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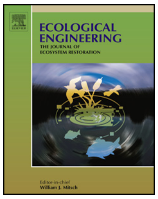

Impact of plants transpiration, grey and clean water irrigation on the thermal resistance of green roofs

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ABSTRACT

Evapotranspiration is one of the important processes in green roof heat and mass transfers. It is usually given in the literature by direct measurement or developed models to estimate both transpiration of plants and evaporation of soil at same time. In this paper, transpiration and evaporation were studied and evaluated separately. The thermal performance of green roof was evaluated in controlled weather conditions using a low-speed wind tunnel and the plants transpiration was measured in term of green roof thermal resistance. Green roof samples with two types of plants were tested. The results showed that plants evapotranspiration represented about 13% of the thermal resistance for ryegrass and about 37% of the thermal resistance for periwinkle. As an application, the impact of grey water on evapotranspiration and green roof thermal resistance was studied using the same laboratory facility. Green roof samples were tested in side-by-side studies using either grey water or clean water for long-term irrigation. Synthetic grey water of repeatable composition was used. Results showed visible effects of grey water on periwinkle but not on ryegrass. The thermal performance for green roofs irrigated with grey water was about 30% lower than those irrigated with clean water.

1. Introduction

Green roofs are suggested to be an effective contribution to reduce the energy consumption of buildings and a potential solution of adapting cities to climate changes (Rosenzweig et al., 2009). This can vary depending on the time of the year, and the amount of water held within the system. In addition to aesthetic considerations, which only apply to landscape architects, green roofs improve storm water management (Mentens et al., 2006; Fioretti et al., 2010; Bruce et al., 2011) and contribute to the reduction of noise (Van Renterghem and Botteldooren, 2011) and a number of polluting air particles and compounds through the plants and by deposition in the growing medium (Yang et al., 2008; Li et al., 2010). Green roofs are intrinsically of greater benefit to biodiversity than more traditional roofing methods (Schrader and Böning, 2006; Brenneisen, 2006); they also reduce carbon dioxide in the atmosphere and produce oxygen through photosynthesis (Li et al., 2010; Feng et al., 2010).

Modelling the thermal behaviour of green roofs requires the study of several interacting phenomena, such as heat and mass transfer and plant physiology. Many green roof studies are available in the literature, ranging from simple to detailed. The first approach considers only the decrease of the roof *U*-value (Niachou et al., 2001; Wong et al., 2003; Santamouris et al., 2007). More detailed models were presented in others studies, with heat balance that considers additional influencing phenomena, such as solar shading by foliage and cooling by evapotranspiration (Del Barrio, 1998; Frankenstein and Koenig, 2004; Sailor, 2008; Ouldboukhitine et al., 2012a).

The evapotranspiration phenomena has recently draw increased interesting by the green roof research community because of its importance on heat and mass transfer at the level of green roof components (Metselaar, 2012; Ouldboukhitine et al., 2012b; Jim and Peng Lilliana, 2012).

Evaporation is the movement of thermal energy from a water surface to the atmosphere involving a change in phase from liquid water to vapor (thermodynamics) that is removed from the surface (aerodynamics). When the solar radiation heats the atmosphere, it provides an energy source to the water surface, able to increase the heat flux that drives transpiration from plant leaves. Penman found that evapotranspiration included two major components,

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solar radiation and aerodynamic resistance, which has been demonstrated using reference vegetation surface having dense foliage and saturated soil growing media. Collaboration between Monteith and Penman extended the theory to unsaturated surfaces by introducing surface resistance which, in the case of vegetation, bears a relation to the stomatal conductance of leaves (Fuchs, 1990; David and Jennifer, 2005).

Based on Penman–Monteith equation for evapotranspiration, an experimental study was performed to adapt Penman–Monteith equation with the type of green roof studied (Ouldboukhitine et al., 2012b). The green roof components were replicated in a tray and suspended in a traction-compression sensor balance. Using a gravimetric technique consisting of monitoring the evolution of the tray weights over time, the evolution of the water reserve of the substrate was determined, which represents the amount of evapotranspirated water. Finally, a correction coefficient was deduced by comparing Penman–Monteith equation numerical results with evapotranspiration experimental results obtained by the performed experiment (Ouldboukhitine et al., 2012b).

The previous studies cited from the literature evaluated the impact of evapotranspiration on heat and mass transfers. However, evaporation and transpiration were given in the same expression; the impact of only plants transpiration on the thermal performance of green roofs is still unidentified. Because of that, it is difficult to assess the importance of plants on green roof thermal performance. In the first part of this study, evaporation and transpiration were measured separately and the impact of plants transpiration on the thermal performance of green roof was evaluated.

Evapotranspiration itself can be influenced by the quality of water irrigation. What would be the effect of grey water irrigation on green roof plants physiology, their transpiration, and the thermal performance of buildings? In another hand, cost for a green roof is typically two times that of a conventional roof surface. Anticipated benefits from the green roof, then, must be demonstrated to outweigh first costs, so questions about the long-term performance naturally arise. A study was performed in the U.K. to characterize alterative recycled waste materials for use as green roof growing media (Chloe et al., 2009). An alternate possible source of green roof irrigation is a building's own grey water, which is produced more-or-less continuously in commercial buildings and must be discharged into the sewage system as waste. Grey water is the effluent from lavatories, sinks, showers, and water fountains. Although grey water is much less polluted than toilet wastes, it typically contains small amounts of nitrogen, phosphorus, BOD, detergents, salts and pathogenic bacteria.

Whether grey water is a viable water source for sustaining green roofs is unknown. The applicability of extensive green roofs in arid environments was evaluated experimentally using intermittent saline irrigation compared with frequent irrigation (Shigeoki et al., 2013). Shigeoki concluded that a better characterization of plants evapotranspiration in relation to stress factors could help in selecting suitable plants and in designing an appropriate irrigation schedule for green roof management systems. In another study, short term testing of grey water on a green roof (Cameron and Berghage, 2009) has shown that levels of BOD in the grey water were significantly reduced by passing it through a green roof medium prior to its discharge. So a green roof may serve as a filter for grey water, but whether the plants can use grey water is uncertain. Supplemental irrigation with grey water may either improve performance (for example, by healthier plant and root growth in dry periods) or compromise performance (possibly by alteration of soil structure or accumulation of nutrients or other pollutants). Furthermore, salts in grey water are known to collect in soil, so greenroofs, with relatively thin soil layers, may not be able to sustain vigorous plant growth as needed for high ET rates.

The other purpose of this study was to evaluate the impact of grey water on green roof evapotranspiration by comparing the thermal performance of typical green roofs under controlled conditions when irrigated regularly with grey water or clean water.

2. Method

The basic method employed was to expose the top of a green roof test section to conditions (temperature, humidity, sunlight, and wind speed) representative of typical summer weather for a local climate. While some of the thermal energy is conducted through the green roof and into the conditioned space below, some is also absorbed by the plants and the soil to evaporate water, thereby reducing the overall heat transmission by evaporative cooling. The phenomenon of evapotranspiration is combination of two separate processes: evaporation and transpiration. Evaporation is the transformation of water into vapor at the surface of the wet growing media and transpiration is the physiological process of transforming water into vapor at the plants surfaces, primarily leaves. The determination of the evapotranspiration can be obtained by direct measurement, or approaches with models that achieve the daily evapotranspiration or in a time step taking into account a number of parameters and physical phenomena (radiation, pressure, wind, etc.) and characteristics of the plants (David and Jennifer, 2005). Research reported in the literature gives both transpiration and evaporation impacts through measurement and approaches evaluating the regrouping both transpiration and evaporation in same time. In this study, we performed an experiment to evaluate separately the impact of transpiration and evaporation on the thermal resistance of green roof. Hence the question, what is the impact of only transpiration on the thermal resistance of green roof?

The laboratory facility test consists of two superposed wind tunnels. The wind tunnel on the top simulates the outside conditions, the side where the green roof trays were positioned. In order to maintain a hot air temperature circulating through the wind tunnel and the trays, heating elements were installed at the level of the blower port. The wind tunnel on the bottom simulates the indoor conditions. It was equipped with an air conditioning to maintain a cold air temperature. The laboratory facility has been designed and constructed that continuously exposes a green roof to constant temperature, wind speed, humidity and sunlight. To attain this control, full scale green roofs could not be accommodated. Rather test roof coupons were prepared that recreated green roofs in all respects others than roof surface area. These are illustrated in Fig. 1. When steady state conditions are maintained, the effective R-value of the greenroof is calculated as $R = \Delta T/Q$, where the temperature difference ΔT is calculated as $\Delta T = T_{\text{hot}} - T_{\text{cold}}$ and Q is the heat flux through the bottom of a green roof and into the conditioned space below.

Radiation has an important impact on the thermal resistance; this impact was studied in (Ouldboukhitine et al., 2012a). It is very important to know the behaviour of the incident radiations when they reach the canopy and what are the most influence parameters affecting this behaviour. However, in this study, the simulated sunlight applied during the test can ensure a good transpiration rate. The analyses are based on the comparison of roofs with and without vegetation to evaluate how much transpiration can affect the green roof R-value.

The green roof trays were exposed to ambient temperature controllable between 25 °C and 60 °C and to ambient relative humidity between 10% and 50% depending of the required test conditions. The wind speed was steady at 2.2 m/s and simulated sunlight of about 100 W/m^2 at soil surface was applied. The bottom of the