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Thermal performance and energy savings of white and sedum-tray garden roof: A case study in a Chongqing office building

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ABSTRACT

This study presents the experimental measurement of the energy consumption of three top-floor air-conditioned rooms in a typical office building in Chongqing, which is a mountainous city in the hot-summer and cold-winter zone of China, to examine the energy performance of white and sedum-tray garden roofs. The energy consumption of the three rooms was measured from September 2014 to September 2015 by monitoring the energy performance (temperature distributions of the roofs, evaporation, heat fluxes, and energy consumption) and indoor air temperature. The rooms had the same construction and appliances, except that one roof top was black, one was white, and one had a sedum-tray garden roof. This study references the International Performance Measurement and Verification Protocol (IPMVP) to calculate and compare the energy savings of the three kinds of roofs. The results indicate that the energy savings ratios of the rooms with the sedum-tray garden roof and with the white roof were 25.0% and 20.5%, respectively, as compared with the black-roofed room, in the summer; by contrast, the energy savings ratios were −9.9% and −2.7%, respectively, in the winter. Furthermore, Annual conditioning energy savings of white roof (3.9 kWh/m^2) were 1.6 times the energy savings for the sedum-tray garden roof. It is evident that white roof is a preferable choice for office buildings in Chongqing. Additionally, The white roof had a reflectance of 0.58 after natural aging owing to the serious air pollution worsened its thermal performance, and the energy savings reduced by 0.033 kWh/m^2·d. Evaporation was also identified to have a significant effect on the energy savings of the sedum-tray garden roof.

1. Introduction

As a result of economic growth and urbanization, buildings consume almost one-third of the total energy consumption and contribute to 40% of the CO_2 emissions in China [1]. Especially, because the city's original surface has been replaced by black roofs and pavements (with an albedo of approximately 0.1–0.2), a shortage of greenery causes a decrease in canopy interception and transpiration in the city, leading to increased temperatures and CO_2 emissions. Worse still, in the summer, it results in urban heat islands (UHIs) and contributes to greater energy consumption, more heat-related deaths, increased peak-hour power demand, and other ecologically adverse impacts [2].

With the increase in the city's high-rise buildings and building density, the low-rise buildings are usually covered by other buildings, so the roofs are the major receivers of solar radiation in this case. Therefore, the insulation performance of the roof is an important factor affecting the thermal comfort and regional microclimate of low-rise buildings (e.g., podium buildings, old buildings, or factory buildings). In particular, the roof surface has a significant effect on the peak energy load and the total energy consumption of air-conditioned buildings, as well as the indoor thermal comfort in non-air-conditioned buildings [3]. The roofs of existing buildings usually consist of a waterproof membrane, insulation, and a structural layer [4], resulting in low reflectance and poorer insulation performance that makes the roofs inadequate to either reduce solar heat gains in summer or to decrease heat losses in winter [5]. The energy consumption due to the roof top accounts for 5%–10% of a building's total energy consumption (the more floors, the lower the percentage) and more than 40% of the energy consumption of the top floor. These problems can be partially solved by retrofitting the rooftop construction. The technique of retrofitting common rooftop surfaces is often regarded as an effective strategy for rendering the buildings more sustainable [6,7]. Specifically, innovative

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Nomenclature

Q_a	Air conditioning power demand intensity in one room (kW/m^2)
Q_{load}	Heat load of the tested room (kW/m^2)
$Q_{envelope}$	Heat gains from the roof, window, and other sources (kW/m^2)
Q_{roof}	Heat gain through the roof (kW/m^2)
Q_e	Heat gain within the room from other interior rooms (kW/m^2)
Q_{window}	Solar irradiance from the window (kW/m^2)
Q_{other}	Heat gain from other sources (e.g., plug load, infiltration, and occupants) (kW/m^2)
Q_{wall}	Heat gain from wall (kW/m^2)
Q_{floor}	Heat gain from floor (kW/m^2)
ΔP	Air-conditioning energy savings (kW)
ΔE	Power savings of room (kWh)
P	Air-conditioning energy consumption (kW)
E	Power consumption of room (kWh)
$A_{adjustment}$	Modification of energy savings (kWh)
ΔC	Air-conditioning energy cost savings (RMB)
d_e	The price of electrical power (RMB/kWh)
Δp	CO_2 emission factor (tCO_2/MWh)
Q_m	Measured air-conditioning energy consumption in one room (kW/m^2)
$EF_{grid,2015}$	The mean marginal CO_2 emission factor in 2015 (tCO_2/MWh)

Greek Symbols

λ	Thermal conductivity of interior wall (W·m/K)
δ	Thickness of interior wall (m)
Δt	Temperature difference between the opposite faces of interior walls (K)
τ	Time (s)
A	The area of interior wall (m^2)

Subscript

a	Air-conditioning
e	Adjacent room
black	Room with black roof
roof	Room with white or sedum-tray garden roof
heating	Heating season
cooling	Cooling season

passive techniques such as cool (reflective) roofs and green (vegetative) roofs for improving the energy performance of buildings have demonstrated strategic environmental, economic, and social benefits [9].

These cool roofs can boost the albedo (solar reflectance) of the exterior surface of the buildings to reduce the solar heat gain, lower the surface temperature, and decrease the heat conduction through the roofs, thereby reducing the cooling load (albeit increasing the heating load) in a conditioned space, or lowering the air temperature in an unconditioned space [10]. Because of the added shade from the plants, the thermal resistance and thermal mass of the soil layer, and approximately 25% of the solar radiation being consumed by the plants' evapotranspiration, only a small heat flux is transferred to the indoor space [7,11] in the case of green roofs, which can improve the thermal performance of roofs and reduce the building's energy consumption in a cooling-dominated climate.

Normally, green roofs are classified as intensive, extensive, or semi-intensive [12]. An extensive roof is characterized by small plants, a thin soil layer (6–25 cm) and simple maintenance. An intensive roof, on the contrary, is heavier and thicker (15–70 cm) and requires more maintenance, while the semi-intensive roof falls in between these two [7]. Extensive roofs are often the preferred option for retrofitting old buildings [4]. However, extensive green roofs have displayed a few drawbacks such as heavy structural reinforcement requirements, drainage issues, high cost, and difficulties with design and construction [13]. In recent years, light sedum-tray garden roof has launched into the market to meet the need for a light-weight planting roof in urban areas [14]. In these systems, the plants initially grow in a freely combined container that is commonly made of PVC plastic. When the plants are more mature, they can be moved to the roof. This technology is not only easy to assemble and combine, but also keeps the roof structure intact to address the issues of storage and drainage, filtering, and preventing root overgrowth. Although it has been recognized in engineering practice, it has been rarely applied or studied.

In some countries, studies of white roofs have been conducted, in which the insulation performance and energy savings were analyzed based on the local climate and building form. White roofs can reflect 55–80% of incident sunlight, making the roof surface stay cooler on clear summer days [13], which decreases the heat gain through the roof, lowers the indoor air temperature, and, thus, makes the indoor space more comfortable in unconditioned buildings; likewise, the white roof can also reduce the cooling load (although it increases the heating load) in a conditioned building. A. Synnefa et al. [16] investigated the application of white roofs to conditioned residential buildings in different climates, and discovered that the white roofs reduced the total cooling load and peak cooling load of conditioned rooms by 18%–93% and 11–27%, respectively, and reduced the maximum temperature of the unconditioned buildings by 1.2–3.3 °C. Based on cool-roof studies performed in China and elsewhere, installing cool roofs is an effective way to reduce a building's energy consumption or improve its thermal comfort [42]. Moreover, white roofs can also reduce carbon emissions and neutralize global warming, as their highly reflective surfaces reflect an amount of radiation that would otherwise have been absorbed by the ground [16]. Cotana et al. estimated that approximately 16,000 tCO2-eq could be offset over 30 years with the installation of approximately 115,000 m^2 of white roofs at a Tunisian factory site [17]. Akbari et al. simulated the long-term effect of the increasing urban surface albedos using a spatially explicit global climate model of intermediate complexity; the results indicated that the global cooling ranged from 0.01 to 0.07 K, which corresponds to a carbon emission reduction of 25–150 billion tons of CO_2 [18].

However, a white roof faces the challenge of natural aging, which worsens its thermal insulation performance. Kelen et al. [19] researched the natural aging of roofs, 12 with standard paint and 8 with highly reflective paint, in São Paulo, Brazil. They found that the albedo of the roof tops sharply decreased, from 0.74 to 0.50, within their first 6 months due to climate and contamination and that a new cool roof could decrease the energy demand for cooling by 72%, as compared to the aged cool roof. Elena et al. [20] found that the surface temperatures of white roofs after aging (with 0.50–0.55 reflectance) were higher than those of newly coated roofs (with 0.71–0.74 reflectance). The albedo of a white roof decreases due to local weather changes, wind erosion, microbial growth, and dust [21]. Chongqing, one of the first cities severely impacted by air pollution, including $PM_{2.5}$, O_3, haze, and smog, is in the Sichuan Basin and has complicated meteorology [22], so the natural aging there will be different than in other places. Compared with white roofs, sedum-tray garden roofs are less effective at reflecting incident light and have a lower global cooling potential. Coutts et al. [23] indicated that the reflectivity of a lighter-colored vegetated roof is 0.21. Similarly, Ekaterini and Dimitris [24] found that a vegetated roof had 27% of its total solar radiation reflected, 60% absorbed by the plants and the substrate medium, and a 13% solar transmittance.