Building and Environment 130 (2018) 27–39

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Effects of the tree distribution and species on outdoor environment conditions in a hot summer and cold winter zone: A case study in Wuhan residential quarters

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ARTICLE INFO

Keywords:
Tree distribution
Tree species
ENVI-met
Cooling and ventilation
Residential quarters

ABSTRACT

Residential district is the important space for people living and outdoor activities. Vegetation is proved to be effectively regulate microclimate. Living in Wuhan, residents have to suffer heat stress in summer and strong cold wind in winter simultaneously. It is necessary to dictate vegetation types and layout in residential area to get comfortable environment both in hot summer and cold winter. This study examined the vegetation influences of residential wind environment in hot and cold seasons by using the ENVI-met model V4. Field measurement validated the performance of ENVI-met model. The simulation was based on multi-story buildings representing the current primary form of residential area in Wuhan. 3 scenarios with three tree arrangements and 8 vegetation species were simulated. Height-to-distance ratio of trees (as "Aspect ratio of trees", ART) was used to describe the tree distribution. Results showed that the impact of vegetation on both heat environment and ventilation depended on tree arrangement, LAI, crown width and tree height. The comparison of 3 tree distributions revealed that trees with an ART < 2 should be a priority to mitigate hot environments due to the large effects on PET reduction in summer. Evergreen species with an ART < 2 also effectively decreased wind speed in winter as well as blocked direct sunlight, resulting in negative effects on PET. Tall trees with a large LAI and canopy diameter should be a priority to improve the comfort of outdoor environments.

1. Introduction

1.1. Background of study

An increasing number of people reside in cities due to rapid urbanization. Residential areas are the primary outdoor spaces for recreational activities. Comfortable outdoor residential environments encourage people to leave their homes and develop social activities. Many cities in China, such as Wuhan, Nanjing and Changsha, are located in hot summer and cold winter zones based on the Building Thermal Design Code of China (GB50176-93) [6]. Residents in this climate zone face high temperatures in summer and strong winds in winter [16]. This type of climate is not conducive to outdoor activities.

1.2. The cooling and ventilation effects of vegetation

Many researchers suggest some effective ways to mitigate high temperatures based on building layouts, building materials, pavements, roofs and landscape environments [2,4,17,24,29,32,35,36,41,48]. Vegetation is an effective method to cool hot temperatures in summer [5,8,46]. The cooling effects of trees are much more obvious than those of grass [23,37] because trees provide more shade, which effectively reduces radiant temperature [31,44]. Various building environments and increased vegetation clearly decrease heat stress [28,33], Ng [50] performed a parametric study in the high-density city Hong Kong and suggested that tree coverage should be approximately 30% of the urban area. This amount of tree planting was feasible and effectively mitigated heat from the environment. Different tree species exert various impacts on cooling because of their different transpiration rates, leaf area indexes, and crown diameters [3,11,40]. Planting patterns and trees layout also influence the decline in hot temperature [10,30]. Vegetation apparently decreases wind velocity due to the drag force of plants' canopies [43]. Plants exert positive effects on strong winds in winter [12,15] and establish a comfortable wind environment. Most

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https://doi.org/10.1016/j.buildenv.2017.12.014
Received 25 September 2017; Received in revised form 13 December 2017; Accepted 14 December 2017
Available online 18 December 2017

previous researchers have investigated the physical characteristics of plants or the relationship of plants and buildings.

Vegetation in China is generally used to create spaces for outdoor activities in residential quarters. Studies on the cooling and ventilation effects of residential vegetation from a spatial view are necessary and interesting. Few studies have simultaneously focused on the cooling and ventilation effects of plants in various spatial compositions. Vegetation in a hot summer and cold winter zone should play a regulatory function to mitigate heat stress and the effects of strong cold winds.

1.3. This research

This research determined the vegetation types and layout from a spatial perspective in a residential area needed to achieve a comfortable environment in a hot and cold environment. This research 1) analyzed the effect of various vegetation distributions and species on summer and winter environments, 2) identified the optimal vegetation distribution to achieve better environments in hot and cold seasons, and 3) determined the most appropriate vegetation species to establish a comfortable environment in Wuhan residential districts.

2. Climate and sites

Wuhan is located in central China (30°35′N, 114°17′ E, altitude 23 m). It includes 8 million urban dwellers, which makes it the 5th largest city in China. Wuhan exhibits a typical tropical monsoon climate with abundant solar radiation, hot summers and cold winters. The summer season occurs from June to September, and the hottest days are concentrated in July and August. The average temperature in July and August is 29.8 °C (Fig. 1), and the extreme maximum temperature reaches 39.4 °C. Wind velocity in the summer is low, with a mean speed of 1 m/s from the southwest. The cold season occurs from December to February. The average temperature in winter is 3 °C. The average wind gust in winter is 4–5 m/s from the north. Average relatively humidity is about 73–77% all year around.

A residential district with multistory buildings was chosen for this study because it was currently the primary form of residential areas. The general land development intensity was extracted from a building survey and land use map of Wuhan in 2013. A general residential block was constructed on a 200 × 200 m area for simulation (Fig. 2). Six-story buildings (12 × 50 m) occupied 31.5% of the total area in this general residential block.

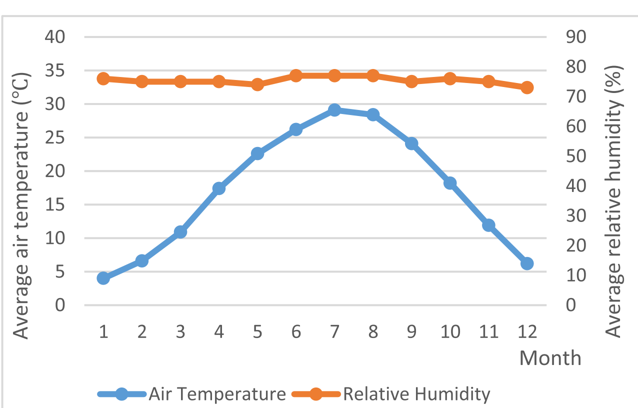

Fig. 1. Monthly temperature and humidity in Wuhan. Data source: China Meteorological Administration, climate data in Wuhan (1980–2010).

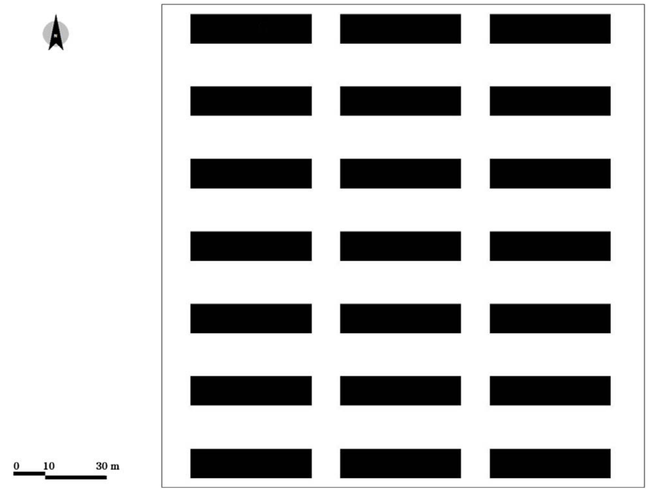

Fig. 2. The general residential block for simulation.

3. Methodology

3.1. ENVI-met model description

ENVI-met is a three-dimensional microclimate model that simulates outdoor environments. It can simulate surface-plant-air interactions of urban environments with a spatial resolution of 0.5–10 m and time resolution of 10 s [28]. ENVI-met is a computational dynamics model that is used to simulate aerodynamics, thermodynamics and radiation balance. The ENVI-met model is widely used to simulate the wind flow, pollutant dispersion, radiation fluxes and soil temperature [30]. Plants in the ENVI-met model are described as a porous media that interacts with surroundings via transpiration, evapotranspiration and photosynthesis. Leaf area density (LAD) is an important parameter that is used to model the turbulence and heat exchange between vegetation and surroundings. LAD may be obtained from the leaf area index (LAI) [11,22,30]. There are also some limitations in the ENVI-met model. Diurnal variations of the air temperature and relative humidity at the boundary conditions of the model area are improved in ENVI-met 4.0, but the wind conditions and cloudiness are not changed. The model cannot calculate the influence of anthropogenic heating, and the radiative fluxes are not calculated as accurately as reality. ENVI-met overestimates turbulent productionκin areas with acceleration or deceleration in the standard κ-εclosure, e.g., the flow around a building, which causes inaccuracies in wind speed [1,19,21].

However, ENVI-met is one of the most widely used models in studies of the impact of vegetation on thermal environments, and it is an effective simulation model [27,39]. Field measurement is commonly used to verify ENVI-met. Many initials settings for simulation including model configuration and boundary conditions are presented in Table 1. The coefficient of determination (R^2), the Root Mean Square Error (RMSE) and the Willmott's index of agreement (d) are widely used to validate simulation results and measurement data.

3.2. Field measurements and ENVI-met calibration

The field experiment was performed in the residential area of Xiyuan, which is located on the west side of Huazhong Agricultural University (Fig. 3) in Wuhan. The site consisted of 6- and 11-story buildings in rows. There were approximately 30 types of plants in the Xiyuan residential block. Trees were divided into 8 categories according to height, crown diameter and ecological habits. Table 2 lists detailed data of 8 typical trees. A meteorological station (no. 1053) was located 1.8 km to the east, at Huazhong Agricultural University. This station provided the meteorological data for the simulation on the