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International Journal of Sustainable Built Environment (2017) 6, 389–399

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International Journal of Sustainable Built Environment

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Original Article/Research

Investigating the effect of urban configurations on the variation of air temperature

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Received 1 September 2016; accepted 1 July 2017

Abstract

High temperatures in urban areas affect the health and wellbeing of urban dwellers. Malacca City has undergone a tremendous growth during the last decades, particularly after its designation as a UNESCO World Heritage Site in 2008. As a result of urban development, two dominant urban configurations were formed in Malacca: the heritage site and contemporary urban areas. This study examines the effects of aspect ratio (H/W) on air temperature in two urban configurations in Malacca. The three-dimensional microclimatic modelling system ENVI-met (version 3.1) was used to simulate the summer time air temperature variation in the typical urban setting of a heritage site and contemporary urban area. Aspect ratio was found to have a considerable influence on the air temperature distribution in both areas. The daytime air temperatures decreased with increasing aspect ratio. The simulation results showed that during the daytime, the heritage site (aspect ratio of 2.6) was warmer than the contemporary urban area (average value of H/W = 1.6), and that cooling occurred more quickly in the latter. The results of this study provide useful information for planning, building and modifying urban structures.

Keywords: Urban planning; Urban climate; Air temperature variation; Urban form

1. Introduction

There is evidence that the mortality and morbidity caused by heat waves is exacerbated by the heat island effect in urban areas (Gabriel and Endlicher, 2011; Gartland, 2012). The number of people living in urban areas is projected to increase from 3.6 billion in 2011 to 6.3 billion in 2050 (United Nations, 2012). Rapid urban expansion accelerates the heat island phenomenon, increases energy consumption and decreases the level of thermal comfort and quality of life (Massetti et al., 2014).

In recent years, the number of studies on the microclimate of cities has increased, mainly due to significant effects on energy consumption (Akbari et al., 1992; Cartalis et al., 2001; Fahmy and Sharples, 2009; Hassid et al., 2000; Kolokotroni et al., 2006; Mirzaei and Haghighat, 2010; Santamouris, 2013), outdoor thermal comfort (Golden, 2004; Guhathakurta and Gober, 2007; Harlan et al., 2006; Santamouris et al., 2007; Sarrat et al., 2006; Watkins et al., 2007) and mortality rates (Changnon et al., 1996; Kilbourne, 1997; Rooney et al.,

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Peer review under responsibility of The Gulf Organisation for Research and Development.

https://doi.org/10.1016/j.ijsbe.2017.07.001
2212-6090/

1998). However, climatic considerations are often neglected in urban design because of the lack of interdisciplinary research and constraints to transferring urban climatic knowledge into urban planning practices (Ali-Toudert and Mayer, 2006; Erell et al., 2012).

The urban climate of tropical cities has been receiving increasing attention (Emmanuel et al., 2007; Roth, 2007). During the day, outdoor thermal conditions in tropical cities are often far beyond an acceptable level for human comfort because of the high air temperature, intense solar radiation and high solar altitude (Emmanuel, 2005). Conditions are particularly intense from noon until early afternoon. In the daytime, direct solar exposure and thermal discomfort cause high levels of heat stress (Jenerette et al., 2011; Chen and Ng, 2013) and during the night, the heat island phenomenon causes an increase in the level of energy consumption for cooling purposes. High night-time air temperatures also reduce the opportunity for night-time recovery from daytime heat stress (Clarke and Bach, 1971).

Integrating urban climatic knowledge into urban planning practices and developing mitigation technologies to adapt to climate change have received further interest in recent decades and the relationship between urban design parameters and pedestrian thermal comfort has been the subject of many studies (Arkon and Özkol, 2014; Johansson and Emmanuel, 2006; Middel et al., 2014). The potential threat of heat-related incidents to human health will be exacerbated if planning professionals exclude climate-conscious urban design from their practices. Therefore, thoughtful design of cities can purposefully alter the thermal environment, manipulate microclimates by altering the surface energy balance and prevent extreme events such as heat waves.

The first heat island study in Malaysia was conducted by Sani (1972), who reported that city centres are associated with higher air and surface temperatures than in the surrounding rural areas. These findings were supported by numerous additional studies in Malaysia (Oliver, 1997; Sani, 1984, 1987, 1991; Sham, 1986). Malaysian cities are growing rapidly and the lack of understanding of the climate of humid tropical cities will likely have adverse effects on architecture, energy requirements, urban environmental planning and management. This is even more important for heritage cities, as they must provide comfortable public places to attract tourists.

Malacca is one of the fastest growing cities in Malaysia, and is the capital of Malacca State. The urban form in Malacca began to change in the middle of the 15th century with the construction of forts by Portuguese and Dutch colonialists. Since then, the city has continued to undergo a series of cityscape alterations. The intensity of these changes peaked in 2008, when the city was designated a UNESCO World Heritage Site. Currently, there are two prominent urban configurations in the city: traditional heritage sites, which are well known for introducing 'shop houses' to the world, and recently constructed city areas, which in this study are referred to as 'contemporary urban areas'. The urban form in the heritage site is dominated by two- to three-storey shop houses on both sides of the narrow streets, whereas contemporary urban areas consist of five- to seven-storey concrete buildings on both sides of wide streets with asphalt pavements. Given the possible physical, cultural and economic effects of heat islands on heritage sites, particularly with respect to tourism, examining the effect of city form on urban climate is essential. To this end, this study aims to investigate the effect of two urban configurations on air temperature variation in Malacca.

2. Literature review

Modification of land surfaces from natural vegetation cover to complex three-dimensional (3D) impervious surfaces leads to the formation of distinctive urban climates (Coutts et al., 2007). In built environments, one of the major factors that dictate urban form is urban geometry. Numerous studies have been conducted to identify what defines urban geometry in terms of geometric ratios. The smallest element in the formation of urban geometry is the urban canyon created by buildings with spaces in between. Oke (1992), defined an 'urban street canyon' as the 'basic geometric unit which can be reasonably approximated by two-dimensional cross-sections, neglecting street junctions, assuming that buildings along the canyon axis are semi-infinite in length'. Urban canyons occupy two-thirds of built-up areas in cities and therefore play an important role in maintaining radiative balance and outdoor thermal comfort. In fact, any alteration in canyon geometry affects energy and radiative budgets, and microclimate and outdoor human thermal comfort (Oke, 1992; Shashua-Bar and Hoffman, 2000; Algeciras et al., 2016). The geometry of a canyon is expressed as its aspect ratio—its height divided by its width—and sky view factor (SVF), which is the degree of canyon exposure to the sky (Oke, 1981). Urban canyons have been investigated by field measurements, numerical modelling and wind tunnel studies (Ahmad et al., 2005; Gao et al., 2012; Karatasou et al., 2006; Moonen et al., 2012; Oke, 1988; Santamouris, 2013).

Research has shown that deeper canyons experience smaller radiative losses (Holmer, 1992; Nunez, 1974; Oke, 1981) and that the penetration of the wind inside deep canyons can significantly decrease thermal discomfort at the pedestrian level (Niachou et al., 2008; Santamouris and Asimakopoulos, 2001). In the hot, humid summers experienced in Dhaka, Bangladesh, an increasing aspect ratio caused a significant reduction in air temperature (Ahmed, 1994). Similarly, in the hot, dry climate of Fez, Morocco, Johansson (2006) found that a deep street canyon has considerably lower air temperature than a shallow street canyon. Shashua-Bar and Hoffman (2004) examined the effects of urban geometry on microclimate by quantifying the aspect ratio and SVF of different urban geometries, revealing that areas with shallow open spaces and wide spacing have air temperatures 4.7 K higher than was recorded for a meteorological reference point. A study in Dubai, United Arab Emirates, demonstrated that canyon configuration, vegetation cover and presence of water are the key parameters reducing the air temperature (Thapar and Yannas, 2007). In a similar study, the effects of SVF and aspect ratio on air temperature variation among urban canyons were investigated. The findings indicated that urban surface geometry is a significant factor determining the distribution of air temperatures throughout the city, and that weather conditions and measurement times influence the intensity of the heat island (Bacon, 1883). Ratti et al. (2003) examined the effect of various SVFs on the thermal performance of urban environments, and reported that lower SVF values lead to better thermal comfort conditions during the daytime. The effect of street design on urban microclimate was investigated in the semi-arid climate of Constantine, Algeria. Higher aspect ratios were found to contribute to lower daytime air temperatures. The study also recommended the incorporation of SVF in urban design because of its significant role in mitigating heat island intensity (Bourbia and Boucheriba, 2010). In hot, humid Colombo, Sri Lanka, Emmanuel and Johansson (2006) found differences of up to 7 K in maximum daily temperatures between urban sites with different aspect ratios. Highly shaded deep street canyons show significantly lower air temperatures at the pedestrian level. A study in Campinas, Brazil, quantified the outdoor thermal comfort levels associated with typical urban canyon configurations. The results showed that urban design parameters such as aspect ratio modify thermal conditions within street canyons. Providing shade in pedestrian areas and on façades was recommended to improve bioclimatic thermal stress, particularly for aspect ratios less than 0.5 (Abreu-Harbich et al., 2013). The effects of building height and density on potential air temperature were quantified in different European cities (Perini and Magliocco, 2014). The study demonstrated that the height of buildings has a significant effect on air temperature and outdoor human thermal comfort. One of the few studies that investigated a large area of a city rather than merely building-to-building relationships was conducted by Dana (2013) in Dubai. This study aimed to examine the effect of organic and structured urban configuration on temperature variation throughout the year. Given the specific site location and alignment of prevailing winds parallel to the roads, the organic configuration showed excellent thermal performance (Taleb and Abu-Hijleh, 2013).

A thorough investigation of available literature in the field of urban heat island effects highlights the lack of investigation and published studies in the context of UNESCO heritage cities, such as Malacca. The current study aims to bridge the gap in microclimatic research related to urban geometry and provides insights into how different urban configurations may affect temperature variation in a city.

3. Methodology

Malacca City is the capital of Malacca State and is located in the south-west part of Peninsular Malaysia (2.29 °N, 102.30 °E). The city is located approximately 147 km from Kuala Lumpur and faces the Straits of Malacca to the west. Malacca experiences high temperatures and humidity throughout the year without remarkable variation. The average daily temperature ranges from 21 °C to 32 °C, and humidity varies from 70% to 90%. Malaysia experiences two dominant seasons. The south-west monsoon occurs from late May/early June to September. The prevailing wind is generally south-west with a speed of 3–7 m/s. The north-east monsoon usually commences in early November and ends in March. During this season, north-easterly winds at a speed of 7–10 m/s prevail. Given that the thermal condition of city spaces is accentuated at lower wind speeds, this study was conducted using the lowest wind speed values to simulate the worst thermal condition scenario. Hence, the study area is modelled with a wind speed of 3 m/s in the south-west direction. In this study, urban configuration refers to a cluster of buildings organised in a certain configuration. Two dominant urban layouts were identified in the city: the heritage site and contemporary urban areas.

Figs. 1 and 2 demonstrate the typical urban layout in the heritage site and contemporary urban areas. The shop house is the dominant unit of the urban environment in the heritage site. A shop house is typically a two-storey building in which the ground floor is used for business purposes and the first floor is dedicated to housing (Yeang, 1992). The heritage core zone is compact. The height of shop houses is limited to two or three storeys, and the average aspect ratio is 2.6. Construction materials in the shop houses include clay tiles for roofs and laterite for walls. The pavements consist of asphalt, concrete and tile. Only a few spaces are dedicated to vegetation. The contemporary urban environment is composed of buildings with various heights (four to six storeys), constructed mainly from concrete. Streets are three times wider than those in the heritage site, and the average H/W is 1.6. Based on LCZ classification of Stewart and Oke, 2009, the heritage site corresponds to LCZ4 (compact low-rise), while the contemporary site classifies as LCZ3 (compact midrise).

4. Validation with field measurements

ENVI-met is a 3D microclimate model, with a typical horizontal resolution of 0.5–10 m in space and 10 s in time (Bruse and Fleer, 1998). The model consists of several submodels, including a) the main 3D model that incorporates buildings and vegetation, and begins at ground level and extends to a height of at least twice the maximum building height. In this module, the air flow around the buildings is calculated; b) a one-dimensional (1D) model located above the main module and stretching to a height of 2500 m; and c) a one-dimensional soil model that extends 2 m below the

Fig. 1. Typical urban configuration in the heritage site (Right: Plan, Left: Typical street view), (2 storey (8 m), asphalt pavement).

Fig. 2. Typical urban configuration in the contemporary urban environment (Right: Plan, Left: Typical street view), (5 storey (20 m) buildings, asphalt pavement).

ground level and is located below the main model. This model calculates the heat and moisture transfer in the soil. Finally, to achieve numerical stability, several lateral borders have been allocated around the main model, creating what is known as the ‘nesting area’.

The basic equations in ENVI-met 3.1 are related to mean air flow, temperature and humidity, turbulence and exchange processes, and radiative fluxes. The complete model system consists of some additional sub-models such as bio-meteorological and particle dispersion models. The mathematical expressions of the atmospheric, soil, vegetation and building models have been comprehensively explained in Bruse and Fleer (1998).

ENVI-met uses Navier–Stokes equations for air movement, E-epsilon equations for atmospheric flow turbulence, energy and momentum equations, and boundary condition parameters. ENVI-met creates a dedicated numerical model for soil, plant, surface and air, and then calculates the relationships among these parameters. ENVI-met can also predict outdoor thermal comfort by using meteorological inputs and human biometeorology factors. Short-wave radiation is calculated in ENVI-met based on the SVF in urban canyons, the albedo of urban surfaces, and the leaf area index (LAI) of vegetation (which affects the calculation of SVF) in the area input file. Long-wave radiation is calculated by considering the horizontal long-wave emissions from the walls. These emissions can come from either the ground or the sky. Surface temperature is calculated on the basis of the balance of all net-wave radiation and heat fluxes from both hemispheres. The vegetation model is formed on a 1D column with a height of zp. “zp” represents the height at the top of the plant.

The soil model is a 1D model with three layers (20 cm, 20–45 cm and 45–175 cm). The type of soil may differ at each level. The thickness of the soil layer increases with depth from the surface. Each grid cell has a soil profile that can be characterised by its thermal and moisture properties. Vegetation in ENVI-met is defined by plant height, LAI and root zone density. Each plant is divided into 10 horizontal layers starting at the ground level. Plants are characterised by their leaf area density (LAD) (i.e., total one-sided leaf area [m^2] per unit layer volume [m^3] in each horizontal layer of the tree crown). The LAD for a specific plant represents the 10 LADs for the different horizontal layers. Unlike the soil and vegetation models, the building model is greatly simplified in ENVI-met because buildings are characterised only by albedo and thermal transmittance (U-value). Further, the same values are applied to all the walls and roofs. In this study, the albedo for the walls and roofs in the heritage site was set at 0.26 (red clay). The albedo of the walls in the contemporary urban area was 0.49 (a combination of white concrete and white marble) and that of the roofs in the contemporary urban area was 0.5 (beige-painted concrete masonry).

Table 1
Initial set up of the model domain (area input file).

Input set up	Value
Number of Z grids	22
Number of X grids	100 (Contemporary site), 260 (Heritage site)
Number of Y grids	160 (Contemporary), 240 (Heritage)
Size of grid cell in m (dx)	1
Size of grid cell in m (dy)	1
Size of grid cell in m (dz)	30 (Contemporary and heritage)
Name of location	Malacca, Malaysia
Position on earth	(2.29° N 102.30 °E)
Number of nesting grids	5
Soil profile for nesting grids	Soils A and B = Loamy soil
Simulation day	10th July 2011
Simulation time	(24 h) starting from 6:00
Wall albedo	Heritage site (0.26), Contemporary site (0.49)
Roof albedo	0.5
Heat transmission walls	0.14 (Contemporary), 1.6 (Heritage)
Heat transmission roofs	0.18 (Contemporary), 0.015 (Heritage)
Initial temperature atmosphere	303
Wind speed and direction	3 m/s Southwest
Relative humidity	80%
Specific Humidity in 2500 m	10
Cloud cover	Clear sky

Several studies have used ENVI-met as primary or secondary simulation software. Some assessed microclimate and thermal comfort conditions in different urban layouts (D'Argent, 2012; Fahmy and Sharples, 2011; Taleb and Abu-Hijleh, 2013; Thapar and Yannas, 2007), including the effects of greenery and vegetation on thermal conditions in an urban environment (Johansson et al., 2013). Others have examined the airflow behaviour in cities (Okeil, 2010). In most studies that have used ENVI-met, comprehensive field measurements were conducted to validate the outputs of the software. Thapar and Yannas (2007) used ENVI-met to validate the findings of field measurements on the temperature and wind variation around specific urban forms. Hedquist et al. (2009) also used the software, along with CFD and field measurements, to report temperature variation in high-density areas. The software can accurately model the effects of building height and shading on surface temperatures.

In this study, two dominant urban configurations were modelled. A model domain was defined through the x, y, and z axes. Each axis has grid cells, and the user defines the size of each grid cell based on the required resolution and size of the study area. The size of the z axis is determined by the height of the tallest building in the model domain. Telescoping mode was applied in Envi-met setting to increase the vertical spatial resolution. In telescoping mode, the grid size expands with the height. In this study, the telescoping factor was set to 10%, and telescoping factor was set to be started after 50 meter. For the heights below 50 meter dz was set to 1. Nesting grids are used in

Fig. 3. Top: Location of the selected areas in Malacca. Left bottom: Selected measurement points in heritage site. Right bottom: Selected measurement points in contemporary urban area.

the model boundary to reduce the errors caused by boundary effects and to ensure that the simulation process is not affected by the model borders. In this study, a model domain was created based on a satellite image of the study site. The image was obtained from Google Earth and uploaded into the area input file to determine the location of site (longitude and latitude in both heritage and contemporary urban sites) and location of the buildings. A georeferenced building footprint map was used to model the buildings. The height of buildings was measured directly in the study area and converted into the model domain. The domain size was created with 100 × 160 × 22-cell grids for the contemporary site and 260 × 240 × 22-cell grids for the heritage site. The domain was rotated 22° clockwise to align its north with the geographical north axis in Malacca. The simulation began at 0600 h and ran for 24 h. Table 1 shows the user-defined settings for the area input file.

In the majority of the studies conducted by simulation, validation is an integral part of the project. In this study, to assess the accuracy of ENVI-met outputs in this study, and to ensure that the model domain is a reliable representative of the study sites, a validation study was first conducted by comparing simulated with measured air temperature. To compare the simulated and measured air temperature, three points (receptors) were selected in the heritage site and three in the contemporary urban area. These points were selected on the basis of various canyon geometries and street orientations so that the validity of the model could be verified for different geometries of urban canyons. Fig. 3 shows the location of the selected points (receptors) in the heritage site and contemporary urban area.

On-site field measurements were performed from 0900 to 2100 h local time on 10 July 2011, under clear sky conditions. July was selected as the time for simulation because the south-west monsoon brings only light winds and thus air temperature will be only minimally influenced by wind. Wind speed records from anemometers did not show a significant difference between the two study areas. Therefore, the simulations were conducted with 3 m/s wind speed from the south-west direction.

HOBO data loggers were used to monitor air temperature at a height of 1.70 m above ground level. Three data loggers in the heritage site, three in the contemporary urban area and one in a suburban area located 20 km from the city were installed to record the variation in air temperature throughout the day. Measurements were conducted at 15-min intervals and converted into hourly data for

Fig. 4. Validating the ENVI-met outputs with field measurement at selected points or heritage site (Top), Contemporary site (Bottom).

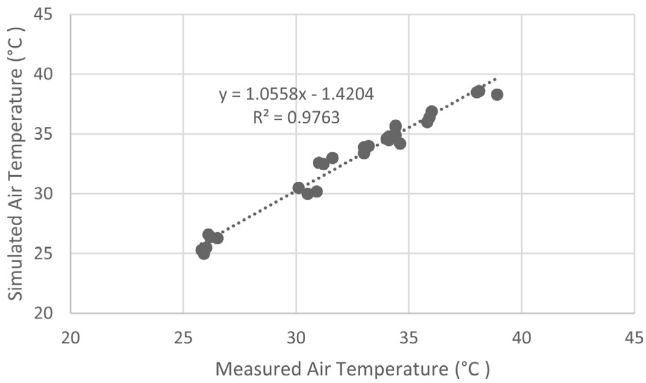

Fig. 5. Correlation between simulation outputs and on-site measurements.

comparison with the simulated hourly air temperature. The data loggers were installed at the centre of streets to reduce the effect of shading from buildings. They were placed in white painted PVC tubes to protect the sensors from direct solar exposure.

The climatic variables employed in the configuration file, including air temperature, relative humidity and wind speed, were obtained from the data loggers (as the average of measured values at different points for each site). The other climatic measurements, including solar irradiance, were obtained from the local weather station in Malacca. After validation, the worst-case scenarios (hottest day with lowest wind speed) was simulated for both heritage and contemporary urban sites. Fig. 4 illustrates the values for the recorded and simulated air temperatures at the selected points. As Fig. 5 indicates, there is a strong agreement between the measured and simulated data, with R2 value of 0.97. Therefore, the accuracy of ENVI-met in generating simulated air temperature variation in the study areas was confirmed. Similar study in Malaysia, examined the thermal performance characteristics of unshaded courtyards and after implementing minor adjustments, the comparison showed high levels of correlation, which indicated an acceptable agreement between the predicted values and the real data of meteorological stations (Ghaffarianhoseini et al., 2015). The discrepancy found between the measured and the simulated values was attributed to the application of the same material for all buildings and the absence of heat storage in the building properties. In another study conducted in Netherlands, the authors found that the patterns of the measured and simulated air temperatures are similar during the first day of measurement, but some inconsistencies on the number and time of the hottest hours were observed during the second day. After the adjustments, the final correlation coefficient between the two sets of data was improved to 0.80 (Taleghani et al., 2015).

5. Results and discussion

Fig. 6 presents the results of the simulation for the hourly averaged air temperature in daytime and night-time air temperatures inside the urban canyons of heritage site and contemporary urban area. The outputs of the simulation were created every 2 s and then averaged from 0900 to 2100 h. Fig. 6 shows that from 0900 to 1700 h the air temperature (at 1.7 m) gradually increases at both sites and then begins to drop in the afternoon, with the heritage site showing decreasing air temperatures earlier than the contemporary urban area. During the day, the heritage site with its more compact urban forms and average aspect ratio of 2.6 recorded lower air temperatures than contemporary urban sites. The maximum temperature difference

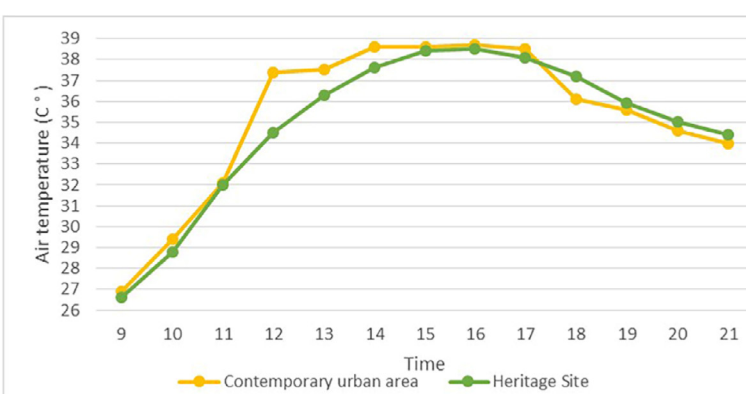

Fig. 6. Hourly averaged air temperature inside the urban canyons in the heritage site (green), and contemporary urban environment (yellow).

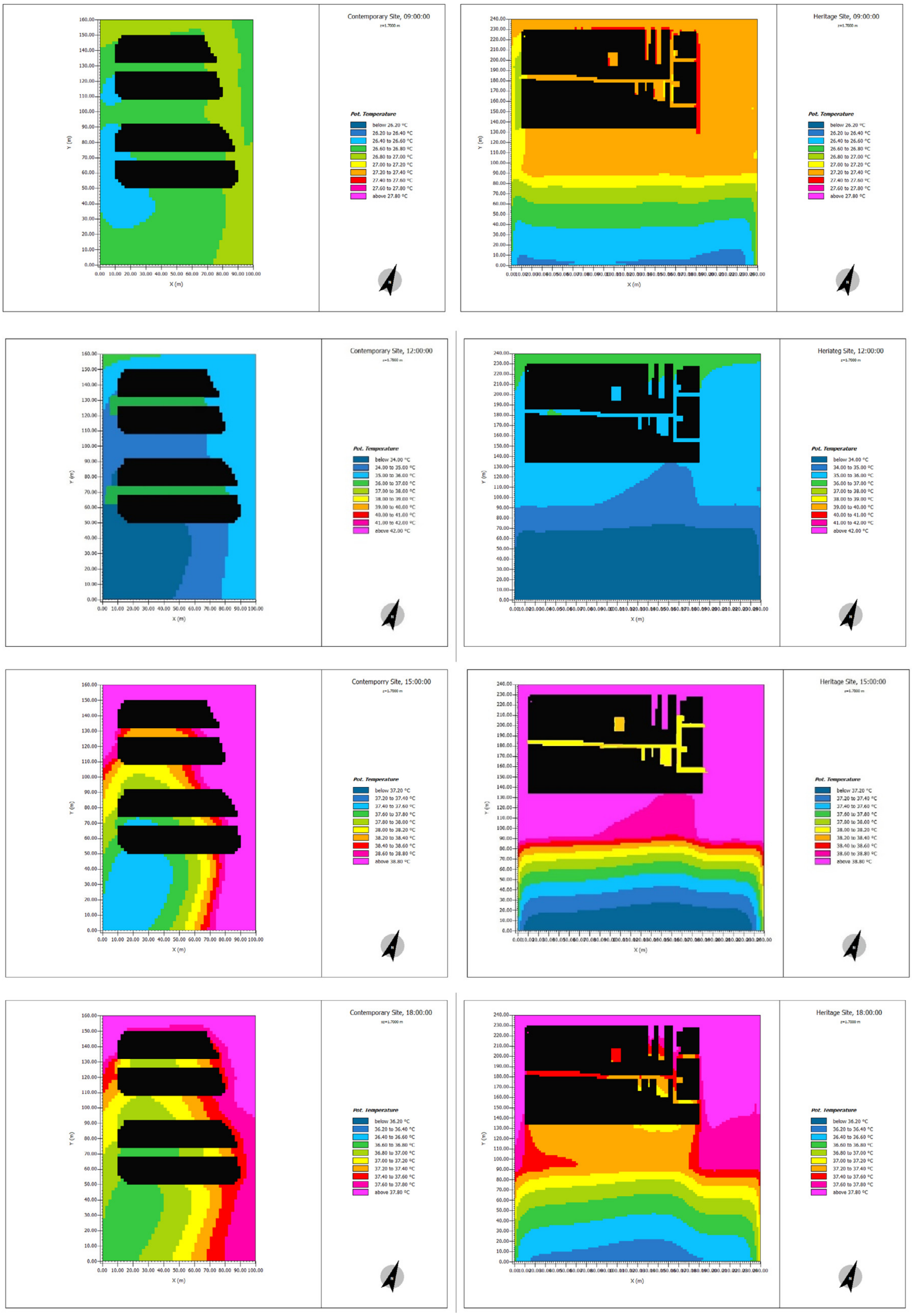

Fig. 7. Temperature variation in heritage site (right) and contemporary urban area (left), the height above the ground: 1.7 m.

of 2.9 °C between these two urban configurations was recorded at noon. The second largest gap was recorded at 1300 h when the air temperature in contemporary urban areas was found to be 1.2 °C higher than that the heritage site. During the day, high values of air temperatures were recorded in the contemporary urban area, where the height of the buildings varied from four to six storeys and the streets were wider than the heritage site. The lower average aspect ratio (1.6) in the contemporary urban area, in conjunction with its low vegetation cover led to higher air temperatures during the day (26.9, 29.4, 32.1, 37.4, 37.5, and 38.6 °C) compared to those recorded at the heritage site (26.6, 28.8, 32, 34.5, 36.3, 37.6, and 38.4 °C).

The LEONARDO software creates a graphical representation of the model domain. LEONARDO allows the user to produce a graphical representation of output parameters at a user-specified height, at 1-h time steps. The spatial distribution of air temperature for both the heritage and contemporary urban sites at 0900, 1200, 1500 and 1800 h is shown in Fig. 7. The distribution of air temperature in the heritage site and contemporary urban area confirms the findings shown in Fig. 7.

During the night, the difference in air temperature between the two sites is generally small. The highest night-time air temperature of 37.2 °C was recorded at 1800 h in the heritage site. At this time, the air temperature difference between the heritage site and contemporary urban area reached its peak (1.1 °C). After sunset, the temperature difference between the two sites was 1.1 °C at 1800 h and 0.3 °C at 1900 h. The temperature difference between the two sites was not significant from 1900 to 2100 h. One possible cause of this increase is that impervious surfaces absorb heat during the day and release it back to the air during the night. However, due to the high aspect ratios in the heritage site, the return of radiation back to the atmosphere occurs more slowly than in the contemporary urban site, which has wide streets and high SVFs. Duration of the exposure to the solar radiation depends on the degree of SVF. The LEONARDO images extracted at a height of 1.7 m correspond to the average height of a standing man; these show that the deeper canyons in the heritage site experience short solar exposure during daytime. This phenomenon results in lower daytime air temperatures in the heritage site.

Another study in Colombo found that the higher levels of shading in deep canyons improve daytime thermal condition (Matzarakis et al., 2006). In the Mediterranean climate of Fez, Morocco, and three cities in Italy, deeper canyons were reported to result in lower daytime temperatures (Johansson, 2006; Perini and Magliocco, 2014).

The findings of this study were similar to those in a study conducted in the hot, humid climate of Dhaka, Bangladesh, which reported a 4.5 K reduction in the daytime air temperature when the aspect ratio increases from 0.3 to 2.8 (Ahmed, 1994). Similar findings were reported for the hot, humid climate of Colombo, Sri Lanka, where narrow canyons had air temperatures 7 K higher than shallow canyons (Emmanuel and Johansson, 2006). Another study in Colombo found that the higher levels of shading in deep canyons improve daytime thermal condition (Matzarakis et al., 2006). In the Mediterranean climate of Fez, Morocco, and three cities in Italy, deeper canyons were reported to result in lower daytime temperatures (Johansson, 2006; Perini and Magliocco, 2014). Although the results of the current study are similar to others reported for hot, humid cities, the air temperature difference between the two types of site in this study are lower than the differences reported between sites in other cities with the same climate classification. This might be due to the nature of the urban canyons studied here or to the effects of longitude and latitude of the cities under study.

The findings of this study contrast with those of Geros et al. (2005) for the sub-tropical Mediterranean climate of Athens, Greece, which showed that deep canyons trap heat and decrease thermal comfort. In the hot, dry climate of El-Oued, Algeria, the air temperature in wide canyons was 4 °C higher than in narrow canyons (Bourbia and Awbi, 2004).

6. Conclusion

Understanding the relationship between built forms and thermal conditions at the pedestrian level is important, particularly in the tropics where the cooling effect is beneficial. This paper reports the results of a simulation study on air temperature variation in two different urban environments: heritage and contemporary urban sites in Malacca. The measurements of daytime and night-time air temperatures were conducted on 11 July 2011 to validate the outputs of the simulation. Simulations were then run for both sites to investigate how urban form can affect daytime and night-time air temperature variation. The relationship between temperature variation and urban configuration was investigated with respect to the aspect ratio. The aspect ratio was found to have a considerable influence on air temperature distribution in the urban area.

The heritage site, with its higher aspect ratio, had lower daytime temperatures than those recorded for contemporary urban areas, which had lower aspect ratios; although the latter areas had cooler nights. The lower daytime and higher night-time air temperatures recorded in the heritage site revealed a clear relationship between air temperature and aspect ratio. The deep canyon represented by the heritage site helped minimise daytime air temperatures by providing more shade. The simulations also revealed that the duration, time of day and spatial distribution of maximum air temperature values within an urban space depend strongly on the aspect ratio. This condition is important to understand for design purposes because the time of frequentation of outdoor spaces and usage of the street are important design criteria. The results of this study are applicable for Malacca and other regions with similar climate. This study is one of the first to be conducted in

Malacca and it is expected that it will help with the integration of knowledge about local climate into urban design practices.

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