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Review

Review of the Numerical Simulation of the Wind and Pollutant Diffusion in Urban Street Canyon under the Influence of Trees

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Abstract: Tree is an essential factor affecting airflow and pollutant diffusion in the urban street canyon. The wind environment in the urban street canyon will be effectively improved by expounding the mechanism and implementing greening measures. Moreover, it will help decrease the pollutant concentration around the street canyon. This paper reviews the airflow and pollutant diffusion numerical simulation in the street canyon under the tree influence. Firstly, the numerical mathematical model used for pollutant diffusion and airflow in urban street canyons under the influence of trees is summarized. The representation of trees' numerical mathematical model in the simulation domain is mainly proposed. Secondly, the wind environment and pollutant distribution factors influencing urban street canyons are elaborated and analyzed, including tree characteristics, layout, street canyon shape, and thermal. Furthermore, current research progress and deficiencies are discussed. Finally, the future research direction of wind environment and pollutant distribution simulation in urban streets under the influence of trees is pointed out.

Keywords: tree; street canyon; numerical simulation; pollutant

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1. Introduction

A street canyon, the micro-unit of urban buildings, is one of the main areas of residents' activities. The airflow above the buildings into the street canyon affects the indoor and outdoor airflow characteristics and pollutant distribution on both sides of the streets. As shown in Figure 1, one of the most relevant characteristics of the street canyon is the presence of a large number of dense foliage tall trees [1]. Trees play an important role in street temperature adjustment, air purification, and environmental beautification [2–5].

Figure 1. Photographs of Liberdade Avenue in Lisbon [1].

The research on the wind environment and the convection–diffusion of pollutants in the street canyon under the influence of trees helps analyze the mechanism of airflow and the law of pollutant distribution in the street canyon, improve the living comfort of the residents on both sides of the street, and especially clarify the ventilation mechanism in the street canyon in order to elaborate the urban heat island effect indirectly. At present, the research on the dynamic behaviors of the street canyon under the influence of trees focuses on wind tunnel experiments [6–8], numerical simulation [5,9–13], and field measurement [14–18]. The number of experimental instruments limits on-site observation and measurement points, and few monitoring points are arranged. The interference of uncontrollable factors such as wind speed, wind direction, traffic flow, building thermal effect, etc., cannot be eliminated. Therefore, it is difficult to accurately compare the differences in air pollution characteristics in street canyons under different vegetation conditions [19]. In the wind tunnel test, air pollutants are forced to pass through the plant model, resulting in more interactions between pollutants and plants, which enlarges the plant sedimentation rate. In addition, when building physical plant models using fibers, foam, etc., the unreality of plant characteristics will also increase the uncertainty of sedimentation rate simulation. It is necessary to propose other plant-modeling methods suitable for the wind tunnel study of building and environmental aerodynamics [19–21]. However, numerical simulation technology makes up for the shortcomings of wind tunnel experiments and field observation in spatial distribution. It has the advantages of less resource consumption, more information acquisition, sensitivity tests can be set up, and quantitative research is easy [5,9–13,22]. Many researchers generally believe that the influences of trees on the airflow and pollutant dispersion in the street canyon are relatively complex dynamic behaviors. For a single tree, the dynamic behaviors include the damping effect of leaves in the tree crown on the airflow and the shearing and blocking effects of tree branches on the airflow, leading to the particularity of the pollutant dispersion in the urban street canyon. In addition, the factors influenced by the genetic characteristics of trees, such as leaf distribution non-uniformity and discontinuity, crown shape, etc., lead to the differences in air flow and pollutant dispersion in the urban street canyon. Different methods have been adopted for numerical simulation of the wind environment in two-dimensional and three-dimensional street canyons under the influence of trees. All the studies revealed the effects of tree layout [23–26], street canyon morphology [27], tree crown position [28], and tree crown shape [11] on airflow and pollution distribution. They also have enriched the numerical simulation research results of the tree-urban street canyon-wind-pollutant coupling system. However, key problems, such as multi-factor coupling, an intricately detailed description of tree features, etc., still need to be effectively solved.

This paper mainly summarizes the studies on air flow and pollutant dispersion in the urban street canyon under the influence of trees. The effects of tree characteristics, tree arrangement and layout, street canyon morphology, and temperature on the wind environment and pollutant dispersion in the street canyon were reviewed by a mathematical model used in the numerical simulation, the present difficulties in the numerical simulation of wind environment and pollutant dispersion in the urban street canyon under the influence of trees were pointed out, and the future research by numerical simulation was given.

2. Characterization of the Trees in an Urban Street Canyon by a Mathematical Model

Table 1 lists the mathematical models used by some scholars in the research on urban street canyon wind environments and pollutant dispersion by numerical simulation software, such as OpenFOAM [29], ANSYS Fluent [30], STAR-CCM+ [31], ENVI-met [32], etc. In the mathematical models, the dynamic information of airflow is described by Navier–Stokes Equations, including mass, momentum, and energy equations. The large-eddy model (LES), Reynolds stress model (RSM), or Reynolds-averaged Navier–Stokes (RANS) model was used to elaborate the turbulent flow of air. The LES is advantageous in computational accuracy, while the RANS model is more prominent in computational efficiency [1,33,34]. The transport of pollutants in the air is generally described under the Lagrangian or Euler framework. Under the Euler framework, the convection–diffusion model outlines the pollutant concentration distribution caused by air convection and turbulence effects. This model ignores the gravity effect of pollutants and believes air and pollutants form a miscible phase. Some scholars also used particles to characterize pollutants based on the Lagrangian framework, but there are some defects, such as high numerical simulation workload, few particles, etc. [28,35–38]. In short, the coupling of the above mathematical models forms the basis of the numerical model for the simulation of airflow and pollutant dispersion in the urban street canyon calculation domain.

In the study on the impact of trees on the wind environment and pollutant dispersion in the urban street canyon, the trunks and branches block the airflow, so the crown forms a damping effect on the airflow. Accurately describing the damping and blocking effects of trees on the airflow is the basis and key to obtaining the aerodynamics information in the urban street canyon. Different researchers adopt different mathematical or physical models to describe trees. Gallagher et al. believed that it is unnecessary to consider tree branches and trunks [39], while Wang and Su et al. believed that the branches and trunks have an essential impact on local airflow and pollutant dispersion in the street [40,41]. When a tree crown is regarded as dense tree vegetation, it can be considered a circle solid in mathematical simulations [34,39,42,43]. However, this method only applies to very dense vegetation. Most researchers studied the influence of the tree crown (leaves) on the airflow using the porous media model and vegetation resistance source model. The basic principle is to achieve the effect of the tree crown on the airflow by adding the source term in the momentum equation, but the expressions of the mathematical model are very different.

Table 1. Mathematical models adopted by different researchers.

References	Energy Model	Turbulence Model	Leaf Model	Pollutant Framework	Software
[9,44]	Off	RANS	Source item	Euler	OpenFOAM
[45]	Off	LES	Source item	Euler	
[34]	Off	RANS	Solid	Euler	ANSYS Fluent
[46]	Off	RANS and LES	Source item	Euler	
[10,47–49]	Off	RSM	Source item	Euler	
[6]	Off	RSM and RANS	Source item	Euler	
[2,50–52]	Off	RANS	Source item	Euler	
[53]	On	RANS	Source item	Euler	
[54]	Off	LES	Source item	Euler	
[42]	Off	RANS	Solid	Lagrange	
[55]	On	RANS	Source item	Euler	STAR-CCM+
[56,57]	Off	RANS	Source item	Euler	PHOENICS
[58]	Off	RANS	Source item	Euler	ENVI-met
[59]	Off	RANS	Source item	Euler	Fluidyn-PANACHE

2.1. Porous Media Model

Gromke et al. used plastics to represent the tree crown in the wind tunnel experiment. They regarded the effect of plastics in the flow area as the distributing resistance attached to the fluid in the simulation. From the mathematical model's description, a source term was essentially added to the momentum equation. The source term comprises a viscous loss term (Darcy Formula) and an inertial loss term. Its mathematical model is described as follows [7,60–63]:

$$\lambda = \frac{\Delta P}{((1/2)\rho U^2)l} \tag{1}$$

$$S = -\lambda\left(\frac{1}{2}\rho|U|U_i\right) \tag{2}$$

where λ is the pressure loss coefficient, ΔP is the difference in static pressure windward and leeward of the porous sample in forced-convection conditions, U is the flow speed, and l is the porous sample thickness in the streamwise direction.

Gromke et al. measured the pressure difference coefficient on both sides of the porous media model in the wind tunnel experiment based on the above mathematical model. Then, they characterized the resistance effect of trees in the urban street canyon [7,8,60,64]. However, the mathematical model fails to characterize the differences in tree characteristics and consider the turbulence effect of leaves on airflow. The parameters are acquired mainly by the experimental measurement results, limiting the mathematical model's application and promotion.

2.2. Vegetation Resistance Source Model

Different scholars have mathematically characterized the trees in urban street canyons by introducing the vegetation resistance source term model into the numerical simulation of the wind environment in urban street canyons. The model characterization is as follows [5,27,59,65,66]:

$$S_u = -\rho C_d LAD|U|U_i \tag{3}$$

where C_d is the resistance coefficient of the vegetation layer, LAD is the leaf area density, U_i is the velocity component in the ith direction, $|U|$ is the velocity modulus, and S_u is the resistance source term.

Considering the influence of leaves on turbulent kinetic energy and turbulent energy dissipation rate of airflow, the turbulent energy term and turbulent energy dissipation rate source term are expressed below, respectively:

$$S_k = \rho C_d LAD\left(\beta_p|U|^3 - \beta_d|U|k\right) \tag{4}$$

$$S_\varepsilon = \rho C_d LAD\left(C_{\varepsilon 4}\beta_p\frac{\varepsilon}{k}|U|^3 - C_{\varepsilon 5}\beta_d|U|\varepsilon\right) \tag{5}$$

where k is the turbulent kinetic energy, ε is the turbulent dissipation rate, S_k is the source term caused by the turbulent kinetic energy, S_ε is the source term caused by the turbulent dissipation rate, β_p is the fraction of the average kinetic energy converted into turbulent kinetic energy caused by resistance, and $C_{\varepsilon 4}$, $C_{\varepsilon 5}$, and β_d are dimensionless parameters.

The above vegetation resistance source model has been continuously optimized and modified, and thus expanded, enriched, and widely used in the numerical simulation of wind environment in the urban street canyon.

The parameters in the model, such as vegetation resistance coefficient, leaf area density, etc., reflect the characteristics of natural trees and, thus, the differences of tree species to a certain extent and consider the turbulence effect caused by leaves [67].

In addition, different scholars considered the deposition effect of pollutants on leaves by adding a source term model to the convection–diffusion equation of pollutants [48,56,59]. The source model can be written as follows:

$$S_{deposition} = V_d CLAD \tag{6}$$

where $S_{deposition}$ is the mass of particles deposited by vegetation per cubic meter, C is the local concentration, and V_d is the particulate deposition velocity on the foliage.

Meanwhile, trees also affect particulate matter in the atmosphere by resuspending particles captured on the plant surface [3,68]. Hong et al. [56] considered this phenomenon using the following model:

$$S_{resuspension} = V_r C_{sink} LAD \tag{7}$$

where $S_{resuspension}$ is secondary pollutants from foliage per unit vegetation volume per unit time, V_r is the particle resuspension velocity from plant foliage, and C_{sink} is the particle concentration deposited on plant foliage.

However, the accurate application of the above model depends on the experiment due to the determination of the vegetation resistance coefficient and leaf area density. Mainly for different tree species, the above parameters change at different external wind speeds [69], impacting the accuracy of the numerical simulation results to a certain extent.

2.3. Model Validation

Moreover, the European Cooperation in Science and Technology (COST) Action 732 improves and assures the quality of micro-scale meteorological models applied for predicting flow and transport processes in urban or industrial environments [25,70–72]. At the same time, mathematical and statistical methods are used to verify the correlation between numerical simulation results and experimental results [1,40]. For example, the statistical model performance indicators of pollutant concentration were used in validating the simulation result and experiment data [40].

3. Characteristic Factors of Trees

The impact of trees on airflow and pollutant diffusion in street canyons includes many factors, such as leaf area density, tree planting layout, crown shape, tree trunk, and whether the trees are continuous. Table 2 shows the investigated factors from some research. What is more, researchers [23,41] believe that changes in local airflow and the distribution of pollutants in the street cannot be ignored, which is different from most studies that believe that the tree branch diameter is small and can be ignored in numerical simulation studies. The shape of trees has an essential impact on the damping effect of wind fields. More and more studies have refined the shape of tree crowns, changing them from the original rectangular shape to other regular shapes (such as circular, triangle, and cone) until they can roughly describe the irregular shape of trees [10,11,27,56]. Finally, the leaf area density of trees is a crucial research factor. When describing trees more accurately, some scholars have adopted a leaf area density curve considering the variation of leaf area density with tree height. Given different leaf area densities to describe the density of leaves, it is often possible to distinguish the impact of trees in different seasons [48,56,65].

Table 2. Studies on tree factors by different references.

References	Tree Trunk	Crown Shape	Tree Layout [1]	*LAD* (m^2 m^{-3})	Tree Continuous
[10]	Off	Abnormal	Random	1.6, 1.06	Continuity/discontinuity
[11]	Off	Rectangle	SW/DW	-	Continuity
[5]	Off	Rectangle	DW	0.5, 1, 2	Continuity/discontinuity
[23,41]	On	-	SW/DW	-	-
[25,26]	Off	Rectangle	SW	1.0	Continuity/discontinuity
[27]	Off	Abnormal	Random	0.85	Continuity/discontinuity
[65]	Off	Rectangle	DW	LAD profile	Continuity
[56]	Off	Triangle, circular, rectangle	DW	0.5, 1.5, 2.5	Continuity
[73]	Off	Cone, expanded paraboloid, spheroid	DW	LAD profile	Discontinuity
[48]	Off	Rectangle	SW/DW	0.5, 1, 2	Continuity

[1] SW: Single row; DW: Double row.

3.1. Tree Branches

The influence of seasonal factors and tree types often impacts the wind environment and pollutant dispersion in the urban street canyon when only the tree branches without leaves exist in winter.

Sabatino et al. used lower leaf area index and leaf area density to characterize the impact of tree branches without leaves on the airflow in the street canyon [49]. This assumption is reasonable for thin branches. However, for the thick branches, it is necessary to consider the shearing and blocking effects of the branches on the airflow. The wind environment and pollutant dispersion in the urban street canyon affected by tree branches are seldom studied due to the difficulties in the physical modeling of tree branches and trunks and poor self-similarity and simple appearance of the physical models of branches and trunks reconstructed by an algorithm. In the open area, Endalew et al. [74] and Bai et al. [75] have proven with wind tunnel experiments that tree branches can change the gas flow rate. That also means that in the street canyon with a more complex building shape, the tree branches and trunks also affect the airflow, i.e., the shearing and blocking effects of the (primary) branches on the airflow [23].

By numerical simulation, Su et al. studied the impact of different tree branches and trunks on the wind environment in the urban street canyon. Their study found that the presence of tree branches and trunks leads to the airflow rate step and discontinuity, and tree trunks notably physically hinder airflow [40]. In addition, different tree branches and trunks have different impacts on the average pollutant concentration in the street canyon. Among them, the complete tree branches and trunks impact the pollutant concentration in the street canyon. As shown in Figure 2, Wang et al. used a tree branch entity model for numerical simulation of the wind environment in the urban street canyon. It is found that the increase in external wind speed significantly affects the flow field shape in the urban street canyon at the $y = -0.7$ m section [23]. The above studies initially reveal the influence mechanism of tree branches on the wind environment and pollutant dispersion in the urban street canyon. However, the numerical simulation of the influence of tree branches on the wind environment and pollutant dispersion in the urban street canyon is still in the initial exploration stage and faces the following technical difficulties: (1) actual tree branch entity modeling; and (2) meshing of computational domains of tree branches in urban street canyons. The former involves characterizing tree branches using the tree trunk modeling with the existing commercial software (such as SpeedTree 7.0 software) according to the specified parameters and tree trunk entity modeling according to the expected research idea. The latter involves the consumption of computing resources by determining the spatial area of the tree branches in the computational domain mesh of street canyon and reducing the number of computational domains meshes by loading an effective resistance source term in these spatial areas. Fortunately, Troldborg numerically predicted and experimentally observed the resistance on the main branches of the three-dimensional model tree and the wind field in its wake in combination with an immersed boundary model representation of the tree, with the results in good agreement [76]. That also means that numerical simulation research in the future can start from two aspects: precise characterization of tree branches and reduction of the number of computational meshes.

3.2. Tree Crown

The tree crown (leaf) is the basis for tree growth and other functional structures. The presence of the tree crown affects the pollutant concentration and airflow in the street [77]. Generally speaking, the crown shape of actual trees has prominent characteristics and mainly depends on the genetic characteristics and environmental factors of trees [78]. After being sheared above the buildings, the airflow enters the street canyon, where air flows at a lower rate due to the damping effect of the leaves in the tree crown.

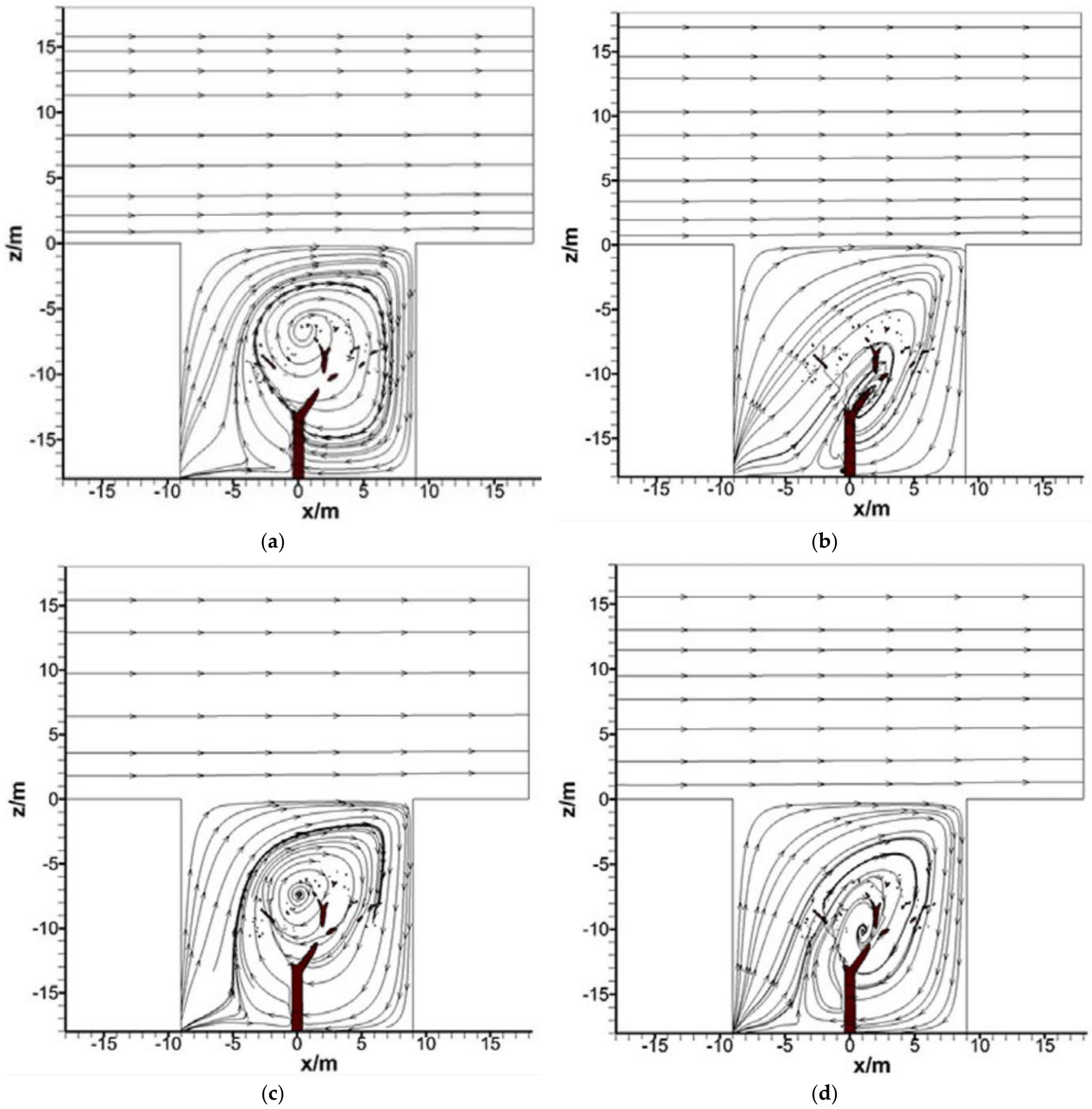


Figure 2. Streamlines at the y = −0.7 m section in canyon at different inflow wind velocities [23]. (**a**) 0.7 m/s. (**b**) 1.7 m/s. (**c**) 3.7 m/s. (**d**) 5.7 m/s.

Gromke et al. explored the impact of trees on the wind environment and pollutant distribution in the street canyon by experimental or numerical simulation methods [7,8,60,64]. They experimentally used polyethylene plastics to make circular or rectangular porous media to characterize the actual trees in the street canyon and study the impact of canyon height-width ratio, crown porosity, tree distribution location on the wind environment, and pollutant distribution in the street canyon. The study shows that the numerical simulation results are consistent with the wind tunnel experiment results when reasonable model parameters are used. Wang et al. considered the randomness of the leaf distribution in the tree crown and studied the influence of tree crown characteristics, including height, porosity, and uniform/random leaf distribution, on the airflow and pollutant concentration field in urban street canyons [79]. Hong et al. [56] simulated the wind environment and pollutant diffusion in the street canyon for triangular, circular, and rectangular crowns. The results show that the crown shape directly affects its resistance effect on airflow, and thus, the pollutant diffusion behaviors and the cylindrical crowns have the best ability to reduce PM2.5. In the numerical simulation, different scholars often ignore the actual characteristics of the tree crown, including the differences in the leaf distribution and actual crown shape [4,7,8,60,64,67]. For example, affected by the growth of branches and trunks, different tree species (phoenix tree and maidenhair tree) have non-uniform and discontinuous leaf distribution and very different crown widths, volumes, and external crown shapes. Therefore, it is necessary to optimize the existing vegetation resistance source model further to predict or evaluate the wind environment and pollutant distribution in the street canyon under the influence of real trees. Fortunately, researchers have numerically simulated the wind environment based on real trees, and their simulation objects have developed from open areas to urban street canyons. Hofman et al. [80] mapped the tree crown shape based on the Laser Radar scanning data and numerically simulated the street canyon's wind environment and pollutant concentration. They believed that the change in the tree crown characteristics (shape, size, and leaf area density) affects the distribution of air flow rate. In Figure 3, Qin et al. obtained the contour curve of trees by fitting and further analyzed the impact of five common trees on atmospheric particle dispersion. It is found that *G. biloba* and *L. chineses* effectively reduce the particle concentration at the pedestrian height [73].

Suppose further studies can solve the difficulty in the research on the leaf distribution difference in space. In that case, they will help to more accurately reveal the impact of the difference between real trees on pollutant distribution and airflow. The possible idea is to establish a mapping relationship with the urban street canyon meshes based on the three-dimensional laser scanning data to describe tree differentiation characteristics accurately.

3.3. Tree Layout

The wind environment and pollutant dispersion in actual urban streets also depend on the interaction of various aspects. One of the more apparent impacts is the tree layout (tree density). Theoretically, the trees in urban streets are planted in very different layouts, including the number of rows of trees, different spacing between trees, and different tree species. These factors influence the accurate prediction of wind environment and pollutant distribution in urban street canyons [2,5].

From Figure 4, Huang et al. [11] studied the influence of tree crowns on the airflow in the street canyon at different heights. It is found that the tree crown higher than the building can effectively improve the air exchange rate in the street canyon. So, the pollutant concentration in the street canyon is low. Wang et al. studied (main) staggered tree branches by numerical simulation. It is found that the (main) branches can significantly improve the airflow in the street canyon [41]. Lin Ding et al. studied the spatial distribution of trees in the typical deep street canyon by numerical simulation. It is found that the non-uniform tree layout scheme without trees planted in the middle of the street canyon can effectively reduce the area of the "tuyere effect" at both ends of the street and the "wind shadow effect" in the middle of the street and improve the wind environment at the pedestrians' breathing level in the whole street canyon [81]. Cui et al. believed that the increasing number of green belts in the street canyon could significantly reduce the ambient air temperature but reduce the average air flow rate in the street canyon, resulting in an increase in pollutant concentration [82]. Using numerical simulation, Wu et al. studied Busan, South Korea's streets. The changes in street width, direction, and canyon aspect ratio influence the microclimate and thermal comfort index more significantly, and tree height influences the street environment more significantly than other tree configuration factors [83]. Wang et al. found from the numerical simulation that the spacing between vegetation and buildings significantly influences the concentration distribution of PM2.5; uniformly distributed trees have the slightest impact on the reduction of PM2.5 concentration [66]. Moayedi et al. discussed the tree layout. It was found that the trees planted in the street center improved the air quality more than those planted in 2 rows, especially the higher trees planted in 2 rows worsened the air quality by 10% [84]. Zhang et al. [85] gave the numerical simulation results to confirm further the results reported by Moayedi. In addition, the layout of trees affects the distribution of pollutant concentrations and the distribution of air temperature. The more trees in the street, the more beneficial it is to reducing temperature [86].

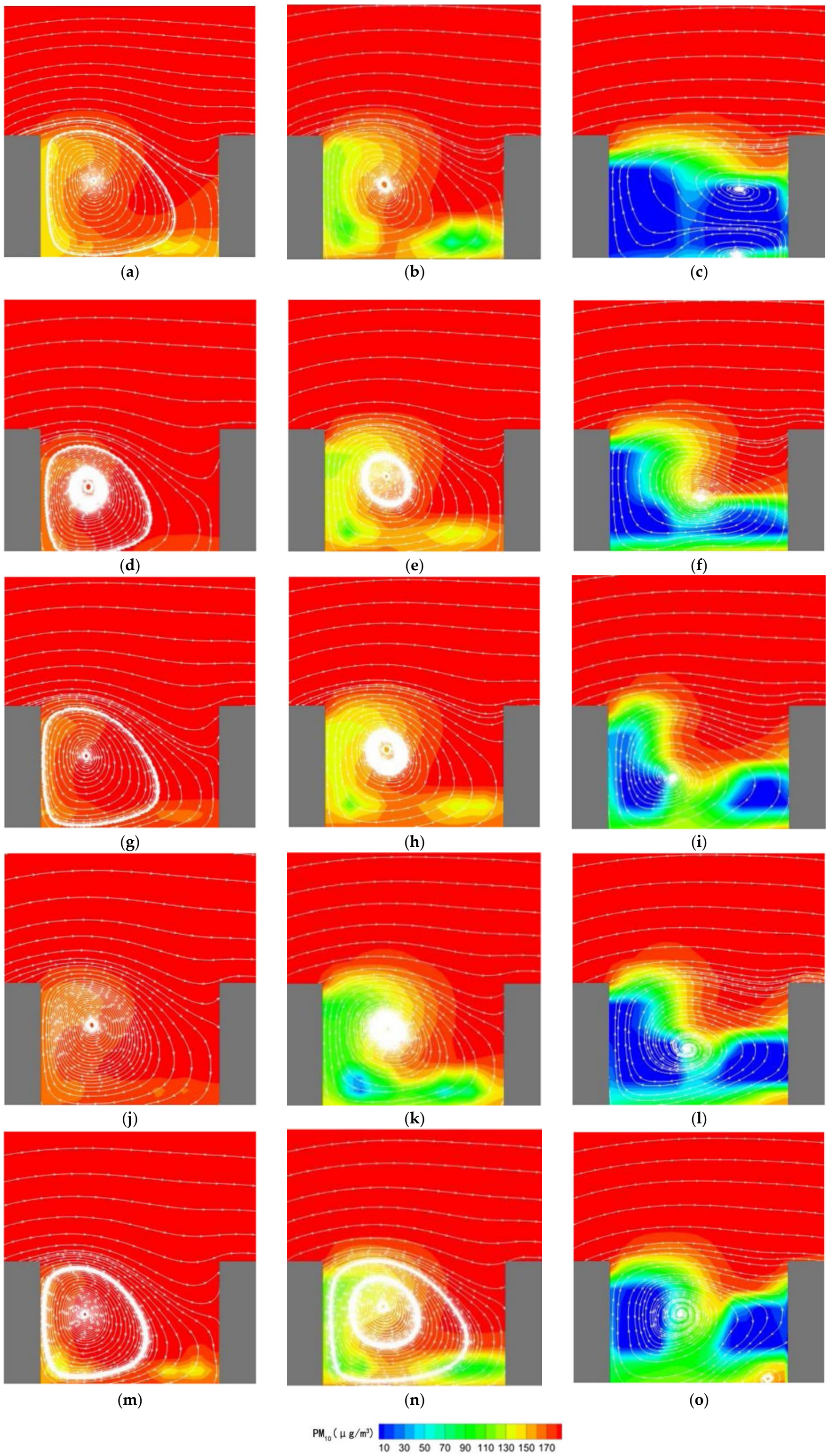


Figure 3. Streamlines and PM10 concentration contours on the vertical plane near the canyon center among five tree species and three growth periods for 5 years (left panel), 10 years (middle panel), and 30 years (right panel) when H/W = 0.9 [73]. (**a**) 5 years *G. biloba*. (**b**) 10 years *G. biloba*. (**c**) 15 years *G. biloba*. (**d**) 5 years *A. chinense*. (**e**) 10 years *A. chinense*. (**f**) 15 years *A. chinense*. (**g**) 5 years *A. buergerianum*. (**h**) 10 years *A. buergerianum*. (**i**) 15 years *A. buergerianum*. (**j**) 5 years *L. chinense*. (**k**) 10 years *L. chinense*. (**l**) 15 years *L. chinense*. (**m**) 5 years *C. deodara*. (**n**) 10 years *C. deodara*. (**o**) 15 years *C. deodara*.

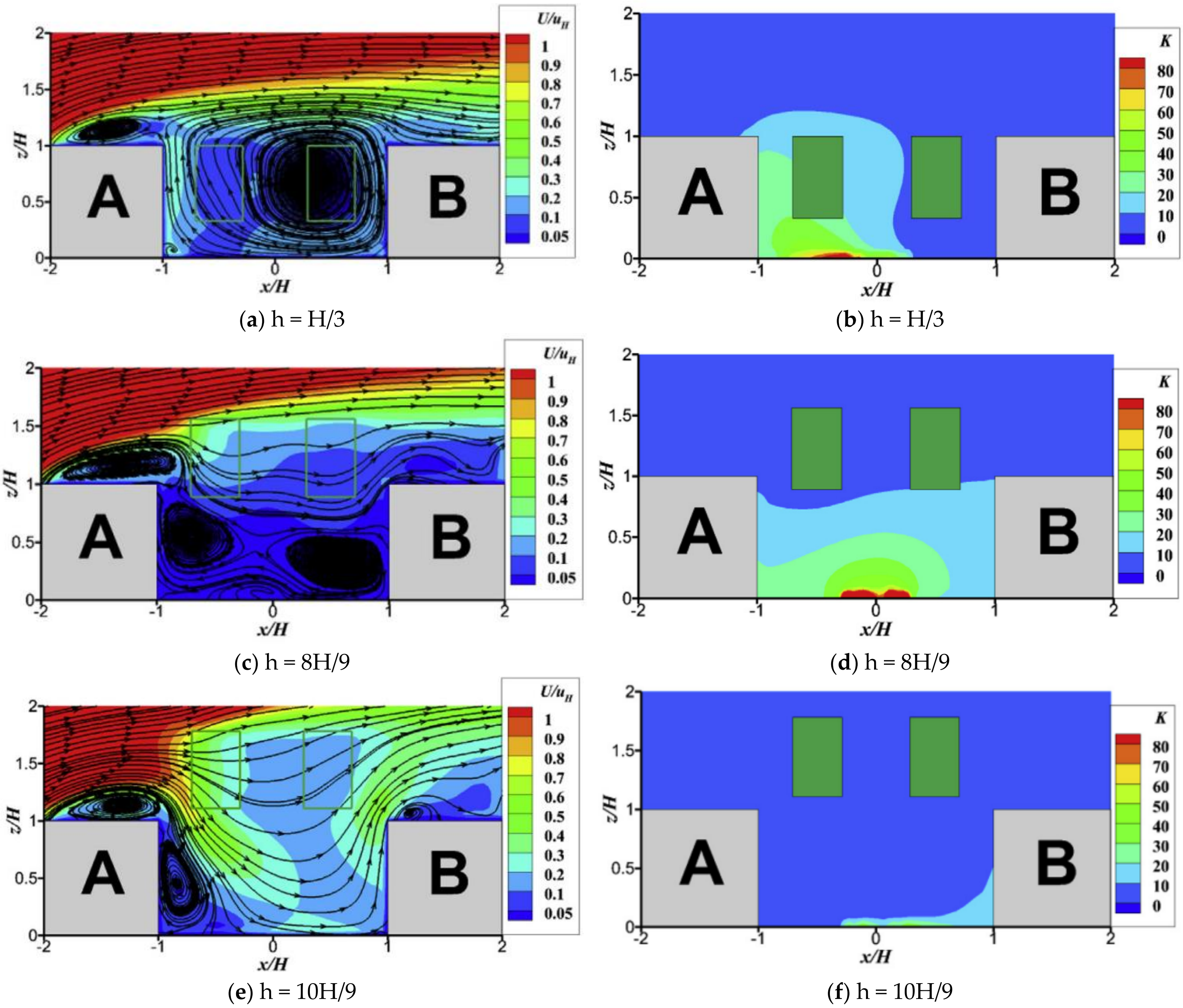
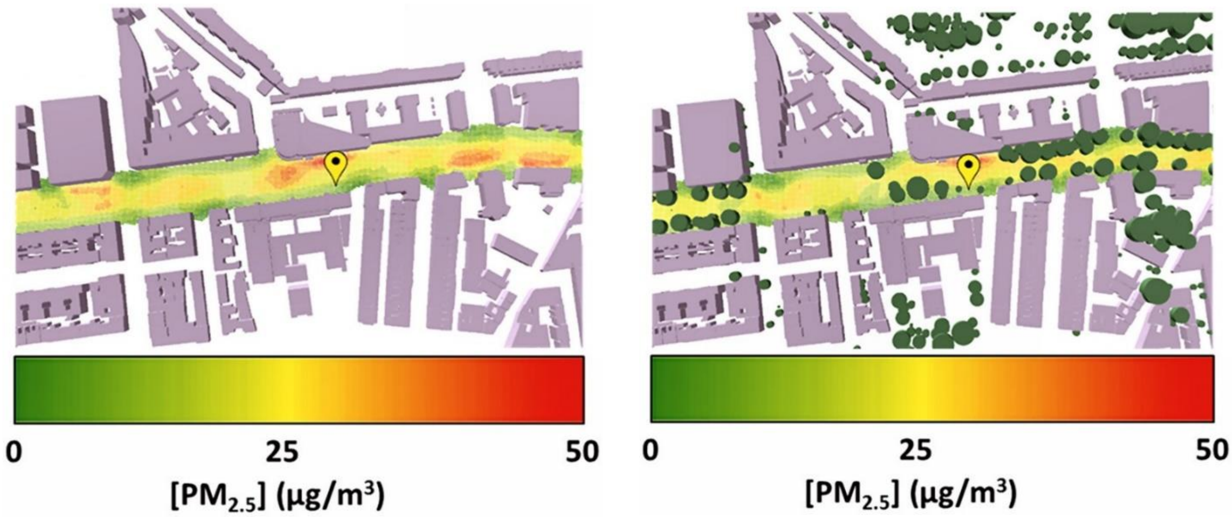


Figure 4. Normalized velocity magnitude contours and streamwise (**a**,**c**,**e**) and dimensionless pollutant concentration contours (**b**,**d**,**f**) on the vertical plane near the canyon center (y/H = 1.0) for the cases with DRTP under different trunk heights [11]. (**a**) h = H/3. (**b**) h = H/3. (**c**) h = 8H/9. (**d**) h = 8H/9. (**e**) h = 10H/9. (**f**) h = 10H/9.

4. Street Canyon Morphology

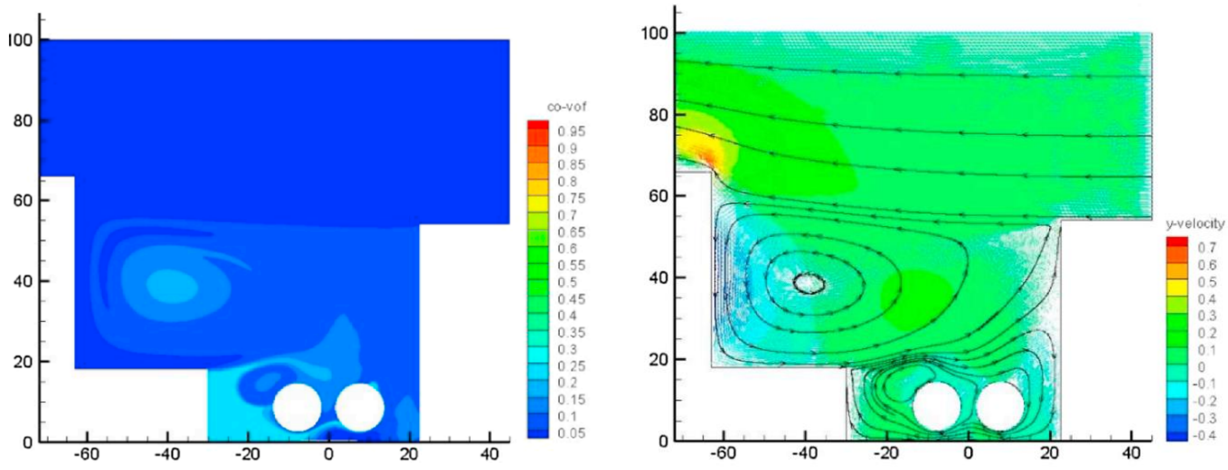
As another aspect that affects the wind environment and pollutant distribution in the street canyon, the street canyon morphology often macroscopically affects the airflow behavior in the street canyon [87]. In general, the impact of building structure on the airflow and pollutant dispersion in the street canyon mainly includes building layout and street canyon shape, i.e., an aspect ratio of the street canyon, street canyon asymmetry, and non-uniformity [88,89].

Zhang et al. [90] studied deep street canyons. It is found that the street canyons have vortices in 2 directions at the height–width ratio of 5 and a much weaker wind environment than that at the height–width ratio of 1 and 3. Gu et al. [91] used windward and leeward buildings with different heights to study the influence of the street canyon non-uniformity on the wind environment. It is found that the non-uniform street canyons can effectively improve the wind environment of the street canyon and have lower pollutant concentration at the pedestrian height than uniform street canyons. What is more, the street canyon's non-uniformity can improve pollutant dispersion. Thus, only the street canyon morphology can lead to more variable airflow effect and pollutant dispersion behavior and combines with trees to provide more complex airflow in the canyon. The existing experimental measurements have confirmed that fine particulate matter (PM) concentration decreases the most in a narrow street canyon in the presence of trees. In contrast, the concentration of coarse particulate matter (PM10) decreases the most in wide-street canyons [92]. Wang et al. [28] used the large-eddy simulation coupled Lagrangian stochastic model to discuss the impact of the height–width ratio of trees in the street canyon on the airflow. It is found that the low trees in the wide-street canyon can strengthen the airflow in the street canyon, while the trees in the narrow canyon have a much smaller impact on the flow field. Due to the influence of isolated vortex, trees increase the pollutant concentration in the street canyon at a specific height-to-width ratio. In Figure 5, Sun and Zhang [34] studied the airflow under the influence of trees in the non-uniform street canyon by numerical simulation. The results show that the morphologies of trees and buildings jointly determine the flow field structure and air flow rate distribution. The increase in the external flow rate does not significantly change the flow field morphology in the street canyon. Jeanjean et al. [10] numerically simulated the aerodynamic effect under the influence of trees in the urban area of London. It is found that the turbulence effect in the street canyon is fragile at a low inflow rate, and the removal of air pollutants by trees in different seasons is 7%. Vranckx et al. studied the actual street canyon by numerical simulation. The presence of trees leads to an 8% increase in the average annual pollutant concentration [44]. Moradpour and Hosseini studied the area near the street by numerical simulation. The results show that the presence of trees reduces the average pollutant concentration, especially PM10 concentration, by 9%, at the pedestrians' breathing height in the study area [59]. Buccolieri et al. found that in the case of the wind parallel to the street, the presence of trees positively affects the removal of pollutants in the areas close to and far from the trees, with the average pollutant concentration at pedestrian height decreased by 18%. In the case of the wind perpendicular to the street canyon, the presence of trees causes additional pollutant concentration [93]. The above studies provide a reference for revealing the mechanism of wind environment and the laws of pollutant convection–diffusion under the influence of trees in the urban street canyon. Further research may focus on the influence of multiple factors, including dynamic wind velocity [22,94], vehicle driving [95], ancillary facilities in street canyons [96,97], etc.



(**a**) (**b**)

Figure 5. *Cont.*



(**c**) (**d**)

Figure 5. Influence of street canyon morphology on pollutant and airflow field. (**a**) PM2.5 concentrations without trees at h = H/3 [10]. (**b**) PM2.5 concentrations with trees at h = H/3 [10]. (**c**) Pollutant concentration under southwest wind at scenario A [34]. (**d**) Flow velocity under southwest wind at scenario A [34].

5. Meteorological Factors

5.1. Thermal Environment

The street canyon's thermal environment affects the human body's thermal feeling and comfort. At the same time, trees can improve the street canyon's thermal environment and reduce the sidewalk's wind velocity [98]. The available field measurements and studies show that complex tree crowns can prevent solar radiation from reaching the ground and thus reduce the heat storage effect of the ground. More importantly, the intercepted energy increases the latent heat flux and reduces the air temperature, and different tree species have different impacts on the air temperature gradient [99,100]. This shows that in addition to trees' damping and blocking effects on airflow, the existing thermal effect can change the wind environment and pollutant distribution in the street canyon.

Gu et al. [65] coupled large-eddy simulation with vegetation resistance and heat source models and proposed a thermal dynamic mathematical model for the wind field in the urban shrubbery street canyon. The simulation results show that compared with the bare street canyon, the introduction of vegetation weakens the intensity of the circulation wind field in the street canyon and reduces the pollutant displacement rate at the top of the street canyon, increasing the pollutant concentration near leeward and windward sides of the green street canyon. Morakinyo et al. [101] studied different trees' impacts on the street canyon's thermal environment. They believed that leaf area index, tree height, and trunk height are the main control factors to improve or aggravate the thermal environment in the street. Zhou et al. [102] studied the airflow characteristics in the presence of trees in the street canyon. It is found that the wind velocity in the street canyon decreases to various extents after trees are planted, and the unreasonable extreme wind velocity is improved to some extent; plants are significant to reduce the wind velocity, stabilize the flow field, and improve the comfort of the pedestrian area; planting trees can reduce the wind velocity around the building, the convective heat transfer on the wall, and the energy consumption of buildings. However, the morphological characteristics of different tree species have different attenuation capabilities for solar radiation and, thus, different potentials for regulating thermal comfort and improving pollutant concentration. In addition, the change in building surface temperature caused by the shadow-casting effect of trees on buildings can help reduce the radiation load of pedestrians and improve thermal comfort, even when the wind environment is weakened, especially in high-density urban street canyons [98]. As shown in Figure 6, Hosseinzadeh et al. considered the influence of vegetation cooling degree. When the vegetation cooling degree increases, the air temperature significantly decreases, and the air temperature at the pedestrian height of planting trees (such as birch) near the buildings' edges can reduce by 2–3 °C [55]. Li et al. found from a numerical simulation that increasing leaf area index and tree density can improve thermal comfort, especially the increasing tree density can reduce the equivalent temperature by 1.1 K. However, a higher leaf area index or tree density leads to the accumulation of more pollutants [53].

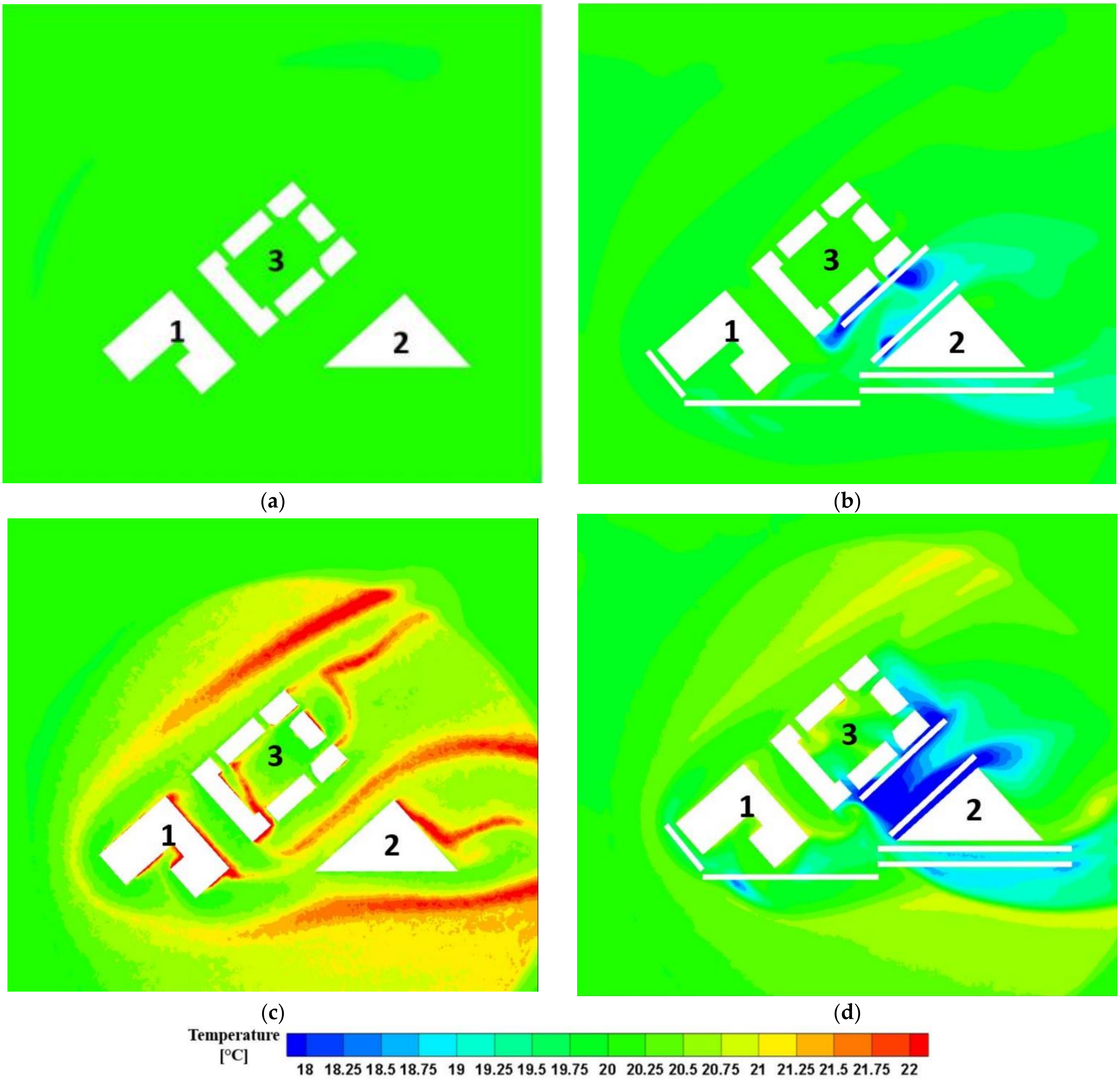


Figure 6. Contours of temperature at the pedestrian level [55]. (**a**) Scenario 1 without vegetation. (**b**) Scenario 1 with trees. (**c**) Scenario 5 without vegetation. (**d**) Scenario 5 with trees.

5.2. Wind Speed and Direction

Wind tunnel experiments and field measurements have found that wind speed and direction impact the diffusion of street pollutants. With the increase in wind speed, the resistance of trees is reduced, and the diffusion of pollutants in the atmosphere is more intense [103]; on the contrary, the aerodynamic effects are more critical at lower wind speeds, causing little turbulent dispersion [10]. The wind direction directly leads to a significant change in the concentration of pollutants in the street, especially when the wind is parallel, and the effect of trees dominated [3]. Unlike the treeless street canyon, the concentration of pollutants in the street is higher when it is perpendicular to the wind direction of the street. When there are trees, the wind direction parallel to the street is conducive to the diffusion of pollutants, and the wind direction perpendicular to the street is weak [4,44].

Hosseinzadeh et al. studied the urban area air quality considering the trees and found that reducing the inlet wind speed can increase the concentration of pollutants [55]. Zhang et al. took roadside vegetation and street canyons as the research objects. They assessed the impact of vegetation on pollutants based on the area-averaged normalized PM concentration per investigated area. The result found that the perpendicular wind had the best vegetation effects, while the oblique wind had the worst vegetation effects among the three wind directions [85]. In asymmetric street canyons, when the wind direction is perpendicular to the street, there will be up-and-down steps due to the difference in the height of buildings on both sides. The presence of trees will disturb the airflow and increase the peak value and distribution of pollutant concentration [34].

6. Conclusions and Prospect

The research on the wind environment and pollutant dispersion in urban street canyons under the influence of trees by numerical simulation is relatively mature. The existing mathematical models for tree description can depict some tree characteristics. Trees in urban street canyons under different factors have been studied by numerical simulation with many beneficial results. These are of great significance for evaluating the reduction efficiency of street trees on street valley pollutants and the ventilation effect in the street to find out the planting design strategy to reduce the exposure risk of air pollution and improve the street ventilation.

Current studies still face many difficulties in guiding the planting of trees in urban street canyons, mainly because (1) the failure to accurately describe the characteristics of trees limits the ability to reflect the difference of tree species in the process of numerical simulation; (2) it is complicated to provide the relevant parameters of the mathematical model for tree characterization, especially resistance coefficient and leaf area density need to be determined according to experiments or field measurements, and the empirical parameters contained in the turbulence model still need to be continuously revised; (3) the influence of multiple complex factors in the street canyon has not been sufficiently studied yet, including the superimposed effects of heat, chemistry, biology, wind direction, tree species, and other factors; and (4) the research on the influence of leaf surface microstructure on pollutant reduction is seldom studied.

Future research should focus on (1) numerical simulation in real situations, including natural street canyon morphology, natural meteorological conditions, differences of tree species, etc., and (2) further consideration of the pollutant settlement, removal, and thermal effect of trees in the mathematical model so that the numerical simulation can completely describe the impact of trees on the pollutant distribution, dispersion, and absorption process in the street canyon.

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