Simulation on the impacts of tree canopy morphology on thermal comfort at the pedestrian level

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Abstract. To explore the role of tree canopy morphology on the urban thermal environment and human comfort, this paper considers the variation of four factors (Top Canopy Height (TCH), Leaf Area Density (LAD), Bottom Canopy Height (BCH) and Canopy Diameter (CD)) and uses an orthogonal experiment method (OEM) to build 25 simulation scenarios. In an idealized model planted with trees, the effects of changes in canopy morphological parameters on air temperature and Physical Equivalent Temperature (PET) at a pedestrian height of 1.5m are simulated and discussed using ENVI-met software. The results show that the air temperatures for 25 different groups differed significantly during the day and less at night. At the hottest time of the day (15:00), there was a difference of 7.8°C between the coolest (ID 11) and hottest (ID 16) groups. TCH, LAD and CD are all negatively correlated with PET, while the BCH is positively correlated with PET. Among the four canopy morphology parameters, CD has the most significant effect on PET at a pedestrian level of 1.5m.

1. Introduction

The endless expansion of cities leads to frequent heat island effects, which in turn increase the incidence of heat stress. It can lead to a life-threatening complication known as heatstroke, which is fatal in up to 80% of cases [1]. In this regard, relevant studies have found that plant communities have a significant cooling benefit on the overall urban environment [2]. In urban park spaces, trees are the greening structural system with the most significant impact on thermal comfort [3].

Numerous studies have confirmed that during the hot summer months, tall trees could effectively reduce air temperature [4] and improve thermal comfort in the shaded area and the surrounding environment [5]. However, most of the current studies focused on the single factor discussion of the relationship between tree canopy morphology and thermal comfort, and few systematic and comprehensive quantitative assessments have been conducted.

The main research purpose of this paper is as follows: 1) to determine the superior and inferior combinations of canopy parameters for their effects on air temperature and thermal comfort, 2) to explore the impact of different canopy parameters variations on air temperature and PET, 3) to establish an optimized prediction formula for the pedestrian thermal comfort. The study can provide quantitative strategies for landscape design and creating a livable and pleasant urban habitat.
2. Methodology

2.1. Research site and scenarios of simulation

The study was carried out in a square idealized settlement model with a side length of 100m (see Figure 1), with a road width of 5m, building heights all at 20m and four small square green areas with a side length of 27.5m in the centre of the site. By planting trees with different canopy morphological in the green area, the effect of individual canopy morphological parameter variations and combinations on the thermal comfort of pedestrians at horizontal height (1.5m) was discussed.

The OEM was used to set up the simulation scenarios, due to the efficiency of simulations could be increasingly promoted to a great extent by decreasing the number of experiments [6]. The SPSS software was used to generate orthogonal experimental tables based on four canopy morphological parameters and five-level. The four items of the Simulation scenario settings were divided into five groups: TCH (6m, 8m, 10m, 12m, 14m), LAD (0.2, 0.6, 1, 1.4, 1.8), BCH (1m, 2m, 3m, 4m, 5m) and CD (5m, 7m, 9m, 11m, 13m). Then, simulation scenarios were created in the ENVI-met software and the results of each scenario were analysed for polar difference, variance, and regression.

2.2. Introduction and parameter setting of the ENVI-met simulation software

ENVI-met 4.4.2 developed by Bruce was chosen for this simulation, which allows for the setting of plant canopy morphology in the Albero module. Many scholars have demonstrated its reliability in simulating cooling effects and thermal comfort [7]. Simulations were carried out for 24h continuously (start form 0:00:00) for several scenario groups using 21 July 2019 as a typical day. The meteorological parameters were set with reference to the Code of Design for Heating, Ventilation and Air Conditioning in Civil Buildings GB50736-2012 [8], and the most frequent summer wind direction from meteorological data in Xi'an was used as the simulated wind direction.

2.3 Selection of thermal comfort evaluation indicators (PET) and settings of the human body parameter

The physiological equivalent temperature (PET) is an indicator developed based on the Munich Energy-balance Model for Individuals. The PET indicator applies to year-round climatic conditions and it’s more accurate in outdoor environments because its calculation involves all relevant effects of heat flow, actual body temperature, and perspiration rate [9].

The previous version of ENVI-met was validated in Freiburg, Germany, to effectively predict the thermal comfort index PET in spring and summer [10]. In this paper, PET is simulated at a horizontal height of 1.5m (The personal human parameters is a 35-year-old man with a height of 1.75 meters and a weight of 75 kilograms, the total metabolic rate is 164.45 and static clothing insulation is 0.90) and obtained from the Biomet tool of the ENVI-met, whose core is the Rayman model.
3. Results

3.1. Effect of different combinations of tree canopy forms on air temperature and PET

As shown in Figure 2, the PET comparisons for different combinations of groups at the highest air temperature moment of the day (15:00). In this study, the range of thermal sensations at the PET scale is shown in Table 4. Specifically, ID 11 was the coolest group, with a PET of 40.62°C. ID 16 was the hottest, with a PET of 48.42°C. The difference between the two groups was 7.8°C. The PET for ID 16 was the highest of all groups, in the "very hot" range, while the PET for ID 11 is in the "hot" range. When the group is changed from ID 16 to ID 11, the thermal sensation is changed from "very hot" to "hot", which is one level lower (‘very hot’ is PET > 41°C and ‘hot’ is 35°C < PET ≤ 41°C).

![Figure 2. Differences in PET under different combinations of canopy parameters (15:00)](image)

3.2. Analysis of orthogonal test

As shown in Table 1. Analysis of variance, ANOVA and regression analysis will be conducted to investigate the effect of tree canopy morphological indicators on PET, respectively.

| Test ID | TCH (m) | LAD (m) | BCH (m) | CD (m) | PET (15:00) |
|---------|---------|---------|---------|--------|-------------|
| 1       | 8       | 0.6     | 4       | 7      | 47.56       |
| 2       | 14      | 0.2     | 2       | 7      | 47.36       |
| 3       | 12      | 0.2     | 3       | 9      | 46.81       |
| 4       | 6       | 0.6     | 5       | 9      | 48.22       |
| 5       | 10      | 0.2     | 4       | 11     | 47.12       |
| 6       | 8       | 1       | 3       | 11     | 44.42       |
| 7       | 12      | 0.6     | 2       | 13     | 42.36       |
| 8       | 14      | 0.6     | 1       | 11     | 42.24       |
| 9       | 14      | 1.4     | 4       | 9      | 43.45       |
| 10      | 12      | 1.4     | 5       | 11     | 43.04       |
| 11      | 10      | 1.4     | 1       | 13     | 40.62       |
| 12      | 8       | 1.4     | 2       | 5      | 47.34       |
| 13      | 8       | 0.2     | 5       | 13     | 47.84       |

| Test ID | TCH (m) | LAD (m) | BCH (m) | CD (m) | PET (15:00) |
|---------|---------|---------|---------|--------|-------------|
| 14      | 12      | 1       | 1       | 7      | 45.17       |
| 15      | 6       | 1       | 4       | 13     | 45.69       |
| 16      | 6       | 0.2     | 1       | 5      | 48.42       |
| 17      | 10      | 0.6     | 3       | 5      | 47.65       |
| 18      | 14      | 1.8     | 3       | 13     | 40.74       |
| 19      | 6       | 1.4     | 3       | 7      | 47.16       |
| 20      | 10      | 1.8     | 5       | 7      | 46.23       |
| 21      | 8       | 1.8     | 1       | 9      | 43.61       |
| 22      | 12      | 1.8     | 4       | 5      | 46.69       |
| 23      | 14      | 1       | 5       | 5      | 46.89       |
| 24      | 6       | 1.8     | 2       | 11     | 44.14       |
| 25      | 10      | 1       | 2       | 9      | 44.32       |
3.2.1. Analysis of extreme differences

![Figure 3](image)

Figure 3. Factor level trend analysis for PET

As shown in Figure 3, TCH (A), LAD (B) and CD (D) are all negatively correlated with PET, and only BCH (C) is positively correlated with PET. Among the four factors, CD (D) had the most significant effect on PET. When the TCH increased from 6m to 14m, the PET decreased by 2.55°C. This probably because the higher the TCH, the greater the obstruction to air flow, resulting in an increase in local wind speed, which can cause a decrease in PET. When the LAD increased from 0.2 to 1.8, the PET decreased by 3.25°C. With increasing of the LAD, the absorption of solar radiation absorption by the trees increased, thus providing a cooling effect on the space under the trees. The PET decreases by 3.95°C as the CD increases from 5m to 13m. This is probably because the larger the CD, the more the canopy shades the direct solar radiation, resulting in less solar radiation at pedestrian height and lower PET values. Besides, as the BCH increases, at pedestrian height the tree absorbs less diffuse light from the sky and surroundings, resulting in higher air temperatures and lower thermal comfort.

3.2.2. Analysis of Variance

As can be seen from F in Table 2 (confidence level $\alpha = 0.05$), for PET at pedestrian level, the magnitude of each influencing factor is: $D > B > A > C$. The results in the table show that the four canopy morphological parameters, TCH, LAD, BCH and CD, all had a significant effect on PET.

| Factors  | Deviation | Degree of freedom (DF) | Mean Square (MS) | F | Significance (Sig.) |
|----------|-----------|------------------------|-----------------|---|---------------------|
| TCH (A)  | 21.564    | 4                      | 5.391           | 9.99 | 0.003               |
| LAD (B)  | 34.584    | 4                      | 8.464           | 16.022 | 0.001              |
| BCH (C)  | 17.994    | 4                      | 4.498           | 8.336 | 0.006               |
| CD (D)   | 54.736    | 4                      | 13.684          | 25.358 | 0.000              |
| Error    | 4.317     | 8                      | 0.54            |     |                     |

3.2.3. Regression analysis

To specifically quantify the extent to which individual canopy morphological parameters contribute to the comfort indicator PET, regression analysis was carried out on the simulation results for each scenario to obtain the following expressions.

$$PET = 53.520 - 0.326 X_A - 1.935 X_B + 0.586 X_C - 0.52 X_D$$

(1)

In equation (1), $X_A$——Top Canopy Height of the tree  
$X_B$——Leaf Area Density  
$X_C$——Bottom Canopy Height of the tree  
$X_D$——Canopy Diameter of the tree
The regression curve has $R^2=0.919$, a high linear correlation between the factors and PET can be found. Based on the regression equation it can be seen that within the parameters explored in this paper, if PET needs to be reduced in summer, measures such as increasing the TCH planting higher LAD tree types and increasing the CD and reducing the BCH could be taken.

4. Conclusion
In this paper, numerical simulations were carried out using the ENVI-met to investigate the impacts of canopy morphology on human thermal comfort. The OEM used to create 25 idealized scenarios. The main conclusions can be drawn as follows.

1) At 15:00, the highest air temperature of the day, ID 11 has a PET of 40.62°C (the coolest), while ID 16 has a PET of 48.42°C (the hottest), with a difference of 7.8°C between the two groups.
2) TCH, LAD and CD are all negatively correlated with PET, while BCH is positively correlated with PET, the CD having the most significant impact on PET at 1.5m pedestrian level.
3) All four canopy morphological parameters have a significant effect on PET at pedestrian level, and the effects were in descending order: CD > LAD > TCH > BCH.
4) Regression equations indicate that measures such as increasing the TCH, using higher LAD species and increasing the CD and reducing the BCH can optimise the thermal comfort for pedestrians.

Acknowledgement
The authors would like to thank Professor Wei Feng for his guidance on this paper and Professor Dian Zhou for the use of the ENVI-met software.

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