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Green roof simulation with a seasonally variable leaf area index

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ABSTRACT

Green roofs can decrease the energy consumption and improve air quality and durability associated with a roofing material. Previous studies have conducted simulations of the energy performance of green roofs over a limited period, and important parameters such as leaf area index (LAI) was set at a constant value. To develop an energy performance model for a green roof with a variable LAI which is suitable for annual simulation, this paper proposes a method to integrate a seasonally variable LAI equation into a green roof model based on an improved Dickinson's equation. After verification with measured data, this equation has a more accurate temperature setting for calculating seasonally variable LAI, the average error and average relative error are improved from 0.34 to 0.09 and 39.3 to 7.1%, respectively. Thus, it can be applied in different climatic regions. To determine the differences of annual energy performance of green roof, this paper compares simulation results of constant and variable LAI values for a two-story building in Shanghai, China. The simulation is conducted on the EnergyPlus platform. The results show that the simulations of temperature, heat flux, and heat load of the building for green roof modeling differ considerably for a constant and a variable LAI. In summer, the calculated latent heat flux is usually underestimated and the sensible heat flux is usually overestimated. Moreover, if the selected LAI value is higher than that of actual data in winter, the calculated latent heat flux is overestimated and the sensible heat flux is underestimated. The simulation results are more relevant for a seasonally variable LAI.

1. Introduction

Green roofs refer to specialized roof structures designed specially to grow vegetation [1]. It can be classified into extensive and intensive green roof, as Fig. 1 shows, where extensive green roof usually grows the kind of vegetation that has a strong vitality, like grass, and does not need too much maintenance as intensive green roof. Soil depth is usually between 5 and 15 cm in such cases, and thus, such roofs are lighter than intensive green roofs. Intensive green roofs have a soil depth of between 20 and 60 cm. The vegetation usually requires higher maintenance as intensive green roof and is relatively more expensive [2]. Extensive green roofs are more widely used because of their advantages considering about economical, less maintenance requirement, etc. All green roofs types comprise vegetation, growing media, a filter fabric, and a drainage layer from top to bottom [3].

One of the most attractive benefits of green roofs is their potential to decrease the roof temperature, resulting in a lower cooling load for a building. Santamouris [4] showed that at the city scale, green roofs decreased the overall average ambient temperature to an extent of 0.3–3 °C. Based on experimental data, Jim and Peng [5] recorded a maximum daily temperature reduction of about 5.2 °C and cooling load reduction 0.9 kWh/m^2 on a sunny day and 0.57 kWh/m^2 on a cloudy day. Apart from weather conditions, the energy performance of a green roof is also influenced by its size, planted vegetation, growth phase of the plant, soil composition, and building type. The leaf area index (LAI) parameter can significantly influence the evapotranspiration effect of a green roof.

The LAI is the ratio of the entire one-sided area of the leaf divided by one unit of ground soil surface area. It is a non-dimensional quantity that is determined by the vegetation canopy [6]. The LAI is related to the behavior and structure of the plant and is a critical parameter for the energy performance of a green roof when the influence of the evaporation rate is considered [7]. Niachou et al. [8] discovered that different vegetation species can result in varied temperature profiles and heat flux characteristics. Simmons et al. [9] also showed that different vegetation species have distinctive behaviors concerning water storage ability and heat transfer processes.

For some vegetation types, the value of the LAI varies significantly over time. The LAI is dependent on the vegetation species, growth stage, temperature, soil moisture content, humidity, radiation, and soil constituents [10–13]. Liu et al. [10] explained that the leaf area index is an important parameter that will vary seasonally for both evergreen and deciduous plants. A significant body

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Nomenclature

$c_{p,a}$	specific heat capacity of air J/(kg·K)
d	thickness of the foliage m
h	coefficient of convective heat transfer W/(m²·K)
I_s	irradiation W/m²
l_g	thickness of the soil m
k	heat conductivity coefficient of soil W/(m·K)
LAI	leaf area index
p_v	steam pressure Pa
$p_{v,sat}$	saturation vapor pressure at the foliage temperature Pa
Q	heat flux W/m²
r_a	aerodynamic resistance s/m
r_{sub}	ground soil resistance s/m
r_s	stomatal resistance s/m
ε	emissivity
ρ	reflectivity
ρ_a	density of air kg/m³
ρ_{af}	air density at the foliage temperature kg/m³
σ	Stefan–Boltzmann constant W/m²•K⁴
vc_f	vegetation coverage
τ	transmissivity
γ	psychrometric constant Pa/K

Subscripts

a	air
g	ground soil
f	foliage
lat	latent
con	conduction
sen	sensible

of work has investigated the variation of the LAI using statistical methods [11–14]. It was found that the LAI is a seasonally variable parameter. Over the past decades, several methods have been developed to evaluate the seasonally variable LAI, Wang et al. [32] compared seasonal trajectory of LAI from remote sensing (RS LAI) with that from a direct method (direct LAI). However, currently, most papers only focus on several weeks simulations, and even though there are annual simulations, the LAI is set at a constant value in these cases.

A constant LAI has been used for various green roof simulations [2,15–20]. Refahi and Talkhabi [15] estimated that for a constant LAI value, energy savings of about 8.5%, 9.2%, and 6.6% could be attained using a green roof in either a hot-dry, warm-dry, or mixed-dry climate, respectively. They claimed that appropriate vegetation should be selected for the green roof depending on the climatic conditions. Kumar and Kaushik [16] analyzed the solar thermal shading effect and cooling potential of a green roof. They found that for a $30m^2$ green roof in Yamuna Nagar (India), when LAI = 4.5, the required cooling potential of a green roof was 3.02 kWh to maintain the indoor temperature at 25.7 °C during a summer day. Tabares-Velasco and Srebric [2] compared the function of a green roof both with and without plants based on a “cold plate” apparatus. They assumed the vegetation was a porous media and evaluated the stomata function and found that the LAI has a large impact on heat flux reduction. Since the parameters applied were constant, they recommended further research should include a dynamic analysis of the process. Chan and Chow [17] simulated the energy performance of a green roof with LAI = 5 using EnergyPlus. They also discovered that by applying certain parameters to the Ecoroof Model, the energy consumption of the air conditioner is estimated to reduce by 0.09%, 1.34%, and 2.81% in different future periods (2011 to 2030, 2046 to 2065 and 2080 to 2099) of different weather conditions, respectively. Hodo-Abalo et al. [18] implemented a green roof as a passive strategy for energy saving and found that by increasing the LAI, solar penetration flux is reduced and the indoor temperature is cooler in summer. They consider the LAI to be constant and use it to calculate the vertical leaf distribution by sinusoidal function. Berardi [19] validated the strategy of using a green roof to mitigate a heat island effect. They found that by increasing the LAI, the cooling effect of the building improved and the temperature decreased by 0.4 °C. During the simulation, the LAI did not change.

This literature review shows that most green roof simulations are conducted for short time periods with a constant LAI. Furthermore, no annual simulations of green roofs with a seasonally variable LAI exist and no one has compared the effect of constant and seasonally variable LAI on the energy performance of green roof. Therefore, the objective of this paper is to develop an energy performance model for a green roof with a variable LAI so that it is suitable for annual simulation with high accuracy. This paper will first propose a method to calculate a seasonally variable LAI that can be applied to different climatic regions. Then, to verify the new method, the simulation results will be compared with experimental data. Finally, to determine the difference between applying a constant and a seasonally variable LAI to a green roof model, a case study will be presented under different climatic conditions in Shanghai over a period of one year, for both constant and seasonally variable LAI values.

2. Seasonally variable leaf area index (LAI)

A LAI is acquired by both direct and indirect methods [6,10,11,14,21]. Direct methods measure the LAI using a leaf area meter or the relationship of the area dimensions of a leaf with a shape coefficient. Indirect methods include the gap fraction method, radiation measurements, and commercial canopy analy-

Fig. 1. A illustration of extensive (a) and intensive (b) green roof.