Numerical Simulation of Street Morphology Based on Outdoor Thermal Comfort under Street Canyon

A Case Study of Guangzhou Xiajiu Pedestrian

by Sibei Liu
University of Hong Kong

Keywords: Pedestrian street, urban street morphology, outdoor thermal comfort, design strategy.

Abstract: Urban pedestrian street plays a significant role in providing citizens a comfortable environment for leisure activities. This study attempts to discuss effects of street morphology on thermal environment and comfort in Xiajiu Commercial Street in subtropical Guangzhou, China. Thermal environment and comfort of the street in a typical hot summer day is evaluated by chosen indices, i.e. Mean Radiant Temperature (Tmrt) and Physiologically Equivalent Temperature (PET). Through modelling and simulation in ENVI-met, differences of street orientation, height to width (H/W) ratio and building arcades as street morphological elements are compared and analysed to understand their efficacy on thermal comfort improvements.
Key findings show streets orientation plays a fundamental role in the quality of thermal enviornments. Street orienting W-E are much more thermally uncomfortable than their nearby N-S canyons in daytime summer. H/W ratio is more influential on N-S canyons than W-E ones. Larger H/W ratio means worse thermal environments. Existing building arcades appear to be the most effective and long-lasting strategy for outdoor thermal comfort improvement. Evaluated morphological elements can be adopted as reference for pedestrian or commercial street design regarding thermal comfort quality in subtropical regions by urban designers and architects in the future.

1. Introduction

1.1. *Urbanization and Climate Change*

The rate of urbanization has accelerated globally and the population density has also been increasing. The World Urbanization Prospects 2018 Revision published by Department of Economic and Social Affairs of United Nations in 2018 has showed that 55% of the global population hithero reside in the urban areas, comparing with 1950, only 30% of people inhabited in urban. Approaching 50% of Asian population residing in urban areas, it means more people remain in rural districts. It is forecast that the urbanization will keep fast in future decades, with an increase to 68% of urban residents by 2050. In China, it is projected that 255 million urban people will be added by 2050.

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1.2. *Urban Microclimate and Related Morphological Scale*

Urban microclimate is indicated by climatological parameters, including air temperature, humidity, solar radiation, wind velocity, precipitation, and so on. Microclimate was defined by Oke, T.R. (1997) as "the climate that prevails at the microscale level" which is corresponding with the scale of plots (or lots) and their aggregation in the concept of urban morphology. It means its climatic indicators and thus microclimate can be affected by morphological properties of the immediate environment, such as plot ratio, builidng density and H/W ratio (Erell, Pearlmutter & Williamson, 2011).

1.3. *Outdoor Thermal Comfort and Evaluation*

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment. The underlying basis of thermal comfort is the "energy budget of a person", i.e. the energy exchange process, which can be assessed by a plenty of physical and physiological parameters e.g. air temperature, relative humidity, wind velocity, radiation, clothing insulation and human activities. In an urban outdoor setting, pedestrians are typically exposed to more natural built enivronments with less sheltering than in interiors, whose comfort is greatly affected by the local urban morphology. This paper, therefore, focuses on the effects of street morphology on surrounding microclimate and human thermal comfort.

Over the past century, more than 100 types of thermal indices have been designed and practiced to predict human thermal response to the surrounding bioclimatic environment (Blazejczyk *et al.*, 2012).

Physiologically Equivalent Temperature (PET) is one of the most broadly adopted indices in thermal comfort studies, which is developed based on the Munich Energy-balance Model for Individuals (MEMI) (Höppe, 1999). Mean Radiant Temperature (Tmrt) is an indicator of radiation for calculation of radiation energy balance between human body and the surrounding. Tmrt has been widely used as an index of radiation heat exchange between human body and environment worldwide (Johansson, 2006). To understand the relationship between outdoor thermal comfort and street morphology quantitatively, this study adopts rational indices, PET as the thermal comfort index and Tmrt as the radiation indicator, to evaluate outdoor thermal environment of a pedestrian street in Guangzhou.

1.4. *Urban Morpholohy and Outdoor Thermal Comfort*

In the past three decades, many studies on human thermal comfort have been carried out in various types of urban morpholoical configuration around four seasons under different climatic zones. Lau et al (2015) investigated the impacts of urban morphology on thermal environments in three cities at different latitude of Europe using the Tmrt as indicator. The paper found that all selected cities had severe heat stress and all the highest Tmrt occurred in open areas in summer. On the contrary, the densely-built areas could help to mitigate the thermal stress in summer and sustain relative constant Tmrt in winter. East-west streets with deep canyons suffered much less than north-south street canyons suffered. Yang, Lau, & Qian (2010) conducted an empirical study to investigate patterns of UHI-day and UHI-night in 3 residential quarters in Shanghai and found that morphological elements i.e. plot layout and density, indicated by site shading factor, were closely related to the day-time UHI pattern. Long-linear layout with low density had the highest day-time UHI, while interspersed layout with high density had the lowest one. Nighttime UHI had not much relation with the selectde morphological elements. The semi-enclosed layout with high density is best to urban thermal conditions. Qaid *et al.* (2016) also investigated outdoor thermal comfort and the UHI intensity at a microscale in various urban morphologies from high-rise residential buildings to the low-rise one and to the suburban areas in Putrajaya, Malaysia. Envi-met V4 Beta software was employed. The study found that the high-rise built environment offered a cooler microclimate and had the lowest UHI due to building shading effects, while the low-rise buildings suffered from the highest UHI effects because of the low wind speed and the direct exposure to solar radiation. Alobaydi, Bakarman, & Obeidat (2016) studied the thermal performance of 3 typical urban configurations (i.e. traditional compact, modern attached, and modern detached) in Baghdad, Iraq. ENVI-met 4.0 was employed to evaluate air temperature (Ta), street surface temperature (Ts), and mean radiant temperature (Tmrt) at the central area of streets. The study found that the urban configuration with larger H/W ratios had lower Ta, Ts, and Tmrt. In shallow detached street canyon, the dissipating effects are better. In comparison, the deep and compact street canyons which had less accessibility of solar radiation to the surfaces could cool the surfaces and decreased the Ta and Tmrt both in daytime and nighttime. The shorter duration of solar radiation reached the surfaces in deep canyons, the shorter period of maxima values of Ts and Tmrt lasted. These findings confirmed that urban morphological elements including more compact urban morphology, higher buidling density, higher H/W ratio, semi-eclosed layout of blocks and shading elements can alleviate thermal discomfort in summer during a day.

Among all the factors that contribute to the quality of outdoor space, the urban microclimate shaped by urban morphology has played an influential role. A comfortable and delightful outdoor space cannot be achieved only by uplifting the diversity of landuse, district denisty and accessibility, but also by upgrading the thermal quality of local environments, further by optimizing the morphological elements such as building density, H/W ratio, street orientation and block layout. Hence, the study focuses on the effects of street morphological elements on radiation control and outdoor thermal comfort upgradation in Guangzhou.

2. Methodology

2.1. *Background of Shangxiajiu Pedestrian Street*

Guangzhou is famous for its prosperous commercial atmosphere, developed business tradition and booming economy of long standing from ancient China. Shangxiajiu Pedestrian Street is located in the old town of Xiguan (now in Liwan District), stretching from Shangjiu Lu in the east, Xiajiu Lu in the middle to Dishifu Lu in the west, and traverses Baohua Lu and Renmin Lu Viaduct at the ends, with approximately 1200 meters long and more than 300 shops (Sun, 2012), and orientating from southwest to northeast. Shangxiajiu is distinguished by a group of historic and cultural architecture based on Qi Lou and teahouses, featuring the unique architectural characteristics of European and local combination styles.

Shangxiajiu Pedestrian Street plays an important role as a public outdoor activity area for both visitors and neighborhood residents, due to its cultural and commercial atmosphere. Apart from attracting many visitors to go shopping along the street, the street creates a good leisure space for nearby inhabitants, workers and commuters to take activities. According to the statistic of the administrative committee, in common days, the average pedestrian volume can peak at 400,000-500,000 person per day while in festivals and holidays, the traffic volume can reach 80,000-1000,000 person per day. Besides, the dominant stayed duration of visitors in a common day was from 1 to 3 hours investigated by Huang Hao (2011).

2.2. *Climate Analysis of Guangzhou*

Guangzhou which lies in the central Pearl River Delta of South China is located on longitude between 112.8°E and 114.2°E and latitude between 22.3°N and 24.1°N and the IIIB climate zone of China (GB50176-93), dominated by subtropical monsoon-influenced humid climate. It has hot, humid summer and warm winter with adequate rainfall summer with higher air temperature lasts from May to October. The mean temperature of the hottest July is 28.7°C. The mean annual temperature and humidity are 22°C, and 78%, respectively(Guangzhou Meteorological Administration Website, 2013). Southeastern wind with lower mean velocity prevails in summer and northerly wind with higher average speed predominates in winter. Stronger global horizontal solar radiation occurs from May to October. Thus, the thermal comfort issue is significant and inlfuential in hotter months in Guangzhou.

2.3. *Street Morphological Analysis*

It has been proved that street morphology and urban design has a significant influence on the quality of microclimate and outdoor thermal comfort. Zeng and Dong (2015) stated that the diurnal microclimate of the street was driven by weather and street structure. The thermal comfort and street microclimate is directly linked to the street form. Urbanization modified the urban morphology and consequently varied thermal condition of local environments.

In this study, according to the Plan for Renovation Old Districts in Guangzhou, the selected planning factors which could affect street microclimate are taken into account including H/W ratio, building coverage and building height for comparing their influence on residents' thermal requirements. Table 1 shows the correlation between urban factors and PET. The plot ratio, building coverage and building height are all positively correlated to PET.

The morphological ensembles in old districts of Guangzhou often consist of low-rise and high-denisty residential buildings inside and commercial buildings outside surrounded by the pedestrian streets. The shop-residential buildings along Shangxiajiu Street is comprised of residential areas on the upper floors and commercial areas on the ground floor (Sun, 2012). In this study, Xiajiu Road is selected as a case to investigate the relationship between street morphology and thermal environments.

According to the statistic data, it is found that the building coverage of old districts is a little high in Guangzhou. For instance, the building coverage in Hualinsi which is the old area in Shangxiajiu Community of Guangzhou is approximately 60%. Plot ratio and building height are also high in old areas in Guangzhou. For example, the plot ratio of domestic area and the average building height of the Hualin Temple are 2.0 and 10m, respectively (Lai *et al.*, 2008).

Table 1. *The effects of urban factors on PET for subtropical cities (Ren, 2010).*

Building volume	Higher building volume leads to higher PET	Building volume, building density, floor area ratio and plot ratio
Ground coverage	Higher ground coverage leads to higher PET	None building areas, building set back, open spaces, building site coverage

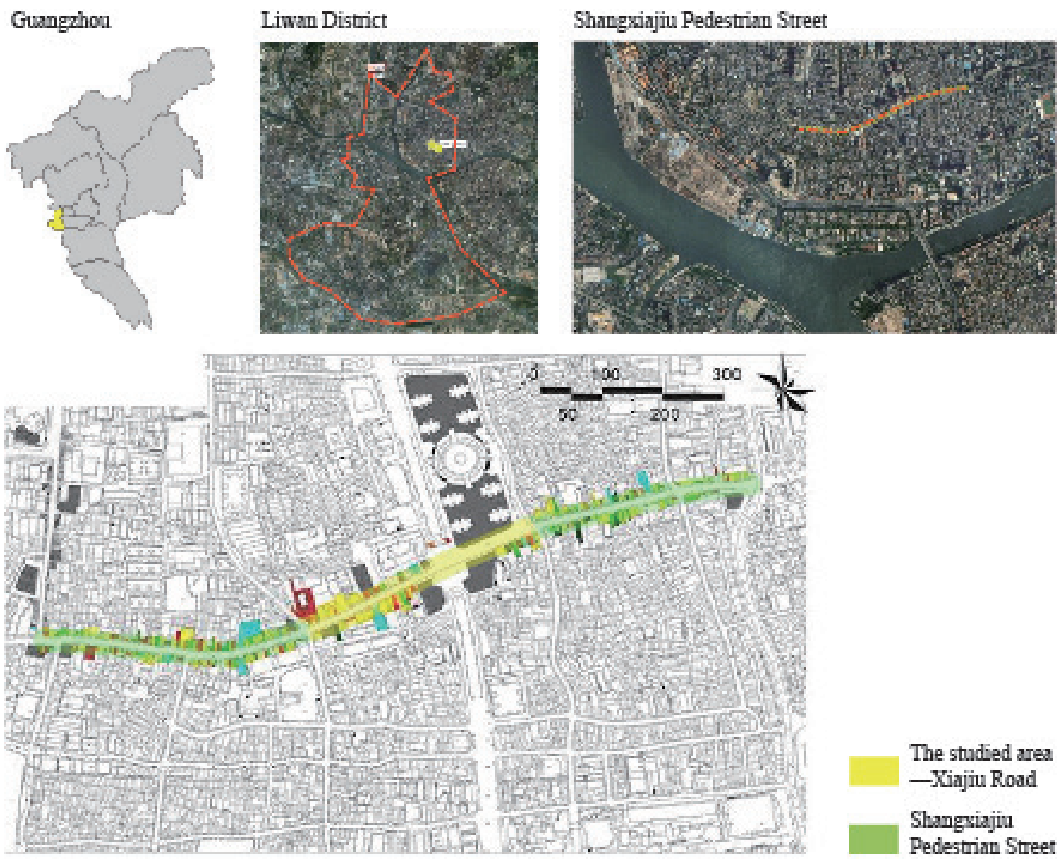


Figure 1. *The selected site (modified image from Huanghao, 2010).*

Figure 2. *The section of Xiajiu Road (modified image from Huanghao, 2010).*

2.4. *The Simulation Tool-- ENVI-met*

This study selected ENVI-met v4.0 to calculate PET and Tmrt of the street enviornments. It is developed by Prof. M. Bruse and his team of University of Mainz for urban environments evaluation and green architecture assessment, employing a three-dimensional computational fluid dynamics and energy balance model (Bruse and Fleer, 1998). The software is developed for microscale environments with a typical horizontal extension from 0.5 to 10 m, a vertical height ranging between 1 to 5m, and a temporal resolution from 24 to 48 hours with a time step from 1 to 5 seconds. Many numerical simulations of the thermal environment studies which were simulated in ENVI-met have verified its validality, reliability and accuracy (Alobaydi, Bakarman & Obeidat, 2016; Qaid *et al.*, 2016; Yang, Lau & Qian, 2011).

Yin (2015) conducted a study on the thermal environment of a traditional arcade street called Enning Road which was connected along with the Shangxiajiu Pedestrian Street. He collected the meteorological data together in Shangxiajiu Pedestrian Street by field measurements and numerical simulation. The meteological data adopted in this study is derived from this study and has been validated.

3. Analysis/Results

The analysis of the PET distribution and T_{mrt} change along the spatial variation and temporal variation in Xiajiu Road will be carried out, at the meanwhile the most significant problem areas and the causal reasons will be pointed out.

Table 2. *The initial variables settings of the ENVI-met.*

Location	23.7N, 113.5E. 12m a.s.l. (Guangzhou, China)
Climate	Subtropical climate strongly influenced by monsoon: hot and humid in summer
Date/time simulated	From 10:00 to 18:00 (8h) on 30 July 2014
Model domain	175 × 130 × 30 grids. Dx= Dy=3m, Dz=6m
Model rotation out of grid north	-27
Meteorology: Basic settings	Wind speed measured in 10m height (m/s): 1.5 Wind direction (deg)= 162 (SE) Roughness length at measurement site= 0.1 Initial temperature of atmosphere (K)= 301.95 Specific humidity at model top (2500m, g/kg)= 20.62 Relative humidity in 2m (%)= 81
Soils and Plants	Initial temperature (0-20cm)= 301K Initial temperature (20-50cm)= 300K Initial temperature (50-200cm)= 301K Soil wetness (0-20m)= 20% Soil wetness (20-50m)= 30% Soil wetness (50-200m)= 40%
Soil and surface	[GS] Granit Pavement (single stones) with an albedo at 0.2

Table 3. *The settings of human factors for PET calculation in the ENVI-met.*

People	35-year-old male
Height	1.75m
Weight	75kg
Clothing insulation	0.4
Activity level	1.21m/s for walking

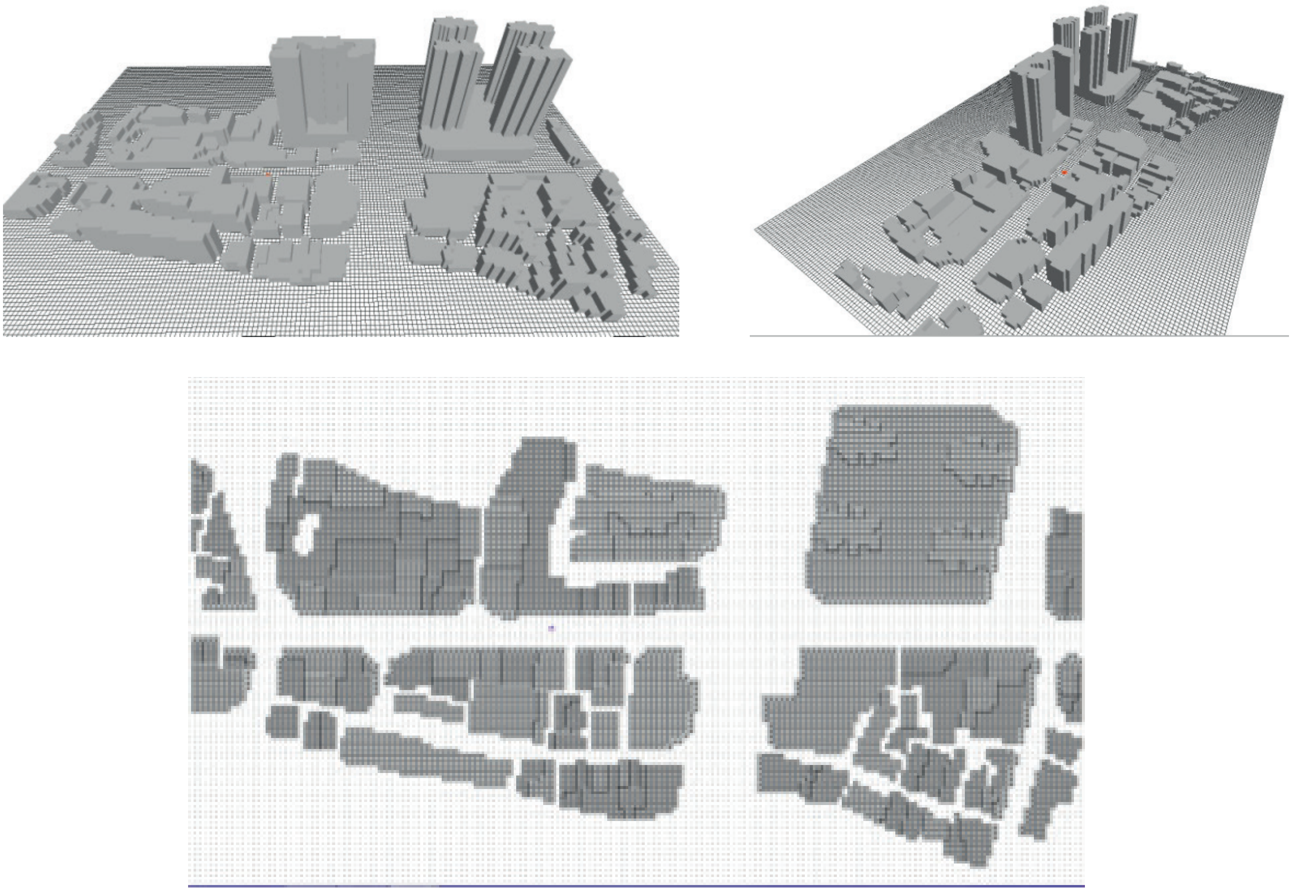


Figure 3. *The modelling of Xiajiu Road in Shangxiajiu Pedestrian Street.*

3.1. *Spatial differences in T_{mrt}*

The simulated T_{mrt} at Xiajiu Road (Figure 4a & b) reveals the T_{mrt} at 1.8m above ground of Xiajiu Pedestrian Street. The relationship of the causal factors of street morphology and the consequent Tmrt spatial distribution can be summarised into four points. Firstly, in the case where the streets are all north-south (N-S), the Tmrt of the street canyon with a H/W ratio around 0.7-1.3 is about 14~21 ºC higher than that of the street canyon with a H/W ratio around 2.0-4.0 in the same street. This is because the main pedestrian street with relatively high H/W ratio is less likely to be shaded by the shadows of buildings on both sides, and then large amount and long lasting incidence of solar radiation and heat is received by the street surface of the wider canyons with lower H/W ratio. Secondly, the H/W ratio has less impact on the thermal environment of the east-west street than on the north-south street. Moreover, the increase of H/W ratio has little effect on the thermal environment improvement of the east-west street. When the H/W ratio increases from 0.7 to 3, the Tmrt has an decrease of only 3-5ºC for the E-W street but a large reduction of 14-21 ºC for the N-S street where the improvement of thermal environment is much more obvious. Third, in the case of similar H/W ratio, the E-W streets are 15-20ºC higher than the MRTs in the north-south streets during the morning and afternoon. The solar radiation in the east-west streets is more severe and the thermal environment is worse during most daytime. Except in the early morning and late afternoon with a lower solar altitude, then the solar radiation can be blocked by the southern buildings of the E-W canyon. This is because Guangzhou is located on the Tropic of Cancer, with a latitude of 23º26' and a solar elevation of 89º64' during the summer solstice. On a sunny day, the N-S street has obvious and large area of building shadows to cover the street surface in the morning and afternoon. On the contrary, as the solar altitude is almost vertical in summer, the E-W street has only very small area of shadows projecting from the south or north side, making it easier to be exposed to the sun for a long time. So compared to the N-S street, the thermal environment of E-W street is even worse. Lastly, in the streets of Xiajiu Road, the widest intersection of the street gains radiation heat, whose Tmrt is 10 to 30°C higher than that of a wide E-W street during daytime. And the area under buidling arcades in Xiajiu Road has around 25 to 35°C lower Tmrt than the exposed middle area has. It is because that the main principle of radiant heat is that when large amount of direct solar radiation and long-wave radiation reach the surface of the street and building, some proportions of short-wave radiation and long-wave radiation are reflected back to sky. Part of direct sunlight and emitted radiation are absorbed by the surface of streets and buildings, and then the energy is transfered into long-wave radiation released from these surfaces. Without shading, the short- and long-wave radiation directly heat up exposed surroundings and human body which contribute to human thermal discomfort (Lau, Lindberg, & Rayner, 2015). This suggests that a denser urban structure and shading elements are able to lower the Tmrt in daytime.

3.2. *Temporal variation in Tmrt*

Data of the daytime evolution of Tmrt is collected from the four observation points set in the model from 11:00 to 18:00 (Figure 4c). Through the analysis of Figure 16, four findings are analysed and pointed out. Firstly, before 15:30, the short-wave radiation obtained at r4 loacted at the wide and open intersection of the street is the highest among the four observation points, which is indicated by Tmrt rangeing between 65 and 75 °C. The evolutionary trajectory of r4 is similar to those of r1 and r2, but the overall Tmrt of r4 is about 3°C higher. The reason is that r4 is located on the most open crossroad, and is exposed to direct sunlight from 10:30 to 15:30. As its surface absorbs more short-wave radiation than the street, the consequent emitted long-wave radiation of r4 heats up its surrounding environments with higher Tmrt than outher receptors at the street. At 15:30, Tmrt at r4 reaches a peak of 75 °C and then dropped sharply to 48.3 °C, due to the shadow of high-rise building in the northwest of r4, blocking the direct solar radiation. Tmrt is greatly fluctuated due to the changes of short-wave radiation and drastically decreases in the case where short-wave radiation is blocked. Second, Tmrt of r2 situating at the south side of Xiajiu Street is the lowest among the four observation points from 10:30 to 12:30, only around 47 °C at 10:30. It keeps an upward trend and its Tmrt trajectory meets those of r1 and r3 until 12:30 under direct sunlight. This is because the Xiaji Road orients from southwest to northeast. The location of r2 on the south side of the road is covered by the shadow of the southeastern building in the morning. When the solar altitude reaches its maximum at noon, the northwest projection of the building gradually disappears and turns to the southeast projection in the afternoon which cannot cover r2 anymore. The r2 is also gradually exposed to direct solar radiation from 12:30 to the evening, resulting in a high Tmrt for a longest duration in the daytime. Next, the Tmrt evolutionary trajectory of the r1 and r3 at the north side and center of the street almost coincide with each other before 14:00, as both of them are exposed to solar radiation before 14:00. 14:00 and 16:30 are time for r1 and r3 shaded by the southwest projection of the northern buildings, respectively, thus their Tmrt drop rapidly. Finally, except r1is blocked by shadows of building at 14:00, r2, r3 and r4 all reach the peak Tmrt around 15:00, which means that the worst thermal environment of Xiajiu Street appears at 15:00 in summer. The causal reason attributes to the synergism of high Ta, intense direct solar radiation and longwave radiation. It should be pointed out that Tmrt is similar in all sun-exposed areas.

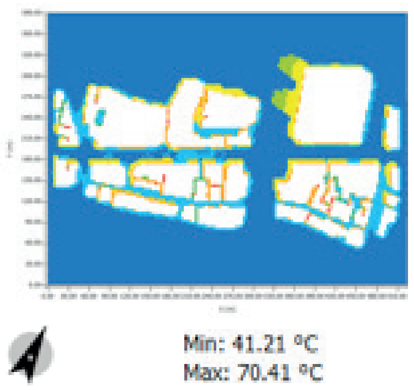


Figure 4a Simulated Tmrt at 11:00

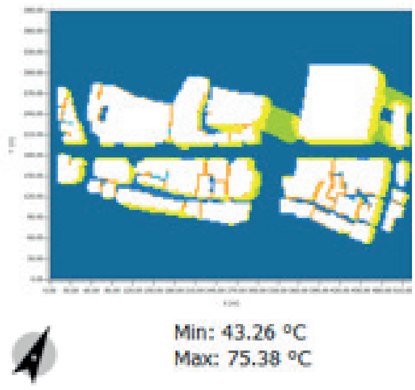


Figure 4b Simulated Tmrt at 15:00

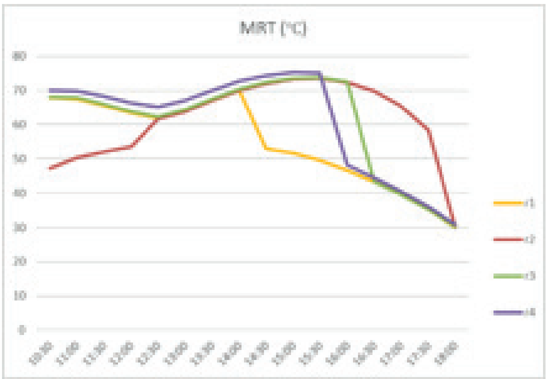


Figure 4c Temporal distribution of Tmrt at 15:00

Figure 4. *Temporal variation of Tmrt of 4 receptors in Xijiu Street during daytime.*

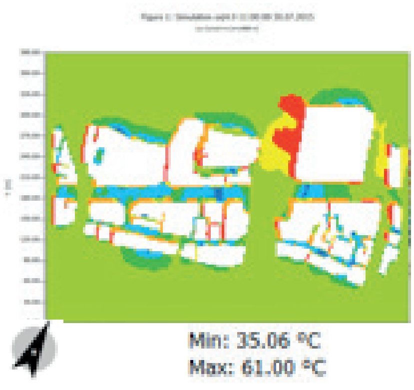


Figure 5a Simulated PET at 11:00

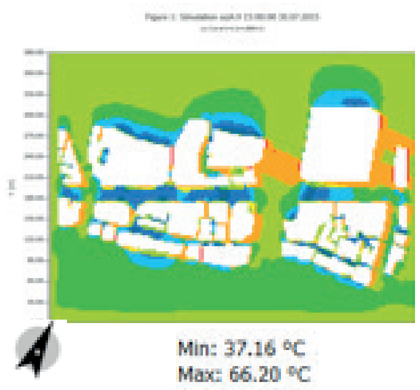
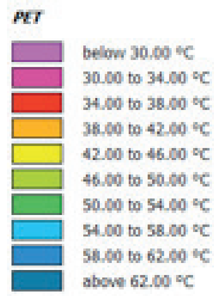


Figure 5b Simulated PET at 15:00



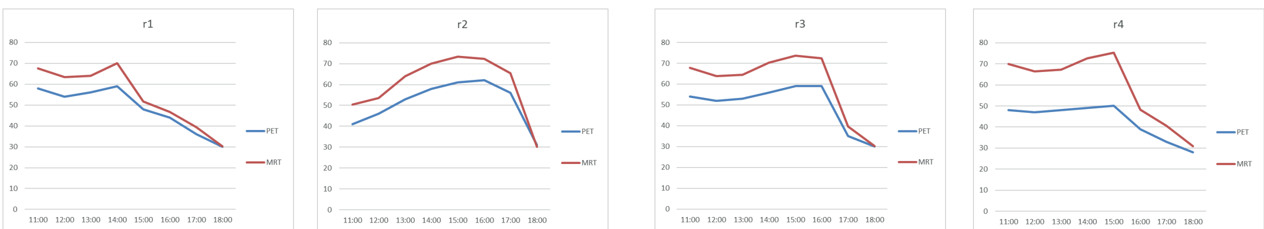


Figure 5c Temporal distribution of Tmrt of r1, r2, r3 & r4 at 15:00.

Figure 5. *Spatial and temporal variation of PET of 4 receptors in Xijiu Street during daytime.*

3.3. *Spatial Variation in PET*

Figure 5a & b show the calculated PETs at 1.8m of Xiajiu Road during 11:00 to 18:00 on 30 July, 2014. As mentioned above, it is assumed that someone is staying in the street. From the graphs, it can be seen that the thermal comfort of Xiajiu Pedestrian Street is relatively unsatisfactory, for example the average PETs can reach 54-56.5 ºC at 11:00, and 56-63 º C at 15:00. According to the street morphology and the spatial distribution of PET, the following four points can be summarised. Firstly, the H/W ratio has a weak effect on the Tmrt and PET of the E-W street, so the street thermal comfort will not change by the modification of H/W ratio. For the north-south street, the increase in H/W ratio has a great improvement on thermal comfort, which can bring 10-18 ºC reduction on PET. Secondly, PET in the E-W street is generally about 10-20 ºC higher than that in the N-S street during the daytime. In addition to the less amount of incidence of solar radiation to the E-W street, the effect of wind speed also contribute to the degradation of thermal comfort in the street. The southeastern prevailing wind in summer in Guangzhou is just perpendicular to the E-W street. Thus, areas at leeward side of Xiajiu canyon and E-W street suffer and thus have higher PET. However, the effect of ventilation on PET is much less than that of Tmrt. It is obvious that the best condition of thermal comfort occurs under the shaded areas provided by arcades across daytime and building shadows in the late afternoon rather than under the exposed area with good wind condition. The PET in arcades has a greatest difference with 10-20ºC lower than that in middle areas of the Xiajiu Road. Moreover, PET in shaded areas is 8.5-14ºC lower than PET in well-ventilated but unshaded areas. Therefore, the effect of reducing radiation on improving thermal comfort is more pronounced.

3.4. *Temporal Variation in PET*

Figure 5c shows temporal distribution of four observation points in the Xiajiu street during the period from 11:00 to 18:00. It is obvious that the temporal trend of PET highly coincides with that of Tmrt during daytime, which reveals that the Tmrt is an important factor determining the thermal comfort in sun-exposed outdoors during daytime. For example, PET of r1 on the north side of Xiajiu Street drops rapidly after 14:00, because buildings cast shadows on r1 from the north side and block short-wave radiation. Also, the worst thermal condition occurs at 15:00 in the simulated day. Therefore, it is important to improve the impact of solar radiation on Tmrt and to upgrade thermal environments.

4. Discussion/Conclusion

This thesis selected Xiajiu Pedestrian Street in Guangzhou to investigate the relationship between street morphology and the Tmrt and sequent the human thermal comfort in summer. ENVI-met was adopted for the numerical simulation to evaluate and assess the Tmrt and PET of the pedestrian street. The morphological elements such as H/W ratio, street orientation and building density were considered as factors and analysed for the variation of thermal comfort. In light of the concepts of microclimate and thermal comfort, Tmrt and PET were selected as indicators to measure the thermal performance of differet morphological elements. The results indicated that the extent of outdoor thermal comfort largely relies on the radiation in the street canyon and the open space under weak wind condition during high-temperature summer in hot and humid subtropical climate.

In light of the observation of the native residents, they more desire shaded area or use umbrella to minimize the heat gain from solar radiation at outdoors. Based on the comparison, building arcades appear to be the most effective and loing-lasting strategy for solar radiation sheltering and outdoor thermal comfort improvement during daytime (Johansson, 2006). The effect of the existing building arcades in the Xiajiu Pedestrian Street for improving the local thermal comfort is quite distinct. Secondly, street orientation plays a fundamental role in the range of Tmrt and thermal comfort and is always decided at the initial stage of the urban formation and design process. In Guangzhou, E-W street canyons sufferes higher Tmrt and worse thermal comfort than N-S streets suffer. Lastly, once street orientation is confirmed, the H/W ratio also greatly affects on the radiation heat gaining and thermal comfort level of the street surface.

Due to the limitation on time and season condition, the study does not carry out the field measurement to validate the result of numerical simulation and to delimit the comfort zone of Guangzhou residents. Tmrt is not calculated according to the properly measured radiation data by field measurements. Therefore, in future studies, the range of thermal comfort zone in street canyon in Guangzhou during summer days should be studied firstly. Then the field measurements will be carried out appropriately for validation purposes and the Tmrt should be measured based on the method which Thorsson *et al.* (2007) suggested.

The effects of street H/W ratio, street geometry and orientation on solar radiation access control and thermal comfort are critical at the initial phase of design process. However, as the street planning decision has always been made regarding the transportation demand as well as political and economic issues, the factors of outdoor thermal environments and sustainability are neglected. Therefore, this study focuses on outdoor thermal comfort analysis of pedestrians based on the effect of street morphology. As urbanization is still rapidly undergoing in China, the number of construction projects for new commercial pedestrian street and block keep increasing. Thus, the forward-looking desicion-making and scientific scenarios for minimizing adverse street environments and human discomfort of newly-built pedestrian will be more likely to appear.

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