Preliminary Study on Influence of Outdoor Trees on Natural Ventilation of Teaching Buildings

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Abstract. The emphasis of this study lied in the impact of tree planting spacing around the teaching building on the indoor wind environment. CFD simulations of the indoor wind environment of teaching building affected by trees were performed utilizing the ANSYS Fluent software using the standard k-ε model with additional source terms. Deciduous broad-leaved trees and coniferous trees were selected as representative tree species for comparison. Five different tree planting spacings were arranged outside the teaching building, and the indoor airflow velocity distribution and pressure distribution were simulated. Then the effects of these different tree layout forms on the indoor ventilation efficiency of the building were compared and analyzed. The results showed that the sum of the total ventilation flow rate in the classrooms rose with the increase of the spacing between trees. However, due to the different location relationship between the tree canopy and the classrooms, the ventilation efficiency of each classroom showed differences. As for tree species, the blocking effect of tall deciduous broad-leaved trees on indoor ventilation was more obvious than that of coniferous trees. This study will have guiding significance for the layout design of vegetation around the building and creating a good indoor ventilation environment.

1 Introduction

Wind is a significant factor affecting the environmental comfort of urban blocks, which is correlated with the urban microclimate, air quality and heat island effect. The complex layout of urban buildings can cause safety hazards of gust or poor air quality in the urban area with low wind speeds. Vegetation is one of the most common ways to improve the outdoor physical environment. Reasonable vegetation layout can reduce heat island effect, improve local wind environment, reduce solar radiation and improve air quality [1,2]. In the last decades, there have been studies highlighting the effects of tree vegetation on air flow barriers and pollutant diffusion around buildings. Wind tunnel test and CFD simulation have been adopted as the main methods in relevant research. Compared with CFD simulation, the results of wind tunnel test in building wind field environment are more accurate, but this method is rarely used in past wind field research with trees. Gromke [3] built a wind tunnel model of urban street canyon with a row of trees in the middle, and used the tracer gas released at the bottom of the model to simulate urban traffic exhaust emissions, which investigated the impact of trees on natural ventilation and pollutant diffusion in street canyon. In more studies, computer simulation was used to calculate the turbulence of air flow in vegetation canopy. Bo Hong [4] simulated the wind environment and comfort of several different building layouts and surrounding trees. The results showed that the case with square enclosed by the building which the facing the wind has better wind environment comfort. Saša Kenjereš [5] tested different additional variables in the RANS turbulence model with vegetation, and applied the selected model to the actual campus scene. Significant progress has been made in the field of outdoor wind environment with trees around buildings, nevertheless there remains a lot of work need to be done for the impact of trees on natural ventilation in buildings. The objective of this study is to find out how the spatial layout of trees around the teaching building affects the outdoor flow field and indoor ventilation. With the help of the porous media model applied to the tree canopy, the teaching building and surrounding trees are modelled and simulated to compare the effects of different tree species and tree arrangement on the indoor natural ventilation and air quality of each classroom. The research results provide suggestions for the arrangement of trees around the teaching building to ensure the indoor air flow efficiency and fresh air inside the classroom, which is beneficial to the health of teachers and students who are often stay in the classrooms.

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2 Methodology

2.1 Governing equations

The standard k-ε model was used in this paper. The governing equations of standard k-ε which including energy, momentum, and mass are shown as follows:

For turbulent kinetic energy $k$

$$
\begin{align*}
\frac{\partial}{\partial t} \left( \frac{k}{\rho} \right) - \nabla \cdot \left( \rho \mathbf{u} \varepsilon \right) = -\nabla \cdot \left( \rho \mathbf{u} \frac{\partial k}{\partial t} \right) = \frac{1}{2} \left( \frac{\partial}{\partial x_j} \left( \nu \frac{\partial k}{\partial x_j} \right) - \frac{\partial}{\partial x_j} \left( \nu \frac{\partial k}{\partial x_j} \right) \right) + \left( \frac{\nu}{\kappa} \right) \left( \frac{\partial k}{\partial x_j} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1k} \varepsilon \left( \frac{\partial \mathbf{u}}{\partial x_j} \cdot \frac{\partial \mathbf{u}}{\partial x_j} \right) - C_{2k} \nu \frac{\partial \varepsilon}{\partial x_j} \frac{\partial k}{\partial x_j} \\
\end{align*}
$$

(1)

For dissipation $\varepsilon$

$$
\begin{align*}
\frac{\partial}{\partial t} \left( \frac{\varepsilon}{\rho} \right) - \nabla \cdot \left( \rho \mathbf{u} \varepsilon \right) = -\nabla \cdot \left( \rho \mathbf{u} \frac{\partial \varepsilon}{\partial t} \right) = \frac{1}{2} \left( \frac{\partial}{\partial x_j} \left( \nu \frac{\partial \varepsilon}{\partial x_j} \right) - \frac{\partial}{\partial x_j} \left( \nu \frac{\partial \varepsilon}{\partial x_j} \right) \right) + \left( \frac{\nu}{\kappa} \right) \left( \frac{\partial \varepsilon}{\partial x_j} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon^2}{k} \left( \frac{\partial \mathbf{u}}{\partial x_j} \cdot \frac{\partial \mathbf{u}}{\partial x_j} \right) - C_{2\varepsilon} \frac{\varepsilon^2}{k} \frac{\partial k}{\partial x_j} \\
\end{align*}
$$

(2)

Modelling turbulent viscosity

$$
\frac{\mu_t}{\rho} = \rho C_{\mu} \frac{k^2}{\varepsilon} 
$$

(3)

Model constants

$$
C_{1k} = 1.44, C_{2k} = 1.92, C_{k} = 0.09, C_{\varepsilon} = 1.0, C_{\varepsilon} = 1.3
$$

(4)

2.2 Source term of tree

The existence of trees in wind field could influence the velocity and turbulence of air flow. To account for this effect in CFD simulations, the canopy can be treated as a porous medium. Thus, the effect of vegetation on turbulence of air flow. To account for this effect in CFD simulations, the canopy can be treated as a porous medium. Thus, the effect of vegetation on the velocity and turbulent kinetic energy, momentum, and mass are shown as follows:

$$
\begin{align*}
\frac{\partial}{\partial t} \left( \frac{k}{\rho} \right) - \nabla \cdot \left( \rho \mathbf{u} \varepsilon \right) = -\nabla \cdot \left( \rho \mathbf{u} \frac{\partial k}{\partial t} \right) = \frac{1}{2} \left( \frac{\partial}{\partial x_j} \left( \nu \frac{\partial k}{\partial x_j} \right) - \frac{\partial}{\partial x_j} \left( \nu \frac{\partial k}{\partial x_j} \right) \right) + C_{1k} \varepsilon \left( \frac{\partial \mathbf{u}}{\partial x_j} \cdot \frac{\partial \mathbf{u}}{\partial x_j} \right) - C_{2k} \nu \frac{\partial \varepsilon}{\partial x_j} \frac{\partial k}{\partial x_j} \\
\end{align*}
$$

(5)

$$
\begin{align*}
\frac{\partial}{\partial t} \left( \frac{\varepsilon}{\rho} \right) - \nabla \cdot \left( \rho \mathbf{u} \varepsilon \right) = -\nabla \cdot \left( \rho \mathbf{u} \frac{\partial \varepsilon}{\partial t} \right) = \frac{1}{2} \left( \frac{\partial}{\partial x_j} \left( \nu \frac{\partial \varepsilon}{\partial x_j} \right) - \frac{\partial}{\partial x_j} \left( \nu \frac{\partial \varepsilon}{\partial x_j} \right) \right) + \left( \frac{\nu}{\kappa} \right) \left( \frac{\partial \varepsilon}{\partial x_j} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon^2}{k} \left( \frac{\partial \mathbf{u}}{\partial x_j} \cdot \frac{\partial \mathbf{u}}{\partial x_j} \right) - C_{2\varepsilon} \frac{\varepsilon^2}{k} \frac{\partial k}{\partial x_j} \\
\end{align*}
$$

(6)

$$
\begin{align*}
\frac{\partial}{\partial t} \left( \frac{\mu_t}{\rho} \right) - \nabla \cdot \left( \rho \mathbf{u} \frac{\mu_t}{\rho} \right) = -\nabla \cdot \left( \rho \mathbf{u} \frac{\mu_t}{\rho} \frac{\partial \mu_t}{\partial t} \right) = \frac{1}{2} \left( \frac{\partial}{\partial x_j} \left( \nu \frac{\partial \mu_t}{\partial x_j} \right) - \frac{\partial}{\partial x_j} \left( \nu \frac{\partial \mu_t}{\partial x_j} \right) \right) + \left( \frac{\nu}{\kappa} \right) \left( \frac{\partial \mu_t}{\partial x_j} \frac{\partial \mu_t}{\partial x_j} \right) + C_{1\mu} \frac{\mu_t^2}{k} \left( \frac{\partial \mathbf{u}}{\partial x_j} \cdot \frac{\partial \mathbf{u}}{\partial x_j} \right) - C_{2\mu} \frac{\mu_t^2}{k} \frac{\partial k}{\partial x_j} \\
\end{align*}
$$

(7)

In the above equation, $C_D$ is the drag coefficient; $a$ is the leaf area density (LAD). However, since the steady state simulations were applied, the time terms were equal to 0.

2.3 Model validation

The calculation model of the tree canopy was validated by the measured data around tree provided by the Architectural Institute of Japan. The measured data mainly related to the data of normalized wind speed and normalized turbulent kinetic energy about the pine tree in Kundao County, Japan. 28 measuring points were placed at 4 different heights and the distance of 0.2H, 0.5H, 1H, 2H, 3H, 4H and 5H (H=7m) from the leeward side of the tree. About the parameters of tree canopy, the drag coefficient $C_D$ was 0.8, and the LAD (leaf area index) was 1.17 m²/m². Fig.1 showed the comparison results between measurement data and CFD simulation [6].

2.4 CFD setting and list of cases

SIMPLE iterative method was used for the coupling of pressure and velocity. A termination criterion of $10^{-4}$ was used for all field variables. In this study, a wind simulation was performed on a teaching building with trees on the windward side, just as shown in the Fig.2 (a). The size of each classroom is 6m×9m×3.5m, and there are three external windows on one side of the external wall, and two front and rear doors and one high window on the side near the corridor. In the simulation of horizontal classrooms, the classrooms on the windward side were named R201, R203, R205, R207 and R209; and the leeward classrooms were named R200, R202, R204, R206 and R208. In order to better compare the influence of different trees on indoor ventilation of buildings, this study selected camphor trees and metasequoia trees as main cases, which are widely planted in school campuses in Nanjing, just as shown in the Fig.2 (b). The case without trees was defined as reference case, and the cases where camphor trees are planted with a spacing of 0m, 2m, 4m, 8m, 12m and 16m around the building were defined as CaseA1, CaseA2, CaseA3, CaseA4, CaseA5 and CaseA6. Similarly, the cases of planting metasequoia trees with different spacings around the building were defined as CaseB1, CaseB2, CaseB3, CaseB4, CaseB5 and CaseB6.

3 Results

3.1 The effect of deciduous broad-leaved trees on building indoor ventilation

Fig.3 and Fig.4 presented the contour graph and pressure graph of teaching building at the height of 1.5 m above building second floor with camphor trees at different intervals in the windward direction. The wind passed through the interspaces between the camphor trees, thus affecting the wind flowed into each classroom. The difference in ventilation is mainly reflected in the classrooms on the windward side of the building, for example, cases with larger spacing between trees (caseA4,
caseA5, caseA6, and Reference Case) had higher ventilation wind velocity and smaller quiet wind area in rooms R201 and R209, compared with cases with small spacing (caseA1, caseA2 and caseA3). In addition, different tree spacing affected the wind direction and velocity in rooms R202, R203, R204. The distribution of wind pressure was related to wind velocities and wind streamlines. It can be seen that the obstruction of camphor trees had a significant impact on the distribution of wind pressure. Due to the blocking effect of tall camphor trees, the average pressure decreased in the classroom on the windward side of caseA1 and caseA2. By contrast, in both cases, the average pressure in the middle classroom was the highest, and the average pressure of the two classrooms in the corner was the lowest. In caseA3, the average pressure of R203 and R207 classrooms had little difference, and was higher than that of R201 and R209 classrooms. The average pressure of R203 and R207 in caseA4, caseA5 and caseA6 increased with increasing distance between trees. Among them, trees in caseA4 and caseA5 had a great blocking effect on R201 and R209, but this blocking effect was reduced in caseA6. Therefore, in caseA4 and caseA5, R201 and R209 have the lowest average pressure, compared with the other three classrooms; however, in caseA6, the average pressure of R201 and R209 was similar to that of R205, but less than that of R203 and R207.

3.2 The effect of coniferous trees on building indoor ventilation

Fig.5 presented the contour graph of teaching building at the height of 1.5 m above building second floor with metasequoia trees. Because of the smaller cross section than camphor trees, metasequoia trees therefore have less wind resistance per tree, even though they have a larger leaf area density. For caseB1 with no spacing between trees, several obvious calm wind zones appeared in the five classrooms on the windward side. Unlike the situation of camphor trees, for caseB2, caseB3, caseB4, caseB5, and caseB6 with different tree spacing of metasequoia trees, the difference of indoor wind flow velocity and streamline distribution was small. As shown in Fig.6, metasequoia trees also had less influence on the indoor pressure of buildings compared with camphor trees. In all of these contrasting cases, the average pressure of the middle three classrooms (R203, R205 and R207) on the windward side of the building is larger than the average pressure of the classrooms at both ends of the building (R201 and R209). With the increase of the spacing between trees, the average pressure of the five classrooms on the windward side of caseB2, caseB3, caseB4, caseB5 and caseB6 increased correspondingly compared with that in caseB1. In fact, in the case of scattered tree arrangement, the average indoor pressure distribution of buildings in caseB4, caseB5 and caseB6 had been basically the same.

3.3 Ventilation flow rate

The ventilation efficiency of each room could be effectively revealed by the ventilation flow rate. As can be seen from Fig.7, for the reference case without trees acting as barriers, the indoor ventilation flow rate of the building was 42.23m^3/s. When trees are closely arranged without spacing, the ventilation flow rate of buildings under the influence of camphor trees was 31.11m^3/s; however, when metasequoia trees were planted around the building, the ventilation flow rate was 37.20m^3/s. It can be seen that the influence of camphor tree on indoor ventilation block of buildings was much greater than that of metasequoia. When the spacing between trees increased to 2m, 4m, 8m, 12m and 16m, the blocking effect of camphor tree decreased rapidly, and the indoor ventilation flow rate increased to 33.58m^3/s, 34.08m^3/s, 35.51m^3/s, 37.13m^3/s and 38.73m^3/s. However, metasequoia trees show much less resistance than camphor trees. Thus, when
metasequoia was arranged in accordance with the same spacings as the above, the change of ventilation flow rate of the building became to 39.54 m$^3$/s, 40.29 m$^3$/s, 41.16 m$^3$/s, 41.54 m$^3$/s, 41.46 m$^3$/s.

![Fig.7. Ventilation flow rate comparison of different tree species with different spacing](image)

### 4 Conclusions

The comparison of wind flow performance in the horizontal classrooms on the second floor showed that the effect of tree spacing on indoor air age and ventilation efficiency was more obvious when trees were densely planted. The wind speed distribution and air freshness of each classroom in the building changed based on the change of tree spacing. When the planting spacing of camphor trees was less than 8m, the air quality of the classrooms at both ends of the leeward side of the building was low, which was not conducive to indoor ventilation. In terms of tree species comparison, this change was more obvious in the cases with camphor trees, which implied that the blocking effect of tall camphor trees on building indoor ventilation was greater than that of Metasequoia trees.

### References

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