Numerical analysis the effect of trees on the outdoor thermal environment and the building energy consumption in a residential neighborhood

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Abstract. Urban greening is an effective measure to reduce the cooling load of buildings. In this paper, the cycle coupling simulation strategy of PHOENICS numerical simulation software and EnergyPlus energy consumption prediction software is established, the outdoor temperature and humidity of typical meteorological month are predicted by multiple regression method. The impact of tree characteristics and foundation layout on the thermal environment of the community is analyzed, and the impact of the building cooling load index and residential energy consumption in the neighborhood is evaluated. The results showed that the canopy height increased by 2 m, the temperature decreased by 0.5%, the wind speed decreased by 5.5%, the relative humidity increased by 1%; the leaf area index (LAI) increased by 1, the temperature decreased by 0.4%, 10%, 0.7%. The order of influence on building energy consumption is: layout > crown height > LAI.

1. Introduction
With the rapid development of the city, urban thermal environment and the corresponding building energy use have been attracted great attention [1-3]. The arrangement and structural diversity of buildings in the city change the local climate into different urban microclimates, because the change of building layout in the urban environment is extremely limited, only by changing the factors easy to adjust in the city to improve the regional thermal environment and building energy consumption. Properly increasing the greening area can not only improve the microclimate thermal environment, but also effectively alleviate the UHI effect and reduce the building energy consumption[4, 5].

Trees affects the airflow in the building complex by blocking and inducing the airflow. The leaves absorb and reflect the solar radiation for photosynthesis and change the ambient temperature. Kong et al. [6] conducted a study on the effect of trees on urban microclimate environment in open space, and measured the impact of different trees on water transpiration rate and cooling. Endalew et al. [7] proved that the detailed modeling is similar to the calculation result of simplifying trees to porous media. Buccolieri et al. [8] studied the relationship between tree and urban air quality and thermal environment, and utilized the optimized simulation equations using momentum source/sink term, turbulent kinetic energy. Currently, the coupling calculation of thermal environment and energy consumption is very helpful for the accurate analysis of the boundary setup of microclimate simulation and energy consumption, but the existing coupling research is less and the software used is limited, so it cannot achieve more accurate and long time scale prediction, so simplifying the calculation model and ensuring the accuracy of calculation has become the focus of the existing studies.
Greening has a great impact on building energy consumption, but most of the current research focuses on the effect of the whole greening on the thermal environment and building energy consumption, and the research on the individual effect of shading and transpiration characteristics of a single greening way (such as trees) is quite limited. Therefore, according to different tree characteristics and basic layout, this paper uses the cycle coupling strategy of PHOENICS and EnergyPlus to predict the thermal environment parameters of the residential area through multiple regression method, and analyzes its impact on the building cooling load index, infiltration effect and building energy consumption of typical meteorological month.

2. Methods

2.1 The theoretical model of PHOENICS

The effect of vegetation on the flow of gas in the regional thermal environment is very important in CFD simulation. In this paper, the Reynolds-averaged Navier-Stokes (RANS) equation and the realizable turbulence closure model are used to simulate the flow of wet air in and around vegetation. The process of turbulence and dissipation in the environment is usually parameterized as turbulent kinetic energy \((k)\) and turbulent dissipation rate \((\varepsilon)\). The additional source terms are as follows:

\[
\begin{align*}
    s_k &= \rho L A IC_4 \left( \beta_p U^3 - \beta_d U k \right) \\
    s_\varepsilon &= \rho L A IC_4 \left( C_{44} \beta_p U^3 - C_{55} \beta_d U \varepsilon \right)
\end{align*}
\]

where \(\beta_p\) is the fraction of mean kinetic energy converted into turbulent kinetic energy by means of drag and takes a value between 0 and 1; \(\beta_d\) is the dimensionless coefficient for the short-circuiting of the turbulence cascade; \(C_{44}\) and \(C_{55}\) are model constants.

When the air flow passes through the vegetation, it is mainly cooled by transpiration on the surface of the leaves. The heat \(H\) \((J)\) required for the change of the object temperature can be calculated according to the following formula:

\[
H' = \frac{P_c}{V} m' \Delta T \frac{1}{V} \Leftrightarrow \Delta T = \frac{P_c}{V} \frac{1}{m' c_p}
\]

where \(H'(W)\) being the heat transfer rate and \(m'(kg/s)\) the mass flow rate. \(\Delta T\) is directly proportional to \(P_c\) and \(V\), and inversely proportional to \(c_p\) and \(m'\).

2.2 The theoretical model of EnergyPlus

The influence of thermal environment on building energy consumption is mainly realized by influencing the heat balance of building envelope and air heat balance. The former one is reflected in the convective heat transfer coefficient on the outer surface of the building, while the latter one is reflected in the influence of air infiltration wind. In order to simplify the calculation of energy consumption, a multi-split air conditioning unit is adopted. TARP convective heat transfer model is used. For forced convection, it is mainly related to the local wind speed, roughness factor of the building surface and perimeter of the building surface.

2.3 Coupling simulation method of CFD and BES

Building energy simulation (BES) is coupled with CFD. On the one hand, BES verifies the dynamic boundary conditions of CFD. On the other hand, CFD provides local air flow information for BES to study building load and improves the accuracy of heat load. The coupling process simulated in this paper is shown in Figure 1, and the loop part in the coupling process is shown in Figure 2. The specific steps are as follows:

The first step is to import EnergyPlus weather file (epw file) into the energy consumption model for simulation. In the second step, the surface temperature of energy consumption simulation is extracted and brought into PHOENICS for simulation. In the third step, the temperature, relative humidity and wind speed in the numerical simulation are replaced by the original temperature,
humidity and wind speed in the EnergyPlus Weather File, and the new meteorological file is imported into the energy consumption model for simulation. The fourth step extracts the building surface temperature simulated by energy consumption, and compares it with the last building surface temperature to ensure the error is less than 10%, otherwise repeat the second and third steps.

2.4 Simulation setup

In the PHOENICS, the actual size of the total calculation area is 1300m×1245m×270m (L×W×H) (5H in the windward direction, 15H in the leeward direction and 5H in the top direction). It consists of a 220m×165m×54m internal area composed of nine buildings with 15 floors each. There are totally 3837600 grids. The central building is the target building. In the EnergyPlus simulation, the central building is set in detail, and the surrounding buildings play a role of shielding. The central building area is about 48600 m², 15 floors in total, six households on one floor. The distance between the east and the west is about 20m, and the distance between the north and the south is about 60m.

In the energy consumption model, the window-wall ratio of the building is set as 30%, the population is set as two people in the bedroom, three people in the living room and one person in other rooms, the lighting load is 5W/m², and the equipment load is 3.8W/m². The variable refrigerant volume system is used as the indoor air conditioning system with the temperature setup of 26°C.

In the numerical model, trees are set using the Foliage object type and User Defined Source. In this paper, the height of the trees crown are 8m, 10m and 12m, respectively, and the center of the tree is 6m away from the wall. Leaf area indexes (LAI) are set to 1, 2, and 3. According to the difference between plant spacing L and row spacing W, the layout of tree foundation between buildings is shown in Table 1. The simulated conditions in this paper are shown in Table 2.

Table 1. Cases of different plant spacing L and row spacing W

| Simulated cases | A1     | A2     | A3     |
|----------------|--------|--------|--------|

Figure 1. Flow chart of coupling simulation
Figure 2. Coupling simulation cycle

Figure 3. Grid distribution in x-axis and y-axis
Figure 4. A neighborhood EnergyPlus model
3. Simulation results of thermal environment in residential area

According to Chinese assessment standard for green building, the time period of 08:00-18:00 is an important index of thermal environment assessment. This paper selects this time period for analysis. The temperature distribution contour at the center height of the tree crown (z=7.5m) is taken as the simulation result for discussion.

| Simulation cases | Crown height (m) | LAI (m²/m²) | Green layout |
|------------------|------------------|-------------|--------------|
| 1                | 8                | 1           | A2           |
| 2                | 10               | 1           | A2           |
| 3                | 12               | 1           | A2           |
| 4                | 12               | 1           | A1           |
| 5                | 12               | 1           | A2           |
| 6                | 12               | 1           | A3           |
| 7                | 12               | 1           | A1           |
| 8                | 12               | 2           | A1           |
| 9                | 12               | 3           | A1           |

3.1 Crown height

In the whole period of time, the rule of temperature change is basically the same. The canopy height is set at 8m, 10m and 12m, and the average air temperature is 29.22°C, 29.07°C and 28.94°C. In other words, the temperature decreases about 0.5% with the increase of the canopy height by 2m. It can be seen that with the increase of canopy height, the air temperature gradually decreases, which means that with the increase of canopy height, the transpiration and sunshade effect of trees are strengthened, and the air temperature around trees is reduced as shown in Figure 5(a). The wind speed is as shown in Figure 5(b). The average wind speed is 0.79m/s, 0.74m/s and 0.70m/s, respectively. That is to say, the wind speed decreases by about 5.5% for every 2m increase in tree crown height. It can be seen that canopy height has a great influence on wind speed. As shown in Figure 5(c), the average relative humidity is 70.74%, 71.44% and 72.22% respectively, that is to say, the temperature will decrease by about 1% for every 2m increase in the crown height. The change is obvious from 11:00 to 13:00, which may be due to the rapid change of air temperature and the increase of wind speed in this period. As a result, the local air temperature is reduced, and the soil model is set to be dehumidified in the early stage of modeling. The long-time irradiation in the morning makes the water vapor evaporate into the air, which comprehensively affects the change of relative humidity.
3.2 Green layout
During the daytime, the maximum temperature appears at about 15:00, as shown in Figure 6(a).
It can be seen from the figure that the cooling effect of A1 and A2 is slightly better than that of A3.
As a whole, the cooling effect of A2 is the best. The average values of air temperature in the three layouts were 29.28°C, 29.05°C and 29.47°C. In other words, A2 is about 0.8% lower than A1, and A2 is about 1.5% lower than A3. There is a certain reduction effect on the wind speed under the three layouts, among which A3, A1 and A2 have different wind speed change rules, so A3 can be considered to "pile up" distribution around the building, so the overall impact on the wind speed is poor. The average wind speed of the three layouts is 0.74m/s, 0.70m/s and 0.79m/s respectively. That is, A2 is about 5.4% lower than A1, and A2 is about 12% lower than A3, as shown in Figure 6(b). The average relative humidity is 71.47%, 72.2% and 70.14% respectively, that is, A2 is about 1.0% higher than A1, and A2 is about 2.8% higher than A3, as shown in Figure 6(c).

3.3 LAI
Figure 7(a) shows the comparison of temperature values of different LAI. It can be seen from the figure that as LAI increases, the air temperature around the target building decreases continuously. The daily average temperature difference of the three working conditions is 29.28°C, 29.17°C and 29.04°C. Before 3 p.m., the temperature difference keeps increasing and then decreasing. When LAI increases by 1, the average air temperature around the target building increases by about 0.4%, and the growth rate is relatively uniform. The wind speed changes greatly around the target building, and even there will be no wind zone. The average wind speed of the three working conditions is 0.74m/s, 0.66m/s and 0.59m/s respectively, that is, when LAI increases by 1, the wind speed decreases by about 10%. The overall trend is shown in Figure 7(b). The average relative humidity of the three working conditions is 71.33%, 71.88% and 72.35% respectively, that is, when LAI increases by 1, the relative humidity increases by about 0.7%. The difference of relative humidity between 11:00 and 13:00 is large, which can be considered as the result of the large difference of air temperature, the high temperature of building surface and the reflection of solar radiation as shown in Figure 7(c).
Figure 7. The effect of different LAI on air temperature, wind speed, relative humidity.

Figure 8. Comparison of target building energy consumption in a typical weather day

Figure 9. Comparison of target building energy consumption in a typical weather month

4. Simulation results of target building energy consumption

This paper compares the differences of thermal environment in different working conditions, and finds that the characteristics of trees and the layout of foundations have influence on the temperature, relative humidity and wind speed around the target building. According to the coupling strategy between the thermal environment and energy consumption software, this paper analyzes the impact of different tree characteristics and foundation layout on the energy consumption of the target building.

4.1 Comparison of building energy consumption of different targets in a typical weather day

Figure 8 shows the comparison of residential energy consumption when different tree characteristics and layout are used. The total energy consumption of different tree characteristics and layout are compared with that of uncoupled working conditions (the original meteorological parameters are used for simulation). The total energy consumption of uncoupled condition is 761.78MJ, and the energy consumption of each condition after coupling is reduced by about 6.5%. Among them, the height of tree crown is 12m, and the energy consumption of layout mode A2 is reduced most, which is 8%. When the height of trees is between 8m-12m, and the characteristics and layout of other trees are kept unchanged, the height of trees is negatively related to the building energy consumption. The height of trees increases by 2m, and the energy consumption decreases by about 0.7%. When LAI is around 1 to 3, and the characteristics and layout of other trees are kept unchanged, the LAI is negatively related to the building energy consumption. The LAI increases by 1, and the energy consumption decreases by about 0.6%. In the condition of basic layout, layout A2 has the better effect on reducing energy consumption, and for residential buildings, greening layout has a greater impact on energy consumption, so the layout should be studied during the planning period.

4.2 Comparison of building energy consumption of different targets in a typical weather month

Figure 9 shows the comparison of typical meteorological monthly energy consumption. From the perspective of the whole typical month, the coupling condition has a greater impact on energy consumption. For the uncoupled condition, the building energy consumption is 38544.88MJ, which is about 4% lower than the average energy consumption after coupling. There is a negative correlation between canopy height and building energy consumption. When the canopy height is 10m, it is about
2% lower than that of 8m and 4% higher than that of 12m; when the LAI is 2, it is 1% lower than that of 1 and 2% higher than that of 3; when the tree layout is A2, the energy consumption is the lowest, which is 36974.25MJ, 4% lower than that of A1 and 6% lower than that of A3. To sum up, the layout has the greatest impact on building energy consumption, followed by tree crown height, and finally LAI.

5 Conclusions
Through the coupling strategy simulation, the influence of different tree characteristics and foundation layout on the thermal environment and building energy consumption of the residential neighborhood is analyzed, and the following conclusions are obtained: (1) The higher the canopy height and LAI, the lower the temperature and wind speed around the target building, and the higher the humidity. The canopy height increased by 2m, the temperature decreased by 0.5%, the wind speed decreased by 5.5%, and the relative humidity increased by 1%. When LAI increased by 1, the temperature decreased by about 0.4%. (2) In the layout of tree foundation, layout A2 has a great impact on the thermal environment. Among them, the average air temperature of A2 is about 0.8% lower than A1, and A2 is about 1.5% lower than A3; the average wind speed of A2 is about 5.4% lower than A1, and A2 is about 12% lower than A3; the average relative humidity of A2 is about 1.0% higher than A1, and A2 is about 2.8% higher than A3. (3) In a typical weather day, the height of tree crown increases by 2m, the building energy consumption decreases by 7.0%; LAI increases by 1, the energy consumption decreases by 0.6%. (4) In a typical weather month, the height of tree crown increased by 2m, the building energy consumption decreased by 3.5%; LAI increased by 1, the energy consumption decreased by 1.5%.

References
[1] Liu, J., Heidarinejad, M., Guo, M., et al. (2015) Numerical Evaluation of the Local Weather Data Impacts on Cooling Energy Use of Buildings in an Urban Area. Procedia Engineering, 121: 381-388.
[2] Zhang, L., Zhang, L., Jin, M., et al. (2017) Numerical Study of Outdoor Thermal Environment in a University Campus in Summer. Procedia Engineering, 205: 4052-4059.
[3] Zhang, L., Jin, M., Liu, J., et al. (2017) Simulated study on the potential of building energy saving using the green roof. Procedia Engineering, 205: 1469-1476.
[4] Li, J., Liu, J., Srebric, J., et al. (2019) The Effect of Tree-Planting Patterns on the Microclimate within a Courtyard. Sustainability, 11(6): 1665.
[5] Liu, J., Heidarinejad, M., Nikkho, S. K., et al. (2019) Quantifying Impacts of Urban Microclimate on a Building Energy Consumption—A Case Study. Sustainability, 11(18): 4921.
[6] Kong, L., Lau, K. K.-L., Yuan, C., et al. (2017) Regulation of outdoor thermal comfort by trees in Hong Kong. Sustainable Cities and Society, 31: 12-25.
[7] Endalew, A. M., Hertog, M., Delele, M. A., et al. (2009) CFD modelling and wind tunnel validation of airflow through plant canopies using 3D canopy architecture. International Journal of Heat and Fluid Flow, 30(2): 356-368.
[8] Buccolieri, R., Jeanjean, A. P. R., Gatto, E., et al. (2018) The impact of trees on street ventilation, NOx and PM2.5 concentrations across heights in Marylebone Rd street canyon, central London. Sustainable Cities and Society, 41: 227-241.