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Toward the practicability of a heat transfer model for green roofs

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ABSTRACT

In this study, a simplified one-dimensional heat transfer model is developed to assess the thermal effects of green roofs at the design stage. Instead of using temperature at the bottom of a green roof as the lower boundary condition, the equations for heat conduction through the surface and bottom of the substrate are adopted. Information required for the proposed model includes meteorological data and the thermal properties of the green roof. The model consists of two parts: the heat balance of the plant layer and substrate surface, and the conduction of heat through the interface of the substrate bottom. To verify the model, a green roof experiment is designed to collect data. Results show high consistency between the calculated and observed data, indicating the capability of the model in estimating temperature and heat flux of a green roof. In addition, the two thermal conditions, with and without a green roof, are analyzed for comparison. Significant differences of temperature and heat flux in summer are 14.5 °C and 302.64 W/m^2 for the cool-down effect, and 4.90 °C and 93.12 W/m^2 for the insulation effect, respectively, demonstrating the marked effects of the green roof in regulating temperature and heat flux.

1. Introduction

Green roofs represent a promising adaptation strategy in the face of climate change, and the number of green roof studies has thus increased in recent years (Sailor, 2008; Jim and He, 2010; MacIvor and Lundholm, 2011; Tabares-Velasco et al., 2012). The thermal effects of green roof result mainly from the shading, insulation, evapotranspiration, and thermal mass of the plants and substrate (Liu, 2004). The high specific heat of water contained in the substrate provides a strong thermal inertia (Nyuk Hien et al. (2007)). Consequently, increasing leaf areas and the substrate thickness would contribute to the energy saving of a building. In addition, evapotranspiration from a green roof brings a cooling effect (Lazzarin et al., 2005). As discovered in experiments, latent heat can override sensible heat on a green surface (Takebayashi and Moriyama, 2007) and leaf transpiration accounts for up to 30% of rooftop cooling (Takakura et al., 2000). The insulation role of green roofs show in the mitigated peak temperature, the blocked heat flux, or the saved cooling and heating loads (Alexandri and Jones, 2007; Sailor, 2008; MacIvor and Lundholm, 2011). It has been argued that green roofs can decrease the energy consumption of a top floor by 58–73% (Spala et al., 2008). In addition, a green roof can lower the temperature at the surface of the building by 20 °C (Teemusk and Mander, 2010), and can decrease the heat flux entering the roof by 60–90%, depending on the roof design (Liu and Minor, 2005).

Green roofs can achieve the expected goal of indoor temperature adjustment if properly designed, but it is necessary to simulate their effectiveness in relation to local conditions before construction (Williams et al., 2010). Table 1 summarizes some of the modeling research with verification process. In reality, the heat and mass transfer processes usually occur simultaneously within a green roof system. Latent heat, delivered by evapotranspiration, is a component involved in both mass and energy models. It affects the water balance of the substrate directly, and indirectly affects the thermal properties of a green roof (Tabares-Velasco et al., 2012). However, the substrate-moisture effects are found insignificant in associated with cooling effect of a green roof (Jim and Peng, 2012), and the effects of the substrate moisture on thermal conductivity are assumed constant in most green roof models (Table 1). The main reason is that the effect of water on the thermal processes in a green roof are described predominantly through the latent heat of evapotranspiration (Tabares-Velasco et al., 2012). In addition, as the change in the thermal conductivity within substrate is not obvious (Bristow et al., 2001), the effect of water on the fluxes related to thermal conductivity could be neglected.

A large body of literature exists related to the thermal modeling of green roofs. However, the application of heat transfer models is limited by unknown boundary conditions. For example, the boundary condition of the temperature at the bottom of a green

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Table 1
Studies related to green roof model verification in recent years.

Authors	Validation target	Heat conductivity	Lower boundary
Tabares-Velasco et al. (2012)	$T_{substrate-surface}$, heat flux, net radiation	Assume constant	Bottom substrate temperature
Djedjig et al. (2012)	$T_{substrate-surface}$	f(Substrate moisture), linear	Bottom substrate temperature
Ouldboukhitine et al. (2011)	$T_{substrate-surface}$	f(Substrate moisture), linear	Roof support temperature
Sailor (2008)	$T_{substrate-surface}$	Assume constant	Conduction transfer function (CTF)
Alexandri and Jones (2007)	Temperature of each nodes, substrate moisture	f(Substrate moisture), logarithmic	Constant internal temperature (20 °C)
Takebayashi and Moriyama (2007)	Substrate moisture, evaporation	f(Substrate moisture), logarithmic	Observed inner temperature

roof is often used, but is unknown at design stage. Table 1 lists the required lower-boundary conditions in previous studies. Thus, replacing the unknown temperature of lower boundary with a reasonable assumption that is independent of the situation after constructing a green roof appears to be the solution. The Food and Agriculture Organization (FAO) of the United Nations have reported that heat conduction beneath dense grass can be approximated as a constant proportion of the net radiation (Allen et al., 1998), and therefore model users do not need prior information relating to the temperature at the bottom of a green roof before it is constructed.

The purpose of this paper is to develop a simplified heat transfer model to simulate the thermal effect of a green roof for design purposes. More specifically, this model is developed to evaluate the temperature and heat flux using given meteorological data and the properties of the green roof. However, the effect of green roof on the indoor temperature of a building is not considered in this study.

2. Material and methods

This study proposes a simplified one-dimensional heat transfer model for a green roof and focuses on simulating the thermal effects of the plant and substrate layers. Heat transfer through a green roof can be partitioned into two stages: the heat budget of the plant layer and the substrate surface, and the conduction of heat through the substrate to the underlying structure. To assess the insulation potential of a green roof, the temperatures of the plants and the substrate and the heat flux through the interface of the substrate bottom are concerned.

2.1. Heat budget of plants and substrate surface

Heat fluxes in the first two layers (Fig. 1) are balanced by the components of net shortwave radiation (R), net long wave radiation (IR), sensible heat (H), and latent heat (LE), while heat conduction (G) is additionally calculated at the substrate surface (all measured in W/m^2). For each component, the subscript f stands for the plant layer, and g represents the surface of the substrate. The relation between absorbed energy and temperature is described as Bhumralkar (1975).

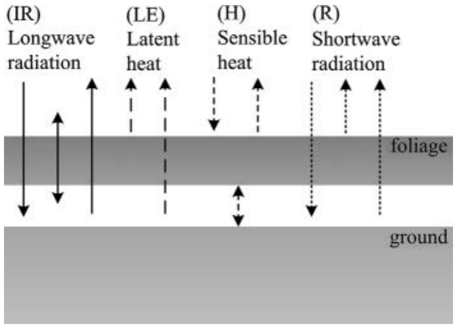

Fig. 1. Heat flux components of the plant layer and the substrate surface.

$$\frac{\delta T_f}{\delta t} = c_1(R_f + IR_f + H_f + LE_f), c_1 = \frac{1}{\rho C_{p,f} h} \tag{1}$$

$$\frac{\delta T_g}{\delta t} = c_2(R_g + IR_g + H_g + LE_g + G), c_2 = \frac{1}{\rho C_{p,g} + \left(\lambda \frac{\rho C_{p,g}}{2\omega}\right)^{1/2}} \tag{2}$$

where T_f and T_g are the average temperature of the plant layer and substrate surface (°C), respectively; $\rho C_{p,f}$ and $\rho C_{p,g}$ are the volumetric heat capacity of the plant and the substrate, respectively (J/m^3 °C); h is the height of the canopy (m); λ is the heat conductivity of the substrate (W/mK); and ω is the frequency of oscillation, which is equal to 2λ/(period of the wave).

The solar radiations absorbed by both layers are calculated based on Tabares-Velasco and Srebric (2012). Required information includes the albedos α_f and α_g, the distinction coefficient of shortwave radiation k_s, the leaf area index LAI, and incoming shortwave radiation R_{in}. The computation of long wave radiation corresponds with that of solar radiation is described in Eqs. (3) and (4). The multiple reflection of long wave radiation between the substrate surface and plants and the reflectivity of long wave radiation are neglected in this study, as they have been proven to be small (Tabares-Velasco, 2009).

$$IR_f = (1 - e^{-k_L \times LAI}) \times [\sigma(T_{a,k} - 20)^4 - \varepsilon_g \sigma T_{g,k}{}^4] - \varepsilon_f \sigma T_{f,k}{}^4 \tag{3}$$

$$IR_g = \varepsilon_g \times e^{-k_L \times LAI} \times \sigma(T_{a,k} - 20)^4 + \varepsilon_g \times \varepsilon_f \sigma T_{f,k}{}^4 - \varepsilon_g \sigma T_{g,k}{}^4 \tag{4}$$

where ε_g is the absorbance or the emissivity of the substrate, σ is the Steven–Boltzmann constant (5.67×10^{-8} W/m^2), k_L is the distinction coefficient of long wave radiation, and $T_{a,k}$,$T_{g,k}$ and $T_{f,k}$ represent the T_a, T_g, T_f of absolute temperature, respectively.

Since it is difficult to separate the latent heat from plants and the substrate, the latent heat of the substrate is obtained by subtracting the amount contributed by the canopy from the total amount of evapotranspiration, as in Eq. (5). The modified Penman–Monteith equation has been widely used to estimate latent heat from a canopy LE_f (Shuttleworth and Wallace, 1985), while total evapotranspiration ET is based on Walter et al. (2000).

$$LE_g = L_{water} \times k_{ct} \times k_{ct} \times ET - LE_f \tag{5}$$

where k_{ct} is cover factor.

Sensible heat is depicted in Eq. (6) and (7). To reduce the complexity of the model, the recommended values of the resistances were adopted, rather than the commonly used multiplying factors (Tabares-Velasco et al., 2012).

$$H_f = \rho C_p \times LAI \times \frac{T_f - T_a}{\gamma_a} \tag{6}$$

$$H_g = \rho C_p \times \frac{T_g - T_f}{\gamma_s} \tag{7}$$

where γ_s is the resistance to heat flux in the boundary layer immediately above the substrate surface (s/m). Because simulating the heat in the substrate by giving the temperature at the substrate