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Experimental quantification of heat and mass transfer process through vegetated roof samples in a new laboratory setup

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ABSTRACT

A new experimental apparatus, "Cold Plate", was designed and built to quantify heat and mass transfer processes for green roof samples inside an environmental chamber. The "Cold Plate" apparatus addressed shortcomings in the existing data sets available for green roof energy balance calculations. Experimental data collected in this apparatus show that evapotranspiration controlled the intensity of all other heat fluxes, depending on the plant and environmental conditions. Also, under the described laboratory conditions, the uninsulated green roof samples with plants showed an average heat flux reduction of 25% compared to samples without plants. This reduction was due to the plants providing extra shading, additional water storage and better water control mechanisms.

1. Introduction

Green roofs are regarded as a sustainable technology that offers several benefits to the society. These benefits are: reduced energy demand for space conditioning, reduced storm-water runoff, expanded lifetime of roofing membranes as well as reduced urban heat island effect when implemented in entire neighborhoods. In general, green or vegetated roofs are specialized roofing systems that support vegetation growth on rooftops [1,2]. Green roofs typically consist of several layers, which include following materials from the top to the bottom of an assembly: (1) drought tolerant plants such as *Sedum* and *Delosperma* species, (2) substrate or engineered soil, (3) filter or cloth membrane, (4) drainage layer, and (5) root resistant layer [1,3]. The plant and substrate layers reduce direct thermal loads, and, therefore, create energy benefits on a green roof via several transport mechanisms that include transfer of both heat and water.

Energy benefits from green roofs have been previously studied by theoretical, experimental and/or a combination of both approaches. From these approaches, the experimental approach has the benefit of its reliability and simplicity as long as an experimental setup is available. Previous field studies have measured one or several of the following parameters: (1) heat flux reduction through the roof, (2) green roof *R*-values, and (3) evapotranspiration for unsteady weather conditions. Additionally, there have been few laboratory studies focused on quantifying the same transport processes.

Several important field experimental studies of green roofs in North America have compared the thermal performance of green roofs for summer weather conditions. Average heat flux reduction through these roofs varied from 18% to 75% when green roof layers were installed [2,4–10]. A large variation of heat flux reduction could be attributed to experimental setups, plant coverage, building design, and local weather conditions. Interestingly, a field study [7] and our laboratory study [11] have found a significant reduction of heat flux from a green roof compared to a bare soil roof. The laboratory analysis found that it is not just the shading, but also the evapotranspiration that improves the thermal performance of the green roof with the presence of plants [12]. This finding was possible due to tightly controlled laboratory experiments with laboratory graded instrumentation.

Calculated *R*-values for green roofs with a shallow substrate (7.5–15 cm depth) measured in field and laboratories experiments varied from 0.37 to 0.85 m^2K/W (1.8–4.8 ft^2 h °F/Btu) [7,11,13]. The difficulty in measuring and then calculating the *R*-value was due to the non-steady state conditions during the test periods [14,15], while *R*-value is by definition a steady-state property that indicates a thermal resistance of homogenous building materials. Thus, due to inhomogeneous green roof layers as well as dynamic heat and mass transfer processes in green roofs, the thermal resistance cannot be modeled with a simple *R*-value used for conventional building materials.

Previous research has shown that the substrate water content plays an important role in decreasing the surface green roof

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Nomenclature

LAI	leaf area index [(leaf area)/(soil surface)]
M	metabolic storage (photosynthesis and respiration) (W/m^2)
$Q_{conduction}$	conductive heat flux through roof (W/m^2)
Q_{ET}	evapotranspiration, or latent heat flux by convection (W/m^2)
Q_{IR}	long-wave radiation (W/m^2)
$Q_{sensible}$	sensible heat flux by convection (W/m^2)
R_n	net radiation (W/m^2)
$S_{thermal}$	thermal storage for substrate, plants (W/m^2)
VWC	substrate volumetric water content
r_s	stomatal resistance to mass transfer (s/m)
γ	psychrometric constant = $C_pP/0.622i_{fg}$
h_{conv}	convective heat transfer coefficient (W/m^2 °C)
r_a	aerodynamic resistance to mass transfer (m/s)
T_{leaf}	leaf temperature (°C)
T_{air}	air temperature (°C)
k	thermal conductivity (W/m °C)
F	view factor
J	radiosity

temperature and the total heat flux through the roof by means of evapotranspiration [2,10,11,16]. Evapotranspiration is a combined process of water loss from the soil (evaporation) and plants (transpiration). Previous research studies have quantified evapotranspiration with weighing lysimeters that directly measure water loss by using a load sensor or scale [17–21]. Alternatively, a few studies have used soil water balance approach [22,23]. The soil water balance is performed by tracking changes in the substrate water content that can be measured with probes based on different measurement methods [17]. In summer conditions, previous studies have calculated that the green roof evapotranspiration absorbed approximately 12–25% of the incoming heat flux, for a dry and wet green roof, respectively [16]. Another study observed evapotranspiration heat fluxes as high as 350 W/m^2 of roof surface area during the peak solar radiation [20,21]. These results show the importance of evapotranspiration in the reduction of thermal loads on a green roof.

There have been previous experimental efforts to understand heat transfer involving plants [24–27] and develop analytical models to predict transpiration over perforated plates [25]. The plates simulate plant resistance to evaporation [25] or the convective studies helped understand the effect plants have on natural and/or forced convection in greenhouses [26,27]. Nevertheless, even with the recently rehabilitated interest in green roofs in North America, our literature review found only two laboratory experiments, which have evaluated green roof thermal performance in two wind tunnels [13,28]. The first wind tunnel study investigated the evaporative cooling effect of green roof samples [28], while the second study calculated R-values for green roof samples [13]. None of these studies were able to measure evapotranspiration rates continuously.

Overall, previous field and laboratory studies have proved that green roofs can significantly decrease the heat flux through a roof. Furthermore, evapotranspiration is found to play a major role in controlling heat gains through the green roof. However, to the best of our knowledge, there is not one single study that has measured all of the important heat and mass transfer processes simultaneously. Such a comprehensive experimental study represents a challenging task required to enable development and validation of green roof heat transfer model components, as well as the existing evaluations of the overall model performance. This paper presents a new experimental apparatus designed and constructed to collect experimental data in an environmental chamber that houses the apparatus. The experimental data were used to validate a predictive heat and mass transfer model for green roofs [29].

2. Heat and mass transfer fluxes

The energy balance for a green roof can be generalized as following [30,31]:

$$R_n = \dot{Q}_{ET} + \dot{Q}_{sensible} + \dot{Q}_{conduction} + S_{thermal} + M \quad (1)$$

In Eq. (1), the net radiative flux (R_n) represents the total incoming/outgoing solar and long-wave radiation. The evapotranspiration (Q_{ET}), a latent heat flux by convection, represents soil evaporation and plant transpiration water loss. The sensible heat flux by convection ($Q_{sensible}$) is the heat flux between a roof and the surrounding air. The conductive heat flux through a roof ($Q_{conduction}$) represents the heat transfer though a roof. Moreover, the thermal storage capacity of plants is typically neglected by most green roof and soil-vegetation models, which is small when compared to the thermal storage capacity of the soil layer. In this study, the thermal storage ($S_{thermal}$) is neglected by assuming quasi steady-state heat transfer, which is correct for slowly changing environmental conditions similar to the experimental conditions in our environmental. In addition, the metabolic storage (M) is neglected because it typically represents around 1–2% of the net radiation [30,32,33].

Previous studies in urban [34], suburban [35], and agricultural environments [36] have measured ratios of latent, sensible, and conductive fluxes divided by the net incoming radiation. These measured ratios showed the importance of evaporation in Eq. (1) to decrease conductive heat fluxes through the substrate. Table 1 summarizes the results from these different outdoor experimental studies [34–36], and compares them to data collected in a laboratory environment [32]. As shown in Table 1, even in dry suburban conditions, the ratio of evapotranspiration to the net radiation is still significant. The results for ET/R_n ratios for the suburban (wet) and agricultural areas are lower than the results found in controlled laboratory experiments with plants, having ET/R_n equal to 0.86 [32]. Table 1 also shows that each heat transfer mechanism may have an important role in the heat flux reduction depending on the water content in the substrate.

3. Experimental setup

Based on the presented literature review, a new experimental apparatus was needed to address shortcomings in the existing data sets available to create a complete energy balance for green roofs. The new apparatus, named "Cold Plate", was designed and built to include laboratory-rated instrumentation and to allow simultaneous measurements of all important heat and mass transfer processes on a green roof.

The design and construction of experimental apparatus for testing green roof thermal properties was a challenging process that included several versions of the apparatus [37]. The design of the new apparatus was inspired by "Hot Plate" C177 and "Hot Box" C1363 ASTM standards [38,39]. The final version of the "Cold Plate" apparatus uses an environmental chamber and its advanced controls system to monitor and supply different environmental conditions. This is achieved by supplying air at a constant flow rate with a variable supply air temperature and humidity to control