Effect of Tree Plantation Location and Crown Shape on Cross-Ventilation of a Generic Building – A CFD Study

Buddika J.W.G
Department of Civil Engineering, University of Moratuwa
Katubedda, Sri Lanka
jwgbuddika@gmail.com

Weerasuriya A.U.
Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology
Hong Kong
auw@connect.ust.hk

Lewangamage C. S.
Department of Civil Engineering, University of Moratuwa,
Katubedda, Sri Lanka
sujeewal@uom.lk

Zhang Xuelin
School of Atmospheric Sciences, Sun Yat-sen University, Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai),
Zhuhai, PR China
zhangxlin25@mail.sysu.edu.cn

***Abstract*— Natural ventilation creates comfortable and healthy indoor environments without consuming energy. However, maintaining adequate natural ventilation is arduous because several factors control its performance, including ambient wind speed and direction, opening configurations, and nearby objects such as vegetation. Among them, the effects of vegetation on natural ventilation are least understood. This study investigated how tree plantation location and crown shape affect the cross-ventilation of a generic building with two openings using Computational Fluid Dynamics (CFD) simulation. The CFD simulations are based on the Reynolds-Averaged Navier-Stokes (RANS) equations and use source terms for momentum, turbulent kinetic energy, and turbulent kinetic energy dissipation rate to model the effects of trees on the wind field. The results show a 23% reduction in ventilation rate for trees at a 2*H* distance upstream of the building (*H* is the building height) compared to the ventilation rate of a building without trees in its surrounding. Beyond this distance, the ventilation rate deficiency steadily decreases with tree plantation distance and has no reduction for trees planted at 15*H* upstream of the building. The cuboid-shaped crown causes the highest ventilation rate reduction of 23% compared to the V-shaped (18%), oval (16%), and conical (10%) crowns. This study recommends no trees with cuboidal crowns planting between 1.5*H* to 2.5*H* distances upstream of the building and maintaining aerodynamic tree crowns to minimize the adverse effects of trees on the natural ventilation of buildings.**

Keywords— Trees, CFD simulation, Cross-ventilation, Tree crown shape, Tree plantation location

I. INTRODUCTION

Buildings can be ventilated naturally or mechanically to remove stale air from indoors and replace it with fresh air to create a healthy living environment [1]. While mechanical ventilation uses fans and other devices, natural ventilation uses the pressure difference between indoors and outdoors. Natural ventilation is cost-effective and environmental friendly because it does not require any fuel to operate [2]. Natural ventilation is driven by wind, buoyancy, or a combination of both [1]. Wind-driven natural ventilation is divided into two categories: single-sided ventilation and cross-ventilation. In single-sided ventilation, wind enters and leaves through the same opening, while cross-ventilation occurs when two or more openings are in opposite or adjacent walls [3]. Cross-ventilation is more effective in creating strong indoor wind circulation and maintaining adequate ventilation rates than single-sided ventilation. However, cross-ventilation depends on many environmental factors and building features such as ambient wind speed, wind direction, turbulence intensity [5], internal and external opening configurations, and objects in the surroundings such as vegetation. Although many studies have explored the ways to utilize wind flow properties and optimize opening configurations [2] [7] to maximize natural ventilation, according to the authors' best knowledge, no research has investigated the effects of vegetation, particularly trees, on the natural ventilation of buildings.

A common practice is to plant vegetation near buildings as they provide shade, cool the surrounding area, and act as a windbreak. As a windbreak, trees slow down wind speed and thus, can significantly reduce the natural ventilation of buildings [6]. Such reduction in ventilation is not desirable because poor ventilation degrades indoor air quality and creates favorable conditions for viruses and bacteria to grow indoors. Stale air under poor ventilation causes various health problems such as dry throat and eyes, concentration disorders, headaches, shortness of breath, poor sleep, and drowsiness [7]. Therefore, it is essential to understand how vegetation impacts natural ventilation and provide guidelines for planting vegetation near buildings to minimize their adverse effects on building ventilation.

The effects of vegetation on wind and, consequently, natural ventilation of buildings vary with three factors: *what type* of vegetation (trees, bushes, etc.), *where* vegetation is located, and *how much* vegetation exist near buildings [8]. This study investigates the effects of plantation location and tree crown shape on the natural ventilation of buildings using Computational Fluid Dynamics (CFD) simulation. In CFD simulation, natural ventilation is modeled as cross-ventilation in a generic building and vegetation as trees. It is assumed that trees are located at various upstream distances from the building, and their foliage has different crown shapes. The effect of trees on natural ventilation is estimated as a percentage reduction in ventilation rates compared to the case without trees in the surrounding.

A. *CFD simulation*

This study simulated a cubic shape building with the dimensions of 5 m × 5 m × 5 m (height (H) × length (L) × width (W)) with two openings on the windward and leeward walls. The width and the height of each opening are 1.68 m × 2.5 m, and the wall thickness is 120 mm. This full-scale building represents the 1:20 scaled-down model tested in a boundary layer wind tunnel by Jiang et al. [9]. The building is placed $5H$ distance from the inlet of a computational domain with the dimensions of $26H \times 11H \times 5H$ [10]. The computational domain has the following boundary conditions: velocity inlet at the domain's inlet, outflow at the outlet, symmetry boundary condition at the lateral sides, velocity inlet at the top, and rough wall at the bottom [11]. Trees with different crown shapes are at various upstream distances from the building (Figure 1).

The computational domain, the building indoor, and tree foliage were discretized into hexahedral cells. The computational grid has small-sized cells near the building walls and inside the building, and larger-sized cells near the computational domain's boundaries. The first cell height near the walls is 0.3 m. The bottom of the computational domain is modeled as a rough wall with the standard wall function, while the building walls are smooth. The CFD simulations in this study were conducted using a commercial CFD software package: Ansys Fluent v.19.2 as the Reynolds-Averaged Navier-Stokes (RANS) equation-based simulations with k-ε turbulence models. The SIMPLE algorithm was chosen for the pressure-velocity coupling, and pressure interpolation is of second order. A second-order discretization scheme was used to solve convective and viscous terms in the governing equations. The simulation convergence was assumed when the scaled residuals reach the minimum value (10^{-6}) and showed no further reduction with the number of iterations [11].

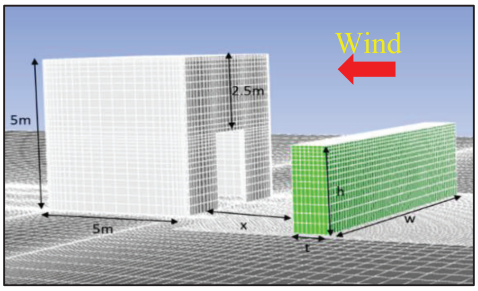

Fig. 1. Grid configuration near the building and vegetation at x distance upstream of the building. h- height of the tree, t- thickness of the tree, and w-width of the tree

1) *Boundary conditions*

Inflow boundary conditions for the CFD simulations were derived using the wind tunnel test data from Jiang et al. [9]. They consist of the profiles of mean velocity (U), turbulent kinetic energy (k), its dissipation rate (ε), and turbulence dissipation Prandtl number (σ_ε) as proposed by Gorle et al. [12].

$$U(z) = \frac{u_*}{\kappa} ln(\frac{z+z_0}{z_0}) \quad (1)$$

$$k(z) = \sqrt{A(In(z+z_0) + B} \quad (2)$$

$$\varepsilon(z) = \frac{\sqrt{C_\mu}\, u_*}{\kappa(z+z_0)} \sqrt{AIn(z+z_0) + B} \quad (3)$$

$$\sigma_\varepsilon(z) = \frac{\kappa^2(-A/_2 + k(z)^2)}{(u_*)^2(c_2-c_1)k(z)[1-E(z+z_0)]} \quad (4)$$

In Eqs. (1)-(4), z is height, u_* is friction velocity (= 0.897 m/s), z_o is roughness height (= 0.00436 m), κ is the von Kármán constant (0.4187), E is equal to 0, C_μ is a constant equal to 0.09, A and B are constants, which are found from curve fitting to the wind tunnel test data, c_1, and c_2 are 1.44 and1.92.

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Trees are not explicitly modeled in CFD simulations. Instead, the effects of trees infused to the wind field by using source terms added to the transportation equations of momentum (Eq. (5)), turbulence kinetic energy (Eq. (6)), and turbulence dissipation rate (Eq. (7)) as proposed by Mochida et al. [12].

$$S_{ui} = -\eta C_d LADUU_i \quad (5)$$

$$S_k = U_i S_{ui} - 4\eta C_d LADU \quad (6)$$

$$S_\varepsilon = \frac{\varepsilon}{k}\left(C_{p\varepsilon 1}(U_i S_{ui}) - C_{p\varepsilon 2}(4\eta C_d LADU)\right) \quad (7)$$

where C_d is the leaf drag coefficient, k is turbulence kinetic energy, LAD is the leaf area density, U is velocity magnitude, U_i is the velocity component in $i = x, y, z$-direction, η is a fraction of the area covered with trees, and $C_{p\varepsilon 1}$, $C_{p\varepsilon 2}$ are two empirical coefficients.

B. *Accuracy of CFD simulations*

Before investigating the effects of trees on cross-ventilation, this study conducted separate grid sensitivity and validation tests for CFD simulation of cross-ventilation and wind flow through vegetation to ensure the accuracy of the simulation technique. The details of grid sensitivity and validation tests are shown below.

1) *Cross-ventilation of buildings*

The accuracy of CFD simulation of cross-ventilation of a generic building is estimated by comparing CFD simulation data and the wind tunnel test data from Jiang et al. [9] for a scaled-down building model (1:20 scale) (Figure 2). This study employed three computational grids: Coarse, Basic, and Fine and calculated the grid convergence index (GCI) [16] to estimate the grid independent CFD simulation results.

The validation test compared the vertical profiles of wind speed components in x- and z-directions in the vertical center plane of the building at three different locations: x = -H/4, 0, and H/4. The CFD simulations were first conducted using standard, realizable, and renormalization group k-ε turbulence models to choose the best turbulence model for this study. A qualitative comparison showed similar agreements between the wind tunnel test data and CFD simulation with all three turbulence models. A quantitative evaluation using four metrics: hit-rate, fractional bias, factor-of-2 observations, and normalized mean squared error revealed the superior performance of the renormalized group k-ε turbulence model (RNG). Therefore, RNG was used as the turbulence model for the CFD simulations of this study.

2) *Tree canopy model*

The AIJ tree canopy model was used for the validation test of the CFD simulation of trees. The tree model is 7 m in height (h) and 2 m in width (w) with 5.8 m tall foliage (Figure 2(b)). Two tree models were created, one with a 1.2 m height and 0.5 m thick continuous tree trunk and another without a tree trunk. A uniform drag coefficient, C_d = 0.6 and leaf area density LAD = 0.85 m^2/m^3 were assumed for the tree [6]. The tree was exposed to a boundary layer wind flow with 5.6 ms^{-1} wind speed at a 9 m height. The effects of the tree were modeled by using Eqs. (5)-(7) with η = 1 and two sets of $C_{p\varepsilon 1}$ and $C_{p\varepsilon 2}$ parameters: {$C_{p\varepsilon 1}$ = 1.5, $C_{p\varepsilon 2}$ = 0.6} and {$C_{p\varepsilon 1}$ = 1.8, $C_{p\varepsilon 2}$ = 1.5}. All these models were modeled in CFD simulation, and the models' accuracy was estimated by comparing CFD simulation data with wind tunnel test data. In addition, the same evaluation metrics were calculated to evaluate the best-performing tree canopy model. The comparison showed the tree model without a trunk, and $C_{p\varepsilon 1}$ = 1.5 and $C_{p\varepsilon 2}$ = 0.6 resulted in the best agreement with the wind tunnel test data. Therefore, this setup was used for the rest of the CFD simulations in this study.

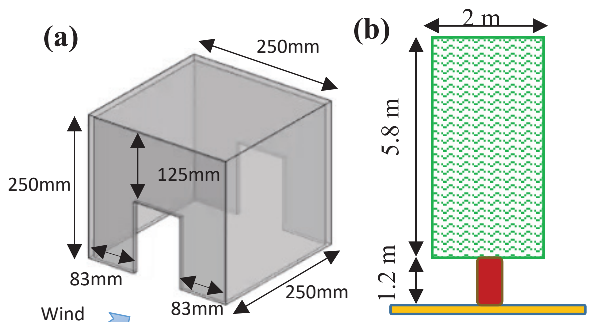

Fig. 2. Dimensions of (a) the 1:20 scale-down building model, and (b) the AIJ tree canopy model (C_d =0.6 and LAD = 0.85 m^2/m^3)

C. *Results and Discussion*

The following subsections compare the cross-ventilation rates of the building with the effect of trees with different crown shapes planted at various upstream locations and without trees in the surrounding.

1) *Trees at different locations*

Trees with a 2.5 m height (h), 1 m thickness (t), and 9 m width (w) cuboidal foliage were modeled in CFD simulations. The foliage is characterized by C_d = 0.6, LAD = 0.85 m^2/m^3 and η = 1. The trees

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were assumed to plant at 0.5H, 1H, 1.5H, 2H, 2.5H, 3.5H, 5H, 10H, and 15H upstream of the building.

Figure 3 shows how the ventilation rate (VR) decreases with tree plantation location. Here, ventilation rate reduction (VRR) is calculated as:

$$VRR = \frac{(VR\ without\ trees - VR\ with\ trees)}{VR\ without\ trees} \times 100\% \quad (8)$$

When trees are at a 0.5H distance to the building, the ventilation rate decreases by 10% compared to the ventilation rate without being affected by vegetation. The ventilation rate further decreases to 19% and 22% for trees at 1H and 1.5H upstream of the building. A maximum VRR of 23% is observed for trees at 2H upstream of the building. Beyond this distance, the ventilation rate gradually increases with tree plantation distance. With trees at 2.5H upstream, the ventilation rate slightly increases by 2% showing 20% of VRR. VRR further reduces to 20%, 14%, and 3% for trees at 2.5H, 5H, and 10H upstream distances and shows no reduction for a 15H upstream distance.

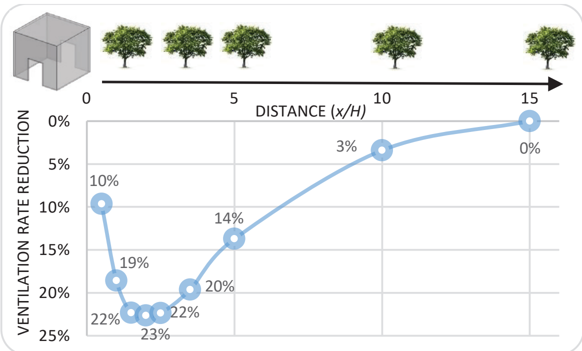

Fig. 3. Tree induced VRR with different plantation locations

Figure 4 illustrates the effect of plantation location using wind speed deceleration (WSD) in the building's center plane compared to the case where there is no tree. WSD is calculated as:

$$WSD = \frac{(u_{i,tree} - u_{i,no\_tree})}{u_{i,no\_tree}} \quad (9)$$

where $u_{i,tree,}$ and u_{i,no_tree} are wind speed components in the x-direction at location i with and without trees. Downstream of the trees at a 0.5H upstream distance, WSD varies from 0 to -0.2, resulting in a minor decrease in ventilation rate (Figure 4(a)). However, when trees are at 1H upstream, a large region with a high WSD from 0 to -0.6 forms near the windward opening (Figure 4(b)). With a further increase in plantation distance, the low wind speed area extends to a 2H upstream distance (Figure 4(c)). The largest WSD of -1.8 is observed in front of the building when trees are planted 2H upstream. Extremely low wind speed near the windward opening for this setting may be a reason for its maximum VRR. Furthermore, a larger area with significantly lower wind speeds (WSD < -2) formed above the opening of the building. A smaller wind speed reduction can be observed for a further increase in plantation distance to 5H (Figure 4(d)). Noticeably, the height of this low wind speed area is approximately equal to the windward opening's height and remains constant throughout the separation distance between the building and the trees. No area with low wind speed is formed for trees at a 15H upstream distance because wind speed has regained momentum to the level of the no-tree case while traversing a long distance between the trees and the building (the result is not shown here). Therefore, trees at 15H upstream of the building cause no ventilation rate reduction or weaken wind circulation indoors.

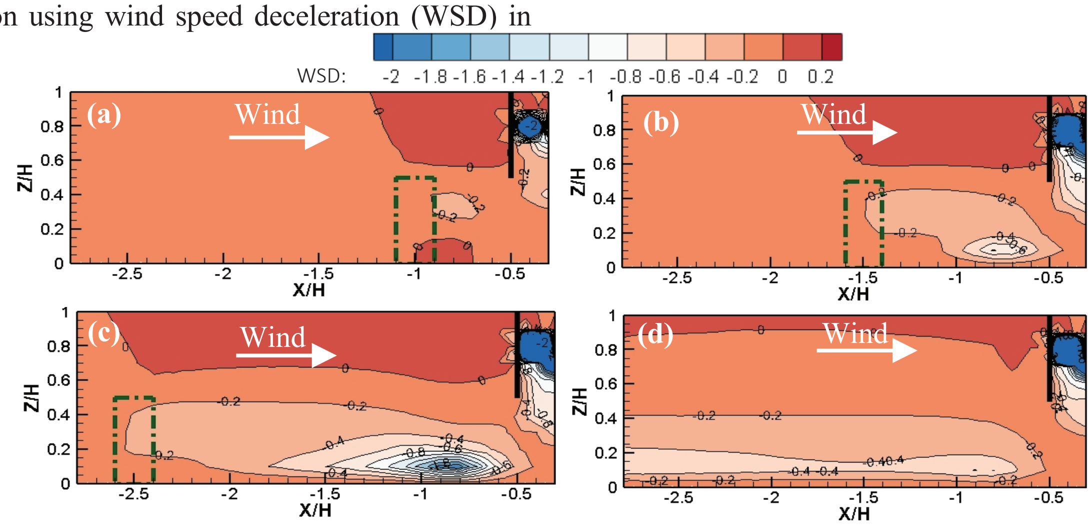

Fig. 4. WSD in the vertical center plane of the building

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2) Trees with various crown shapes

Four simplified crown shapes: cuboidal, oval, conical, and V-shape, were used for estimating the effects of tree shape on the ventilation rate of buildings. All trees are 2.5 m in height, 9 m in width, and 1 m in depth at their thickest point and are planted at a 2*H* distance upstream of the building. The tree foliage is modelled with *LAD* = 0.85 m^2/m^3 and $C_d = 0.6$.

Figure 5 shows how VRR varies with trees with four crown shapes. The largest and smallest VRR are for trees with cuboidal (23%) and conical (10%) crowns. However, the tree with a V-shaped crown, which can be considered as an inverted conical shape, causes an 18% decrease in ventilation rates. The tree with an oval crown reduces ventilation by 16% compared to the ventilation rate of the building without no trees in its surrounding.

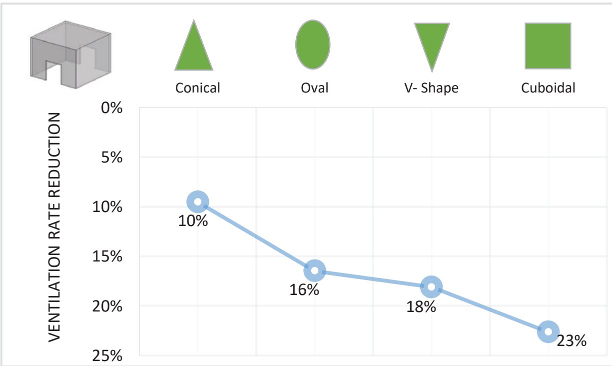

Fig. 5. Variation in VRR with tree crown shape

Figure 6 shows the distribution of WSD near trees with different crown shapes to illuminate how tree shape affects wind speeds. Figure 6(a) shows that WSD varies from 0 to -0.6 near the windward opening for trees with conical crowns. Compared to the conical crown, the oval crown creates a comparatively large low wind speed area, with a maximum WSD of about -1.4 (Figure 6(b)). This low wind speed area spreads from the tree to the windward opening and extends up to half the opening height. These modifications cause a higher VRR compared to the conical shape crown. Wind speeds slightly increase downstream of the trees with a V-shape crown (Figure 6(c)) but still cause about 2% more VRR than the tree with an oval crown. A possible explanation is that despite increased wind speed outdoor, the V-shape crown does not improve indoor wind circulation, as seen from the WSD pattern indoors, which is quite similar to that for cuboidal and oval crown shapes. The largest low wind speed area with the maximum WSD of -1.8 extends from the tree with the cubical crown to the windward opening resulting in the highest VRR (Figure 6(d)).

Figure 7 illustrates the WSD distribution in the vertical center plane of the building for a tree with a cuboidal crown planted at a 2*H* upstream distance of the building. A significant decrease in wind speed is observed near the left top corner of the building, indicating possible stagnation of aged air. Moreover, wind speeds in the wind jet that carries fresh air into the building, suffer a 0.2 – 0.6 times reduction compared to the no-tree case. These facts point out that trees planted near the buildings significantly affect ventilation rates and indoor air circulation.

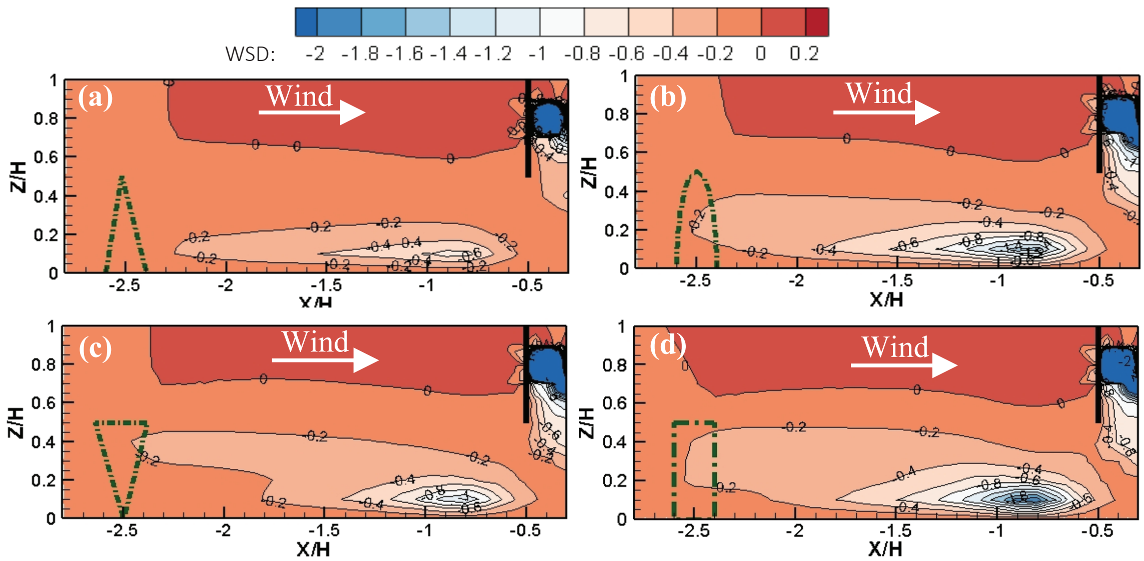

Fig. 6. WSD in the vertical center plane of the building

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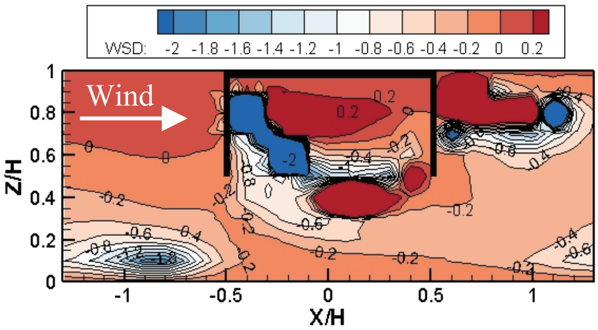

Fig.7. Distribution in WSD for the tree with a cuboidal crown at a 2H distance upstream of the building.

D. *Conclusion*

This study used CFD simulations to investigate the effects of tree plantation location and crown shape on the cross-ventilation rate of a generic building. The following findings of this study are essential for choosing tree plantation locations and maintaining crown shapes to minimize the ventilation rate reduction of buildings.

- The magnitude of wind speed decreases downstream of trees. The largest decrease in wind speeds occurs at 1.5*H* to 2.5*H* downstream distances of trees. Therefore, trees should not be planted at 1.5*H* to 2.5*H* distances upstream of ventilation openings.

- Trees with smaller cross-section areas at the top of the foliage, such as conical and oval crowns, cause the minimum reduction in ventilation rates. In contrast, trees with cuboidal crowns can reduce ventilation rates by 25%. Therefore, it is advisable to maintain aerodynamical crown shapes such as conical or oval for trees planted closer to buildings.

- Trees upstream of buildings cause air stagnation near the windward top corner of the space prompting some visible effects such as mold growth. In addition, one can detect a noticeable slowdown of wind speed at the windward opening. If such evidence has been found, one should take necessary actions to minimize the adverse effects of trees on ventilation rates and indoor air circulation.

References

[1] N. Cardinale, M. Micucci, and F. Ruggiero, “Analysis of energy saving using natural ventilation in a traditional Italian building,” *Energy Build.*, vol. 35, no. 2, pp. 153–159, Feb. 2003.

[2] K. Kosutova, T. van Hooff, C. Vanderwel, B. Blocken, and J. Hensen, “Cross-ventilation in a generic isolated building equipped with louvers: Wind-tunnel experiments and CFD simulations,” *Build. Environ.*, vol. 154, pp. 263–280, May 2019.

[3] Y. Jiang and Q. Chen, “Effect of fluctuating wind direction on cross natural ventilation in buildings from large eddy simulation,” *Build. Environ.*, vol. 37, no. 4, pp. 379–386, Apr. 2002.

[4] X. Zhang *et al.*, “Cross-ventilation of a generic building with various configurations of external and internal openings,” *Build. Environ.*, vol. 207, p. 108447, Jan. 2022.

[5] R. Ramponi and B. Blocken, “CFD simulation of cross-ventilation for a generic isolated building: Impact of computational parameters,” *Build. Environ.*, vol. 53, pp. 34–48, Jul. 2012.

[6] G. Kang, J.-J. Kim, and W. Choi, “Computational fluid dynamics simulation of tree effects on pedestrian wind comfort in an urban area,” *Sustain. Cities Soc.*, vol. 56, p. 102086, May 2020.

[7] A. Cincinelli and T. Martellini, “Indoor Air Quality and Health,” *Int. J. Environ. Res. Public. Health*, vol. 14, no. 11, Art. no. 11, Nov. 2017.

[8] W. Y. Ng and C. K. Chau, “Evaluating the role of vegetation on the ventilation performance in isolated deep street canyons,” *Int. J. Environ. Pollut.*, vol. 50, no. 1/2/3/4, p. 98, 2012.

[9] Y. Jiang, D. Alexander, H. Jenkins, R. Arthur, and Q. Chen, “Natural ventilation in buildings: measurement in a wind tunnel and numerical simulation with large-eddy simulation,” *J Wind Eng Ind Aerodyn*, p. 24, 2003.

[10] C. Gorlé, J. van Beeck, P. Rambaud, and G. Van Tendeloo, “CFD modeling of small particle dispersion: The influence of the turbulence kinetic energy in the atmospheric boundary layer,” *Atmos. Environ.*, vol. 43, no. 3, pp. 673–681, Jan. 2009.

[11] X. Zhang, A. U. Weerasuriya, and K. T. Tse, “CFD simulation of natural ventilation of a generic building in various incident wind directions: Comparison of turbulence modelling, evaluation methods, and ventilation mechanisms,” *Energy Build.*, vol. 229, p. 110516, Dec. 2020.

[12] C. Gromke, B. Blocken, W. Janssen, B. Merema, T. van Hooff, and H. Timmermans, “CFD analysis of transpirational cooling by vegetation: Case study for specific meteorological conditions during a heat wave in Arnhem, Netherlands,” *Build. Environ.*, vol. 83, pp. 11–26, Jan. 2015.

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