Energy and Buildings 151 (2017) 406–417

Contents lists available at ScienceDirect

Energy and Buildings

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

Water-to-air-heat exchanger and indirect evaporative cooling in buildings with green roofs

Umberto Berardi[a,*], Pablo La Roche[b], Jose Manuel Almodovar[c]

[a] Faculty of Engineering and Architectural Science, Ryerson University, Toronto, ON, Canada
[b] Department of Architecture, Cal Poly, Pomona, United States
[c] Universidad de Sevilla, Spain

ARTICLE INFO

Article history:
Received 8 March 2017
Received in revised form 31 May 2017
Accepted 26 June 2017
Available online 6 July 2017

Keywords:
Green roof
Passive cooling
Evaporative cooling
Thermal energy storage
Heat sink
Energy saving

ABSTRACT

Green roofs have been proposed for energy saving purposes in many countries with different climatic conditions. However, the energy saving potential of green roofs depends on several aspects, such as the climate characteristics or the building loads. For this reason, the authors have been working on ways to modify the thermodynamic behavior of green roofs through passive low energy systems operating according to rules based on the relationships between the indoor and outdoor temperatures. This paper discusses the improvements in indoor thermal comfort which can be obtained by adopting water-to-air heat exchangers and indirect evaporative and radiant cooling strategies in buildings with green roofs. The study specifically looks at the effect of combining a simple evaporative/radiant system that cools the water pond where the water-to-air heat exchange occurs. Ad-hoc built test cells were investigated in southern California for over a year. Overall, the water-to-air heat exchangers proved to cool the indoor air in the test cells by almost 10 °C when the exterior temperatures were above 35 °C. In this system, the heat from the interior of the cells that could not be absorbed by the green roof, was transferred to the coupled water sink, and then dissipated into the atmosphere. This study shows that the benefits of the water-to-air heat exchange and of the evaporative cooling system are promising, while the water consumption is limited. Finally, the experimental investigation summarizes the benefits of combining green roofs and evaporative and radiant cooling of a water-to-air heat exchanger as a solution for building cooling and proposes simple equations to anticipate their temperature cooling effects.

1. Introduction

The building sector's energy consumption and greenhouse gas emissions are around 35% of total worldwide [1]. Given these high energy and resource consumptions, various energy efficient technologies have been proposed to obtain low-energy buildings [2]. In this context, green roofs are often identified as a valuable technology for making buildings more sustainable [3].

Green roofs are generally built to enhance the energy saving in buildings, while they show many other benefits [3–5]. Consequently, green roofs have been proposed in many countries with different climatic conditions and building characteristics. However, literature shows that the energy saving potential of adopting a green roof strongly depends on the climate and building characteristics. In particular, the increase in the thermal capacity of green roofs compared to traditional roofs may also raise the building cooling and heating loads [6–8]. This occurs because the green roofs stay warmer during night time compared to other light weight roof typologies and continue warming the interior of the building during the cooler hours of the day.

Recent studies discussed the development of green roofs adopting variable insulation strategies thanks to a plenum located below the green roof, with a sensor-operated fan that coupled the green roof with the indoor environment as required [8]. Following this kind of studies, the present paper investigates the cooling potential of buildings with green roofs that are coupled with water that acts as a heat storage sink that cools the indoor air, lowering its temperature. In particular, this paper describes the experimental measurements done for over a year in test cells with a water-to-air heat exchanger (WAHE). A parametric analysis of the different variables of this last system is presented in order to determine its energy saving potential [9,10].

* Corresponding author.
E-mail addresses: uberardi@ryerson.ca (U. Berardi), pmlaroche@csupomona.edu (P. La Roche), jmalmodovar@us.es (J.M. Almodovar).

http://dx.doi.org/10.1016/j.enbuild.2017.06.065
0378-7788/

The basic premise of this paper is to allow a building to transfer towards the WAHE the excess heat that the green roof has not been able to absorb and control. The goal is to increase the indoor comfort of buildings with green roof through the optimal design of a WAHE.

The following section presents a brief overview of studies about the energy saving of green roofs, WAHE, and evaporative cooling strategies. Sections three describes the experimental analysis done in some test cells located in southern California, US. Section four discusses the results of the experimental works and shows the advantages of the evaporative cooling of the WAHE for buildings adopting green roofs. The study concludes by reporting some future directions of research.

1.1. Benefits of green roofs

Green roofs have often been advertised as technologies for promoting energy savings in buildings by reducing the variation of the indoor temperature [11,12]. However, the building loads and the envelope characteristics play an important role in the potential cooling benefits of green roofs. Generally, in non-insulated buildings, the impact of green roofs is higher than in insulated ones. In fact, the better the insulation of the roof is, the lower their contribution to the indoor thermal balance becomes.

Green roofs reduce the indoor temperature through shading of the rooftop layer and controlling the direct solar radiation, a condition that is particularly beneficial in warmer climates [13–16]. 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 are the three main parameters playing a role in the possible cooling potential [17]. Recent studies in the Mediterranean climate found that with higher plant density, green roofs may provide a reduction in the cooling energy consumption of 50% when compared to a conventional roof [10,18]. The benefits of green roofs in cold climates have also been acknowledged [19–21]. However, contrasting results have been found in climates with different weather conditions during the year.

Mukherjee et al. [22] investigated the effect of three different parameters for the performance of green roofs over a single story office building. The parametric study, which included variables such as the Leaf Area Index (LAI), the substrate depth, and the insulation thickness showed that green roof assemblies for Phoenix and Los Angeles always perform better than the base case roof. Overall, the best performance resulted in Phoenix with an 8% reduction in the energy use intensity (EUI), while Chicago showed the lowest performance, with an average reduction in the EUI of 2.4%. In Los Angeles, the LAI had the largest impact on the effect of a green roof; the most important parameter affecting the EUI of green roofs in Phoenix and Chicago was the insulation thickness [8]. The outcome of these studies suggested that a non-insulated green roof can be advantageous only in climates with a strong cooling-dominated season [23–25], while in the other cases, using an insulating layer below a green roof should be preferred. In fact, if the green roof is above a well-insulated roof, then its energy balance is decoupled from that of the building and the excessive solar radiation is better control; contrarily, if the green roof is above a poorly insulated roof, its energy balance significantly affects the building [8,26].

Previous studies show that ad-hoc strategies should be developed to maximize the cooling potential of a green roof with an insulation layer below, while still being able to cool the space below. In particular, moving from the recently discussed smart green roofs [8], there is a need to create green roofs with more capacity to dissipate the internal loads during warmer periods. The present study proposes to improve the performance of green roofs combining it with the WAHE in a water pond and to increase the potential of this last system using evaporative and radiant cooling.

1.2. Benefits of WAHE and evaporative cooling

In literature, several studies have investigated earth-to-air heat exchangers (EAHE), as systems that use the ground for heat storage and dissipation [27,28]. Less research about WAHEs exists, although a WAHE has some advantages compared to an EAHE. In fact, a water based system has a higher performance because the water dissipates the heat more easily than the soil as the water has a higher thermal capacity and thermal conductivity [29,30]. A WAHE consists of a water tank or pond that cools the air that will enter the building, reducing the energy needed for cooling. It is not uncommon to have space available to place a water pond close to a building and to be able to use this water pond for a WAHE. Since the building does not have to support the weight of such a sink, such a system is cheaper and can often be deeper and store more water than roof ponds, increasing its potential as a heat sink [31,32].

The working principle of WAHE is commonly used in deep water source cooling (DWSC) systems that have been adopted in the last decade in some North American cities [33]. The DWSC is a form of air cooling which uses a large body of cold water as a heat sink. A heat exchanger in the water works at temperatures from 4 °C to 12 °C drawn from deep areas within lakes, aquifers or rivers. As the highest density of water is reached at 4 °C, the bottom of a deep body of water is often at this temperature, allowing a DWSC to have high thermodynamic efficiency. For example, ten years ago, a DWSC system started to operate in Toronto as a part of the downtown cooling district system that extends into the Lake Ontario for 5 kilometers, reaching a depth of 83 m. This system actually has a cooling power of 207 MW and serves over 3 M m^2 of office space [33].

In general, the energy efficiency of systems which exchange heat with a heat sink (for example in ground source heat pumps) depends on the sink temperature [34]. The principle of using the soil as a thermal sink dates back to the ancient Greeks and Persians. During the Middle Age, caves were used in Italy to precool the air before it entered a building [35]. EAHE are generally classified in closed loop or open loop systems according to the direct pumping of indoor air or exterior air from the building to the ground by means of heat exchangers. Due to the high thermal inertia of the soil, temperature fluctuates much less below the ground than at surface level. In particular, at sufficient depth, the soil temperature is stable and lower than the outdoor temperature in summer and higher in winter, so that when the indoor air is drawn through the buried pipe, the air is cooled in summer and heated in winter. An EAHE system consists of a network of pipes through which air is transported by a fan. In summer, the air supplied to a building is cooled because the soil temperature around the heat exchanger is lower than the ambient temperature. During the winter, the process is reversed and the air is pre-heated.

In EAHE, the heat is transferred to the surrounding soil by conduction through the pipe thickness and by convection with the pipes' internal surface. These heat transfer modes are transient and three-dimensional, making the problem often hard to solve numerically [34–37]. A model for multiple-pipes EAHE was proposed by Hollmuller and Lachal [36]. More recently, Ghosal et al. [37] developed a model to assess the performance of an EAHE connected to a greenhouse. Given the limits of the numerical model for EAHE, an experimental approach is often preferred in this kind of studies.

In the system described in the present paper, the heat exchanger is located in a water pond (WAHE). Moreover, in order to cool the water sink, water is sprayed above the insulation floating above the water sink during night hours. This results in a water consumption for (indirect) evaporation during this time. However, it is important to remember that a large quantity of water is used for energy production in any fossil fuel plant [38]. The raw water usage, which is defined as the water used in the plant processes for purposes such