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Heat transfer in a lightweight extensive green roof under water-freezing conditions

Ciril Arkar*, Suzana Domjan, Sašo Medved

Laboratory for Sustainable Technologies in Buildings, Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, Ljubljana 1000, Slovenia

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ABSTRACT

This paper presents a study of the thermal response of lightweight extensive green roofs with lightweight mineral wool growing media in wintertime in water-freezing conditions. A model of green roof heat and mass transfer was developed, which considers sensible as well as latent heat accumulation in plants and lightweight mineral wool growing media using an apparent heat capacity method. The model was validated with in-situ experiments. The influence of latent heat storage on the thermal response of a green roof was studied for different climatic conditions. The results of numerical analyses showed that the process of water freezing further improves the energy efficiency of green roofs, because the peak heat flux at the inner surface of the roof is up to 30% lower in comparison to the non-vegetated roof. It is shown that latent heat storage significantly contributes to decreasing heat losses during wintertime, which are approximately 5% to 20% lower in comparison to non-vegetated roofs.

1. Introduction

Green roofs are elements of built environment that are recognized as having a high positive influence on urban microclimate and living comfort in cities, since they address many environmental issues, such as urban heat island mitigation, water retention and detention, sink of CO_2, and other pollutants [1,2]. At the building scale, green roofs enable the more efficient use of energy in buildings in summer as well as in winter due to different energy saving processes. Green roofs' layers increase thermal resistance, increase thermal capacity and, thus, the ability for heat accumulation, while vegetation enables shading and cooling through evapotranspiration. As a result, outer surface peak temperatures are lowered, heat accumulation is enhanced, and peak heat flux on roofs' interior surfaces is lowered and shifted towards night-time hours. Other frequently citied benefits of green roofs include enhanced architectural appearance and improved construction tightness and durability [1,3]. Due to energy, environmental, and social benefits, green roofs are recognized as a bioclimatic technology and sustainable construction systems [1,4] and are becoming a predominant solution in connection with urban planning and building envelope retrofitting especially in the form of extensive green roofs because of low additional structural load, low maintenance and low cost in comparison to intensive solutions [1,5].

Regarding the building energy performance, the advantages of green roofs, in comparison to non-vegetated roofs are most commonly studied for summertime conditions, when observed differences in surface and roof construction temperatures and inner surface heat fluxes are larger than in other periods of the year. This is evident from the whole year research results [1,6,7] in which reported green roofs' energy savings are larger in summer (building cooling season) than in winter.

Nevertheless, green roofs also impact buildings' thermal response and energy performance in winter conditions. Zhao et al. [8] compared measured energy consumption for heating for identical buildings with identical heating systems. Their results showed that during a period without snow energy consumption for heating of buildings with green roofs was 23% lower in comparison to the energy consumption of buildings with the reference roof. Virk et al. [9] evaluated the impact of green roofs on the heating demand of typical office buildings, considering current climate and future climate scenarios. The results showed a reduction in heating demand of 12% when applying a green roof to a uninsulated building, while a negligible influence of a green roof was observed in the case of an insulated base-case roof with an added 20 cm insulation. La Roche and Berardi [7] showed that a reduction of energy consumption for heating in buildings with green roofs depends on climatic conditions. Increased energy consumption is noted for a building with green roof in Chicago's climatic conditions. A similar increase in energy consumption for a green roof in comparison to a conventional roof was observed in a study by Moody and Sailor [10] for a case of severe winter climate conditions. Getter et al. [6] presented and evaluated yearly in-situ monitoring results for green and gravel roofs. The average heat flux in winter was 13% lower with the green roof. From the results for the sunny winter

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* Corresponding author.
E-mail address: ciril.arkar@fs.uni-lj.si (C. Arkar).

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Nomenclature

c_{app}	apparent specific heat (J/kg K)
c_p	specific heat (J/kg K)
d	thickness (m)
E_L	long-wave downward radiation (W/m^2)
G_0	solar radiation on horizontal plane (W/m^2)
H	daily solar irradiation on horizontal plane (kWh/m^{2}day)
h	height of plants (foliage) (m)
h	convective heat transfer coefficient (W/m^{2}K)
K_{cb}	basal crop coefficient (–)
K_e	soil evaporation coefficient (–)
K_r	soil evaporation reduction coefficient (–)
K_s	water stress coefficient (–)
k	thermal conductivity (W/mK)
k	von Karman's constant (0.41)
LAI	leaf area index (m^2/m^2)
$\dot{m}$	mass flow rate (kg/s m^2)
p_v	vapor pressure (Pa)
q	heat losses (kWh/m^2)
$\dot{q}$	heat flux (W/m^2)
Δq	reduction of heat losses (%)
r	latent heat (J/kg)
r_a	aerodynamic resistance (s/m)
r_l	bulk stomatal resistance (s/m)
r_s	bulk surface resistance (s/m)
T	absolute temperature (K)
t	time (s)
u	wind speed/velocity (m/s)
U	thermal transmittance (W/m^{2}K)
x	node width (m)
z	height above green roof (m)

Greek symbols

γ	psychrometric constant (Pa/K)
Δ	slope of saturation water vapor pressure curve (Pa/K)
σ	Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W/m^{2}K^4)
ε	emissivity (–)
θ	temperature (°C)
ρ	density (kg/m^3)
ρ	albedo/reflectivity (–)
τ	transmissivity (–)
ψ	volume fraction (m^3/m^3)

Subscripts

a	air, ambient air
av	average (daily)
$calc$	calculated
$conv$	convective
e	exterior
f	foliage (plants)
gm	lightweight mineral wool growing media
gr	green roof
hw	heavyweight
i	indoor
lat	latent
lw	lightweight
max	maximum
mf	mineral wool fibres
n	n-th node
net	net
rc	roof construction
rr	reference roof
sat	saturation
se	exterior surface
si	interior surface
w	water

day with no snow cover, it is evident that the temperatures and thermal response of the green roof are noticeably different than on the days with ambient air temperatures above 0 °C.

In our previous study of lightweight green roofs' thermal performance [11], it was shown that at ambient air temperatures close to or below 0 °C, a green roof's thermal response is considerably different due to the water in the growing media phase change transition. Analyses also showed that a greater reduction of heat losses in comparison to those of a reference roof is observed in days in which water undergoes phase change transition. Furthermore, Tang and Qu [12] in their study showed that in the case of water freezing in the soil the mean heat flux for a green roof is 19% lower than with a traditional roof, while the difference was around 16% in the case of no phase change conditions. They also emphasized that green roof models do not consider the phase change process and that the same models are used for summer and winter time performance evaluation of green roofs. This can be anticipated from some presented numerical results [13,14]. Ascione et al. [14] used EnergyPlus whole building energy simulation software [15], which includes a module to estimate the thermal behaviour of green roofs. EnergyPlus is the most commonly used commercial tool for green roof performance studies [1]. The current ECO roof model in EnergyPlus is suited to regular green roof substrates composed of a mix of mineral and organic components; it is not adapted to lightweight mineral wool growing media, which has a very high water retention capacity and low thermal conductivity and density (equal to mineral wool thermal insulation) in a dry state. Although EnergyPlus enables the modelling of phase change materials in building constructions, this cannot be applied to moistened green roof growing media. Green roof models were also developed for TRNSYS software [13,16]; however, these models are not available within the TESS component library.

The objective of this research is to evaluate the influence of latent heat accumulation in green roofs' growing media on the thermal response and thermal performance of green roofs during winter climatic conditions that enable water freezing and melting. Particular attention was given to the development of a green roof heat and mass transfer model, which takes into account phase change phenomena and the variable thermal properties of moistened lightweight mineral wool growing media as well as to the validation of the model. In addition, analyses of green roofs' thermal performance in comparison to a reference roof were made for different wintertime climatic conditions. Studies evaluating the thermal response by considering latent heat accumulation in growing media throughout the winter period have not been found in the literature.

2. Green roof model

A green roof consists of several layers that are placed on top of a load-bearing roof. The load bearing roof is usually named (denoted) as a reference roof in comparative performance analyses of green and non-vegetated roofs. Generally green roofs are classified as: extensive, with a growing media (substrate) depth between 5 cm and 20 cm and overall weight 70–170 kg/m^2; and intensive, with a growing media depth between 20 cm and 60 cm and weight in the range from 290 kg/m^2 to 970 kg/m^2 [5,13]. In this research, a model was developed for lightweight extensive green roofs with