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An investigation of sensible heat fluxes at a green roof in a laboratory setup

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ABSTRACT

During the last few years, several models have been proposed for the calculation of green roof thermal behavior, but the validation studies of such models are lacking a comprehensive set of highly accurate data. In this study, an experimental laboratory setup was used to create different environmental conditions and to measure sensible heat fluxes to/from a vegetated roof assembly. This experimental setup has been successfully used for different wind velocities (0–3 m/s) to create free and forced convection conditions around green roof tested samples. Furthermore, our study proposed a “basic model” for calculations of the convective heat transfer at green roof assemblies, which is a modified version of the Newton’s cooling law, calibrated and then validated with different sets of data. For forced convection flow regimes, the proposed “basic model” resulted in RMSE (Root Mean Square Error) of 11 W/m^2 and R^2 value of 0.81. Similarly, the model provided RMSE of 6.6 W/m^2 and R^2 of 0.90 for sensible heat fluxes with free convection conditions. In the future, this model will be used in on-site experimental studies to understand its performance under wind conditions that exhibit a much wider range than the studied velocity range near the leaf canopy.

1. Introduction

Vegetation has been used on building roofs and walls since ancient times, with the most famous example of the Babylonian gardens in Mesopotamia. A widespread use of roof vegetation has significantly increased in recent years. Fig. 1 shows an example of contemporary use of vegetation for a traditionally-designed house in Norway. Some European countries have explored opportunities for use of extensive green roofs since the 1970s [1]. The specific purposes of green roof installations vary, but generally hinge upon stormwater reduction or improved building energy efficiency and often both. As stormwater concerns in urban settings have become ubiquitous, green roofs have been introduced as a viable and effective method for reducing urban stormwater runoff from roof surfaces [2].

The types of growing media and roof assemblies vary, but most green roofs consist of a drainage layer, a root barrier, and a waterproof membrane as shown in Fig. 2. A green roof growing media depth is typically between 0.05 and 0.3 m [3], while the vegetation layer can incorporate different plants depending on the local climate [4]. A green roof has numerous benefits that include improved air quality, reduction of the “heat-island effect,” sound attenuation, building envelope protection, esthetic value, and stormwater detention, in addition to the reduction of energy absorbed by the roof assembly [2,5–7]. One of the ecological functions a green roof provides is its stormwater management capacity. Nevertheless, to take full advantage of green roofs, building designers need quantitative assessments of green roof benefits.

Horizontal building surfaces, such as roofs, experience high thermal loads during summer conditions in climates such as the Mediterranean or some U.S. climate regions. Green roofs may offer an adequate solution to this problem [8]. Theoretical and experimental analyses of different roof assemblies to promote cooling mostly focuses on evaporative and radiative heat transfer mechanisms. The green roof vegetation shades this type of roof assemblies from direct solar radiation, and it also cools the roof by means of evapotranspiration from the vegetation layer [9]. The vegetation layer also absorbs large quantities of solar energy during the diurnal biological functions. An incoming amount of solar radiation can affect the internal temperature of a building. Out of the total incoming solar radiation, approximately 27% is reflected, 60% is absorbed by the plants and the soil through evaporation, and 13% is transmitted into the soil [10,11]. As a result, green roofs can control the temperature of the roof assembly and protect the roof membrane from temperature extremes. During summer weather

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Fig. 1. Traditional green roof with native vegetation in Norway [1].

conditions, the vegetation and soil layers can reduce the cooling energy costs for buildings, such as warehouses, which have a relatively large roof area when compared to the vertical wall area of such buildings [12].

Greenroofing in the world is a burgeoning industry. With the spread of greenroofing comes the need to understand and predict the thermal effects associated with adding a soil and vegetation layer to a building envelope. Several previous studies have evaluated the thermal properties of green roofs. It is well known that vegetated roof coverings, or green roofs, can lower rooftop surface temperatures in warm climates [7,9,13]. The magnitude of temperature reduction and resulting reduction of heat flow into structures is dependent upon many factors associated with a green roof's construction and with the climate of the area. Cooler surface temperatures translate into decreased heat transfer through roofs into the occupied space thereby reducing cooling loads in warm months.

In both cool and humid climates, evaporative potential limits the cooling effects transpiration and evaporation provide. However, in a study conducted in Singapore (wet and tropical conditions), it has been observed that vegetation can consume solar heat gain through evapotranspiration and photosynthesis [14]. This consumption of solar heat implies that passive cooling is occurring. In cooler areas, other parameters including thermal mass may become significant factors in determining green roof thermal performance, where performance in this case is equated with heating load reduction. This study reveals that, rooftop vegetation caused a negative heat flux during most of the day compared to a positive, downward heat flux for an adjacent bare roof, in a tropical environmental [14].

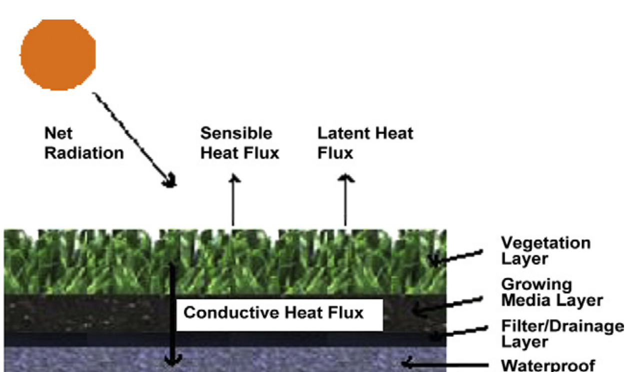

Fig. 2. A schematic of a typical green roof layers, and energy balance at the vegetation layer.

Other studies have revealed similar passive cooling capabilities. They describe green roof effects in Mediterranean climates where wet winters and dry summer conditions dominate. In addition, planted roofs not only insulate, but also can provide passive cooling for building interiors via evaporative cooling [7,9,15]. A limited number of studies have observed green roof effects in winter. In one such study it is predicted that soil moisture, a thermal mass contributor, may be the essential factor in the insulating capacity of green roof systems in winter [9].

An experimental study measured and also calculated sensible heat fluxes to/from a green roof sample using a formulation suggested by Wang [16] in a laboratory environment [11,17]. However, in these studies, sensible heat fluxes were obtained indirectly from an energy balance, and the suggested equations for sensible heat flux calculations are only strictly valid for free convection conditions. Thus, the main purpose of the present paper is to develop a model for sensible heat flux calculations at a green roof with different convection conditions. In addition, different theoretical and semi-empirical methods are compared with experimental sensible heat flux data obtained from a new experimental apparatus, cold plate, under controlled laboratory conditions. In this study, three different types of convective heat transfer models are compared, and effects of the green roof with different airflow velocities are considered for free and forced convection regimes.

2. Methodology and theory

Understanding sensible heat fluxes at surfaces covered with a plant material is challenging because the surface is rough and porous. Moreover, surface temperature distribution is not homogeneous because the leaf temperature depends on many factors such as sensible and latent heat transfer, which change depending on several environmental parameters. The vegetation layer behaves as an attenuator of heat fluxes in a green roof. This effect must be taken into account for calculations of sensible and latent heat fluxes. Previous studies have followed experimental and theoretical methodologies to understand the thermal behavior of vegetated roofs. In a majority of these experimental studies, the thermal behavior of vegetated roof assemblies was investigated using the environmental weather conditions [18]. A few laboratory studies also attempted to understand the thermal behavior of plant materials [19]. All of the existing studies looked at the thermal behavior based on the overall energy balance for the roof assembly with the exception of one laboratory study with a cold plate apparatus, which provided detailed data on all important heat transfer mechanisms individually [11,17,20]. In this study, additional experimental data were collected in the cold plate apparatus to include different airflow regimes. Furthermore, convective heat transfer at a green roof was examined with different theoretical models and the model predictions were compared to measured data.

2.1. Energy balance

Several authors suggested time dependent energy balance approach for modeling green roof heat fluxes as shown in Fig. 2 [11,15,21–23]. All relevant energy fluxes should be considered when calculating an energy balance as following:

$$R_n - G - L - H = 0 \quad (1)$$

where R_n is the net radiation [W/m^2], H is the sensible heat flux [W/m^2], G is the soil heat flux [W/m^2], and L is the latent heat flux