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Comparative study of the thermal performance of the novel green (planting) roofs against other existing roofs

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ABSTRACT

The aim of this paper is to carry out a comparative study into the thermal performance of two novel green (planting) roofs against three existing roofs, i.e. the exposed roof and the ceramic and clay laid evaporating roofs. This involved the brief theoretical analyses of the heat and mass transfer processes and the energy balance equations applied to the roofs and most importantly, the dedicated measurement of the selected building roofs in Guangzhou (China), located at a typical sub-tropical climatic region. As a result, the temperature and air conditioning power consumption data within five selected testing rooms with different roof configurations were recorded, compared and analyzed. Of the five testing rooms that had the roof structure of (1) 100 mm soil planting, (2) 200 mm soil planting, (3) ceramic layer, (4) clay layer, and (5) no additional layer (exposed), respectively, the rooms with the green (planting) roofs had the lowest indoor air temperature (in average), which were around 0.95 °C, 0.8 °C and 0.5 °C lower than that of the rooms with the exposed, ceramic and clay laid evaporating roofs, respectively. Meanwhile, the inner surface temperatures of the planting roofs were 3.8 °C, 3.7 °C and 2.8 °C lower than that of the above three roofs. These indicated that the green (planting) roofs had the better thermal performance than the clay and ceramic laid evaporating roofs and exposed roof, thus creating the cooler indoor environment, better thermal comfort, and reduced air conditioning power consumption over others. Taking the room with the exposed roof as the reference, the air conditioning power reduction ratios of the green roof and the clay and ceramic laid evaporating roofs were 15.2%, 11.9% and 7.3% respectively, indicating that the green and evaporating practices played the effective role in reducing the building's air conditioning loads. Further, the thickness of the planting soil was found to have little impact to the thermal performance of the roof with 25 mm thickness thermal insulation board, as long as it was in the range 100–200 mm. To brief, the research helps understand the heat and mass transfer mechanisms and energy consumption characteristics of different roof structures, and thus contribute to design a better thermal-performed green roof and energy efficient buildings under the sub-tropical climatic conditions.

1. Introduction

The green (planting) roof can provide an efficient, cost-effective and sustainable strategy to relieve some widespread environmental problems associated with urbanization. This practice could help reducing the building's energy consumption and improve its thermal environment, leading to the reduced roof surface and indoor air temperature. Further, it could mitigate the heat island effect and minimize the storm water frequency caused by the high density high-rising building blocks, thus extending the building's life span and offering high-quality green amenity spaces (Jim & Tsang, 2011). In this regard, numerous research works have been undertaken to investigate the thermal and energy performance of the green action and its best practice, briefed below.

Onmura, Matsumoto, and Hokoi (2001) studied the thermal insulation performance of a light vegetation roof which indicated that the roof's outer surface temperature could be reduced by 10–30 °C. Zhao, Tan, and Tang (2009) and Zhao and Xue (2006) studied the thermal performance of the sedum lineare planting roof which, based on the Shanghai's weather condition, indicated that the roof's outer surface temperature was reduced by around 16.0 °C compared to the bared roof, while its inner surface temperature was reduced by about 3.3 °C, and the indoor air temperature by around

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Nomenclature

CE	the abbreviation of ceramic roof;
E	the abbreviation of exposed roof;
G-2	the abbreviation of green roof-2 with 200 mm thickness planting soil;
$q_{convection}$	the heat transferred by convection, W/m^2;
$q_{long\text{-}wave}$	the heat gain from long-wave radiation, W/m^2;
q_{solar}	the solar radiation, W/m^2;
$q_{transpiration}$	the heat loss by transpiration, W/m^2;
α	the solar radiation absorptivity of green roof;
$\theta_{i,max}$	the highest inner roof surface temperature under the indoor natural ventilation condition, °C;
Δt_k	the peak-to-valley-difference of the outdoor air temperature, K;
CL	the abbreviation of clay roof;
G-1	the abbreviation of green roof-1 with 100 mm thickness planting soil;
$q_{conduction}$	the heat transferred into room, W/m^2;
$q_{evaporation}$	the heat loss by evaporation, W/m^2;
$q_{photosynthesis\text{-}respiration}$	the solar energy converted by photosynthesis and respiration, W/m^2;
$q_{storage}$	the heat storage by plants and soil, W/m^2;
$t_{e,max}$	the maximum summer outdoor air temperature, °C
Δt_d	the peak-to-valley-difference of the roof's inner surface temperature, °C (or K);
φ	the ratio of the peak-to-valley-difference of the roof's inner surface temperature to that of outdoor air temperature;

2.0 °C. Bai, Feng, and Liu (2001) tested the thermal insulation effects of a range of green roofs in Chongqing, China, and found that the surface temperature of vegetation layer were 3.8–7.2 °C lower than that of the exposed roof surface, and its maximum temperature fall was in the range 11.1–24.0 °C. Luo, Liu, and Kang (2009) tested the clay soil based green roof which indicated that its surface temperature was 1.6–19.7 °C lower than that of the exposed roof. Niachou, Papakonstantinou, Santomouris, Tsangrassoulis, and Mihalakakou (2001) studied a green roof which concluded that the roof's surface temperature was reduced by 14.0 °C, and the indoor air temperature was lowered by 2.0 °C in average and 3.0 °C in maximum. Santamouris, Pavlou, Doukas, and Mihalakakou (2007) undertook the study into a green roof which indicated that the timing proportion of the over 30 °C indoor air temperature was about 15%, 53% less that of bared roof. Yang and Guo (2011) studied the thermal insulation performance of light modular vegetation roof and his experiments indicated that the bottom surface temperature of the vegetation layer was 4.0–12.7 °C lower than that of the bare roof without vegetation layer.

Numerous researchers have taken a series of investigations into the energy saving potential of the green roofs. Jaffal, Ouldboukhitine, and Belarbi (2012) indicated that compared to the normal roofs, the green roof could lead to around 2 °C reduction in the indoor air temperature, and around 6% saving in the annual energy consumption. Tabares-Velasco and Jelena (2011) pointed out that the heat transfer flux of a fully covered green roof could be 18–75% lower than that of the roof without planting (green-treated) and under the controlled laboratory condition, the heat flux within the planting roof was around 25% lower than that within the non-planting roof. Niachou et al. (2001) proved that the thermal insulation effect of a vegetation roof in winter was more significant than its evaporative cooling effect in summer. He further indicated that a close relationship was in existence between the vegetation roof, its thermal insulation performance and evaporation cooling effect. If the original roof had a good heat insulation performance, the vegetation layer above the roof has little added value to further improve its thermal insulation and evaporative cooling effects. Santamouris et al. (2007) indicated that the cooling load of a green roof covered room could be 6–49% lower than that of the room without green roof, and the room's thermal comfort temperature zone was wider than that of the room without green roof. Wong et al. (2003) conducted a dedicated simulation against the green roof which indicated that the annual energy savings of a garden planting roof relative to a normal roof was around 0.6–10.5%, mainly due to the reduced building cooling load. Castletona, Stovin, Beckc, and Davison (2010) pointed out that although the green roof could improve the thermal performance of the roof, it cannot replace the roof's original insulation layer. Oberndorfer et al. (2007) suggested that the functions of transpiration and photosynthesis that vegetation has established could improve the thermal performance of the roof and meanwhile, reduce the heat radiation striking on the roof by 5–20%. Zhao et al. (2009) suggested that the power saving per unit of roof area was 0.1066 kWh/(day m^2), while the power saving per unit room volume was 0.0333 kWh/(day m^3), leading to 20.9% of power saving in the daytime and 18.4% of power saving at night.

Overall, the green (planting) roofs have better thermal insulation and energy saving performance than the roof without planting. Designing an appropriate green roof to improve its thermal insulation and evaporative cooling performance is therefore a major concern for the researchers, engineers and end users. Researches on this topic were numerous but presented very different outcomes, mainly owing to the significant variations in the roof structures and materials, as well as the climatic conditions. This situation has somehow misled the building engineers in evaluating the thermal insulation and energy saving performance to the green roofs, and thus impeded their wider deployment. In particular, studies into the green roofs under the sub-tropic climatic conditions in the full-sized building scale by experimental measurement have not yet been undertaken. To provide the real-time operational data of the green roofs relative to the conventional roof, this paper carried out the experimental investigation into two green roofs and other three conventional roofs under the sub-tropic (Guangzhou) climatic conditions at the full-sized building scale, which was aimed for recommendation of the favorite roof structures to enable the functions of both evaporation cooling, thermal insulation and energy saving, and to provide the power consumption data for the rooms with green roofs and other conventional roofs. The research will help understand the heat and mass transfer mechanisms associated with the green roofs, and provide the experimental data in relation to the roof's structural optimization. The results of the research could be well used to design a better thermal-performed roof structure and energy efficient buildings under the sub-tropical climatic conditions.

2. Heat and mass transfer mechanisms applied to the green roofs and other conventional roofs

Two main types of green roofs are commonly applied (Jim & Tsang, 2011): intensive and extensive. An intensive roof has a deeper substrate (>20 cm) that can accommodate shrubs and trees, while an extensive roof has a thinner substrate (about 5–20 cm) catering to grasses, herbaceous plants and drought-tolerant sedums. Most currently used green roofs are the extensive type, which is comprised of several layers laid in sequence: root barrier, drainage and storage layer, filter layer, soil (substrate), and vegetation. Root barriers are commonly installed to prevent root damage to the building structure. The vegetation and substrate layers contribute notably to the energy conservation and storm-water management (Oberndorfer et al., 2007). An engineering example