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Passive cooling of the green roofs combined with night-time ventilation and walls insulation in hot and humid regions

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ABSTRACT

Green roof and night-time ventilation are promising passive cooling strategies. These two strategies and walls insulation have been researched separately in many studies. In this paper, a new strategy combining the three techniques together is discussed. Based on the analyses of a field experiment of a single-story building with green roof in Shanghai, a model was established using DesignBuilder software and validated with the experimental building. And then, the model with green roof was simulated in three cases: no ventilation, night-time ventilation and night-time ventilation combined with walls insulation. Results show that when the night ventilation operated, the indoor temperature under green roof decreased while the air change rate increased. With the improvement of external walls insulation, the cooling effect of the night ventilation becomes more obvious for the extensive green roofs. Additionally, a simplified multiple regression model is proposed to assess the passive cooling of green roof which combined with night ventilation and walls insulation in hot and humid regions. According to the model, for a building with green roof, the indoor average temperature can be reduced by up to 2.3 °C compared with the building combined with night ventilation and walls insulation together.

1. Introduction

With the development of economy and the acceleration of urbanization process, there are more and more energy consumption, especially in the building sector. Studies show that the building sector's energy consumption and greenhouse gas emissions estimate accounted for 35% of total. Especially in the United States, it is estimated to account for more than 40% of total (GhaffarianHoseini et al., 2013; Zhou et al., 2014).It not only leads to a serious energy crisis, but also brings about global warming directly and an increasing number of extreme weather conditions (Frank, 2005). At the same time, as people's quality of life and economic conditions improve, the indoor thermal comfort expectations have also increased, which gives rise to an increase in building cooling demand (Artmann, Jensen, Manz, & Heiselberg, 2010). In this context, the pertinent studies about build environments, such as various sustainable approaches and environmentally responsive energy efficient technologies, are very important.

Roof is a significant component of the building envelope, and as a thermal barrier it is also important to evaluate the thermal performance of buildings. As an efficient technology encompasses many benefits in terms of environmental sustainability, green roofs have attracted more and more researchers' attention all over the world. Many studies have analyzed the thermal performance of green roofs in different climates and different regions (Bates, Sadler, & Mackay, 2013; Chen, 2013; Jaffal, Ouldboukhitine, & Belarbi, 2012; Parizotto & Lamberts, 2011).The surveys and experiments in Hong Kong, Greece and Singapore have shown that the use of green roofs effectively decreased the indoor temperature (Heidarinejad & Esmaili, 2015; Niachou, Papakonstantinou, Santamouris, Tsangrassoulis, & Mihalakakou, 2001; Tam, Wang, & Le, 2016), and reduced the cooling load of the space by 17–79% (Wong, Chen, Ong, & Sia, 2003).

Green roofs is a strategy to improve indoor comfort and reduce energy consumption, and also have many other benefits. Various studies indicated that the benefits of green roofs are related to the environmental quality enhancement and ecological preservation, which are embodied in mitigating urban heat island effect (UHI) (Coutts, Daly, Beringer, & Tapper, 2013; Ihara, Kikegawa, Asahi, Genchi, & Kondo, 2008; Kosareo & Ries, 2007), reducing carbon footprint (feng Li et al., 2010; Feng, Meng, & Zhang, 2010), mitigating air pollution (Speak, Rothwell, Lindley, & Smith, 2014; Stathopoulou, Mihalakakou, Santamouris, & Bagiorgas, 2008), enhancing water runoff quality and stormwater management (Speak, Rothwell, Lindley, & Smith, 2013; Vijayaraghavan, Joshi, & Balasubramanian, 2012), their potential for noise attenuation (Connelly & Hodgson, 2015; Renterghem & Botteldooren, 2011), and extend 30 the lifespan of the waterproof membrane (Saadatian et al., 2013). Besides, the environmental benefits

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Table 1
Material and thermal characteristics of the building.

		Material	d (mm)	λ (W/mK)	ρ (kg/m^3)	c (J/kg K)
Vertical wall	Outside	Masonry mortar	25	0.81	1500	2000
	⇓	Brick	240	1.00	1200	2000
	inside	Masonry mortar	25	0.81	1500	2000
Cross wall	Outside	Masonry mortar	20	0.81	1500	2000
	⇓	Brick	120	1.00	1200	2000
	inside	Masonry mortar	15	0.81	1500	2000
Bare roof	Outside	Rigid waterproof layer	30	1.74	2300	920
	⇓	Membrane waterproofing	5	0.2	600	1470
	inside	Cement mortar	15	0.92	1800	1050
		Concrete hollow slab	115	1.05	2250	920
		Masonry mortar	15	0.81	1500	2000
Green roof	Outside	Substrate layer	80	1.00	1800	200
	⇓	Plain concrete	50	1.20	2500	1500
	inside	Rigid waterproof layer	30	1.74	2300	920
		Membrane waterproofing	5	0.2	600	1470
		Cement mortar	15	0.92	1800	1050
		Concrete hollow slab	115	1.05	2250	920
		Masonry mortar	15	0.81	1500	2000

of green roofs are not only limited to the new buildings, but also promising for retrofitting projects; hence green roofs have been widely used.

Many studies have shown that green roofs have a significant cooling effect on non-air-conditioned buildings, in which the indoor temperature of green roofs is significantly lower than the common roofs during the daytime but higher than the common roofs at night. The experimental investigation of a light roof in Shanghai by He, Yu, Dong, and Ye (2016) showed that the indoor air temperature was about 2.5 °C higher for green roof than common roof at night when the doors and windows of both rooms were locked. The cool outdoor air and sky long-wave radiation at night make the outside surface of common roofs be cooled quicker and easier than green roofs.

Therefore, the use of green roof stand-alone to cool the interior space of buildings could not decrease the indoor temperature to the expectation of occupant, while the green roof combined with the night-time ventilation would be a preferable solution. An experimental study in summer by Roche and Berardi (2014) demonstrated that the green roofs used as thermal mass combined with night-time ventilation are beneficial to the indoor thermal environment. But this article did not further analyze the factors that might affect the cooling effect of the combination of the two technologies.

The basic idea of night-time ventilation is to cool down the building structure at night in order to provide a heat sink during the following day (Artmann et al., 2010; Artmann, Manz, & Heiselberg, 2007, 2008). In this situation, the building behaves as a cold sink during the day and the objective is to take out all this stored energy in the structure thus to change its behavior to hot sink during the night, and these charge and discharge of energy in the building structure are made cyclically through the circulation of air (Antonopoulos & Koronaki, 2000; Kalogirou, Florides, & Tassou, 2002; Ramponi, Angelotti, & Blocken, 2014; Roach, Bruno, & Belusko, 2013; Santamouris, Sfakianaki, & Pavlou, 2010; Shaviv, Yezioro, & Capeluto, 2001; Yam, Li, & Zheng,2003).

In addition, the insulation performance of exterior walls is also an important factor in building's passive cooling. Because the poor insulation performance of walls will cause that the indoor thermal comfort of occupants is difficult to reach. The use of strategy combining green roofs with night-time ventilation would better decrease the indoor temperature if the walls are insulated.

The aim of this study is to develop a methodology to analyse the combined effect of green roof, insulated walls and night-time ventilation, and use DesignBuilder to examine the effectiveness in a sample building with the aforementioned method. The results can be used in design to improve the inside comfort, and we hope to encourage architects and engineers to properly consider the optimal combination of them when planning, designing, building and renovating dwellings.

2. Method

The published literature has theoretically analyzed the energy performance of buildings and the potential to improve indoor thermal environment with green roofs, night-time ventilation or walls insulation separately by using models generated in various thermal simulation software programs. In order to obtain more information about the cooling effect of green roofs combined with insulated walls and night-time ventilation, an experimental building with green roof in Shanghai, China, has been simulated using DesignBuilder software. This study aims to determine the energy saving and thermal comfort improving potential of green roofs combined with walls insulation and night-time ventilation together.

2.1. Experimental method and process

Shanghai is located in the eastern coastal areas of China, and at the west coast of the Pacific Ocean. It is the typical city in the hot and humid regions with high outdoor temperature and plentiful rainfall in summer. In addition, the climate is conducive to the growth of plants. Therefore, there is a great passive cooling potential of the use of green roofs.

The experimental building is a warehouse in Shanghai, which is oriented to the south and has no shelter from other facilities. The structure type of the single-story building is transverse bearing brick masonry wall systems, and the detailed composition of the building elements and the thermal properties of the building materials are given in Table 1.

It was divided into four rooms, and the floor plan of the building is shown in Fig. 1. The area of each room is about 23 m^2. Room 2 and room 3 were elected as experimental object to measure for the subsequent comparison, and room 3 is under green roof, and the rest of the rooms are under bare roof. The plant used in this experiment is Sedum lineare, which is a plant genus of the Crassulaceae family, and it is about 10–15 cm high. The substrate under plant is about 8 cm thick. The doors were closed which means the air change rate is 0 ach and no inner heat gain in the rooms.

The measured thermal physical parameters included: the local meteorological data (ambient temperature, solar radiation); indoor air temperature; inner and outer surface temperature and heat flux of the