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Numerical simulation of the impact of different vegetation species on the outdoor thermal environment

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ABSTRACT

Rational layout of vegetation can significantly alleviate the urban heat-island effect and improve outdoor thermal environment. However, quantitative researches about the impact of different vegetation species on the outdoor thermal environment are still scarce and the actual engineering problem that what's the best choice, grass, shrub or trees cannot be responded. Meanwhile, a three-dimensional model which can accurately predict the effect of green on thermal environment and guide the green design is urgently needed. Thus, a finite volume method with unstructured mesh is used to simulate the impact of vegetation on the outdoor thermal environment for three common vegetation species, namely: trees, shrub and lawn. Special attention is paid on the variation of air temperature at 1.5 m, surface temperature, PET, WBGT, wind speed and pressure with these species. The study could be described as follows: A simulation method including the model of three-dimensional vegetation is developed for predicting and evaluating the outdoor thermal environment and its accuracy is confirmed by comparing simulation results and field measured data; For different evaluation standards and areas, the sequence of the improvement of different species on outdoor thermal environment is quite different: For air temperature at 1.5 m and thermal comfort and safety (PET and WBGT), the sequence is trees > lawn > shrubs, but for surface temperature, the sequence is lawn > shrubs > trees; For these areas located in the downstream of planting area, trees and shrub can reduce the wind speed and decrease the pressure of the building. But for these areas located in the downstream of without planting area, they can increase the wind speed and the pressure; Suggestions are provided to guide the arrangement of these species in planning stage to achieve the purpose of optimizing outdoor thermal environment in summer and outdoor wind environment in winter.

1. Introduction

Under the background of low-carbon development, alleviating the urban heat-island (UHI) is one of the important countermeasures to achieve energy conservation and pollution reduction. However, the outdoor thermal environment represented by the UHI phenomenon that accompanies urbanization is deteriorating in recent years during summer, especially in mega cities like Tianjin in China. 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 led to numerous research and various mitigating measures (Mochida et al., 2008). The contributing factors of current deterioration in the outdoor environment include the changes of artificial coverage and reduction of green areas (Wong et al., 2007). Therefore, rational layout of vegetation is accepted as effective means of easing the UHI, which could reduce residential energy consumption by providing a better outdoor boundary condition (Ng et al., 2012). As such, there have been many proposals on outdoor wind and thermal environment from the view point of landscape greening design (Chen et al., 2004; Ooka et al., 2008; Shahidan et al., 2012). However, these researches mostly focused on qualitative study, little is known of qualitative understanding. In order to guide the design directly, people are not satisfied with the existing qualitative understanding, and hope to get a quantitative awareness of the impact of green on outdoor thermal environment to respond to such actual engineering problem that what is the best choice for different plant types.

To respond to such pending problems, some experimental quantitative studies about the impact of green on the outdoor thermal

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environment have been carried out. Klemm et al. (2015) studied the impact of urban parks on thermal comfort by means of questionnaires. They found that green infrastructure improves generally perceived thermal comfort. Using experiment measuring, Susorova et al. (2014) investigated the effects of climbing plants on facade thermal performance and local micro-climate was conducted for several days in July 2013 on university buildings in Chicago. The experiment involved measurements of facade surface temperature, air temperature, relative humidity, absolute humidity, and air velocity near the four facades of different orientations in the existing buildings. Tan et al. (2015) studied the effects of plant evapotranspiration rate and shrub albedo on the reduction of mean radiant temperature in a rooftop garden with three plant types by field measurement. They found that different plants have different characteristics and impact on temperature reduction. By modifying the canopy density of trees and quantity and the albedo values of ground materials, Shahidan et al. (2012) investigated the optimum cooling effect of trees with ground materials in mitigating the urban heat island (UHI) and the benefits towards building energy performance in a tropical climate.

Since experimental measurements can only be carried out in the stage which outdoor thermal environment has formed, little is known of the phenomena in the design and planning stages. Therefore, the numerical simulation has become a powerful tool for solving this problem. Using the ENVI-met computer simulation model and measurement, Srivanit and Hokao (2013) investigated the importance of greening as a potential method for passive cooling and for use in reducing ambient air temperatures, especially at a pedestrian level. Perini and Magliocco (2014) investigated the influence of several types of green areas (vegetation on the ground and on roofs) on temperature mitigation and on comfort improvements for different atmospheric conditions and latitudes in a Mediterranean climate by ENVI-met Version 3.1 BETA V. Based on those studies, it is possible to understand the impact of different green types on the outdoor thermal environment. However, inadequate understanding still exists: 1) Quantitative comparison among common plant types are still scarce, leading to such actual engineering problem that what's the best choice, grass, shrub or tree unsolved. 2) Those studies rarely pay attention to the difference of the resistance among different plant types to flow, which has significant effects on the outdoor wind environment and pedestrian comfort in residential district. 3) In those studies, one-dimensional vegetation model is used to calculate the radiation of the plant and the resistance of the plant to the flow. So, a three-dimensional model which can accurately predict the effect of green on thermal environment and then guide the outdoor green design is urgently needed.

To solve these pending problems and to provide a comprehensive understanding of the impact of green on outdoor thermal environment, a finite volume method including three-dimensional vegetation modal with unstructured mesh is used to predict and evaluate the outdoor thermal environment. Meanwhile, a quantitative study about the influence of different green types on the outdoor thermal environment is carried out, which can be used to guide the arrangement of different green types in the design and planning stages. It also can be used to achieve the purpose of optimizing an outdoor thermal environment in summer and an outdoor wind environment in winter.

2. Methodology

In this section, a simulation method based on the project of animation park of Tianjin Eco-city is developed by using Computational Fluid Dynamics (CFD) simulation technology and field measured data. Meanwhile, the accuracy of the simulation method is confirmed by comparing the simulation results and the field measured data. The simulation method intends to achieve following objectives:

Scope: The scope of the study on outdoor micro-climate expands from a single architectural outdoor thermal environment to neighborhood scale, from the qualitative description of macro-climate and thermal environment to the quantitative study of the micro-climate based on the city-based geographical features;

Methods: The method will be combined with CFD, heat transfer, architecture, urban planning and landscape architecture;

Value: Through the establishment and verification of the model, this paper aims to provide a method that contains three-dimensional green model under solar radiation, and to offer a simple, accurate and effective simulation method for architects, urban planners as well as designers who engaged in urban designing, planning and management.

2.1. Field measurement

A field measurement was carried out in Tianjin, which is located in north China (39.03 N, 117.68 E). Tianjin has a population of more than 15 million and endures a warm temperate monsoon climate. The study area is located in National Animation Industry Park in Tianjin eco-city, as shown in Fig. 1(a). From Fig. 1(a), it can be seen that the environments surrounding of the study area (National Animation Industry Park) was either abandoned farmland or constructing areas when measured, details are as follows: Both of the northeast and southwest of the animation park are abandoned farmland and the northwest and southeast of the park are constructing areas. Meanwhile, the nearest distance between these areas and the measuring point is 261 m. Thus, the effect of neighbor areas on the thermal environment of the study area can be ignored.

In order to compare to the impact of different green types on outdoor thermal environment and to verify the accuracy of the simulation method, four measurement points and a portable weather station are installed in the Animation park to obtain the air temperature and wind speed data. Fig. 1(b) shows the layout of the portable weather station and sensors. The portable weather station is used to measure the parameters of the mainstream and points 1,2,3,4 are located in square, grass, shrub and trees, respectively. Meanwhile, all of the points are sited 1.5 m from the ground. Table 1 shows the detailed information about the instruments used in the field measurement. Meanwhile, in order to ensure the accuracy of the measurement, all instruments in the laboratory are calibrated by professional institutions annually, and all instruments will self-calibrate in every test. Air temperature was collected by the HOBO data logger which was mounted in a radiation shield, shown in Fig. 2. The air temperature was sampled once per 1 min and wind velocity was sampled once per 4 Hz. The formal measurement was carried out from 20th April to 4th May and 17th July to 2nd August 2015. These field measured data are used to verify the accuracy of the simulation method in the next section.

2.2. Numerical simulation

All numerical simulations are carried out using the software package Fluent 13.0. As far as this paper is concerned, the software Fluent does not include the gradient model of the wind speed, the resistance and evapotranspiration model of plant, which are extremely important for modelling the impact of trees on outdoor thermal environment. Thus, source terms are added to the Momentum equation, Energy equation and Quality equation, and all source terms of the equations in Section 2.2 are loaded on Fluent 13.0 by the user defined functions (UDF).