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Comfort and energy savings with active green roofs

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ABSTRACT

Green roofs have been proposed for energy saving purposes in many countries with different climatic conditions. However, their cooling and heating potential strongly depends on the climate and building characteristics. In particular, the increase of the thermal capacity of green roofs compared to traditional roofs, if not controlled with insulation, may lead to higher cooling and heating loads. This paper discusses the energy saving potential of green roofs adopting a variable insulation strategy. A system consisting of a plenum located between a green roof and the room underneath and a sensor-operated fan that couples (or decouples) the green roof mass with the indoor environment was developed. The fan is activated and stopped using temperature based rules; the plenum is ventilated only when the fan works, creating a variable insulation system. Four cells with an insulated traditional roof, a non-insulated green roof, an insulated green roof, and a green roof with the variable insulation system have been tested in a hot and dry climate with mild winters over several years. This paper compares and discusses different plenum control algorithms. Results are particularly promising because the variable insulating system proved to adjust the thermal capacity of the roof effectively. In summer, the non-insulated green roof and the green roof with variable insulation system achieved the lowest indoor temperature; in winter, the insulated traditional roof and the variable insulation green roof system achieved the highest indoor temperatures. Measurements are hence compared with simulations. Finally, the energy saving potential of the new green roof system is evaluated.

1. Introduction

It is difficult to determine the exact amount of energy used by the building sector, however different sources estimate the building sector's energy consumption and greenhouse gas (GHG) contribution at around 35% of emissions worldwide with a larger percentage in industrialized nations such as the United States where estimates range above 40% of total [1–3]. As these high percentages are significantly related to the high energy and resource consumption of buildings, various sustainable approaches and environmentally responsive energy efficient technologies have been proposed and implemented to design low-energy buildings. These include advanced eco-technologies, energy efficient systems and renewable energy sources [3]. In this context, green roofs are often identified as a valuable strategy for making buildings more sustainable [3–5]. This paper investigates the energy saving potential of innovative green roofs.

Green roofs, also named "eco-roofs", "living roofs" or "roof gardens", are roofs with plants in their final layer. They are generally built to enhance the energy saving in buildings, but they have many other benefits [5,6]. In fact, their vegetation layer realizes photosynthesis processes, whereas their soil layer allows absorption of rainfall, often resulting in improvements of the water runoff quality [7]. Recent papers offer a complete review of the main environmental benefits of green roofs [8,9].

Green roofs have been proposed in many countries with different climatic conditions and building characteristics. However, their cooling and heating potential strongly depends on the climate. In particular, the increase in the thermal capacity of green roofs compared to traditional roofs, if not controlled, has shown to raise the cooling and heating loads [8,10]. Consequently, this paper aims to discuss the development of a smarter green roof adopting variable insulation strategies thanks to a plenum located between the green roof and the room underneath, and a sensor-operated fan that couples (or decouples) the green roof with the indoor environment as required.

After having investigated through dynamic simulations cases in which green roofs lead to increase energy use intensity (EUI), the paper describes experimental measurements done over several

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Legend

$C_{e,g}$	latent heat flux bulk transfer coefficient at ground layer
C_f	bulk heat transfer coefficient
C_{hg}	sensible heat flux bulk transfer coefficient at ground layer
$c_{p,\mathrm{air}}$	specific heat of air at constant pressure
F_f	net heat flux to foliage layer (W/m^2)
F_g	net heat flux to ground surface (W/m^2)
H_f	foliage sensible heat flux (W/m^2)
H_g	ground sensible heat flux (W/m^2)
$I_s^{\downarrow}$	total incoming short-wave radiation (W/m^2)
$I_{ir}^{\downarrow}$	total incoming long-wave radiation (W/m^2)
l_f	latent heat of vaporization at foliage temperature (J/kg)
l_g	latent heat of vaporization at ground temperature (J/kg)
K	soil thermal conductivity, water dependent
L_f	foliage latent heat flux (W/m^2)
L_g	ground latent heat flux (W/m^2)
LAI	leaf area index (m^2/m^2)
q_{af}	mixing ratio for air within foliage canopy
$q_{f,sat}$	saturation mixing ratio at foliage temperature
$q_{g,sat}$	saturation mixing ratio at ground temperature
Q_{cond}	conduction heat
Q_{irr}	radiation heat
Q_{conv}	convection heat
Q_{evap}	evapotranspiration heat
r''	surface wetness factor
T_{af}	air temperature with in the canopy
T_f	foliage temperature
T_g	ground surface temperature
T_∞	ambient temperature
V_∞	air velocity
w_{af}	wind speed within the canopy
α_f	albedo (short-wave reflectivity) of the canopy
α_g	albedo (short-wave reflectivity) of ground surface
ε_f	emissivity of canopy
ε_g	emissivity of the ground surface
ε_1	$\varepsilon_g + \varepsilon_f - \varepsilon_g \times \varepsilon_f$
ρ_{af}	density of air at foliage temperature
ρ_{ag}	density of air at ground surface temperature
σ	Stefan–Boltzmann constant
σ_f	fractional vegetation coverage

years in cells with different roof technologies. Different plenum control algorithms are presented and discussed, in order to find the way to maximize the energy saving potential of variable insulating green roofs. The basic idea of this paper is to adjust the thermal capacity of a green roof in the most effective way to increase comfort and reduce the energy consumption. For this scope, the optimal strategy for the variable insulating green roof is searched and simulated in different climates.

The following section presents an overview of energy saving studies about the adoption of green roofs and describes the heat transfer processes in green roofs. In section three, the energy saving potential for cooling and heating purposes through green roofs are discussed through parametric simulations of green roofs with different leaf area, soil depth, and insulation thickness in different climates. Sections four describes the experimental analysis done in some test rooms located in California, US, with insulated traditional (cool) roof, non insulated green roof, insulated green roof and variable insulation green roof. Section 5 discusses the results of the experimental works, compares these with the simulation results, and shows possible advantages of variable insulation green roofs in different climate. The study concludes by reporting future directions of research.

2. Energy saving with green roofs

2.1. Literature review

Green roofs are often pointed as efficient technologies in reducing the variation of indoor temperature and the energy consumption of buildings both in warm and cold climates [10,11]. However, the building envelope characteristics play an important role over the potential of green roofs. Generally, in non-insulated buildings, the impact of green roofs is much higher than in insulated ones, whereas the better the insulation of the roof, the lower their contribution. Moreover, the characteristics of the energy load of the building (prevalence of cooling or heating loads) affect the contribution of green roofs [11]. In warm climates, green roofs potentially reduce the indoor temperature through shading of the rooftop layer and reducing the direct influence of solar radiation [12,13]. In warm climate, the importance of the climate characteristics, and in particular, of the level of rainfall has often been pointed. Simmons et al. stated that extensive green roofs possess great potential for the climates of subtropical regions with high temperatures and strong rainfall [14]. A related study in Greece found that green roofs reduce the energy utilized for cooling between 2% and 48% depending on the area covered by the green roof, with an indoor temperature reduction up to 4 K [15]. Similarly, Spala et al. demonstrated that the integration of green roofs in buildings contributes to energy saving in different Greek cities [16]. However, the respective findings showed that green roofs significantly decreased the cooling loads, while their influences on the reduction of heating loads was marginal in that country. In a recent study in Singapore, the temperature variations of a typical roof and a green roof were compared: the analysis showed the positive impact of green roofs in reducing the variation of the surface temperature [17].

According to Jim and Tsang, who analyzed the effectiveness of green roofs in the warm and humid climate of Hong Kong, the plant form, type, and biomass structure play a notable role in cooling potential [18]. A recent study by Olivieri et al. in a Mediterranean climate found that once the density of plants in a green roof is increased, although a roof structure substantially insulated with a U-value of 0.24 W/m^{2}K, the green roof reduced cooling consumption of 60% in comparison to a conventional roof [19].

The benefits of green roofs in cold climates are often acknowledged [21–24]. In a detailed study in Canada, Liu and Baskaran showed that the daily surface temperature variation with a green roof was approximately 6 °C, compared to a variation up to 45 °C occurring with a traditional roof [20]. From a long-term perspective, a study compared the green roof and a cool roof for houses in St. Louis, MO, using a life cycle approach over a 10-year period, and showed significant advantages for the house with the green roof [21]. Zhao evaluated the reduction of the heat flow thanks to green roofs in extreme climates with highly snowy winters [22].

Contrasting results have been found in climates with different weathers during the year. In a study performed in the Midwestern of U.S., with hot and humid summers but cold and snowy winters, researchers found that that the impacts on the surface temperature and the heat flux are high in summer (167% on average) and low in winter (13% on average) [23]. Likewise, the respective study recommends increasing the depth of growing medium layer and providing irrigation in that region.

Recently, several studies have looked at the same green roof in different climates to explore advantages and disadvantages of the