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Numerical studies of the outdoor wind environment and thermal comfort at pedestrian level in housing blocks with different building layout patterns and trees arrangement

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ABSTRACT

Alleviating the urban heat-island effect (UHI) is one of the important means to meet energy conservation and pollution reduction targets by demand side. Rational architectural layout and landscape design are significant measures to achieve building energy efficiency and sustainable building. In this study, the effects of building layout patterns and trees arrangement on the outdoor wind environment and thermal comfort at the pedestrian level were investigated by using Simulation Platform for Outdoor Thermal Environment (SPOTE). The conclusions were summarized as follows: 1) it has been found that trees arrangement, buildings layout patterns and their orientations with respect to wind have significant effects on the outdoor wind environment and pedestrian level thermal comfort. The long facades of building, which are parallel to the prevailing wind direction, can accelerate horizontal vortex airflow at the edges and obtain pleasant thermal comfort and wind environment at pedestrian level. 2) Configurations that contain a square central space articulated by buildings and oriented toward the prevailing wind can offer better exposure to air currents as a result of attenuated revised standard effective temperature (SET*). Such configurations are regarded as the optimum building layout patterns and trees arrangement.

1. Introduction

Under the background of low-carbon development, several countermeasures are conducted for energy conservation and pollution reduction, and alleviating the urban heat-island (UHI) is an important link. However, the outdoor thermal environment represented by the UHI phenomenon that accompanies urbanization is deteriorating in recent years during summer, especially in residential areas. The contributing factors of current deteriorations in the outdoor environment include the changes of artificial coverage and reduction of green areas [1]. In line with the rapid urbanization and growing of urban population, there are increasing concerns on the quality of urban environment. In this respect, urban thermal environment is one of the major concerns, which had lead to numerous research and various mitigating measures [2]. Therefore, architectural design and planting trees are accepted as effective means of easing the UHI, which could reduce residential energy consumption by providing a better outdoor boundary condition [3]. As such, there have been many proposals on outdoor wind and thermal environment from the view point of architectural design and landscape greening design [4–6].

The arrangement of buildings has been assumed to be the main countermeasures to improve outdoor microclimate by changing the layout of buildings (buildings shape, height and planning pattern) and the buildings coverage ratio for a given background [7,8]. Some studies have been carried out to propose solutions for some regular or particular cases, such as simulating several aerodynamic effects that may occur around buildings depending on wind tunnel tests [9], investigating the relationship between the average wind velocities at pedestrian-level and building density of actual residential buildings [10]. In addition, the relief effect of trees arrangement has also attracted attention, based on their shading of solar and long-wave radiation and production of latent heat from their planting. Ooka et al. used multi-objective genetic algorithm and coupled simulation to pursue the optimum arrangement of

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trees for designing a pleasant outdoor environment [5]. Hong et al. combined geometrical models and numerical simulation to discuss optimal tree design for indoor ventilation in the residential district [11]. However, most of these studies have been concerned with proposing an evolution method to measure the effects of these techniques on outdoor microclimate. The effects of different building layout patterns and trees arrangement on the outdoor thermal environment in housing blocks have not been established yet. Appropriate buildings layout patterns and trees arrangement are very important to design a comfortable outdoor environment in residential areas [12,13]. However, recent design often neglected these aspects [14]. For the designers, it is useful and necessary to develop a design method to determine the optimum arrangement in the view point of creating a comfortable outdoor environment.

Under the present circumstance, significant progress has been made in the field of sustainable building design [15]. However, there is still more to be done for reducing building reliance on non-renewable energy resources for mega cities like Beijing in China. With the aid of Simulation Platform for Outdoor Thermal Environment (SPOTE), numerical simulation and comparison are carried out to investigate the effects of different building layout patterns and trees arrangement on pedestrian level wind environment and thermal comfort in housing blocks, in order to provide references for designing a comfortable outdoor microclimate in urban residential districts.

2. Methodology

2.1. Details of SPOTE model

In this study, Simulation Platform for Outdoor Thermal Environment (SPOTE), consisting of an air model, vegetation model, underlying surface model and a general radiation calculation model, is chosen for numerical simulation, and coupled calculation of radiation, convection, conduction and airflow are carried out considering the vegetation influences. The details of sub-models of SPOTE are introduced as below.

2.1.1. Air model

A standard k–ε model is employed by applying extra terms in the flow, momentum, and energy equations for the aerodynamic effect of vegetation. The drag force of vegetation canopy is presented with a term F_i added in the i component of momentum equation, as well as F_k and F_ε added into the transport equations of turbulent energy (k) and energy dissipation rate (ε), respectively, for denoting the effects on turbulent flow field. F_i, F_k, and F_ε are derived by applying the spatial average to the basic equations.

$$F_i = -\frac{1}{2}C_d\eta a\langle u_i\rangle\sqrt{\langle u_i\rangle^2} \tag{1}$$

$$F_k = \langle u_i\rangle F_i - 4C_d\eta a\sqrt{\langle u_i\rangle^2}k \tag{2}$$

$$F_\varepsilon = \frac{\varepsilon}{k}\left(C_{p\varepsilon1}\langle u_i\rangle F_k - C_{p\varepsilon2}4C_d\eta a\sqrt{\langle u_i\rangle^2}k\right) \tag{3}$$

where C_d is the drag coefficient; η is the green coverage ratio, and a is the leaf area density [m^2 m^{-3}]. By comparing the numerical results with field measurements, the model coefficients $C_{p\varepsilon1}$ and $C_{p\varepsilon2}$ are respectively defined as 1.8 and 0.6 [16].

In addition, the functions of vegetation on temperature and humidity are applied using the following equation:

$$\frac{\partial\langle\theta\rangle}{\partial t} + \langle u_j\rangle\frac{\partial\langle\theta\rangle}{\partial x_j} = \frac{\partial}{\partial x_i}\left(\alpha\frac{\partial\langle\theta\rangle}{\partial x_i} + \frac{\nu_t}{\sigma_\theta}\frac{\partial\langle\theta\rangle}{\partial x_i}\right) + \frac{1}{\rho c_p}2LAI\alpha_c(\langle\theta\rangle - \langle\theta_p\rangle) \tag{4}$$

$$\frac{\partial\langle d_a\rangle}{\partial t} + \langle u_j\rangle\frac{\partial\langle d_a\rangle}{\partial x_j} = \frac{\partial}{\partial x_i}\left(D\frac{\partial\langle d_a\rangle}{\partial x_i} + \frac{\nu_t}{\sigma_w}\frac{\partial\langle d_a\rangle}{\partial x_i}\right) + \frac{1}{\rho\Lambda}2LAI\alpha_w(\langle d_a\rangle - \langle d_{a,p}\rangle) \tag{5}$$

where θ is the air temperature [K]; α is the convection coefficient for heat exchange [W (m^{-2} K^{-1})]; ρ is radiation absorptivity; C_p is the air heat capacity at constant pressure [J (kg K)$^{-1}$]; θ_p is the temperature of leaves [K]; d_a is the absolute humidity of air [kg kg^{-1}]; D is the diameter of leaves [m]; LAI is the leaf area index; Λ is the latent heat of vaporization of water [J kg^{-1}], and α_C [W (m^{-2} K^{-1})]and α_W [kg (m^{-2} s^{-1} kPa^{-1})] are the convective coefficients for heat and mass exchange, respectively.

2.1.2. Heat balance for vegetation

The surface temperature and the complex radiation process of the vegetation canopy are calculated with the heat balance equations as follows.

$$\varphi_{rad,SR} + \varphi_{rad,LR} + \varphi_{conv,p-a} + \varphi_{trans,p-a} = 0 \tag{6}$$

$$\varphi_{conv,p-a} = 2\alpha_c(\theta_p - \theta) \tag{7}$$

$$\begin{cases}\alpha_c = \rho C_p/r_a \\ r_a = A(D/W)^{0.5}\end{cases} \tag{8}$$

$$\varphi_{trans,p-a} = 2a\frac{0.625\Lambda\rho}{c_p p(r_a + r_i)}\Delta p_{p-a} = 2a\alpha_w(d_{a,p} - d_a) \tag{9}$$

where $\varphi_{rad,SR}$ is the short-wave solar radiation intensity absorbed by leaves [W m^{-2}]; $\varphi_{rad,LR}$ is the long-wave heat radiation absorbed by leaves [W m^{-2}]; $\varphi_{conv,p-a}$ is the sensible convective heat transfer between leaves and air in the vegetation canopy [W m^{-2}]; $\varphi_{trans,p-a}$ is the heat exchange of leaves transpiration [W m^{-2}]; A is the surface area of leaves [m^2]; W is the air velocity at leaf surface [m s^{-1}]; ($r_a + r_i$) is total resistance in transpiration [m s^{-1}] [17]; p is atmospheric transmittance.

The transportation of radiation including solar and long-wave radiation among vegetation canopy and around surfaces is calculated with a generalized radiation simulation system using the Monte-Carlo method, in which the non-transparent objects and half-transparent objects are processed with 2D and 3D basic units respectively for calculating the decay of emitted tracer ray [18]. Considering the symmetrization rule of radiation for the calculation of DEA (Direct Exchange Area), TEA (Total Exchange Area) can be obtained by Geb-Hart method [19]. So, the radiative heat transportation from one grid to another in a gray space can be easily computed. The short wave (solar radiation) and long wave radiant fluxes incident to the plant canopy are calculated with a decay exponential function respectively as $exp(-lka)$, where k is the absorption coefficient for long-wave and short wave and l is the length by which radiant flux passes through the plant canopy.

2.1.3. Underlying surface model

The Underlying surface model is created using the following equations:

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