

Theoretical and Experimental Study of Foliage Heat Transfer Model and its Application in Urban Outdoor Environment

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ABSTRACT: Foliage can significantly improve the outdoor thermal comfort in residential communities. However, quantitative study on the cooling effect of foliage on outdoor environment is still insufficient so far. In this paper, a comprehensive foliage heat transfer model was developed. Meanwhile, field measurements were conducted in Jiading Campus, Tongji University, Shanghai, China to verify the model. The calculated foliage surface temperature and soil temperature showed good agreement with the measured data. When using the transient foliage heat transfer model on two consecutive summer days in Shanghai, it was found that the foliage surface temperature was greatly impacted by the solar radiation intensity and evapotranspiration. The calculated average foliage surface temperature was 1.8 °C lower than the air temperature and 5.9 °C lower than bare ground temperature. Finally, the foliage sub-model was integrated with CFD simulation to study the outdoor thermal environment of Jiading Campus, Tongji University. It showed good agreement with the experimental results. The foliage exhibited important effects on ameliorating outdoor thermal environment and mitigating urban heat island.

KEYWORDS: foliage heat transfer model; urban heat island effect; outdoor thermal environment; coupled CFD simulation

1 INTRODUCTION

With the acceleration of urbanization, the urban heat island (UHI)(Oke T 1987)phenomenon has become considerably worse, which directly affects human outdoor thermal safety and thermal comfort. UHI is caused by the replacement of natural, vegetated landscapes with impervious infrastructures as well as large quantities of waste heat from anthropogenic activities. The heat island phenomenon in densely built urban residential communities was extensively investigated by many scholars in different locations. In order to improve community microclimate, many kinds of relief means (Giridharan R et al. 2007) such as greening, high albedo paints and permeable pavement have been investigated. Other studies focused on urban planning, architecture design and environment engineering to ameliorate microclimate (Stewart ID et al. 2012). Hong Chen (2009) developed a coupled simulation scheme to study the effect of different mitigation measures on different urban blocks in Tokyo and results showed that the effectiveness of moderation countermeasures differed according to the configuration of the urban blocks. Feng Yang (2010,2011,2013) conducted UHI-site-measurement in 12 residential communities in Shanghai and

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2.2 Model Validation

To validate the foliage heat balance model, site measurement was carried out on June 7th, 2014 in Jiading Campus, Tongji University, Shanghai, China. The measured typical foliage is a large lawn and its σ_f is defined as 0.5 in calculation. The testing day and three days before are all sunshine thus the influence of the rainfall could be ignored. The parameters such as air temperature, relative humidity, wind velocity, solar radiation intensity and foliage surface temperature are recorded by home-made micro weather station, which is shown in Figure 2. The recorded outdoor meteorological parameters were listed in Table 1.



Figure 2. Home-made micro weather station diagram

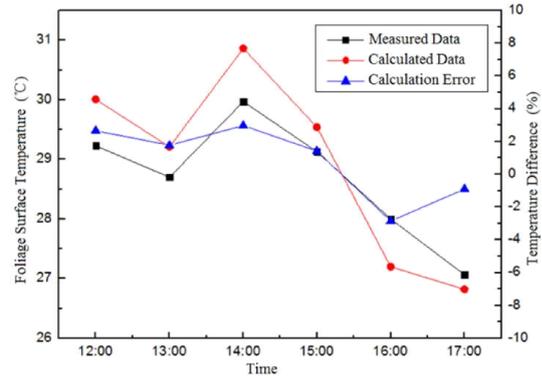


Figure 3. Contrast analysis of the measured and calculated foliage surface temperature

Table 1. Recorded outdoor meteorological parameter

Time	Relative humidity %	Wind velocity m/s	Air temperature °C	Direct solar radiation W/m ²	Diffuse radiation W/m ²	Foliage surface temperature °C
12:00	50.04	1.38	30.69	401.71	250.93	29.23
13:00	56.21	1.14	30.16	452.87	163.03	28.70
14:00	45.64	0.98	32.11	494.67	154.61	29.97
15:00	62.65	0.95	31.70	346.10	108.18	29.13
16:00	54.16	0.84	29.73	241.30	84.20	28.00
17:00	55.71	0.91	29.71	201.90	42.66	27.07

On the basis of the measured parameters, theoretical foliage surface temperature can be calculated using Equation 11, and the contrast analysis was shown in Figure 3. The absolute errors between calculated and measured data at different time nodes are less than 1.0 °C, and the mean absolute error is 0.6 °C; relative errors at different time nodes are less than $\pm 3.0\%$ and the mean relative error is 2.1%. Comprehensively considering the effect of measurement equipments' precision and the reading error, the theoretical calculated results can be thought accurate.

2.3 Theoretical Analysis

Theoretical analysis of foliage's cooling effect on ameliorating outdoor thermal environment and mitigating urban heat island is conducted through the transient heat

balance model. Artificial grass was chosen as the research object, and two consecutive summer days (48 h) in Shanghai were selected for calculation. Local meteorological parameters such as the hourly solar direct radiation, diffuse radiation and air relative humidity parameters were shown in Figure 4. Special weather conditions like rainy days, cloudy days, etc. were not taken into account. The calculated hourly foliage surface temperature and soil temperature were listed in Figure 5.

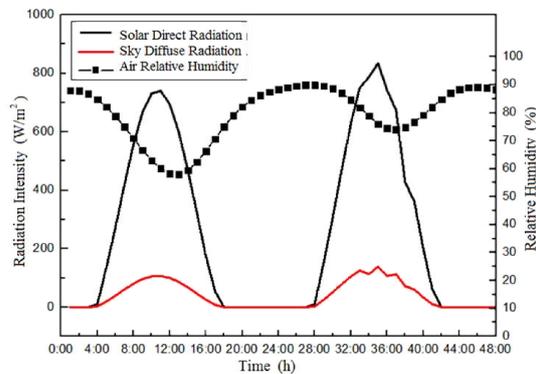


Figure 4. Local meteorological parameters of two consecutive summer days in Shanghai

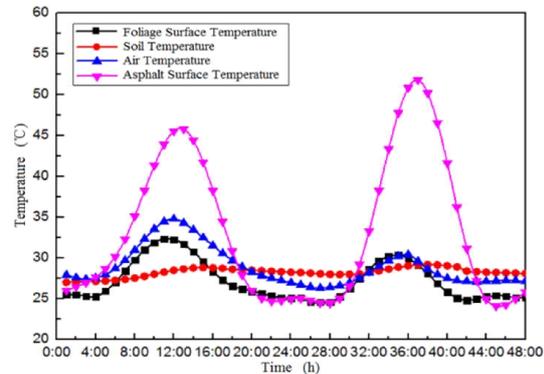


Figure 5. Hourly temperature of different underlying surface

From Figure 5, it can be found that foliage surface temperature was lower than local air temperature at most time. Hourly temperature difference between foliage surface and local air changes along with the hourly solar radiation intensity and air parameters. The average temperature difference was 1.8 °C. The maximum air temperature of 34.8 °C was reached at 12h. At the same time, foliage surface temperature was 32.2 °C, which was 2.6 °C lower than local air. It was shown that vegetation can greatly ameliorate outdoor thermal environment at the worst weather condition. At night, on account of the absence of solar radiation, foliage surface temperature was further reduced due to the outgoing long-wave radiation. In this research, foliage layer was taken as a porous medium and its thermal inertia was small which consequently leads foliage surface temperature to change synchronously with air temperature. It can be observed from Figure 5 that at some time like 31h, foliage surface temperature was higher than air temperature. This is because the higher air relative humidity weakens the foliage evapotranspiration. When compared with asphalt surface temperature, foliage's cooling effect became more apparent. At 37h, the asphalt surface temperature was as high as 51.8 °C and the foliage surface temperature was just 29.6 °C. The temperature difference reached 22.2 °C. In the whole 2 days (48h), the average foliage surface temperature was 1.8 °C lower than air temperature and 5.9 °C lower than bare asphalt ground temperature. According to the temperature of the two different types of underlying surfaces, the thermal comfort at pedestrians' height of foliage surface can be predicted to be far better than that of the bare asphalt ground. The 12h was taken as an example to analyze the foliage surface heat budget, and details can be seen in Table 2. Direct solar radiation was the main heat gain item, accounting for 58.96% of the total heat gain; vegetation evapotranspiration was the main cooling item, accounting for 62.08% of the total heat dissipation. Foliage surface

temperature was greatly affected by solar radiation intensity and evapotranspiration, and strong evapotranspiration play a key role in reducing surface temperature. From the above, evergreen broad-leaved vegetation is recommended to improve outdoor thermal environment because under the same radiant heat gain, broad-leaved plants' transpiration is stronger than that of coniferous plants, thus its surface temperature will be lower and accordingly the thermal comfort at pedestrian's height is improved.

Table 2. *The foliage surface heat budget of 12h*

Heat gain	Heat exchange capacity(W/m ²)	Percentage (%)	Heat dissipation	Heat exchange capacity(W/m ²)	Percentage (%)
Direct solar radiation	260.26	58.96	Long-wave radiation	167.41	37.92
Diffuse radiation	37.67	8.53			
Convection heat transfer	143.08	32.41	Evapotranspiration	273.99	62.08
Heat storage capacity	0.37	0.08			

3 NUMERICAL SIMULATION

3.1 Simulation Scheme

Based on the theoretical foliage heat transfer model, a CFD tool for predicting the outdoor thermal environment using a coupled simulation method of convection, radiation, conduction and foliage sub-model was developed. The simulation scheme was shown in Figure 6. Firstly assuming that the entire underlying surface is asphalt ground, solving the temperature distribution in the flow field. Secondly using the air parameters above the foliage surface together with theoretical foliage heat transfer model to calculate the foliage surface temperature under certain conditions. Thirdly changing boundary conditions for more iterative calculations until the residual of two foliage surface temperatures fall within the acceptable range. With the accurately calculated foliage surface temperature, the temperature distribution within a community can be calculated more precisely. This numerical simulation was performed on the experiment target—the dormitory area in Jiading Campus of Tongji University.

3.2 Comparison between Simulation and Experimental Results

Five characteristic points, which was shown in Figure 7, were chosen to contrast the measured data and simulated results and the details were listed in Table 3. P1 represents the upstream flow meteorological parameters; P2, P5 are on behalf of the hard underlying surface and P3, P4 represent the air parameters 1.5m high above the foliage surface. Analysis showed that the absolute error was controlled within ± 2 °C and relative error within 5%, thus the modeling results can be thought to be reasonable. According to the simulation results, when the height was greater than 5m, the location and properties of the underlying surface nearly have no impact on air temperature. The vertical temperature distribution of 0-1.5m was further studied, as can be seen in Figure 8. It was obvious that foliage can significantly decrease air temperature at pedestrians' height and improve outdoor thermal comfort. Thus, within different communities, trees are recommended to be scientifically and rationally

planted as more as possible to improve outdoor physical environment.

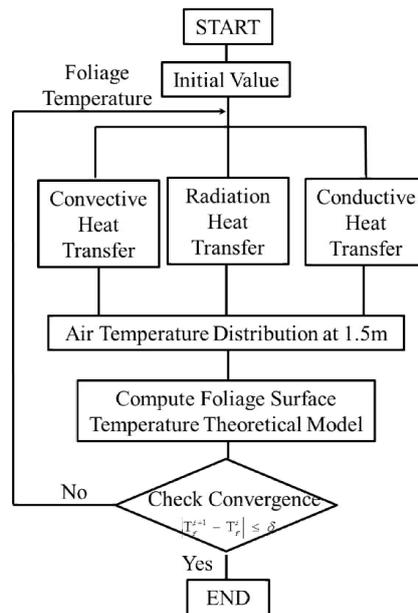


Figure 6. Flowchart for predicting outdoor thermal environment

Table 3. Analysis of the measured data and simulated results at 1.5m

	Measured air temperature(°C)	Simulated air temperature(°C)	Absolute error (°C)	Relative error (%)
Point 1	35.27	35.03	-0.24	-0.68
Point 2	32.76	34.11	1.35	4.12
Point 3	34.01	34.05	0.04	0.12
Point 4	33.59	34.50	0.91	2.71
Point 5	33.59	34.61	1.02	3.02

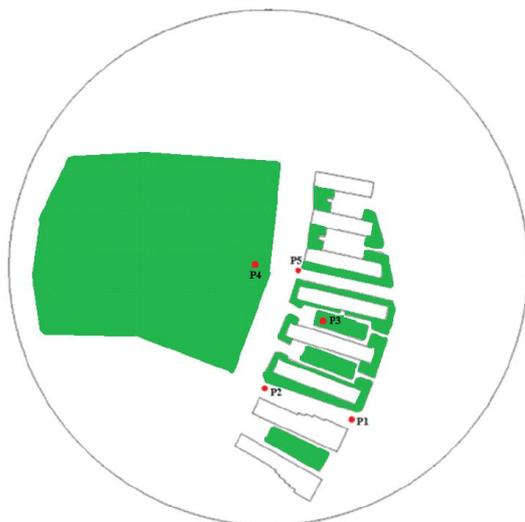


Figure 7. Diagram of numerical model and arrangement of the measuring point

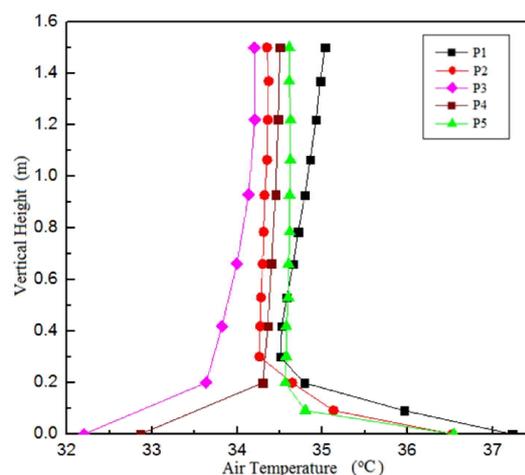


Figure 8. Vertical temperature distribution of characteristic points at the height of 0-1.5m

4 CONCLUSIONS AND LIMITATIONS

This paper developed a foliage heat transfer model and integrated it into CFD simulation. Field measurements were carried out in Jiading Campus, Tongji University, Shanghai, China and the measured data were compared against the simulated results to validate the theoretical model and the coupled CFD simulation scheme. The simulation results indicated that foliage surface temperature was greatly influenced by local radiation intensity and evapotranspiration. Calculation on 2 consecutive days in Shanghai showed that the average foliage surface temperature was 1.8 °C lower than air temperature and 5.9 °C lower than bare asphalt ground temperature. The foliage sub-model coupled with CFD simulation demonstrated that foliage plays an important role in mitigating urban heat island. Based on the coupled simulation method developed in this paper, further numerical studies will be conducted focusing on the temperature distribution and thermal comfort evaluation on pedestrians' height in the future.

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