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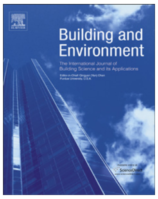

Thermal performance of different configurations of a roof pond-based system for subtropical conditions

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ABSTRACT

Indirect Evaporative Cooling Systems (IECS), characterized by the use of wetted roof or wall surfaces for structural cooling without increasing indoor air humidity, consist of an interesting bioclimatic strategy still not quite explored in Brazil. This study aims to evaluate the thermal performance of an IECS by means of experiments with test cells in a subtropical location. Experiments were carried out for Curitiba, Brazil (25.5°S, 49°W, 910 a.m.s.l.) with two equal-sized small test cells, first with a control cell without the roof pond and with each test cell fitted with roof ponds, for testing different modes of operation of the IECS. Configurations of the system encompassed: a) conventional roof pond-based IECS; b) roof pond with sealed water reservoir, naturally ventilated and fully shaded (for testing the effect of thermal mass without the evaporative function); c) IECS with an unshaded roof pond. The relative contributions of evaporation and shading have been assessed. The year-round evaluation showed a high cooling performance of the IECS for the subtropical location tested.

1. Introduction

The driving force of evaporative cooling systems is the process of evaporation, which is the phase change of water from liquid to vapour. This phase change results in the cooling of the wetted surface and of the surrounding air therefore increasing the moisture content of the air. The limit of such cooling potential is given by the wet-bulb temperature (WBT). A rough estimate of the cooling potential of evaporative cooling systems is proposed by Givoni [1], who suggests that in the case of a direct evaporative cooling system air temperature can be reduced to about 70–80% of the WBT depression, or the difference between the dry-bulb temperature (DBT) and the WBT. Thus, the basic climatic criterion for the applicability of evaporative cooling is the WBT depression.

There are several possible configurations of passive evaporative cooling systems [2] [3], many of which have been discussed in the literature for the last five decades such as roof ponds with or without moveable insulation, roof ponds with shading elements, natural draft cooling towers, among other systems. One of the most reported systems of indirect evaporative cooling system consists of using roof ponds directly over the area to be cooled. The pond's water temperature will be close to the average WBT and the ceiling, cooled by the pond, acts as a heat sink to the space below it. As summarized by Sharifi & Yagamata [3], “roof ponds provide cooling benefits through indirect evaporative cooling and/or radiant cooling”. Although such a system could also be advantageous in winter for space heating due to an increase in thermal mass, the majority of published papers on the subject or over 70% of the papers reviewed in a recent literature survey [3] focus on its use for cooling purposes only. According to the same literature review, from over 70 papers reviewed there is a lack of studies in the climatic region evaluated in this study (Köppen-Geiger's Cfb climate region). Cfb regions are characterized as having a warm temperate climate, fully humid with warm summer and at least four months with average temperature exceeding 10 °C [4].

Yannas et al. [5] describe diverse configurations of roof ponds; basically the components of an unsprayed roof pond system are shown in Fig. 1. As for their thermal performance, the driving factors related to these three components are: a) a high thermal conductivity of the container or the slab element in contact with the room immediately underneath so as to provide close thermal coupling between the water body and the occupied space; b) the way water is stored (in bags or within the roof parapet for generating thermal mass) and whether the water will be consumed by

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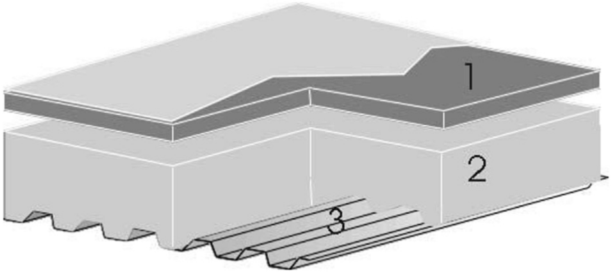

Fig. 1. System components of a roof pond, excluding the spraying function with (1) pond cover, (2) water container, (3) pond support [4].

evaporative fluxes; c) if the roof pond will need to be covered during periods of intense solar radiation in order to avoid overheating of the water body or high evaporation rates (by shading or floating elements). The roof pond variant tested in this study is termed “ventilated roof pond”, according to classifications described in a literature survey [6].

Experiments with ventilated roof ponds integrated in real buildings show interesting results when the evaporative function is present. Kharrufa and Adil [7] present results obtained for a shaded roof pond system with and without auxiliary mechanical equipment (fan) for increasing convection in the attic space. The field study was carried out under the arid conditions of Baghdad, Iraq (33.3°S, 44.4°E). For the test-building evaluated, with internal floor area 28 m^2, built with typical building materials in Iraq and detached from other neighbouring buildings, an average indoor temperature drop from a base-case scenario (roof without pond) was about 3.4 °C with the pond, peaking at 4.5 °C, when mechanically assisted.

Gonzalez et al. [8] tested the thermal performance of an indirect evaporative passive cooling system (IEPCS) used in an experimental house, in Maracaibo, Venezuela (latitude 10.34°N, longitude 71.44°W, elevation 66 m a.m.s.l.) with a hot-humid climate type. The experimental house, meant for social housing, was built according to principles of bioclimatic architecture; total built area was 87 m^2. The IEPCS, consisting of a shaded and naturally ventilated roof pond, was installed on the ceiling of the bedrooms area. In the system, water is exposed to an air flow assisted or not by small fans in a roof pond (thickness of the water layer variable) over which a metal roof, painted externally in white color and insulated internally with 10 mm polystyrene, protects the pond from direct solar radiation. The IECPS showed an average cooling potential for reducing indoor temperatures about 0.8 °C lower than the outdoor temperature. Reduction of the daily maximum temperature reached up to 2.4 °C under optimal operation conditions.

The test cells used in our study are based on the modules and configurations evaluated by Gonzalez et al. [9] in Florianópolis, Brazil, and before that in Maracaibo, Venezuela [10]. Since the two locations are located in regions already with distinct climatic conditions, it was decided to use very similar modules in order to allow inter-comparisons of results obtained in each experimental study. Aim of the research was to test an indirect evaporative passive cooling system (IECS) in compact test cells for the subtropical conditions of Curitiba, Brazil, which belongs to a climatic region classified according to Köppen-Geiger as Cfb. The testing of several configurations of the passive system allowed us further to identify contributions of the different components of a roof pond-based indirect evaporative cooling in terms of their thermal benefits, namely the increase in thermal mass due to the water body and the shading of the roof pond.

2. Materials and methods

2.1. Location

Curitiba (25.5ºS, 49ºW, 910 a.m.s.l.) is located in a tropical climate zone in a relatively high-altitude region of Brazil (Cfb/Köppen-Geiger). It often experiences unstable meteorological conditions with large daily and annual air temperature fluctuations. Average air temperature in summer is approximately 20 °C, though average air temperature in winter is quite low for tropical standards, averaging 13 °C in June/July. From Curitiba's TMY data, plotted on Givoni's Building Bioclimatic Chart adjusted for hot developing countries [11], thermal discomfort due to cold is much more significant than heat stress: 70% of the yearly hours in cold against less than 10% in heat. The passive strategy of evaporative cooling is suggested as a feasible means to overcome thermal discomfort due to heat in just 2% of the annual daytime hours. Even though the theoretical applicability of evaporative cooling techniques is not promising for Curitiba, the estimated potential for an existing system based on such strategy and applied to an experimental dwelling was considered to be significant [12], responding with nearly 90% of the annual cooling demand in such location.

2.2. Experimental setup

Two test cells were tested, one of which with an Indirect Evaporative Cooling System (IECS) in its original configuration. In addition, a second experimental cell was tested in different configurations: as a control module; with the roof pond used as thermal mass (sealed container, naturally ventilated above); and with open roof pond without cover. Both units are made of lightweight, low-density wood panels all around (walls and floor), white-painted and with an internal 4.5 cm thick layer of expanded polystyrene, which ensured a low U-value of 0.70 W/(m^2. K). The ceiling/roof construction of the IECS module consists of a metallic water reservoir, white-painted with approximately 6.5 cm of water. Underneath the wooden roof cover there is a 1.5 cm-thick layer of EPS; a ventilated air layer was left between the roof pond and the cover to enhance evaporative processes. Resulting indoor air volume is the same in both units, 0.14 m^3.

At a first stage, during 24 days in spring (29 October 2014 through 21 November 2014), two test cells were used for testing the IECS against a control unit (CtrlU) (Fig. 2). CtrlU is covered by a roof made of the same composition of the walls, but with an increased insulation thickness of 15 cm.

At a second stage of the research, during 40 days during late spring/early summer, from 29 November 2015 until 7 January 2016, the control unit was turned to another possible configuration of the original IECS, which had the reservoir filled with water but without evaporative function. The shaded, 6-cm naturally ventilated air layer above the roof pond is kept as in the IECS (named ‘thermal mass with ventilation’ or ‘TM_{vent}’) but the pond is sealed on top with the same metallic material as the reservoir's. For this second run we used two test cells, each fitted with a roof pond. This second configuration explores the increase in heat capacity of the roof component without allowing evaporation to take place (Fig. 3).

A third comparison, tested during 3 dry days with clear sky conditions within a very rainy summer (19–21 January 2016), consisted of removing the shading element (the roof over the IECS, named ‘$IECS_{unshaded}$’), with both cells having evaporative effect (Fig. 4).

Initially (during the first stage), T/RH data loggers were used for monitoring indoor air temperatures in both units and for recording ambient temperature and humidity outdoors, in 15-min intervals, at a central position in both test cells, as shown in Fig. 2. NOVUS