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Accumulated snow layer influence on the heat transfer process through green roof assemblies

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ABSTRACT

A green roof can reduce the peak thermal cooling loads and reduce the building energy consumption during the summer. It is also necessary to understand the thermal performance of these green roof assemblies during the winter when affected by an accumulation of snow on the rooftops. This study presents an experimental investigation and discusses the snow influence on the heat transfer processes through green roof assemblies. The on-site experiments were conducted in the outdoor test facility in Pennsylvania, U.S.A. during the winter of 2010/2011. The experiments were conducted on green roof buildings and on reference buildings for comparison. The collected data included the local meteorology, building operation data, and manually measured snow properties. The measured heat fluxes show that the heat flow though the green roof assemblies compared to the typical roof assemblies were reduced by approximately 23% when there was not an accumulated snow layer. However, this difference in the heat flux was only 5% when the roof structure had an accumulated snow layer. To quantify the snow effects on the heat transfer through green roof assemblies, the Johansen method was then used for snow conductivity calculations on rooftops. These equations should be a part of the total energy balance for the snow covered green roof assemblies because the snow layer significantly altered the heat transfer through these roof assemblies.

1. Introduction

Green roof assemblies reduce the building's energy consumption by reducing the thermal loads through the building's roof in summer cooling conditions. Green roof assemblies also affect the building's energy load calculations when compared to the traditional roof assemblies. Specifically, green roof assemblies include additional roofing layers: (1) drainage layer, (2) substrate layer (growing media), and (3) vegetation layer. A number of previous studies performed experiments with green roof assemblies under summer conditions, and proved the ability of green roof assemblies to reduce the cooling loads utilizing experimental and numerical methodologies [1–5]. However, a few studies explored the influence of green roof assemblies on the building's heating loads as well as the influence of an accumulated snow layer on the heat transfer through the roof assembly. A study evaluated the green roof performance under mild winter conditions, and concluded that the influence of green roof assemblies is unimportant when focusing specifically on the heating loads [6]. However, the thermal performance of green roof assemblies may vary for different climate zones [5], so the results from regions with mild winters may not properly represent regions with cold winters. Another study, conducted in a cold climate, measured the thermal performance of a green roof versus a gravel roof. This study found that the temperatures of the insulation top layer and the roof membrane top layer were nearly identical for the two types of roof assemblies [7]. Another study confirmed that snow eliminates the potential heating energy savings by installing green roof assemblies, but the total energy savings were proved to be statistically significant regardless of the accumulated snow [8]. Additionally, an experimental study indicated that the snow layer has a strong influence on the heat transfer through the roof assembly, and reported that, with an accumulated snow layer, the green roof and the reference roof had

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Nomenclature

K_{snow}	snow conductivity, W/(m·K)
K_{sat}	thermal conductivity of saturated snow, W/(m·K)
K_{dry}	thermal conductivity of dry snow, W/(m·K)
Ke	Kersten number, dimensionless
θ_{sat}	degree of saturation of the pores, dimensionless
ΔT	temperature difference of snow surface and bottom layer, °C
T_s	snow surface temperature, °C
T_b	snow bottom temperature, °C
T_a	temperatures of the air, °C
$T_{snowpack}$	temperature of the snowpack, °C
K_{ice}	ice conductivity, constant, 2.2 W/(m·K)
K_{air}	air conductivity at $T_{snowpack}$, W/(m·K)
K_{water}	water conductivity at 0 °C, constant, 0.5475 W/(m·K)
ρ_{snow}	snow density, g/cm^3
ρ_{ice}	ice density, constant, 0.9167 g/cm^3
c	constant, when $T_{snowpack} < 0$ °C, c = 0.15, when $T_{snowpack} = 0$ °C, c = 0.3
V_{pores}	relevant fractions for bulk volume of pores in the snow dimensionless
V_{water}	relevant fractions for bulk volume of water in the snow, %
Q_{snow}	heat flux through the snow layer, W/m^2
$Q_{long\text{-}wave}$	downward long-wave radiation, W/m^2, measured from SURFRAD station
Q_e	flux of the latent heat (evaporation, sublimation, condensation) at the snow/air interface, W/m^2
Q_p	flux of heat from rain, W/m^2
Q_r	heat flux through the roof, W/m^2
Q_m	energy flux available for melt, kJ/(m^2·s)
Q_{sn}	net short-wave radiation flux absorbed by the snow, W/m^2
Q_{si} Q_r	incident and reflected radiation on the snow surface, W/m^2
Q_{ln}	net long-wave radiation flux at the snow/air interface, W/m^2
Q_{li}	the downward long-wave radiation at the snow-air surface, W/m^2
Q_{le}	upward radiation emitted by the snow surface, W/m^2
Q_h	convective or sensible heat flux from the air at the snow/air interface, W/m^2
D_h	bulk transfer coefficient for sensible heat transfer, kJ/(m^3·°C), liter
D_e	bulk transfer coefficient for latent heat transfer, kJ/(m^3·mbar), liter
U_Z	wind speed at the reference height, z is taken between 1 and 2 m, m/s
l	average snow depth, m
Δl	decrease of snow depth per day, m/d
h_f	latent heat of fusion, constant, 333.5 kJ/kg
B	thermal quality or the fraction of ice in a unit mass of wet snow, %
e_{air}, e_s	vapor pressures of the air and the snow surfaces, respectively, kPa
A	snow albedo, dimensionless
α	constant related to the inverse of the air-entry pressure, cm^{-1}
$q_{j,\theta}$	heat flux for time θ, W/m^2
$T_{s,abs}$	absolute temperature of the snow surface, K
ε_s	emissivity of snow, constant,0.97
σ	Stefan–Boltzmann constant, 5.64 × 10^{-8} W/m^{2}K^4

relatively the same seasonal heat losses [9]. However, the existing studies did not provide a calculation method to estimate the effect of snow on the heat transfer process through green roof assemblies. Therefore, for a better understanding of the thermal performance of green roof assemblies during the winter, the current study aims to experimentally validate a set of equations to account for the snow effect on the heat transfer through the green roof assemblies located in cold regions.

2. Experiment description

This study performed the on-site experiments in an outdoor test facility located in central Pennsylvania, USA. The data collection equipment was installed during the summer and fall of 2010. After the adjustment and calibration of the equipment, the data collection process lasted from the end of November 2010 until the end of February 2011. The data collection recorded two types of data: (1) heat flux, temperature and weather data continuously collected by the data acquisition system, and (2) snow properties discretely collected by manual measurements.

2.1. Layout of experimental site

The experimental site is located at the Russell E. Arson Research Center of the Pennsylvania State University near Rock Springs, PA, which is 24 km south from State College, PA, U.S.A. There are six identical buildings with a footprint area of 4.65 m^2 and a volume of 1.8 m × 2.6 m × 2.6 m. The buildings are spaced 6 m from each other and arranged in a 2 × 3 grid to ensure independent indoor and outdoor environments for all of the buildings. Specifically, the arrangement reduces the mutual blocking of wind, rain, and snow by the buildings, and allows for consistent exposure to the sun and weather elements. Among the six buildings, three of them have green roof assemblies with both a vegetation layer and a substrate layer. One building has a bare soil roof assembly with only a substrate layer and no vegetation layer on the rooftop. Finally, two buildings are reference roof buildings with neither a substrate layer nor a vegetation layer on the top of the original roof assemblies. All six buildings were constructed identically with the same wall assemblies, and the same locations of doors and windows. All roofs have a light slope (1/12) to maximize the solar exposure. Fig. 1 shows an overview of the experimental site with the building arrangement.

All of the six buildings have the same insulation layers with identical heating devices and air conditioning systems. A 1 kW thermostat controlled heating device is located at the south wall, and a 3 kW air conditioning system is installed in the north wall window of each building. The wall materials, from inside to outside, are 6.35 mm plywood, 89 mm fiber glass batting insulation with a thermal resistance (R-value) of 2.3 (m^2·K)/W and 6.35 mm oriented strand board (OSB) sheets. The materials of the reference roofs with the order from the inside to the outside are 6.35 mm OSB sheets, 89 mm fiber glass batting insulation, 19.05 mm plywood, and water proofing layer.

2.2. Green roof materials

The components of the green roof assemblies were identical for each building with a green roof. Beyond the roofing layers that the