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A heat transfer model for assessment of plant based roofing systems in summer conditions

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ABSTRACT

This paper presents a quasi-steady state heat and mass transfer green roof model that can be incorporated in different energy simulation software or calculation procedures. The model considers heat and mass transfer processes between the sky, plants, and substrate. This paper also presents new equations to calculate (1) substrate thermal conductivity for green roofs, (2) substrate resistance to calculate green roof soil evaporation, (3) and set of compiled stomatal resistance functions to calculate plants' transpiration. The model is validated with robust experimental data that consists of surface temperatures, conduction heat flux, convection heat flux, net radiation and evapotranspiration. The data was obtained from laboratory experiments using a new "Cold Plate" apparatus set in an environmental chamber. The validation shows that the model predicts the heat and mass transfer accurately, except that it tends to underestimate peak evapotranspiration rates.

1. Introduction

Green roofs are specialized roofing systems that support vegetation growth on human-made structures such as rooftops [1,2]. Green roofs are classified as extensive and intensive green roofs. Extensive green roofs when compared to intensive green roofs have lower weight, lower capital cost, minimal maintenance, and a substrate depth between 5 cm and 15 cm [1,3]. Typical weight increase on the roof due to extensive green roof materials is from 72 kg/m^2 to 169 kg/m^2. In comparison, intensive green roofs have higher capital costs, wider planting selection, higher maintenance requirements, and increased substrate depth between 20 cm and 60 cm, which results in increased weight on the roof from 290 kg/m^2 to 968 kg/m^2 [1]. Thus, intensive green roofs cost more than extensive green roofs because they required additional structural support, require irrigation and have a deeper substrate layer [1,4]. Moreover, extensive green roofs are the most common green roof, representing about 2/3 of the total green roof area installed in North America [5]. Therefore, our modeling efforts focus on extensive green roofs as a more economically viable solution to be adopted in buildings.

From top to bottom, a typical green roof consists of several layers: (1) vegetation, (2) substrate, (3) filter membrane, (4) drainage layer, and (5) root resistance layer. Plants used on green roofs range from native plants and grasses to drought tolerant plants such as *Sedum* and *Delosperma* species, which belong to the cactus family of plants. Therefore, *Sedum* and *Delosperma* are hardy succulent plants, and have the ability to survive in drought conditions by limiting their water loss due to transpiration. Substrate is a lightweight porous soil-like layer that supports plant growth by retaining moisture and nutrients [3]. The substrate typically represents a mineral mix of sand, expanded clay, vermiculite, perlite, gravel, crushed brick, peat, organic matter and some soil [1]. The filter or cloth membrane prevents drainage clogging by containing the substrate and roots, and sometimes comes coupled with the drainage layer. The drainage layer transports the rainfall runoff to the roof drain, and ventilates/aerates the substrate and consists of large size gravel, expanded clay, lava and pumice stone or plastic/polystyrene webbing or chambers, resembling an egg carton shape. Finally, the root resistance layer prevents root penetration into the roof membrane [1,3,6].

Plants' architecture can be characterized by plants' height. A more relevant characteristic for thermal performance modeling is the leaf area index (LAI) [7]. Definition of LAI varies depending on the field of study or approach taken [8]. The most common

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definition of LAI is the projected or shadow leaf area divided by the ground area. However, other studies recommend the use of half of the total intercepted leaf area divided by the ground area as a more robust definition for all types of leaves [9].

Most of the water losses in plants (transpiration) are through plant stomata. Stomata are adjustable small pores in the leaf that allow the entry of gases needed for photosynthesis such as CO_2, and the release of O_2 and water vapor. Thus, this is a natural control mechanism that allows plants to control their transpiration rate by opening and closing their stomata [10–12]. Thus, when modeling green roofs, it is important to accurately understand the physiological behavior of typical plants used on green roofs.

Green roofs are regarded as a sustainable technology that potentially offers several benefits to society and the environment depending on the building design and location of the building. Among the most cited benefits are: (1) reduced building energy demand on space conditioning, (2) reduced storm water runoff, (3) expanded lifespan of roofing membranes, and (4) reduced urban heat island effect in cities. To understand the potential for reduced cooling energy demand, the thermal performance of green roofs has been investigated worldwide using three different approaches: (1) field or laboratory experimentation, (2) theoretical/numerical studies, and (3) a combination of laboratory or field experiments with numerical models. Field experimental studies have focused on measuring:

- heat flux reduction [2,13–18],
- green roof R-value [16] and/or
- evapotranspiration rates [19–22].

All of these field experimental studies measured these different green roof thermal performance parameters under unsteady weather conditions and using field instrumentation. In contrast, there are only few laboratory studies focused on quantifying the same thermal performance [23–28]. These laboratory studies tried to minimize stochastic weather forcing on heat transfer by controlling environmental conditions and to improve the accuracy of collected data by using laboratory-rated instrumentation. However, these studies did not measure all of the heat and mass transfer processes simultaneously, which is important for validation of model components, rather than just evaluating overall heat transfer rates. In addition, field or laboratory experimentation has the limitation of representing only a few different climates or building designs. These limitations can be overcome with a comprehensive and reliable heat and mass transfer model for green roofs.

Modeling the thermal performance of green roof is challenging due to the complex heat and mass transfer through the roof resulting from the shading, insulation, evapotranspiration, and thermal mass [29]. As a result, the modeling of green roofs is not an easy task because the thermal properties of a green roof depend on dynamic factors such as the plant growth, substrate thermal properties, and substrate water content. Based on an extensive literature review, the first modern theoretical green roof model was developed in India [30]. Since then, researchers have modeled green roofs by using steady state R-values [16,31,32] and accounted for plant materials by further adjusting the radiative/spectral properties [2,13,33], and/or by using equivalent albedo that combined a constant latent heat flux and/or photosynthesis rate [34,35].

More robust models have implemented energy and mass balance across the roof and calculated evapotranspiration rates. There are several models that use an energy balance modeling approach across green roofs [30,36–40]. The simpler versions of these models use the quasi-steady-state approach [38–40], which is similar to models for heat transfer on vegetated surfaces [41]. Other studies account for the thermal storage of the substrate [30,37]. In addition, a couple of models have simulated green roofs by coupling heat and mass transfer processes. A coupled heat and mass transfer model took into account water movement in the substrate, but it required knowledge of water content changes [22]. Looking also into the urban heat island effect, another study concluded that adding mass transfer into the analysis improved predictions of surrounding air temperatures [42]. A different model grouped convective and radiative heat transfer into an adduction coefficient and calculated evapotranspiration using the Penman equation. Thus, the model performed well when the roof was wet, but not in dry conditions, because the Penman equation does not contain a term to account for stomatal resistance [43]. Finally, a recent green roof model [44] presented an adaptation of Soil-Vegetation-Atmosphere Transfer (SVAT) schemes used in meso-scale meteorological analyses or general circulation models [45]. The parametric study of this model showed that increased soil thickness and LAI can result in building energy savings during winter and summer. However, high LAI values in winter are uncommon, as many plants are dormant, thus losing their leaves, which decreases LAI. Overall, previous green roof models have conducted heat and/or mass balance across green roofs to quantify thermal performance of green roofs. While different models agree that LAI plays an important role in reducing heat fluxes through a green roof, there is a disagreement about the role of substrate depth. Among the models that perform energy and/or mass balances, evapotranspiration is typically modeled with the Vapor Pressure Deficit (VPD) method [30,42,44,46]. As a result, most complete green roof models account for plant stomatal resistance and the resistance of substrate/soil to control water loss.

A complete green roof model should cover all of the relevant heat and mass transfer phenomena as well as their interactions. The main differences between models are: (1) factors affecting stomatal resistance, (2) convective heat transfer coefficient, and (3) substrate thermal conductivity. In order to understand these differences, it is necessary to experimentally quantify individual heat and mass transfer processes, so that modeling and laboratory work can address the remaining unanswered questions. In addition, some of these models were validated using only green roof surface temperatures obtained from field measurements. Nevertheless, a complete validation should also include heat transfer fluxes, such as heat flux through the green roof, convection, radiation, and evapotranspiration rates at the roof surface. An exhaustive literature review did not find a study that simultaneously measured all of the important heat and mass transfer processes in a green roof. Thus, the objective of this research study is to develop a model that is validated with a detailed heat and mass transfer data set from a new experimental apparatus "Cold Plate."

2. Green roof model

Previous research studies have shown that a green roof covered with plants has a different thermal performance from a green roof without plants [26,27]. A green roof has a different thermal performance from a bare substrate roof because of the plants' shading, transpiration, and wind shielding. However, it is also important to accurately model the performance of a green roof without plants because most of green roofs will not be 100% covered by plants through their lifespan. Thus, this study first considered a green roof without plants and then considered a green roof with plants. The green roof model without plants represents the worst case scenario when green roof is not yet established or all plants are dead. Therefore, this study presents both bear and fully-covered green roof models. Finally, these two models are combined in a model for partially-exposed/partially-covered green roofs,