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Modeling the heat diffusion process in the abiotic layers of green roofs

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ABSTRACT

Green roofs have been increasingly installed to alleviate some common environmental problems. The thermal benefit of living vegetation on rooftop has been extensively studied. The individual and joint contribution of the non-living green roof layers, namely soil, rockwool (water storage) and plastic drainage layers, to thermal performance of green roof has seldom been assessed. This study evaluates the insulating and cooling effects of these abiotic materials. A one-dimensional theoretical model was developed to assess the heat diffusion process in the layers. The model was validated with empirical results from three experimental plots. A calibration procedure was successfully applied to determine key model parameters. The model can capture the most critical features of temperature variations and thermal performance of common abiotic green roof materials. The appreciable water-retention capacity of rockwool plays the dual role of supplying water to the soil to enhance evaporative cooling, and increasing the specific heat capacity of the green roof. The plastic drainage sheet with ample air spaces serves as an excellent thermal insulator. The model remains robust despite seasonal and weather variabilities. Our research findings contradict with some researches in the temperate region that the thermal dissipation in green roofs with dense vegetation is lower than thermally insulated bare roofs. The theoretical model could be used to simulate the micro-environmental conditions and predict the thermal performance of different materials to improve green roof design.

1. Introduction

Planting vegetation on rooftops provides an efficient, cost-effective and sustainable strategy to relieve some widespread environmental problems associated with urbanization. They include reducing the quantity of stormwater discharged from buildings [1–5], suppressing roof surface, ambient and indoor temperature, ameliorating the urban heat island effect, lowering energy consumption [6–9], extending the life span of the roof membrane [4], and offering high-quality green amenity spaces.

Two main types of green roofs are commonly installed: intensive and extensive. Intensive green roofs have a deeper substrate (>20 cm) that can accommodate shrubs and trees. Extensive green roofs have a thinner substrate (about 5 cm) catering to grasses, herbaceous plants and drought-tolerant sedums. Extensive green roofs incur less maintenance requirement and cost. Its light weight permits retrofitting on structures with limited load bearing capacity. Most green roofs are extensive [10].

A modern green roof is constituted by several layers laid in sequence: root barrier, drainage, soil (substrate), vegetation, with or without a water storage layer which is placed either below or above the drainage sheet. Sometimes, the drainage layer may be combined with the filter layer on extensive green roofs. Root barriers are commonly installed to prevent root damage to building structure. The vegetation and substrate layers contribute notably to energy conservation and stormwater management [11]. Vegetation can absorb and dissipate large quantities of solar energy through biological processes. Some of the remaining solar radiation is absorbed by the substrate surface to raise its temperature. The surface heat then diffuses into the deeper soil layer and the concrete roof slab as heat flux.

A rockwool layer is often placed between the drainage and the soil to enhance the water retention capacity of the green roof system, and to reduce the substrate depth and hence the total weight of the green roof system. It is a highly porous inorganic material (porosity about 80%) composed of chemically inert silicate fiber material extracted from volcanic rocks. The material is commonly installed for wall and ceiling thermal insulation in buildings. Since the late 1960s, a more compacted and higher density type of rockwool board has been used as a growing medium in some European countries [12]. Rockwool has properties similar to soil to provide a porous medium for plant growth. Its significantly higher porosity permits a high capacity to hold plant-available moisture. Excess water in the substrate and rockwool is discharged by gravity flow to the drainage layer.

Green roofs have recently generated significant interest in a number of cognate fields, including landscape architecture, building design, environmental management, thermal engineering, and

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Table 1
The model parameters and values used in the theoretical calculations.

Model parameter	Value
Solar absorption coefficient	$\alpha_s = 0.75$
Soil surface emittance	$s = 0.9$
Mass density of water	$\rho_w = 1000\ \mathrm{kg\ m^{-3}}$
Specific heat capacity of water	$c_w = 4186\ \mathrm{J\ kg^{-1}\ K^{-1}}$
Product of mass density and specific heat capacity of soil	$\rho_s c_s = 1.34 \times 10^{-6}\ \mathrm{J\ m^{-3}\ K^{-1}}$
Maximum volumetric water content of soil	$W_{g,s} = 0.435\ \mathrm{m^3\ m^{-3}}$
Saturated moisture potential of soil	$\Psi_{p,s} = -0.218\ \mathrm{m}$
Hydraulic conductivity of the soil	$K_{g,s} = 3.41 \times 10^{-5}\ \mathrm{m\ s^{-1}}$
Maximum volumetric water content of rockwool	$W_{R,S} = 0.8\ \mathrm{m^3\ m^{-3}}$

urban water management. Thermal and energy performances have been intensively studied, with a focus on the role of vegetation. The contributions of the drainage, water storage and substrate layers, however, have received little attention. Their hydrothermal properties could significantly influence the energy budget, heat flux and temperature regime of the green roof. The heat storage, insulating and evaporative cooling effect of these abiotic components of the green roof system deserve detailed studies.

Our study examines the non-living layers of a green roof to explore their thermal properties and behavior. The study objectives include: (1) understanding the heat diffusion process in the abiotic layers by comparing modeled values and experimental results; (2) determining the role of soil, rockwool and drainage as insulating layers in roof greening; (3) finding the coefficients of heat diffusion and water transport equations for rockwool; and (4) using the findings to derive recommendations for green roof design and management.

2. Experimental design

Three experimental plots without irrigation and vegetation cover were set up on the rooftop of the Runme Shaw Building at the University of Hong Kong (Fig. 1). A proprietary multiple-layer green roof system (Nophadrain, Kirkrade, the Netherlands) was laid directly on the tile surface with a 2% gradient to shed drainage water. A root barrier was laid at the bottom of all plots. The plot design progressed from the minimal to the full complement of the abiotic layers to evaluate the effects of the layers:

- Plot 1: soil (5 cm sandy loam soil)
- Plot 2: soil (5 cm sandy loam soil) and drainage layer (2.5 cm high impact polystyrene)
- Plot 3: soil (5 cm sandy loam soil), rockwool (4 cm silicate fiber), and drainage layer (2.5 cm high impact polystyrene)

Thermister type soil temperature sensors (S-TMB, Onset Hobo, Pocasset, MA, USA) were installed at the interface between layers, and soil moisture sensors (S-SMC, Onset Hobo) were installed in the middle of the soil layer. The data were sampled and stored in data loggers (H21, Onset Hobo) at 15-min interval from March 2008 for 18 months. In order to understand their thermal properties, theoretical analysis is employed to investigate the effect of soil, rockwool and drainage materials on the building roof. A weather station (Onset Hobo) was set up near the experimental plots to take air temperature, soil surface temperature, dew point temperature, rainfall, wind speed, wind direction and solar radiation data. The plots were kept clear of spontaneous vegetation by regular weeding using the physical extraction method. All experimental parameters are expressed in SI units (Table 1).

3. Thermal performance assessment

3.1. Theoretical models for the soil layer

At the soil surface, energy fluxes in conductive, radiative, sensible and evaporative modes affect the soil surface temperature. The energy budget of the upper surface of soil is governed by the following equation:

$$q_0 + q_{ar} - q_{sr} = q_e + q_c + q_d \qquad (1)$$

where q_0 is the absorbed solar radiation, q_{ar} is the long wave radiation between soil and atmosphere, q_{sr} is the long wave radiation between soil and sky, q_e is the heat loss by evaporation, q_c is the heat loss by convective heat transfer, and q_d is the heat transfer from the soil surface into the soil [13,14].

The absorbed solar radiation depends on the intensity of incident solar radiation I and the solar absorption coefficient α_s as:

$$q_0 = \alpha_s I \qquad (2)$$

The long wave radiation between soil and atmosphere has the following relationship with air temperature T_a and dew point temperature t_d (in °C) [14]:

$$q_{ar} = \sigma T_a^4 (0.802 + 0.004 t_d) \qquad (3)$$

where σ is the Stefan–Boltzmann constant. The limits of Eq. (3) depend on which empirical relationship of dew point temperature is used in the calculation. For instance, the temperature limit for Magnus–Tetens formula is between 0 °C and 50 °C [15], and the temperature limit for Meng and Hu's approach is between 0 °C and 65 °C [14].

The long wave radiation between soil and sky relates to the surface temperature of the soil T_0, thus:

$$q_{sr} = \varepsilon \sigma T_0^4 \qquad (4)$$

where ε is the surface emittance of the soil (see Table 1 for the value [13]).

The modified Penman's formula [16] is used to estimate the evaporation rate:

$$E_s = 0.35(e_0^0 - e_d)(0.5 + 1.863 \times 10^{-2} U_2) \qquad (5)$$

where U_2 is the average wind speed measured at 2 m height above the ground, e_0^0 is the saturated vapor pressure at the evaporation surface, and e_d is the actual vapor pressure in the air at 2 m height above the surface.

Since it is difficult but not impossible to measure the saturated vapor pressure and actual vapor pressure, the following empirical relations [16] have been employed in this research:

$$e_0^0 = 4.12 \times 10^{-10} (1.06)^{T_a} \qquad (6)$$

$$e_d = \left(\frac{RH}{100}\right) e_0^0 \qquad (7)$$

where RH is the relative humidity (%) near the evaporation surface.

The evaporative flux from the soil is thus given by:

$$q_e = E_s L \qquad (8)$$

where L is the latent heat of evaporation.

The heat loss by convective heat transfer can be approximated by the Newton's law of cooling [14]:

$$q_c = h_c (T_0 - T_a) \qquad (9)$$

where h_c is the convective heat transfer coefficient. It varies as $\Delta T^{1/4}$ for laminar flows and as $\Delta T^{1/3}$ for turbulent flows.

The solar energy is first absorbed by the soil surface. When the soil surface reaches the thermal balance, the surface temperature