Energy and Buildings 150 (2017) 118–131

Contents lists available at ScienceDirect

Energy and Buildings

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

Optimal parameters of green roofs in representative cities of four climate zones in China: A simulation study

Chao Zeng[a], Xuelian Bai[b,c,**], Lexiang Sun[b,c], Yunzhou Zhang[b,c], Yanping Yuan[a,*]

[a] School of Mechanical Engineering, Southwest Jiaotong University, 610031 Chengdu, PR China
[b] Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, Chongqing University, Chongqing, 400045, PR China
[c] National Centre for International Research of Low-Carbon and Green Buildings, Chongqing University, Chongqing, 400045, PR China

ARTICLE INFO

Article history:
Received 25 December 2016
Received in revised form 26 April 2017
Accepted 30 May 2017
Available online 3 June 2017

Keywords:
Green roof
Optimal properties
Energy consumption
Comfort performance

ABSTRACT

The energy performance of green roofs is influenced by many factors and the regulation differs significantly to each other in different climate zones. Previous research on green roofs confined to a single climate zone with a single set of properties, lacking comparative studies. In this study, a simulation was used for determination of the optimal parameter settings for green roofs in different climate zones. Firstly, a simulation model was established, and a field experiment examined the bias of the model. Leaf area index, plant height, and soil thickness were used as variables. Harbin, Beijing, Chongqing, and Guangzhou were selected as representative cities of four climate zones in China. For quantification of energy savings and indoor thermal comfort improvements, both cool and conventional roofs were simulated alongside green roofs for comparison. Optimal parameters of green roofs were found to be closely related to meteorological conditions in each city. In terms of energy savings, the recommended soil thickness and leaf area index in the four cities are 0.3 m and 0.5, respectively. The optimal plant height is 0.3 m, except in Beijing, where it is 0.1 m. Optimized green roofs are recommended for heating-dominated cities, while cool and green roofs perform similarly in cooling-dominated areas.

1. Introduction

With rapid urbanization, environmental problems in cities have grown tremendously. The installation of green roofs is considered as an effective strategy of mitigating environmental degradation. Both research and practice have revealed many advantages of green roofs, including mitigating the urban heat island effect [1–4], decreasing storm water runoff [5,6], enriching biodiversity [7,8], and cleaning runoff water and air [9,10]. In addition, green roofs improve the energy efficiency of buildings [11,12]. Therefore, they are widely used in countries such as Singapore, Germany, the United States, and Japan.

Green roofs provide passive cooling to the building environment [12,13]. Meanwhile, because the thermal mass of green roofs is so great, temperature decrement and attenuation occur. In Athens, a study of a green roof system installed in a nursery school building reported reductions in the building-wide cooling load of 6–49% and in that of the top floor of 12–87% [14]. Further, a comparison of a green roof system with a light growing medium and a steel-decked reference roof indicated that the green roof could reduce heat gain by an average of 70–90% in summer and prevent heat loss by 10–30% during winter in Canada [15]. A simulation study found that the indoor temperature, for a non-air conditioning status of the building, was decreased up to 1.1 K during a typical summer day and was increased up to 0.7 K during a typical winter day as a result of installing green roofs in Athens [16]. The surface temperature of the green roof is found to be up to 15 K lower than that of a conventional roof [17]. Research has also found that green roofs can reduce roof membrane peak temperatures and impose a 5-h delay of peak temperature from 2:00 to 7:00 p.m. [18] owing to the thermal mass effect [19]. Overall, increased shade, better insulation, and the higher thermal mass of the roof system all improve thermal performance with green roofs [20,21].

Energy savings depend on many factors, such as green roof type, depth and composition of the growing media, plant selection, irrigation type, and insulation specifications [22,23]. Theodosius's parametric study of various characteristics of green roofs revealed

* Corresponding author at: School of Mechanical Engineering, Southwest Jiaotong University, 610031 Chengdu, PR China.
** Corresponding author at: Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, National Centre for International Research of Low-Carbon and Green Buildings, Chongqing University, Chongqing, 400045, PR China.
E-mail addresses: xuelianbai@cqu.edu.cn (X. Bai), ypyuan@home.swjtu.edu.cn (Y. Yuan).

http://dx.doi.org/10.1016/j.enbuild.2017.05.079
0378-7788/

Nomenclature

C_{eg}	Latent heat flux bulk transfer coefficient at ground layer
C_f	Bulk heat transfer coefficient
C_{hg}	Sensible heat flux bulk transfer coefficient at ground layer
$C_{p,a}$	specific heat of air at constant pressure (1005.6 J/kg K)
F_f	Net heat flux to foliage layer (W/m^2)
F_g	Net heat flux to ground surface (W/m^2)
H_f	Foliage sensible heat flux (W/m^2)
H_g	Ground sensible heat flux (W/m^2)
I_S	Total incoming short-wave radiation (W/m^2)
I_{ir}	Total incoming long-wave radiation (W/m^2)
l_f	Latent heat of vaporization at foliage temperature (J/kg)
L_f	Foliage latent heat flux (W/m^2)
L_g	Ground latent heat flux (W/m^2)
LAI	Leaf area index (m^2/m^2)
q_{af}	Mixing ratio for air within foliage canopy
$q_{f,sat}$	Saturation mixing ratio at foliage temperature
$q_{g,sat}$	Saturation mixing ratio at ground temperature
T_{af}	Air temperature with in the canopy (K)
T_f	Foliage temperature (K)
W_{af}	Wind speed with in the canopy (m/s)
a_g	Albedo (short-wave reflectivity) of ground surface
ε_f	Emissivity of canopy
ε_g	Emissivity of the ground surface
ε_1	$\varepsilon_g + \varepsilon_f - \varepsilon_f\varepsilon_g$
p_{af}	Density of air at foliage temperature (kg/m^3)
δ	Stefan-Boltzmann constant (W/m^2 K^4)
δ_f	Fractional vegetation coverage

that leaf area index (LAI), climate zone, and soil thickness are the main factors in the cooling effect. Further, the most important parameter of a foliage layer is the LAI [24]. Doubling the canopy LAI (from 3 to 6) could accomplish a 50% reduction in roof heat flux [25]. As LAI increases, the energy savings for cooling increase, while those for heating decrease [26]. In terms of soil thickness, Teemusk found that a 100-mm substrate layer in the garden could decrease temperature fluctuations significantly in the summer [27]. Another study conducted by N. H. Wong produced an reduction in annual energy consumption of 1 MWh (soil thickness = 0.1 m) to 5 MWh (soil thickness = 0.9 m) in a green roof simulation from that with conventional roofs [27]. Therefore, it is important to consider the plant coverage in green roof simulations and building energy demand predictions [28].

The energy-saving and thermal comfort performances of green roofs also vary with meteorological conditions. Sailor analyzed the effects of roof design on building energy consumption in four cities representing diverse climatic conditions in the United States. It's found that different outdoor meteorological conditions were found to require different construction and insulation plans for green roofs [26]. While numerous studies conducted in the aforementioned locations have illustrated that green roofs enhance energy performance, Jim and Tsang found that they have a negative effect on energy performance in Honking [27]. Therefore, further research must be carried out under different climatic conditions.

China accounts for one-fifth of the world's total area. Based on the coldest and hottest monthly mean temperatures, China can be divided into four climate zones from north to south: severe cold, cold, hot summer and cold winter, and hot summer and warm winter zones. These climate zones exhibit huge differences in solar radiation, air temperature, humidity, wind speed, and other outdoor weather conditions. Domestic green roof research has only considered the applicability and application in a single city, such as Shanghai, Guangzhou, and Beijing [29–31]. Further, China is quite behind other parts of the world in terms of research on green roof plant applicability and parameter settings. Most researches have focused on the green roof with a single set of properties [32,33]. Therefore, more effort is needed to find out the effect of green roof properties on its energy performance. Moreover, comparisons of green roof performance across different climate zones will contribute to the regulation of green roof settings throughout China and zones with similar meteorological conditions.

This study firstly explored the optimal properties for green roofs in different zones in China and then compared properties between different cities. A field experiment in Chongqing was used to verify the accuracy of the model in this study. Harbin, Beijing, Chongqing, and Guangzhou were selected as representative cities of China's four climate zones. Soil thickness, plant height, and LAI were selected as the main properties affecting the energy savings of green roofs. Secondly, a comparative study of energy consumption and indoor comfort was conducted for green, conventional, and cool roofs. Once the references (roof types and properties) for comparison are defined and articulated, the applicability and specific properties of green roofs can be determined.

2. Models and methodology

2.1. Simulation model and field test

2.1.1. Simulation model

This study used the green roof module developed by Portland State University and introduced in the standard versions of EnergyPlus beginning in April 2007 [23,26]. The energy budget of the planted roof was divided into foliage layer (F_f) and ground surface (F_g) budgets [23]. The various parameters for latent and sensible heat flux are described in some detail below, and the equation set was reduced to the simultaneous solution of the two equations for the foliage and ground.

As the light shoots at the ground, part of the light shoots on the surface of the vegetation, the left brings a certain thermal radiation to the soil. Radiation of the two part has same mechanism but different emission coefficient. As is shown in the equation (1) and (2), the sort of plant has a great influence on short- and long-wave radiations through its unique physical parameters, such as the fractional vegetation coverage δ_f,the emissivity of canopy ε_f or ground surface ε_g, the albedo of the canopy α_f and the ground surface α_g. In addition to short and long-wave radiation incident, the model used in the energy plus accounts for sensible and latent heat transfer from both foliage and soil layer. The sensible and latent heat transfer are shown in Eqs. (3)–(6).

$$F_f = \sigma_f \left[I_s^{\downarrow} \left(1 - \alpha_f\right) + \varepsilon_f I_{ir}^{\downarrow} - \varepsilon_f \sigma T_f^4 \right] + \frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} (T_g^4 - T_f^4) + H_f + L_f \quad (1)$$

$$F_g = (1 - \sigma_f) \left[I_s^{\downarrow} (1 - \alpha_g) + \varepsilon_g I_{ir}^{\downarrow} - \varepsilon_g T_g^4 \right] - \frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} (T_g^4 - T_f^4) + K \times \frac{\partial T_g}{\partial z} + H_g + L_g \quad (2)$$

Sensible heat flux between the soil surface and air is dependent on the temperature difference between them and the wind speed within the canopy. Thermal conductivity, specific heat capacity, and density for dry soil media are also the positive factors affecting the sensible heat flux. Inspite the factors mentioned above, LAI, a