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Simplified model for green roofs and walls for integration in building simulation software

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Abstract

Green roofs and walls (GRW) of buildings implemented at an urban scale are promoted as effective measures to reduce the urban heat island effects and increase building resilience against extreme weather events such as heat waves and rainstorms. At a building level, GRW serve as retrofit measures to alleviate interior overheating and reduce cooling energy use of particularly old buildings with inadequate insulation levels. Many theoretical and empirical models have been developed to evaluate the performance of GRW via computer simulation. However, a very few models have explicitly been integrated into existing building simulation software. This paper develops a straightforward model designed for easy integration into any building simulation tool to assess the GRW effects. The model conceptualizes GRWs —whether plants on horizontal or vertical setups, with or without a growing medium—as an optical system where the plant canopy and growing medium are treated as transparent homogeneous layers with equivalent optical and thermal properties. The model simulates the evapotranspiration latent heats of the green surface as reflected components of incident solar radiation. The model's accuracy is confirmed by comparing its predictions for evapotranspiration latent heat and soil temperature with an existing green roof model. The proposal model allows simulators to evaluate any combination of green vertical walls and horizontal roofs across different building types. By facilitating a broader evaluation of GRW configurations, this model contributes significantly to urban sustainability efforts, providing a practical tool for architects and urban planners aiming to mitigate climate impacts on buildings.

Keywords:

Green roof, green wall, urban heat island, building simulation, nature-based solution, overheating

1. Introduction

Green walls and roofs (GWR) applied to buildings on a large urban scale are advocated as resilient and sustainable nature-based solutions to combat urban heat island effects, purify outdoor air and reduce cooling energy of buildings (Calliari et al., 2022; Anderson et al., 2023). At the urban level, GWR can reduce temperature of building exterior surfaces due to their wind shielding and solar shading effects, and increase conversion of solar energy to evapo-transpiration latent heat. At the building level, GWR can reduce heat gains through building envelopes from high outdoor temperatures and incident solar radiation. However, the benefits of GWR depend on building insulation level, air tightness and treatments of other urban surfaces such as roads, pavements and green lands.

Modelling green building surfaces, composed of plants and growing media (soils), is a challenging task due to the complex interaction of various heat transfer mechanisms, including radiative and convective heat exchange, solar-driven transpiration of plants, moisture diffusion in the growing media and evaporation at the air-soil surface. Modelling green roofs (GRs) have received considerable attention and many models based on heat and mass conservation with various complexities have been developed (Sailer, 2008; Feng el al., 2010; He and Jim, 2010; Tabares-Velasco and Srebric, 2012; Djedjig et al., 2012; Quezada-García et al., 2020). Of these models, only the Sailer model was incorporated into the EnergyPlus software (DOE, 2024), but it is restricted to only one GR surface per building. Similarly, several models have been developed for green walls (GWs). The simplest models account only for the shading and wind effects of GWs, without accounting for the moisture diffusion and evapotranspiration effects (Freewan et al., 2022; Banti et al., 2023; Pragati et al., 2023). Advanced models accounting for the mass and heat balances and evapotranspiration effects have been developed based on the physics of GR models (Malys et al., 2014; Scarpa et al., 2014; Dahanayake and Show, 2017; Djedji et al., 2017; Arenghi et al., 2021). However, none of these models have been directly integrated into existing building simulation software, except the Djedji et al model, integrated into TRNSYS software. Dahanayake and Show (2017) and Arenghi et al. (2021) used an indirect integration of their models into EnergyPlus using run-time coupling with the Energy Management System of the software.

The goal of this paper is to develop and validate a simplified model to evaluate the thermal performance of GWR of buildings using building simulation.

2. Approach

The proposed approach treats the green surface, composed of a plant canopy layer alone or both canopy and soil layers, as either a single- or double-glazed optical system with equivalent thermal and optical properties. The evapotranspiration latent heat of plants and soil are simulated as solar reflected components. The following assumptions are used:

- Plant canopy layer is opaque to solar and thermal radiation, but may not cover the entire soil surface

so that a portion of the incident solar or sky thermal radiation can directly reach the underlying soil layer if present or the building surface.

- The soil layer is regularly irrigated to maintain sufficient moisture content (≥ the minimum residual moisture) so that evapotranspiration latent heat persists over time (to avoid plant wilting and soil drying).
- Moisture evaporation from the soil layer and transpiration from the plants are driven by incident solar radiation (the contribution of the outdoor temperature is negligible; Sailer 2008; Feng et al., 2010).

2.1 Equivalent optical properties

Figure 1 shows a schematic configuration of a general green surface (in a vertical or horizontal position) and the equivalent optical system. The green surface is composed of a plant canopy with or without a soil layer. The latter is represented by one opaque layer and the plant canopy is represented by an air space layer and a plant layer. The plant layer is assumed homogenous, porous and translucent to sunlight. The presence of the air space layer is dependent on the type of the green surface and how the model is implemented in building simulation software as will be discussed later.

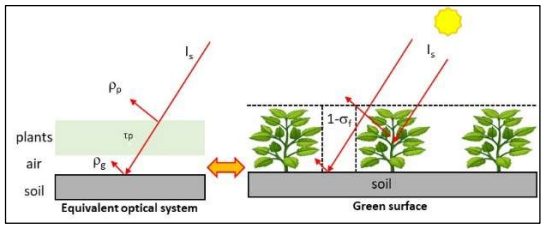

Fig.1. Schematic of the green surface and its equivalent optical system

The latent heats evaporated from the moist soil layer and transpired from the plant leaves are proportional to the absorbed solar radiation and are therefore treated as reflected components of the incident solar radiation. Based on the optics of multilayer systems (Laouadi and Parekh, 2007), the total front reflectance (albedo, R_f) of the optical system and the total absorptances of its plant and soil layers (ABS_p, ABS_g) are expressed as follows:

$$R_f = \rho_p + \frac{\tau_p^2 \cdot \rho_g}{1-\rho_g \cdot \rho_p} \quad (1)$$

$$ABS_p = \alpha_p + \frac{\tau_p \cdot \rho_g}{1-\rho_p \cdot \rho_g} \cdot \alpha_p \quad (2)$$

$$ABS_g = \frac{\tau_p}{1-\rho_p \cdot \rho_g} \cdot \alpha_g \quad (3)$$

Where (τ_p, ρ_p, α_p) are respectively the intrinsic solar transmittance, reflectance and absorptance of the plant layer, and (ρ_g, α_g) are the intrinsic reflectance and absorptance of the moist (not dry) soil layer (Table 1).

Similarly, the total front equivalent solar reflectance ($R_{f,eq}$) of the system accounting for both the reflected components of the incident solar radiation and the solar-driven evapotranspiration latent heat of the system is expressed as follows:

$$R_{f,eq} = R_f + \rho_{p,e} + \rho_{g,e} = \rho_{p,eq} + \frac{\tau_p^2 \cdot \rho_{g,eq}}{1-\rho_{g,eq} \cdot \rho_p} \quad (4)$$

Where ($\rho_{p,e}$, $\rho_{g,e}$) are, respectively, the reflectances accounting for the evapotranspiration latent heats from the plant leaves and soil layer, and ($\rho_{p,eq}$, $\rho_{g,eq}$) are, respectively the equivalent reflectances of the plant canopy and soil layers accounting for both the intrinsic reflectance and evapotranspiration heat components. By virtue of Eqs. (1) and (4), The front equivalent reflectances ($\rho_{p,eq}$, $\rho_{g,eq}$) are expressed as follow:

$$\rho_{p,eq} = \rho_p + \rho_{p,e} \quad (5)$$

$$\rho_{g,eq} = \rho_g + \frac{[1-2\rho_g \cdot \rho_p]}{\left\{1+\rho_p \frac{\rho_{g,e}}{\tau_p^2}\right\}} \cdot \frac{\rho_{g,e}}{\tau_p^2} \quad (6)$$

Given the fact that the evapotranspiration latent heat is mainly driven by solar radiation and that the soil contains sufficient moisture content, the reflectances ($\rho_{p,e}$, $\rho_{g,e}$) may be expressed as follows:

$$\rho_{p,e} = \frac{L_p}{I_s} = C_p \cdot ABS_p; \quad \rho_{g,e} = \frac{L_g}{I_s} = C_g \cdot ABS_g \quad (7)$$

Where I_s is the solar radiation incident on the green surface, L_p is the transpired and evaporated latent heat of the plant canopy, L_g is the evaporative latent heat of the soil layer, and (C_p, C_g) are constants to be determined.

Table 1. Intrinsic optical properties of the plant and soil layers. Note that σ_f is the plant area coverage ratio, and ρ_f and ε_f are, respectively the solar reflectance and emissivity of plant leaves

Property	Plant layer	Soil layer
Solar transmittance	$\tau_p = 1 - \sigma_f$	0
Solar reflectance	$\rho_p = \sigma_f . \rho_f$	ρ_g
Solar absorptance	$\alpha_p = 1 - \tau_p - \rho_p$	$\alpha_g = 1 - \rho_g$
Infrared Transmittance	TIR = 1 - σ_f	0
Emissivity	$\varepsilon_p = \sigma_f . \varepsilon_f$	ε_g

2.1 Equivalent thermal properties

The equivalent thermal properties of the system include those for the air space, plant canopy and soil layers. The thickness of the air space layer is an input, specified based on the green surface model implementation in building simulation software. The thermal resistance of the air layer is therefore calculated by the simulation software using suitable built-in correlations. As for the plant canopy layer, the latter is assumed to be homogenous and porous with effective thermal properties for the density, heat capacity and thermal conductivity. These are determined using volume-averaging formulations of porous media (Quezada-García et al., 2017). However, the plant canopy layer has usually a high porosity (> 50%), making it difficult to determine the effective thermal conductivity. The latter is not only a

function of the thermal conductivities of still air and plants, but also a function of radiation and forced or natural convection within the air volume pockets. Forced convection from wind speed and radiation heat exchange increase the effective thermal conductivity, thus reducing the temperature gradient within the canopy layer. As a first approximation, the effective thermal conductivity of the plant canopy layer can be assumed to take high values (> 1 W/m^2.°C; or very low thermal resistance < 0.1 m.°C/W). This is consistent with existing green roof models (e.g., Sailer, 2008), which assume no temperature gradient within the canopy layer. Radiative and wind convective heat transfers at the outdoor exposed surface of the canopy layer are handled in the simulation software using the inputs for the equivalent emissivity of the plant canopy layer (Table 1) and suitable built-in convective correlations. Finally, the thermal and optical properties of the soil layer should be determined when the soil moisture content is at least equal to the minimum residual moisture content (not at a dry state).

2.3 Model implementation in simulation software

There are two ways to implement the model in building simulation software, depending on their modelling capabilities. The first and direct method is to include the transparent multi-layer system (Fig. 1) as part of the opaque construction of the building surface to simulate green roofs or walls. The equivalent optical and thermal properties of the system are then used as inputs. This option is, however, dependent on whether the simulation software has the capability to fully model optical systems incorporating a mixture of opaque and transparent glazing elements such as using window or Trombe wall constructs. If this direct implementation is not possible, then the second method is to use the feature of movable transparent (insulation) surfaces in the simulation software. In this case, the soil layer (if present) will be part of the construction of the building surface, but with its equivalent properties as inputs (namely the solar reflectance, Eq. (6), and thermal conductivity). The plant canopy layer will represent the movable surface with its equivalent properties. If the air space is not present or not permitted by the simulation software, and the plant canopy layer shares a common interface with the soil layer, then the reflectance ($\rho_{g,e}$) of the soil layer will be added to the equivalent reflectance of the plant canopy layer as follows:

$$\rho_{p,f,eq} = \rho_p + \rho_{p,e} + \rho_{g,e}; \quad \rho_{g,f,eq} = \rho_g \qquad (8)$$

The model can easily integrate into EnergyPlus software using the second method and Eq. (8). Furthermore, the adaptive convective correlations at the exterior surface of the canopy layer are used instead of the default ones.

3. Results and Discussion

3.1 Determination of model constants

The model constants (C_p, C_g) in Eq. (7) are determined by calculating or measuring the evapotranspiration latent heat from the plants and soil layers and incident solar radiation. Since the measurement option is not available, the simulation results of the EnergyPlus model of green roof are used to fit the formulations of Eq. (7). The inputs of the green roof model are shown in Table 2. The simulations are conducted in the whole month of July for the city of Ottawa (Ontario) using a calibrated building model of long-term care homes (Laouadi et al., 2023). The total solar absorptance of the plant canopy and soil layers are, respectively ABS_p = 0.65 and ABS_g = 0.20. The model constants are therefore C_p = 0.46 and C_g = 0.27. The overall constant for both plants and soil C_{pg} = 0.41.

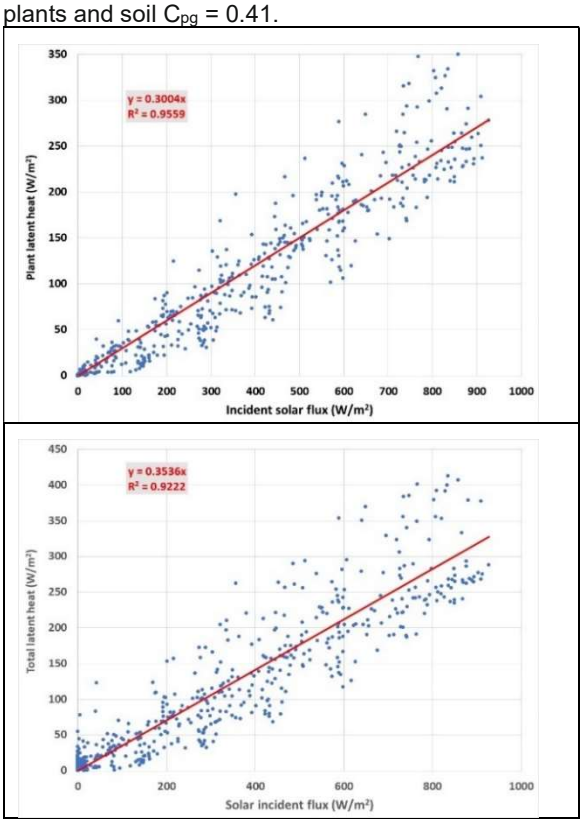

Fig.2. Latent heat transfer of plant canopy (top) and combined plant and soil (bottom) versus incident solar radiation

3.2 Model validation

The predictions of the proposed model are compared with the EnergyPlus simulations of its green roof model applied on the roof of a long tern care building. More details on the building model may be found in Laouadi et al. (2023). Table 2 lists the construction and inputs of the green roof. The green roof is regularly irrigated from 7 to 9 AM daily at a rate of 2 mm/h.

Fig. 3 compares the model predictions with EnergyPlus simulations for the latent heat transfer of the plant layer. The model predictions are in excellent agreement with the simulation data. The difference in the peak data on some days is due to the constant optical and thermal properties of the model over the simulation period, while they are hourly calculated in EnergyPLus.

Table 2. Input data of the green roof (other properties are default values of EnergyPLus)

Plant layer: Coverage area ratio σ_f = 0.74 Thickness = 200 mm Leaf area index LAI = 2 Leaf emissivity ε_f = 0.95 Plant emissivity ε_p = 0.7 Leaf reflectance ρ_f = 0.22 Plant transmittance τ_p = 0.26 Plant reflectance ρ_p = 0.16 Plant total absorptance ABS_f = 0.65 Plant equivalent solar reflectance, Eq. (8), $\rho_{p,eq}$ = 0.51 TIR = 0.26 Effective conductivity=3 W/m^2.K
Soil layer: Thickness = 100 mm Absorptance α_g = 0.7 (dry), 0.74 (moist) Saturation volumetric moisture content = 0.3 Residual volumetric moisture content = 0.1 Emissivity ε_g = 0.9 Conductivity = 0.35 (dry), 0.39 (moist) W/m^2.K Total absorptance ABS_g = 0.2
Filter/drainage layer: 25 mm recycled polyethylene
Water protection layer: 3 mm recycled polyester mat
Root barrier layer: 0.36 mm high density polyethylene film
Existing roof: EPDM membrane 132 mm ISO insulation 150 mm concrete deck

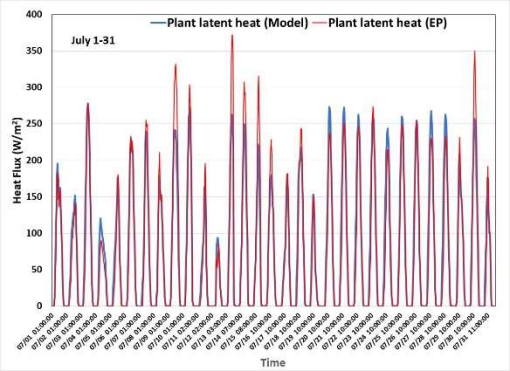

Fig.3. Comparison of latent heat of plants as predicted by the model and EnergyPlus

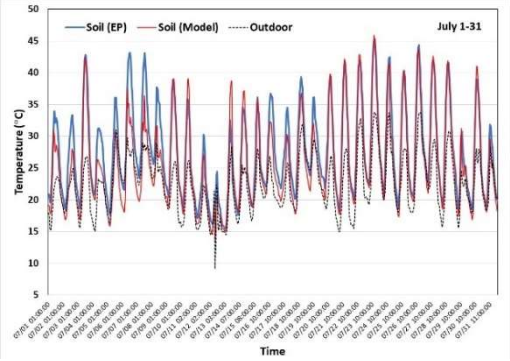

Fig.4. Comparison of soil temperature as predicted by the model and EnergyPlus

Figure 4 compare the soil temperature as predicted by the model and EnergyPlus. Once again, both predictions show good agreement.

4. Conclusion

This paper proposed a simplified model of green surfaces composed of plants and growing media for integration into building simulation software to predict their performance when applied to building surfaces (in either a horizontal or vertical position). The model treats the green surface as an optical system in which the evapotranspiration latent heats are simulated as reflected solar components. The model was successfully validated with the green roof model of EnergyPLus. The model enables simulations of any combination of green roofs and walls on any exterior building surface.

Acknowledgements

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