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Urban heat island and wind flow characteristics of a tropical city

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Abstract

Urban Heat Island (UHI) has become a growing concern to the quality of densely built urban environments, particularly in tropical cities. Wind speed has widely been reported to have decreased the intensity of heat island effect in urban areas. The cooling effect of the wind helps to mitigate the adverse effects of heat island on the micro climate and human thermal comfort. This paper investigates the existence of heat island in Muar, one of the fast growing cities in southern part of Malaysia and its possible causes, and then examines the effects of different urban geometry on the wind flow. The results of this study indicate that the chaotic development in Muar has caused reduced ventilation in urban canyons. The heat island intensity in the city center was recorded as 4 °C during the day and 3.2 °C during the night. Investigation of various urban geometry modifications showed that step up configuration was the most effective geometry as it can distribute the wind evenly allowing the wind to reach even the leeward side of each building.

Keywords: UHI; Wind speed; Thermal comfort; Geometry modification; Tropical

1. Introduction

Over 61% of the world's population is projected to live in urban areas by 2030 (Economic and Division, 2012). The rapid urbanization has turned the cities into densely populated urban areas with less greenery and more impervious surfaces. Loss of vegetation increases the heat storage in the ground layer and building fabrics and contributes to the higher level of air and surface temperature in urban areas compared to their rural surrounding areas (Oke, 1982). This phenomenon which is known as "Urban Heat Island" (UHI) has become a rising concern to the quality of densely built urban environments (Wong and Yu, 2005). According to Landsberg (1981), UHI is a reflection of total microclimate changes caused by urban surfaces alterations. Akbari et al. (2001) described UHI as the areas that tend to have higher air temperatures that their rural surrounding areas due to the gradual surface modifications and replacement of natural vegetation by buildings and roads. Synnefa et al. (2007) defined UHI as the increased ambient temperature of urban areas due to warmer surfaces. Another definition of UHI indicates that urban heat island is a product of micro-climatic variations due to "man-made" interventions and modifications to the natural environment (Kolokotroni et al., 2006).

UHI occurs both during the day and night, but according to Oke (1987), the maximum intensity of heat island occurs 3–5 h after sunset. This is because cities retain much of its heat in roads, buildings, and other structures that prevents them from cooling down. The phenomenon has been well documented since the beginning of last century (Schmauss, 1925) and detailed research have been carried out for 60 years (Chandler, 1961; Oke and East, 1971; Lee, 1975; Lyall, 1977; Landsberg, 1981). Short term and long term measurements were conducted to investigate

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the heat island effect by various methodologies in cities with different size and climatic characteristics (Arnfield, 2003; Santamouris, 2007; Santamouris and Georgakis, 2003; Santamouris et al., 2001). Urban heat island may be considered as an asset in high-latitude cities, due to its role in reducing the energy needed for heating purposes, but many tropics, where all year round, wet or wet–dry seasons prevail, are subjected to heat- related illnesses and high level of energy consumption. In tropics, heat island causes further reliability on air conditioning and thus higher energy use. Application of air conditioning itself will increase the outdoor temperatures through emitting the excess heat to the urban air and more cooling will be required (de Schiller and Evans, 1998; Baker et al., 2002). It is found that for the city of Athens, where the mean heat island intensity exceeds 10 °C, the cooling load of urban buildings may be doubled, the peak electricity load for cooling purposes may be tripled especially for higher set point temperatures, while the minimum COP value of air conditioners may be decreased up to 25% because of the higher ambient temperatures (Santamouris et al., 2001). Factors generating UHI are believed to be the mutual response of over eleven manmade and natural factors (Rizwan et al., 2008; Memon et al., 2010). Che-Ani et al. (2009) summarized the factors generating and defining the intensity of heat island into two broad categories; first is the meteorological factors such as the air temperature, wind speed and direction, level of humidity and cloud cover and second is the urban design parameters, such as density of urban areas, percentage of built up ratios, aspect ratio of urban canyons, sky view factor, building construction materials and urban form.

Several studies have been undertaken to document the UHI of cities in temperate regions (Chandler, 1965; Oke and Maxwell, 1975; Ackerman, 1985; Magee et al., 1999; Runnalls and Oke, 2000), but similar information is scarce for tropical cities (Sham, 1973; Padmanabhamurty, 1979; Jauregui 1986, 1997; Deosthali, 2000; Chow and Roth, 2006). In Malaysia heat island studies were pioneered by Sham, since 1972 (Sani, 1972, 1990; Sham, 1986). Sham investigated the impact of Kuala Lumpur growth on night-time temperature pattern during 1972, 1975 and 1980. The study indicated that the intensity of the heat island had increased considerably followed by increasingly larger areas representing higher temperatures. Sani (1972) conducted comprehensive research regarding UHI in Kuala Lumpur. The study analysed both air temperature distribution and air pollution levels in the city and observed urban–rural temperature difference of 4.4–5 °C. Mobile surveys were carried out in the city of Johor Bahru, Malaysia in March (rainy season) and September (dry season) 2008. The nocturnal urban–rural temperature difference recorded only 2 °C in the rainy day, but it reached a maximum of 4 °C in the sunny day (Kubota and Ossen, 2009). Many Malaysian towns are subjected to rapid population growth, a process in which land use, urban form, and ground cover changes (Johansson and Emmanuel, 2006). On the other hand, urbanization is very fast in tropics, and design issues related to urban climate are normally neglected. Muar is one of the fast growing cities in southern part of Malaysia. Unplanned and rapid urban development in Muar can alter the microclimate of this tropical town, thus changing the air temperature and wind pattern. Furthermore, wind speed has widely been reported to have lessened the intensity of heat island effect in urban areas (Morris et al., 2001; Kim and Baik, 2002; Memon et al., 2010). Therefore, this paper aims to identify the existence of heat island in Muar, one of the fast growing cities in southern part of Malaysia and its possible causes, and then examines the effects of different urban geometry on the wind flow pattern.

2. UHI and wind flow

The factors affecting the occurrence and intensity of heat island can be broadly classified into two categories. First category is the meteorological factors including wind speed and direction, humidity and cloud cover. The second category is basically the product of city design, such as density of built up areas, aspect ratio, sky view factor (SVF) and construction materials. This paper deals with heat island effects caused by city configuration and it investigates the impact of urban layout on the wind velocity. Several studies discussed the role of urban geometry on micro climate. Shashua-Bar et al. (2004) investigated the effect of urban geometry on the micro-climate. Their findings show that areas with shallow open spaces and wider spacing recorded temperatures 4.7 °C higher than baseline measurements taken from a meteorological reference. Other research used field measurements to study how urban form may affect the microclimate in different areas in Dubai (Thapar and Yannas, 2007). Comfort surveys showed that higher relative humidity levels are more acceptable by people when there is substantially more airflow. However, the increase in airflow does not necessarily increase the acceptance of higher temperature levels (Ahmed, 2003). Bourbia and Boucheriba (2010) investigated street design and its impact on urban microclimate in semi-arid climate and they found that the higher the aspect ratio, lower the temperature. They suggested that the SVF should be incorporated in urban geometry design as it plays a key role in mitigating the effect of urban heat islands. In a research investigating the relationship between thermal performance and urban morphology and linking them to climatic responses, Golany (1996) stated that the configuration of a city can assist wind circulation and affects wind velocity which in turn influences the temperature variations. He pointed out that city morphology directly affects the movement of the wind within it, depending on its design, shape, and orientation of the roads within it. Morris et al. (2001) investigated the association between urban heat island intensity and wind speed and cloud cover from a network of monitoring stations in and around the large city of Melbourne, Australia. Their main findings showed that calm winds and clear skies result in increased means of urban heat island values. In summer, it was found that an increase of wind speed by 1 m/s causes a 0.14 °C reduction in the intensity of heat island. It was also revealed that, by increasing the cloud cover by 1 okta, UHI decreases by about 0.12 °C. Wind speed is an important parameter in urban areas influencing the health, outdoor/indoor comfort, air quality and the energy consumption of the buildings (Memon and Leung, 2010; Rajagopalan et al., 2008; Yang and Li, 2011). The cooling effect of wind helps to mitigate the adverse effects of heat island on the micro climate and human thermal comfort. In tropical regions such as Singapore, a wind velocity of 1–1.5 m/s creates cooling effect which is equivalent to a 2 °C drop in temperature (Erell et al., 2011). It also contributes to the reduction of carbon dioxide emissions and reliability on mechanical air conditioners (Fung et al., 2006; Kolokotroni et al., 2006). Furthermore, the air pollution in cities can be dissipated by appropriate wind induced airflows (Kato and Huang, 2009). The wind pattern changes as it flows through the urban settlements (Patz et al., 2005). Generally, winds are categorized into three groups depending on the intensity of the built environment: isolated roughness flow, wake interference flow and skimming flow which are classified by the ratio (H/W) of building height (H) to the distance between building arrays (W) (Oke, 1992). The wind pattern is not only the result of weather condition, but also depends on the occurrence of different flow regimes, including the wind speed and geometrical variables related to the buildings situated in urban settlements and open spaces (Ok et al., 1996). The dimension, shape and placement of the open spaces are determined by built forms (Serteser and Ok, 2009). Understanding the relationship between built forms and wind induced airflow is important, particularly in tropics where cooling effect of urban winds is beneficial.

Most of the studies carried out to understand the correlation between the built form and wind speed focused on the combination of field measurements and simulations (Yoshie et al., 2007; Tominaga et al., 2008; Asfour, 2010; Li et al., 2010; Zhang et al., 2011). Some studies employed wind-tunnel and field experimental studies (Jones et al., 2004; Nelson et al., 2007; Kubota et al., 2008). Wind-tunnel modeling and numerical modeling (CFD) were applied in a study conducted by Jones et al. (2004) to examine the pedestrian wind environment. The results of the two methods were closely similar to each other in predicting the wind flow patterns through the complex urban environment. Kubota et al. (2008) investigated the relationship between the building density of a residential neighborhood and the average wind speed at pedestrian level by doing several wind tunnel experiments. They found that by increasing the building's coverage ratio, the wind speed decreases; however there were disagreements in the detailed location and extent of the severe areas, which necessitates the need for CFD verification. Omar and Asfour (2010), examined the effect of building grouping patterns on the wind flow and the potential passive cooling through the ventilation. The study revealed that, grouping patterns of buildings and their orientation towards the wind, affect the wind behavior tremendously. Zhang et al. (2011) examined the wind pattern around various building arrangements by using both CFD simulation and wind tunnel experiments. The study found that maximum wind speed and vortex occur on the windward surface. It was also found that the formation and pattern of the wind around the buildings is strongly depending on the building layout and wind direction. Ma and Chen (2007) investigated the wind environment of six high-rise buildings through a numerical simulation method based on the Reynolds time-averaged equation and renormalization group (RNG) k–ε turbulence. The buildings were situated in two rows and three columns. By changing the horizontal distance between each column, eight different grouping patterns of the buildings were achieved. The wind speed and velocity vector at pedestrian height (2 m) of surrounding buildings were compared. The results indicate that once the six buildings are in an "S" pattern or in two parallel rows (paratactic type), the wind environment is more beneficial. While "Y" shaped form or semi-closure leads to a serious roadway effect.

To summarise, a thorough look at the literature available in the field of urban microclimate and the impacts of building and urban forms highlights a lack in investigations relating UHI to urban configurations on a city scale (Taleb and Abu-Hijleh, 2013). Many of the investigations provide strong evidence and findings limited to building-to-building relationships, defined as different ratios (Kakon et al., 2009; Giannopoulou et al., 2010; Hwang et al., 2011; Abreu-Harbich et al., 2013). This paper, therefore, aspires to bridge the gap in micro-climatic research related to urban design and give insight on how different urban configurations may impact temperature and wind variations.

3. Description of the study area

The city of Muar is located at 2°3′N 102°34′E, west coast of South Peninsular Malaysia, with a population of 150,000 people. The climate of Muar is characterized by high air temperature, with the average daily maximum of 33–34 °C, high level of humidity and consistent rainfall throughout the year (Malaysian Meteorological Department, 2010a). There are two dominant monsoon seasons in Muar: south west monsoon and north east monsoon, but the daily average temperature is constant throughout the whole year. The south-west monsoon season usually occurs in the late May or early June and ends in September, whilst the north-east monsoon which is identified by steady easterly or north easterly winds. However, north east monsoon has less impact on Muar compared to east coast Malaysia because it is blocked by Titiwangsa mountain range, which divides Malaysia peninsular between its east and west coast. Kubota and Supian Ahmad (2006), in a study of six Malaysian cities state that the mean wind velocity in the inter-monsoon periods is similar with those in the southwest monsoon periods. Also the wind speed is relatively low in the southwest monsoon period compared to northeast monsoon period and in order to investigate the worst case scenario southwest wind direction is adopted in the simulation.

In the city center, which is the focus of this study, unplanned vertical and horizontal development has blocked the wind flow in some areas thus deteriorating the thermal condition of the urban environment. The city centre of Muar is dominated by pre-war colonial buildings as well as recently built medium rise shopping malls and hotels. The built environment is arranged along the river bank, as shown in Fig. 1. Most of the buildings in the city centre area are two- storeyed or above. The average day time air temperature of Muar has been increased by 1.2 °C since 1969. In fact, the air temperature of Muar has been increasing 0.3 °C every ten years (Malaysian Meteorological Department 2010b). Due to the increased air temperature, people of Muar experience extreme thermal discomfort while walking in the streets, particularly during daytime. Higher night time air temperatures in outdoor spaces cause further reliability on air conditioners in indoor spaces.

4. Existence of UHI in Muar

In order to examine the existence of heat island in Muar, fixed station measurements were conducted in July 2011. Measurements were carried out three times during the day: 2.30–3.30 pm (warmest time of the day), 7.30–8.30 pm (when temperature begins to drop) and 11.30 pm to 12.30 am as maximum heat island intensity in tropical cities occurs in this period of the day (Tso, 1996). The instruments employed in this study were HOBO data loggers, with the operating range of 20–+70 °C and RH accuracy of ±5%. Data loggers were installed inside a white color cylindrical tube in order to get protected from the sun and possible precipitation. The tube was open on both sides for ventilation. The tube was placed in a motorbike basket and the measurements were conducted at the height of 750 mm from the ground. The data was automatically recorded with 5 s interval. Fig. 2 shows the three measurement locations each at the city centre and the suburb.

It is found that, city center area is warmer and drier during the day and night. Fig. 3 shows the temperature recorded during the measurement. The heat island intensity in the city center was recorded as 4 °C during the day and 3.2 °C during the night. After sunset, by 12.30 am, the air temperature dropped by 6 °C in city center and suburb. The average humidity levels during the day were 50% in the city centre and 70% in the suburb. The humidity levels increased during the night and by 12.30 am, the humidity level at the city centre and suburb were 86% and 99% respectively.

Development of the city centre along the river was executed without prior planning and regulations regarding building height and spacing. After world war 2, the skyline of the city has been altered significantly by introducing high rise buildings. The height of the buildings in the city centre has been changed from 3 to 4 storeys to 20 storeys. As a result of such unplanned development, the wind flow is obstructed within city centre intensifying the heat island effect. This causes thermal discomfort for the pedestrians.

As shown in Fig. 1, most of the buildings stand facing the river, preserving the original height of the city along with some tall buildings randomly placed on top of them. The width and length of the road have been kept constant since the establishment of the city; therefore the added height to the existing buildings has changed the geometry of urban canyons. The overall height of the buildings increases in its south–west, where hotels, shopping malls and business offices have been located. A closer look at these buildings reveals that they block the wind entering the city centre. However, no quantitative investigation was conducted to examine the effect of these morphological changes on the micro-climate. The following section discusses the effect of different geometrical scenarios on the micro-climate using numerical simulations.

5. Numerical modeling

Numerical simulations were conducted using IES Virtual Environment to examine the wind pattern in Muar city centre. k–ε turbulence model was adopted to enable the effect of turbulence to be predicted. The basic equations describing the indoor airflow consist of conservation

Fig. 1. View of the Muar city centre.

Fig. 2. Measurement locations.

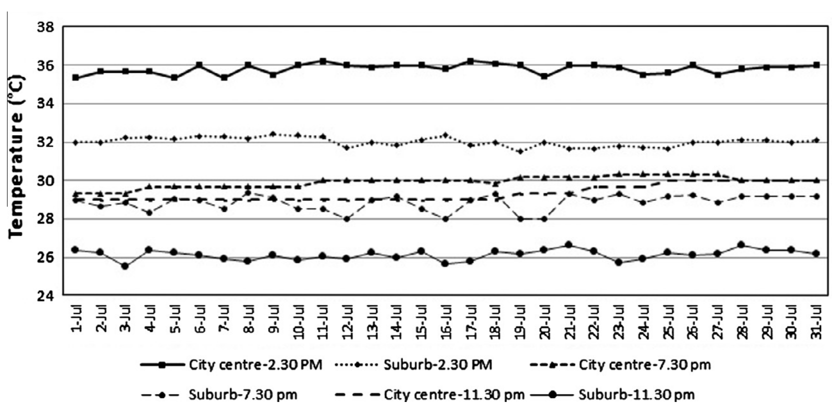

Fig. 3. Temperature measured at the city centre and suburb.

equations of continuity, momentum, and energy for a turbulent, buoyancy-affected incompressible fluid, together with two additional transport equations for the turbulent kinetic energy and its dispersion rate. The k–ε model assumes that the turbulence viscosity (μ_t) is linked to turbulence kinetic energy (k) and dissipation (ε) via the relation $\mu_t = C_\mu \rho(k^2/\varepsilon)$ where $C\mu$ is a constant and ρ is the fluid density. In this case, the external analysis tool, microflow, which models the wind flow around or in between buildings, is used to simulate the overall microclimatic condition of Muar. The area simulated has a radius of 500 m within the city centre where major business activities taking place. Fig. 4 illustrates the boundary of the selected area, situated in Muar city centre and Fig. 5 shows the modeled area in IES software. The model has an area of approximately 600 × 450 m. After modeling the original layout, a number of scenarios were tested to investigate the

Fig. 4. The boundary of study area.

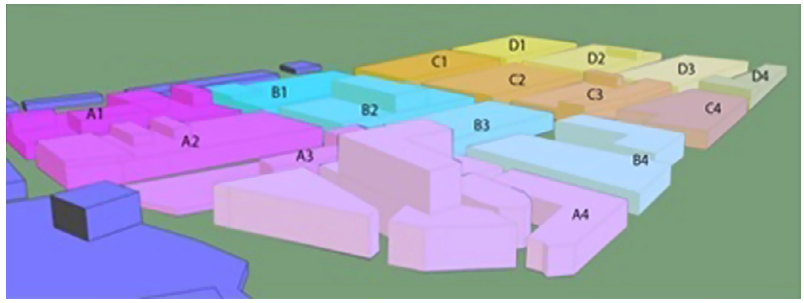

Fig. 5. City centre, modeled in IES.

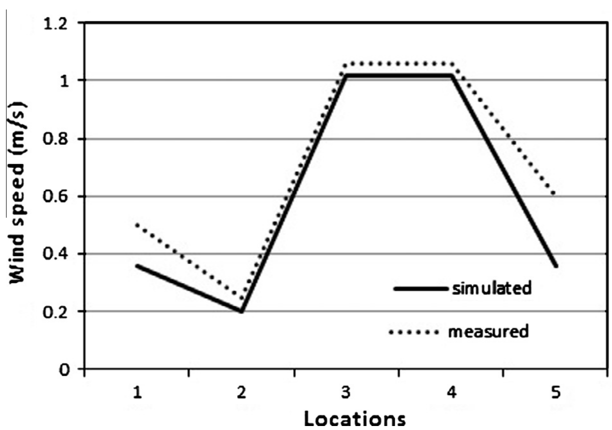

Fig. 6. Comparison of measured and simulated wind speeds.

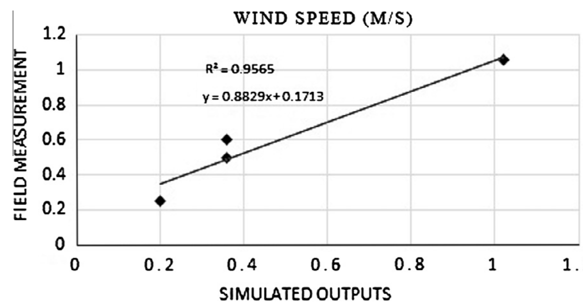

Fig. 7. Correlation between measured and simulated wind speeds.

effectiveness of different urban configurations on reducing the air temperature, thus mitigating the heat island effect.

As shown in Fig. 4, the study area consists of four rows of buildings and three main canyons. Most of the canyons are asymmetrical with average height of two to three storeys. The buildings with more than five to six storeys are situated on the western side of the study area, in Blocks A and B. Block A4 is the densest area in the entire study area. Block B4 is open space and is mainly used as car park. Block A3 includes built up space and open space for of religious gatherings. Kuala Lumpur weather data which is similar to Muar weather data is used as the input for simulation. According to the site characteristics, different wind scenarios were considered for simulation: south–west winds representing the monsoon months (May–September) and north–west winds (November–March) which are the prevailing winds. Five locations as shown in Fig. 4 were selected for analysis of wind speed. The wind speeds were measured using a handheld Kanomax hotwire anemometer with an accuracy of ±5%. The readings displayed digitally were recorded after every minute for a duration of 10 min for each location. Due to the limited number of instruments, it was not possible to do simultaneous measurements. But the wind speed measurements in the five locations were performed within an hour. The measurements were repeated for morning, afternoon and night. The average wind speeds were calculated and compared against the simulated results. Very low wind velocities were discarded when finding the average. Fig. 6 shows the comparison of measured and simulated wind speeds for southwest wind direction. The correlation coefficient R^2 is 0.96 which shows a good fit (Fig. 7). Wind speeds measured at locations 1 and 5, which are closer to the river, are higher compared to the simulated results. This can be attributed to the local pressure difference caused by the water body. For each direction, three wind speeds namely low (2 m/s), medium (3.5 m/s) and high (5 m/s) were tested. Various geometry scenarios as listed in Table 1 were explored in order to improve the wind flow in the city centre. These scenarios were examined to identify the appropriate building height that would not block the wind flow.

Table 1
Different scenarios of urban geometry in Muar city center.

Geometric variation 1	Reducing the height of high rise towers
Geometric variation 2	Open up high rise buildings by one storey
Geometric variation 3	Adding off scale sky scrapers
Geometric variation 4	Step up configuration

6. Results and discussions

6.1. Geometric variation 1

In this scenario, the height of the high rise buildings, situated in Block A4 was reduced to match the average height of the medium rise buildings. As a result, the entire study area is transformed to 3–4 storeys. This scenario helps to identify the effectiveness of removing tall buildings situated

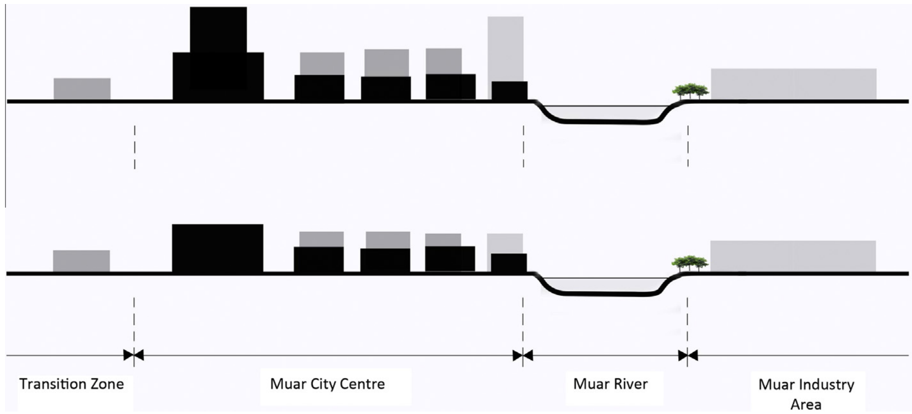

Fig. 8. Geometric variation 1.

on the windward side. Fig. 8 indicates a cross-section of the site before and after implementing this geometrical variation. The existing tall buildings help to draw the wind into the streets and by removing them, less wind will be drawn into the streets. Fig. 9 shows the wind velocity profile at heights 1.5 m, 5.5 m and 10 m from the ground representing low, middle and upper parts of the canyon. Fig. 10 shows the wind speeds at 1.5 m height. It was found that there is no significant difference in the wind speed. However, the reduced height helps to ventilate the spaces uniformly so that each building is naturally ventilated. It was found that the wind flow at the courtyard near urban Block B4 has been reduced by the removal of the tall tower in front of it. At location 3, the wind speed reduced from

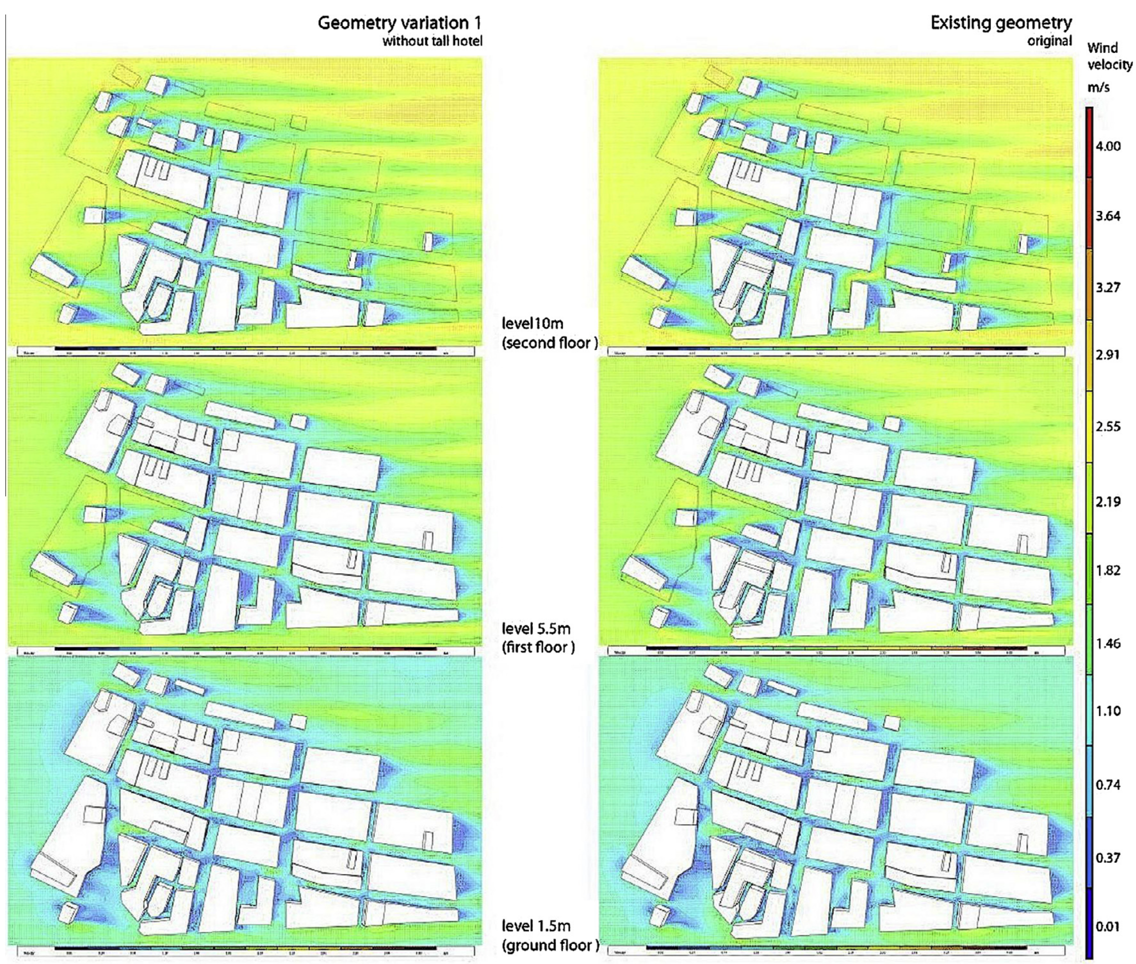

Fig. 9. Velocity profile with geometry variation 1.

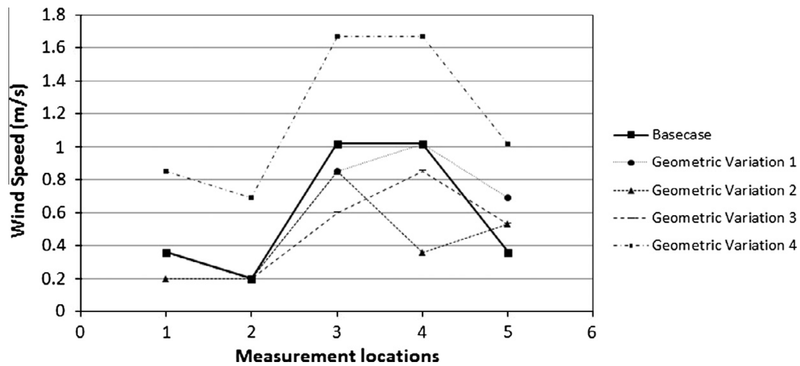

Fig. 10. Wind speeds for various scenarios.

1.02 m/s to 0.85 m/s. The results reveal that removal of few buildings from the layout may not necessarily improve the wind flow on the street level. But, it can assist in dissipating the heat at higher levels. This in turn reduces the temperature of the fresh air intake for air conditioning, thus reducing the cooling load of those buildings.

6.2. Geometric variation 2

In this scenario, an opening equivalent to the height of a single storey building was cut through the middle of the tall building so that the wind can penetrate through (Fig. 11). This scenario investigates whether the intensity of heat island can be mitigated through permeable design. It was noted that tall buildings draw wind into the streets, whereas the permeable design causes most of the wind to penetrate through the building without entering the streets. The angle between the horizontal wind direction and the building blocks determines the level of wind flow at pedestrian level. The results revealed that the opened up spaces have created a ‘tunnel’ for the wind to pass through, without entering the city grid. As the wind enters the hollow section, velocity increases due to the Venturi Effect, but the wind is directed upwards without entering the streets. Fig. 10 shows that, for most of the locations, wind speed at 1.5 m height were reduced. The wind speed at location 1 reduced from 0.36 to 0.2 m/s and the wind speed at location 3 reduced from 1.02 to 0.85 m/s and for location 4; the wind speed reduced from 1.02 to 0.36 m/s.

6.3. Geometric variation 3

This scenario simulates the future development of the Muar city centre by adding more high rise buildings (Fig. 12). Buildings with 80 m height are added to the existing urban blocks located at B3, C2 and C3. The height is double the height of the tallest buildings group in urban Block A4. The results indicate that off scale sky scrapers create strong winds in the immediate urban canyon located in front of them. However, they form large wind shadows in the next urban canyon at the neighboring block. At location 3, the wind speed reduced from 1.02 to 0.6 m/s. It was also found that high rise buildings create strong wind at higher levels but they do not necessarily create strong winds at pedestrian levels. The results show that the overall wind velocity was affected by this scenario and wind shadows were created in most of the streets.

6.4. Geometric variation 4

In this scenario, application of step up configuration to enhance the wind flow in the city center is tested. A step-up configuration is defined as an urban configuration where the height of the upwind building is less than the height of the downwind building. Fig. 13 shows the interaction between the step-up urban configuration and the prevailing wind. The step up configuration allows the wind to reach the leeward side of each building. The simulation indicates that there is not much difference when the subsequent

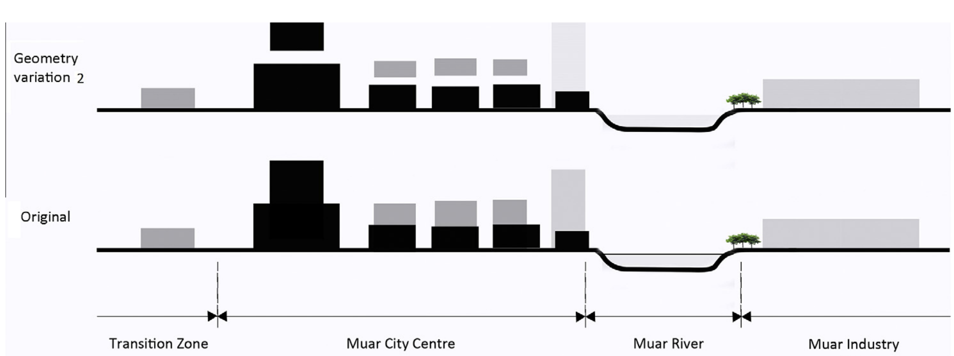

Fig. 11. Geometric variation 2.

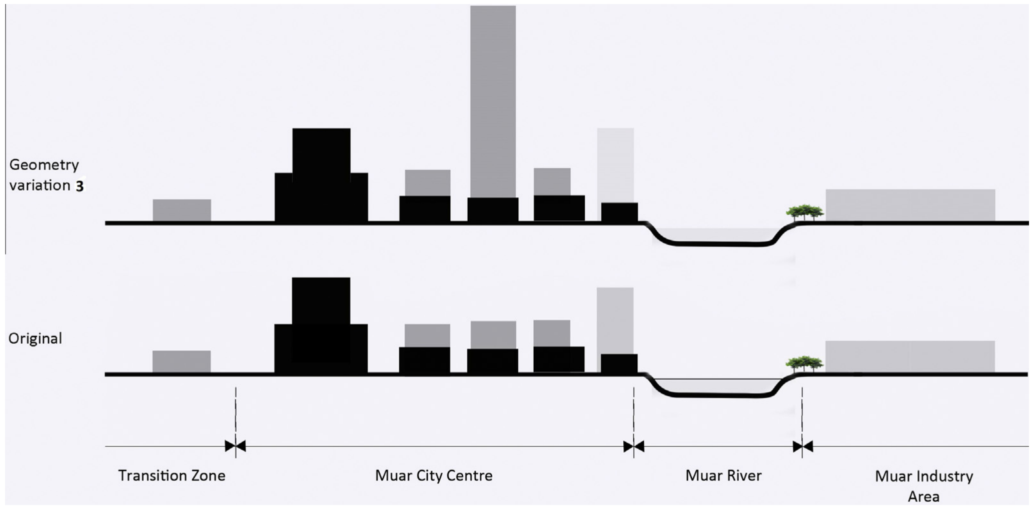

Fig. 12. Geometric variation 3.

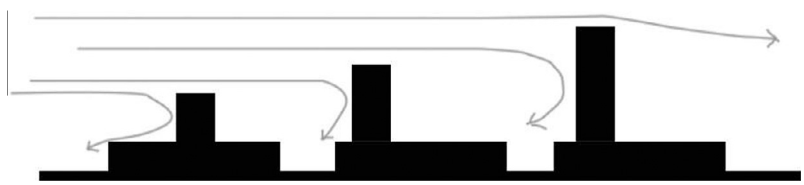

Fig. 13. Geometric variation 4.

Fig. 14. Comparison between mountain shape and articulated urban configuration.

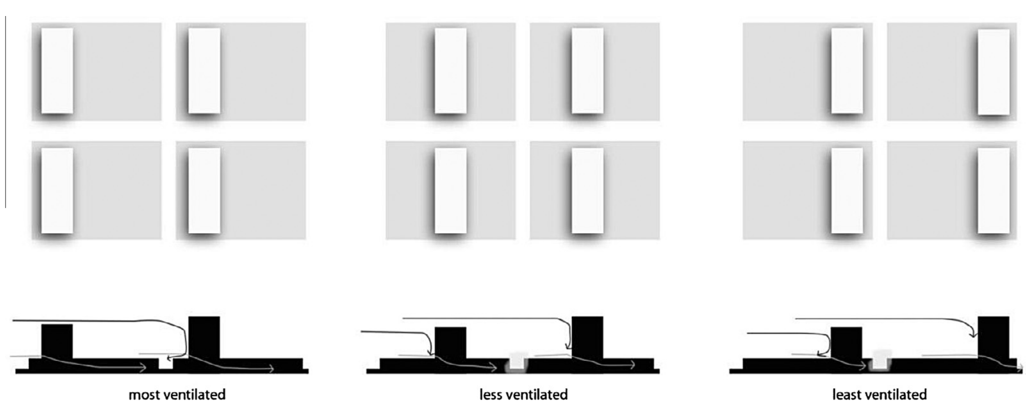

Fig. 15. Positions of towers in the step up configuration, plans (top), sections (bottom).

stepping up is with an increment of either one storey or two storeys. Fig. 14 shows a mountain shaped urban profile (left) where taller buildings are densely built together. It was found that articulated geometry created by scattering the taller buildings (right) gives a higher level of ventilation at the pedestrian level. Fig. 10 indicates that wind speed at all the locations increased significantly. At location 1, the wind speed increased from 0.36 to 0.85 m/s; and at location 2, the wind speed increased from 0.2 to 0.69 m/s. At locations 3 and 4, wind speed increased from 1.02 to 1.67 m/s whereas at location 5, wind speed increased from 0.36 to 1.02 m/s.

Fig. 16. Breaking the urban blocks to increase wind flow.

In addition, different positions were tested to place the building towers and it was found that the position of the building towers significantly affect the wind flow (Fig. 15). It was found that the towers need to be placed in the windward side in order to gain maximum ventilation. Placing the towers in the middle of the urban block or towards the leeward side is not as effective as placing the block towards the windward side. The optimum spacing between buildings that allow for maximum wind flow needs to be examined further.

In the planning and design of urban blocks, areas with low wind velocity could be shaded and covered with trees. As a result, thermal discomfort in less ventilated urban areas will be compensated by the shading and evapotranspiration of green spaces especially in tropical climate. Fig. 16 illustrates a cross-section of a step up urban block; where the areas with low wind velocity can be vegetated and shaded so that in addition to providing a buffer zone for the next step up configuration, they can be create thermally comfortable public spaces.

7. Conclusion

Cities consume more energy compared to rural areas, particularly in tropics, due to the cooling activities, urban transportation, commercial and industrial activities. The high level of energy consumption is intensified by heat island effect. Many strategies have been identified to mitigate the heat island effect. Air flow is considered as one of the key factors in reducing the heat island.

This research confirmed the existence of heat island in Muar city center and examined the role of city configuration and building layouts on a macro-scale. The results of this study indicate that the chaotic development in Muar caused reduced ventilation in urban canyons. Combination of tall buildings and narrow streets entrap heat and reduce the air flow, resulting in high temperatures. The significance of the third dimension, namely building height, in the process of urban planning was highlighted through testing different geometry modifications and their impact on the air flow at pedestrian level. Of the many scenarios tested, step up configuration was found to be most effective in improving the overall natural ventilation. Step up configuration can distribute the wind evenly and allow the wind to reach the leeward side of each building. This improves the overall natural ventilation and thermal comfort at pedestrian level. The results can be applied to other tropical cities.

Effort should be made to systematize all current knowledge concerning the effects that built form and vegetation has on the urban micro climate. This would greatly facilitate the work of architects and planners to consider urban microclimate in the very first steps of their projects. Application of numerical modeling in city planning can help the urban planners to consider the town planning from the thermal comfort point of view. Local planners can examine the combination of different planning scenarios to identify the best configuration in the context of any cities.

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