The impacts of trees’ canopy occupation on pedestrian thermal environment of township streets

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Abstract. This paper measures the effect of trees’ canopy occupation on township street pedestrian thermal environment by ENVI-met software. The demonstration experiment was conducted in two streets with different features; street A (NE-WS) with 28% buildings coverage and 0.36 AR (street aspect ratios, H/W), street B (N-S) with 63.85% buildings coverage and 1.39 AR. The results show that trees’ canopy occupation ratio (TCR, VTC/Vstreet) influences the average temperature at pedestrian height. The average temperature increases in the morning, whereas it decreases at noon and in the afternoon. It seems that TCR needs an offset to work on wider street, such as in street A, where the average temperature drops when TCR is greater than 0.15 (noon case, 12:00) and greater than 0.05 (afternoon case, 16:00). For every 0.1 increase of TCR (VTC/Vstreet), the average temperature drops by 0.06℃ (street A, 12:00), 0.118℃ (street A, 16:00), 0.124℃ (street B, 12:00), 0.1℃ (street B), respectively. We can conclude that increasing the space occupation of trees’ canopy in the street can improve the pedestrian thermal environment, especially, the street with a small street aspect ratio. At the same time, we suggest that wider and taller trees shall be planted for street greening.

1. Introduction
The street thermal environment is one of the urban microclimate, and the main influencing factors are building distribution, the underlying surface, and vegetation. Climate and environmental characteristics are relatively consistent and easy to improve[1]. The street thermal environment at pedestrian level is closely related to human daily life. Several studies demonstrate trees can help to regulate and improve the thermal comfort of a surrounding environment[2]. Planting trees would reduce the PMV value by 1.75 on average (Ceren Altunkasa et al, 2020) [3]. Vaz M et al. found that in London, the cooling distance was most strongly related with tree canopy [4]. Tan Z et al. found that planting trees can lower the temperature by at least 0.3℃ in subtropical cities with high-density buildings [5]. In Cairo, 50% canopy cover reduces air temperature in high density built up areas by 0.5 K(Amir A et al, 2020) [6]. And increasing canopy coverage in open spaces by 25% to 50% can reduce PET temperature at pedestrian level by 0.5 ℃ to 8.7 ℃ (Ma Xuan et al, 2019) [7]. This shows that increasing the number of trees will have a positive impact on the thermal environment.
However, most of the existing thermal environment studies are focused on urban heat island \cite{8,9}, urban thermal comfort \cite{10}, and evaluating urban overheating mitigation strategies \cite{11-13}, with only a few studies focusing on townships. With the rapid development of economy today, we pay attention to the greening of township streets. What role do trees play in the pedestrian thermal environment of township streets? In this paper, ENVI-met was used to simulate the air temperature of pedestrian level in two streets in order to explore the value of trees’ canopy occupation ratio of street space on pedestrian thermal environment.

2. Methods

2.1 Study area and data
This study focuses on two streets located in Yuexi County, Anhui Province, China(30°39′~31°11′N, 115°55′~116°33′E). The satellite image (Google Earth) was shown in figure 1(a). One is street A (NE-SW) with a street aspect ratio (AR) of 0.36 and trees with low LAD (LAD is the leaf area density). The other one is street B (N-S), which has a street aspect ratio of 1.39, trees planted only at the intersection, no tree planted inside. The detail information of these streets were shown in Table 2, their 3D models were shown in the figure 1 (b) and figure 1 (c). In the 3D models, the red shaded area is the horizontal area of pedestrian level. The blue shaded area is the average building height. For the 3D model of the street, this paper uses buildings of Google Earth image as reference to sketch the base map, field investigation to obtain the building floor data of two streets to estimate the building heights, and estimates the building heights. The 3D model was built in ENVI-met according to the base map and the building heights.

![Image of study area and 3D model](image)

**Figure 1.** Studied area and 3D model.

| Street | Street length(L) | Street width(W) | Building density(K) | Average height of buildings on both sides(\(\overline{H}\)) | Street aspect ratio (AR) | Street orientation |
|--------|------------------|-----------------|---------------------|-----------------------------|------------------------|-------------------|
| A      | \(\approx160m\)  | \(\approx28m\)  | \(\approx28\%\)    | \(\approx10m\)              | \(\approx0.36\)        | NE-SW             |

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The indexs in the table 1 such as the average building height ($H$), building density ($K$) and street aspect ratio (AR) were calculated according to formulas (1)–(3):

1. Building density ($K$) is the ratio of building area ($S_{\text{building}}$) to region of interest ($S_{\text{interest}}$), showed as formula (1).

   \[
   K = \frac{S_{\text{building}}}{S_{\text{interest}}} \tag{1}
   \]

2. Average height of buildings on both sides ($\bar{H}$), showed as formula (2), $H_i$ is the height of a building, $S_i$ is the area of the corresponding building.

   \[
   \bar{H} = \frac{\sum^n_i H_i S_i}{\sum^n_i S_i} \tag{2}
   \]

3. Street aspect ratio (AR) is ratio of the average height of buildings on both sides ($\bar{H}$) to street width $W$, showed as formula (3).

   \[
   AR = \frac{\bar{H}}{W} \tag{3}
   \]

Collecting the air temperature data at pedestrian level of the two streets from May 17 ~ 23, 2020 (from 8:00-9:00 a.m, 11:30-12:30 p.m. and 15:00-16:00 p.m.) 2020. The points measured were located in the middle of the streets (point A-1, B-1), under tree (point A-2, B-2) and at the intersection (point A-3, B-3), the location of measuring points is shown in figure 2(b). The measured data will be used to verify the simulation results.

2.2 Simulation case design of ENVI-met

The brief schematic diagram of the computing domain of the software is shown in figure 2(a). As in figure 1, red shaded area represents the horizontal area of pedestrian level, the blue shaded area is the average building level, and its height ($\bar{H}$) is calculated by formula 2. The purple wireframe in figure 2(a) is the region of interest, the range of interest selected for street A and street B is 100 * 160m, with a resolution of 2 * 2 * 3m. The main 3D model is limited to the middle of calculation domain, the height of the calculation domain $h > H_{\text{max}}$, $H_{\text{max}}$ is the maximum height of the building. $W$ is the street width of the region of interest. $L$ is the street length of the region of interest.

| B | $\approx$160m | $\approx$14m | $\approx$63.85% | $\approx$19.57m | $\approx$1.39 | N-S |
|---|----------------|--------------|----------------|----------------|-------------|-----|
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(a) Schematic diagram of calculation domain

(b) Trees’ planted position

(c) Tree canopy main parameters (height, width)

Figure 2. Compute domains and tree’s change.

| Case name | Canopy height (ch) | Canopy width (cw) | Trees coverage in street area (S🏷/S_street) | Trees’ canopy occupation ratio in street space (TCR, V_{tc}/V_{street}) |
|-----------|-------------------|------------------|---------------------------------------------|-------------------------------------------------|
| (1) Reference cases |                   |                  |                                            |                                                 |
| A-Nt      | 0m                | 0m               | 0                                           | 0                                               |
| B-Nt      | 0m                | 0m               | 0                                           | 0                                               |
| (2) Real cases |                   |                  |                                            |                                                 |
| A-current | 3m                | 1m               | 0.0112                                      | 0.0033                                          |
| B-current | 7m                | 7m               | 0                                           | 0                                               |
| Ach2cw1   | 2m                | 1m               | 0.0085                                      | 0.0017                                          |
| Ach3cw3   | 3m                | 3m               | 0.0763                                      | 0.0229                                          |
| Ach5cw5   | 5m                | 5m               | 0.1781                                      | 0.0891                                          |
| Ach5cw7   | 5m                | 7m               | 0.3138                                      | 0.1569                                          |
| Ach7cw5   | 7m                | 5m               | 0.1781                                      | 0.1247                                          |
| Ach7cw7   | 7m                | 7m               | 0.3138                                      | 0.2197                                          |
| Bch2cw1   | 2m                | 1m               | 0.0179                                      | 0.0018                                          |
| Bch3cw3   | 3m                | 3m               | 0.1607                                      | 0.0246                                          |
| Bch5cw5   | 5m                | 5m               | 0.3750                                      | 0.0958                                          |
| Bch5cw7   | 5m                | 7m               | 0.6607                                      | 0.1688                                          |
| Bch7cw5   | 7m                | 5m               | 0.3750                                      | 0.1341                                          |
| Bch7cw7   | 7m                | 7m               | 0.6607                                      | 0.2363                                          |

Table 2 shows the simulation case design in this paper:
There was no tree was planted in the streets of the ‘Reference cases’.

The ‘Real cases’ in table 2 will be constructed according to the current situations of two streets. These cases will simulate the pedestrian thermal environment of street A and street B from May 17, 2020 to May 23, 2020, that simulated data use to compare with measured data by calculating the correlation coefficient $R^2$ and root mean square deviation $RMSD$. The closer $R^2$ is to 1 and $RMSD$ is to 0, the more effective the simulated value is. The $RMSD$ is shown in equation (3), where $T_s$ is the simulated temperature, $T_m$ is the measured temperature recorded in the investigation, and $N$ is the data record items.

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N} (T_s - T_m)^2}{N}}$$

‘Planting cases’ in table 2 will changing canopy height and canopy width, as shown in figure 2 (c). In ENVI-met, the entire canopy model is confined to a cube consisting of 1*1*1m cells, with each cell in the model represents a specific LAD value [14], figure 2 (a) shows the tree canopy model in ENVI-met software. According to the study of Li Zhang et al [15], the impact of vegetation on both heat environment and ventilation depended on tree arrangement, LAI (leaf area indexes), crown width and tree height. When changing the canopy height and canopy width, the leaf area density, trunk height (3m) and planting spacing unchanged. And according to CCJJ75-97 code for planning and design of urban road greening [16], trees are usually planted between 4 and 8m and should not block the driving line of sight. In ‘Planting cases’, the trees distribution is shown in figure 2 (c) with a planting spacing of approximately 8m. In the table 2, the trees coverage in street area ($S_{tc}/S_{street}$) is shown in equation (4), where $W$ is the width of the street, $L$ is the length of the street, $num$ is the number of trees planted in the street, $j$ is the jth tree, $tp_j$ represents the tree projection area of the jth tree. Trees’ canopy occupation ratio in street (TCR, $V_{tc}/V_{street}$) is the ratio of $V_{tc}$ to $V_{street}$. The formula as shown in figure 2, $\overline{H}$ is average height of buildings on both sides.

$$S_{tc}/S_{street} = \frac{\sum_{j=1}^{num} tp_j}{W \times L}$$

The detail parameters of model are shown in table 3.

| Parameter                      | Value                                      |
|--------------------------------|--------------------------------------------|
| Simulation grid settings       | 210*270*30, 1m*1m*3m                       |
| Wind speed                     | 1.90m/s                                    |
| Wind direction                 | 185°                                       |
| Temperature range              | Minimum:16.7°C (6:00), Maximum 31.3°C (14:00) |
| Average relative humidity      | 68%                                        |

3. Simulation verification

Figure 3 shows the scatterplot graphs of the comparison between the measured and simulated air temperatures [6, 17, 18]. $R^2$ of each point are $> 0.7$ and $RMSD$ of each point are $< 0.43$. According to previous experience [1, 17], the value of $RMSD$ and $R^2$ in this paper are within the acceptable range. Therefore, it can be considered that the simulation results are relatively reliable.
4. Simulation results and analysis

4.1 Difference in pedestrian thermal environment between the two streets

Figure 4 and figure 5 respectively show the simulation results of pedestrian temperature at A Street and B Street in the morning (8:00), noon (12:00) and afternoon (16:00). In the morning, the east side of street A is blocked by building shadow due to the influence of sunlight, so the temperature on the west side of the street is higher and the temperature on the east side is lower. The building at the southeast corner of street B is higher, south of the street the street is obscured by the building shadow, so the temperature is lower. At noon, the building shadow area formed by sunlight is smaller. Compared with that in the morning, the east-west temperature distribution of the two streets is relatively uniform, but the temperature on the east side of the street is still slightly lower than that on the west side. The higher temperature area of street valley changed from north of street valley (in the morning) to south of street valley (at noon). In the afternoon, the temperature at the windward junction of two street valley is higher. Compared with street A, the temperature of street B is relatively lower, which could be due to the dense buildings on both sides of street B.
Figure 4. Street A pedestrian thermal environment.

Figure 5. Street B pedestrian thermal environment.
4.2 The impacts of trees’ canopy occupation on pedestrian thermal environment of township streets

Taking the difference between ‘Planting cases’ and ‘Reference case’ to gain the pedestrian temperature spatial difference $C_{ij}$ of the street which caused by trees. The each grid temperature difference ($C_{ij}$) and average temperature difference ($\bar{C}$) caused by trees can be obtained from equations (5) and (6):

$$C_{ij} = C_{ij}^{P-x-y} - C_{ij}^{P,Ni}, x \in \{2,3,5,7\}, y \in \{1,3,5,7\}$$

$$\bar{C} = \frac{\sum_{K}^{K} C_{ij}}{K}, K = i* j$$

Where, $i$ and $j$ represent the abscissa and ordinate of the simulated grid, $P$ represents street A or street B, $x$ is the crown height of the tree, $y$ is the crown width of the tree, $P-x-y$ represents the case in table2, $C_{ij}^{P-x-y}$ is the temperature of each grid point simulated in the scene with trees (Planting cases), $C_{ij}^{P,Ni}$ is the temperature of each grid in the scene without trees (Reference case), $C_{ij}$ is the difference value of each grid, $K$ is the number of grids. The simulation difference of between ‘Planting cases’ and ‘Reference case’ was shown in figure 6 and figure 7, respectively. The red squares show where the trees are planted.

It shows that in the two streets, the pedestrian temperature increases with the increase of tree canopy in the morning, but the temperature rises range does not exceed 0.15 °C, and the smaller the tree canopy, the smaller the overall temperature rises range. While an increase in tree canopy causes a local temperature rise, it has a local cooling effect in the tree planting area (blue area in the above figure), and an increase in tree canopy increases the cooling range. Compared to the morning, the cooling range provided by trees at noon and afternoon increases.
Figure 6. Street A-Effects of trees on pedestrian thermal environment.
Figure 7. Street B-Effects of trees on pedestrian thermal environment.

In order to explore the relationship between the space occupation of tree canopy in the street and the pedestrian thermal environment, calculate the trees’ canopy occupation ratio (TCR, Vtc/Vstreet) of each case and the average temperature difference of pedestrian temperature in the street brought by trees, and create the scatter diagram (figures 8 and 9). This is used to describe the difference of average pedestrian temperature when planting trees or not.
At 8:00 am, trees increased rather than decreased the average temperature of the pedestrian environment in streets A and B. At 12:00 noon, when the TCR value of street A is greater than 0.15, trees can reduce the average temperature. At noon, the average temperature of street B decreases with the increase of TCR value. Through linear fitting, the average temperature decreases by about 0.124 °C every time the value of TCR increases by 0.1. In the afternoon, when the value of TCR
occupied by the canopy space of street A is greater than 0.05, the average temperature of pedestrian level in the street begins to decrease. Through curve fitting, it is found that there is a convex quadratic function relationship between the average cooling value and TCR. When TCR > 0.05, the average temperature of pedestrians in street A decreases by at least 0.05°C every time the value of TCR increases by 0.1. In the afternoon, the average temperature of pedestrian height in street B also decreases with the increase of TCR. Through linear fitting, the average temperature decreases by about 0.1 every time the value of TCR increases by 0.1°C. The influence of the space occupied by trees on the overall ambient temperature varies between the two streets. The possible reason is that the morphological structure of the two streets is different, resulting in the difference of the thermal environment in the streets. Generally speaking, the shading effect of trees is an important reason why trees can cool the hot environment. Compared with street B, street A has low buildings and wide streets, which will be exposed to more sunlight, resulting in higher temperature. Therefore, when less space is occupied by trees in the street valley, the cooling effect brought by trees is minimal.

4.3 Discussion

The results of this study are in line with previous studies of urban streets [19], which showed that street with smaller AR have higher temperature. Furthermore, the results of this study agree with others urban streets studies, which showed that larger tree canopies can help cool the streets [4, 5, 7]. But the findings of this study differ from those of Amir [20] and Justine et al [21]. There show that trees do not always cool streets in Cairo and no cooling effect from increased canopy occupancy in Manchester. The main reasons for these are geographical location and street shape.

5. Conclusion

This paper designs different tree’s crown volume inside the township street to explore the impact of trees’ canopy occupation ratio on the pedestrian thermal environment, the following findings are obtained:

The geometry of a street will have an impact on the pedestrian thermal environment. Street B has a good shading effect and low temperature at pedestrian level because of the dense buildings. Trees can reduce the pedestrians temperature around them at noon and in the afternoon mainly due to their shading effect, thus, taller trees have better cooling effect. Street A is relatively wide and open, its TCR (Vtc/Vstreet) is small, the cooling effect of trees is not obvious. It seems that the TCR needs an offset to work on wider street, such as in street A, the average temperature of pedestrian reduces, when its TCR is greater than 0.15 (noon, 12:00) and greater than 0.05(afternoon, 16:00). There is a linear relationship between the TCR and the average cooling value in street B during noon and the afternoon. According to linear fitting, it is found that every time the TCR of street B increases by 0.1, the average temperature decreases by approximately 0.124 °C (noon, 12:00) and by approximately 0.1 °C (afternoon, 16:00).

Based on the above analysis, there is a suggestion for street A; more mature and tall trees should be planted to provide a significant shading effect in the pedestrian area, and the TCR should be greater than 0.15. On the basis of making rational use of street space, it is recommended to plant trees on street B, which lacks tree greening.

Reference

[1] Lao Z M, Ying-Min L I, Deng X J 2017 J. Environ. Sci. Numerical simulation of thermal environment in Zhongshan urban streets based on ENVI-met 37 3523-3531
[2] Petri A C, Wilson B, Koeser A 2019 Land Use Pol. Planning the urban forest: Adding microclimate simulation to the planner’s toolkit. 88 104117
[3] Altunkasa C, Uslu C 2020 Sust. Cities Soc. Use of outdoor microclimate simulation maps for a planting design to improve thermal comfort. 57 102137
[4] Vaz Monteiro M, Doick K J, Handley P 2016 *Urban For. Urban Green*. The impact of greenspace size on the extent of local nocturnal air temperature cooling in London. 16 160-169

[5] Tan Z, Lau K K-L, Ng E 2016 *Energy Build.* Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. 114 265-274

[6] Aboelata A, Sodoudi S 2020 *Build. Environ.* Evaluating the effect of trees on UHI mitigation and reduction of energy usage in different built up areas in Cairo. 168 106490

[7] Ma X, Fukuda H, Zhou D 2019 *Sol. Energy.* The study on outdoor pedestrian thermal comfort in blocks: A case study of the Dao He Old Block in hot-summer and cold-winter area of southern China. 179 210-225

[8] Chatterjee S, Khan A, Dinda A 2019 *Sci. Total Environ.* Simulating micro-scale thermal interactions in different building environments for mitigating urban heat islands. 663 610-631

[9] Aboelata A, Sodoudi S 2019 *Build. Environ.* Evaluating urban vegetation scenarios to mitigate urban heat island and reduce buildings’ energy in dense built-up areas in Cairo. 166 106407

[10] Ma X, Fukuda H, Zhou D 2019 *Tourism Manage.* Study on outdoor thermal comfort of the commercial pedestrian block in hot-summer and cold-winter region of southern China-a case study of The Taizhou Old Block. 75 186-205

[11] Battista G, de Lieto Vollaro R, Zinzi M 2019 *Sol. Energy.* Assessment of urban overheating mitigation strategies in a square in Rome, Italy. 180 608-621

[12] Wu Z, Dou P, Chen L 2019 *Sust. Cities Soc.* Comparative and combinative cooling effects of different spatial arrangements of buildings and trees on microclimate. 51 101711

[13] Wang Y, Ni Z, Chen S 2019 *J. Clean Prod.* Microclimate regulation and energy saving potential from different urban green infrastructures in a subtropical city. 226 913-927

[14] Yang Y, Gatto E, Gao Z 2019 *Build. Environ.* The “plant evaluation model” for the assessment of the impact of vegetation on outdoor microclimate in the urban environment. 159 106151

[15] Zhang L, Zhan Q, Lan Y 2018 *Build. Environ.* Effects of the tree distribution and species on outdoor environment conditions in a hot summer and cold winter zone: A case study in Wuhan residential quarters. 130 27-39

[16] Bei-Bei L I, Qin J P, Li-Rong Q I 2018 *J. Environ. Sci.* Emission Characteristics of Wind Erosion Dust from Topsoil of Urban Roadside-Tree Pool. 39 1031-1039

[17] Taleghani M, Marshall A, Fitton R 2019 *Sol. Energy.* Renaturing a microclimate: The impact of greening a neighbourhood on indoor thermal comfort during a heatwave in Manchester, UK. 182 245-255

[18] Liu Z, Cheng W, Jim C Y 2021 *Build. Environ.* Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4. 200 107939

[19] Andreou E 2013 *Renew. Energy.* Thermal comfort in outdoor spaces and urban canyon microclimate. 55 182-188

[20] Aboelata A 2020 *Build. Environ.* Vegetation in different street orientations of aspect ratio (H/W 1:1) to mitigate UHI and reduce buildings’ energy in arid climate. 172 106712

[21] Hall J M, Handley J F, Ennos A R 2012 *Landsc. Urban Plan.* The potential of tree planting to climate-proof high density residential areas in Manchester, UK. 104 410-417