Energy and Buildings 127 (2016) 762–773

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Thermal and energy performance assessment of extensive green roof in summer: A case study of a lightweight building in Shanghai

Yang He[a], Hang Yu[a,*], Nannan Dong[b], Hai Ye[c]

[a] HVAC&GAS Institute, School of Mechanical Engineering, Tongji University, Shanghai 201804, P.R. China
[b] Department of Landscape Studies, College of Architecture and Urban Planning, P.R. China
[c] Department of Architecture, College of Architecture and Urban Planning, P.R. China

ARTICLE INFO

Article history:
Received 27 February 2015
Received in revised form 3 April 2016
Accepted 5 June 2016
Available online 11 June 2016

Keywords:
Extensive green roof
Evapotranspiration
Cooling effect
Energy balance
Correlation analysis

ABSTRACT

Green roofs have been recognized as an effective way to increase urban green space and improve building micro-environment. This paper investigated the thermal and energy performance of an extensive green roof under free-floating[1] and air-conditioned conditions in Shanghai, a coastal city with hot and humid summer. A field experiment was conducted on two full-scale rooms of a building from 30/07/2014 to 31/08/2014. One room was covered by a green roof while the other one was covered by a common roof. The results show that solar radiation has the strongest correlation with green roof's cooling effect, and the correlation between solar radiation and heat flux through green roof is negative in free-floating condition but positive under air-conditioned condition. Outdoor temperature is the most correlated factor of green roof's temperatures but the least correlated one for green roof's cooling effect. Energy balance analysis indicates that evapotranspiration and long wave radiation dissipate most of heat gain for green roof, and soil water content has a significant impact on energy balance. This paper presents the basic thermal characteristic of extensive green roof in Shanghai and also make it possible for further validation of hygrothermal transfer model of green roof system.

1. Introduction

Green roofs have been developed since ancient time when people paid more attention to landscape value of green roofs, and the ancient “Hanging Gardens of Babylon” is a famous case in point. However, benefits of green roofs are far more than that. With the rapid urbanization, city tends to be high plot ratio, high density and high rise while green space shrinks, environment and energy problems become more urgent than before. And green roofs are considered as one of the effective ways to deal with these challenges and improve city image. More and more areas have issued incentive policies to promote the development of green roofs.

Green roofs can miti gate city runoff and serve as a means of storm water management by storing and releasing rainwater in an effective way [2–4]. Furthermore, by providing ecological habitats, absorbing noise and reducing air pollution, green roofs contribute to people's health and compensate for distressed or lost ecosystems [5]. In terms of energy conservation, the combined effect of shading, evapotranspiration and thermal insulation make green roofs play an important role in microclimate modulation and building thermal performance improvement. The depressed temperature fluctuation of waterproof membrane helps to extend the lifespan of building materials [6,7].

According to the thickness of substrate, green roofs are typically divided into two categories, including intensive roofs and extensive roofs [8]. Intensive green roofs are built with thick substrate layer that is often more than 20 cm. They are heavier and can support small trees, shrubs and bushes, thus require more maintenance such as watering, weeding and fertilizing. The latter, however, are established with thin substrate, which only can bear light plants such as sedum species, therefore need less maintenance. Intensive green roofs are often established for human rest and entertainment. Although better in some aspects, it's less commonly used than extensive green roof for extra structural reinforcement and expensive maintenance. And extensive green roofs are often the preferred option for retrofitting of old buildings, the structural capacity of which are often very small.

Green roofs are usually made up of four major compound components from top to bottom namely: (1) plants layers (2) substrate layers and filter membrane (3) drainage layers (4) waterproof

---

* Corresponding author.
E-mail address: tjyuhang@163.com (H. Yu).

[1] Free-floating here means no heating or cooling system affecting the internal conditions of the room.

http://dx.doi.org/10.1016/j.enbuild.2016.06.016
0378-7788/

Nomenclature

q_{stor}	Heat storage, W/m^2
q_{ns}	Net heat gain from solar radiation, W/m^2
q_{late}	Latent heat from evapotranspiration, W/m^2
q_{sen}	Convective heat transfer, W/m^2
q_{nl}	Net heat gain from long wave radiation, green W/m^2
q_{con}	Heat conduction through the roof, W/m^2
q_{solar}	Solar radiation, W/m^2
c_{sub}	Heat capacity of soil, J/(kg K)
c_w	Specific heat of water, J/(kg K)
c_{ca}	Specific heat of plants, J/(kg K)
c_{str}	Specific heat of structural layer, J/(kg K)
l	Latent heat of vaporization, kJ/kg
t_a	Ambient air temperature, °C
t_s	Temperature of substrate layer, °C
t_{ca}	Temperature of canopy layer, °C
t_{str}	Temperature of structural layer, °C
R	Evapotranspiration rate, kg/m^{2}s
v	Wind speed above the canopy, m/s
e_a	Partial water vapor pressure, pa
d	Substrate depth, cm

Greek letters

β	Solar radiation reflectivity
γ	Long-wave absorptivity
ε	Long wave emissivity
σ	Stefan-Boltzmann constant, W/(m^{2}K^4)
ρ_{sub}	Volume density of substrate, kg/m^3
ρ_{ca}	Areal density of plant canopy, kg/m^2
ρ_w	Volume density of water, kg/m^3
ρ_{str}	Areal density of structural layer, kg/m^2
ϕ_{sub}	Volumetric proportion of substrate solid phase
ϕ_w	Volumetric water ratio of substrate
κ	Cloud cover correction factor
τ	Time, s

Subscripts

g	Green roof
co	Common roof
sub	Substrate layer
str	Structural layer
ca	Canopy layer

membrane, insulation layer and structural layer. And the substrates and plants of green roofs are greatly different from that of ground greenery. The substrate is usually engineered lightweight soils, which has large water holding ability and permeability. Its major components are aggregate (a porous lightweight materials), sand and organic matter [9], which depend on local availability and cost of materials. Plants selected for green roofs should often meet some requirements, including excellent drought tolerance, low growth rate and fast establishment etc. The most commonly used plants worldwide for extensive green roofs are sedum species, they belong to succulent plants and have unique CAM[2] photosynthesis that can reduces water loss, and exhibit strong adaptability to various climates [10]. Other species recommended for extensive green roofs includes Euphorbiaceae and Portulacaceae [11]. It is suggested that mixed species have advantages over single species. Not only can they enrich the roofs, but also improve biodiversity and the ability to resist disease and degradation [1].

Thermal and energy performance of green roofs received many attention in the past few years. Field or laboratory experiments have been conducted in different regions [12–16], and the results show that thermal performance of extensive green roofs depends on multiple factors which mainly can be divided into external and internal ones. External factors refer to climate conditions, including solar radiation, wind velocity, rainfall (irrigation), temperature and humidity. Internal factors include the geometrical and hydrothermal properties of plants and substrate, volumetric water ratio, thermo-physical properties of building structural layer and insulation layer. In order to understand these phenomenon deeply, different models have been developed [7,17–22]. Eco-roof is one of the most cited models [19], which has been also adopted by Energyplus software. However, because of various configurations and materials involved in local green roofs, many researchers have stressed the importance of further validation [23,24]. What's more, some disputes exist in thermal study of green roofs. For example, Liu et al. conducted measurement on two extensive green roofs with different substrate depth [25]. They found that little thermal contribution came from vegetation, and thicker substrate tended to have better thermal performance. However, Orna's results indicated that cooling effect of bare soil roofs was much weaker than that of any other extensive green roofs, and plants shading played an important role [26]. In terms of energy balance, there are also some divergences. Lazzarin's data showed that, 25% of total heat gain in summer was consumed by evapotranspiration and 13% by convection and long wave radiation [27]. By contrast, Feng chi's result indicated that evapotranspiration accounted for 51.5%, the proportion of convection and long wave radiation was 37.8% [28]. Because of various factors affecting the process of hygrothermal transfer, including external and internal ones, further experiments and data are needed for comprehensive understanding of local green roofs.

In this paper, there were two lightweight rooms located in Shanghai. One roof was retrofitted into green roof, and the other one remained common roof for comparison. A field measurement was conducted to study thermal performance and energy balance of extensive green roof under free-floating and air-conditioned conditions. And correlation analysis was carried out to evaluate the impact of various factors on thermal performance of green roof.

2. Study location and methods

2.1. Study location

Shanghai (31.2N, 121.5E), a city located at the west coast of Pacific Ocean and the east rim of Asian continent, belongs to the north subtropical monsoon climate with four different seasons, plenty of sunshine and rainfall. Summer and winter are long while spring and autumn are short. The average temperature of summer reaches 30.9 °C. So far there is a total of 200 million m^2 roof in Shanghai, while only 120 thousand m^2 is green roof, accounting for only 0.19% of the roof area that is available for greening. And Shanghai plans to build 1 million m^2 green roofs during the 12th Five-Year Program.

The experiment setup was situated at Jiading Campus of Tongji University (Fig. 1). Free-floating condition was performed from 30/07/2014 to 20/08/2014, and air-conditioned condition was conducted from 25/08/2014 to 31/08/2014.

---

[2] CAM here means crassulacean acid metabolism, also known as CAM photosynthesis, is a carbon fixation way the evolved in some plants as an adaptation to arid conditions.