban areas. Los Angeles, CA, United States: Earthscan Publications.

Givoni, B. (1998). Climate considerations in building and urban design. New York: Van Nostrand Reinhold.

Givoni, B. & Noguchi. (2004). Outdoor Comfort Responses of Japanese Person's. In Proceedings of the American Solar Energy Society: National Solar Energy Conference 2004, 9-14 July, Portland, OR.

Kariminia, S., Ahmad, S. S., & Saberi, A. (2015). Microclimatic conditions of an urban square: Role of built environment and geometry. Procedia - Social and Behavioral Sciences, 170, 718–727. doi:10.1016/j.sbspro.2015.01.074.

Lundgren, K., & Kjellstrom, T. (2013). Sustainability challenges from climate change and air conditioning use in urban areas. Sustainability, 5(7), 3116–3128. doi:10.3390/su5073116.

Ng, E. (Ed.). (2009). Designing high-density cities: For social and environmental sustainability. London: Earthscan Publications.

Ohashi, Y., Genchi, Y., Kondo, H., Kikegawa, Y., Yoshikado, H., & Hirano, Y. (2007). Influence of air-conditioning waste heat on air temperature in Tokyo during summer: Numerical experiments using an urban canopy model coupled with a building energy model. Journal of Applied Meteorology and Climatology, 46(1), 66–81.

doi:10.1175/jam2441.1.

Oke, T. R. (1987). Boundary Layer Climates. (2nd ed.).: Routledge.

Oke, T. R. (1981). Canyon Geometry and the Nocturnal Urban Heat Island: Comparison of Scale Model and Field Observations. Journal Climatology, 1, 237-254.

Photovoltaic Education Network. (2015). Sun Position Calculator. Retrieved July 2015, from www.pveducation.org.

Sachindra, D. A., Ng, A. W. M., Muthukumaran, S., & Perera, B. J. C. (2015). Impact of climate change on urban heat island effect and extreme temperatures: A case-study. Quarterly Journal of the Royal Meteorological Society, 142(694), 172–186. doi:10.1002/qj.2642.

Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., & Assimakopoulos, D. N. (2001). On the impact of urban climate on the energy consumption of buildings. Solar Energy, 70(3), 201–216. doi:10.1016/s0038-092x(00)00095-5.

Tremeac, B., Bousquet, P., de Munck, C., Pigeon, G., Masson, V., Marchadier, C., Meunier, F. (2012). Influence of air conditioning management on heat island in Paris air street temperatures. Applied Energy, 95, 102–110. doi:10.1016/j.apenergy.2012.02.015.

US Environmental Protection Agency (EPA). (2013). Climate Protection Partnership Division US. Reducing Urban Heat Islands: Compendium of Strategies, Urban Heat Island Basics.

United States Environmental Protection Agency. (2015). State and Local and Energy Program. US EPA 2015.

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. doi:10.1016/j.enbuild.2015.06.046.

Yola, L. and Siong, H. C. (2015). Urban Configuration Effect on Urban Microclimate and Thermal Comfort. 9th South East Asian Technical University Consortium (SEATUC) Symposium 2015.

Yola, L. and Siong, H. C. (2014). Modeling and Simulation Approach of Assessing Urban Form (A Review). International Journal of Emerging Trends in Commerce, Humanities and Social Science (CEHSS).

Yola, L. and Siong, H. C. (2013). Understanding Vertical City Concept. 4th International Graduate Conference on Engineering, Science, and Humanities. Universiti Teknologi Malaysia.