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Evaluating the potential of an indirect evaporative passive cooling system for Brazilian dwellings

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ABSTRACT

The purpose of this study is to assess the applicability of an indirect evaporative passive cooling system (IEPCS) in prototypical dwelling modeled for locations across the Brazilian territory. The thermal performance of the IEPCS is analyzed, originally developed for a dwelling located in hot-humid Maracaibo, Venezuela (Vivienda Bioclimática Prototipo – VPB-1). Diverse configuration modes were tested as part of the experimental field study, from which predictive formulas were generated and validated. The paper shows results of the expected thermal performance of the IEPCS for 411 Brazilian cities, which were obtained from the application of predictive formulas to a database consisting of TMY (Typical Meteorological Year) climate files. The efficiency of the passive cooling system was evaluated for each city with regard to its capability in reducing indoor temperatures relative to outdoors as well as Degree-Day percentages above the upper limit of the adaptive comfort zone. Detailed results for four Brazilian locations are also discussed. Results suggest that the system is capable of ensuring thermal comfort conditions for most of the cities evaluated. Average indoor temperatures reached reductions up to 2.5 °C below outdoor conditions; such reductions depend fundamentally on the wet bulb temperature depression. From such results, it is suggested that the IEPCS could have a great applicability in Brazil with a strong potential for improving indoor comfort conditions and, in the case of air-conditioned buildings, also promote a reduction of the energy demand on HVAC.

1. Introduction

In hot humid locations, it is recommended by bioclimatic building design that indoor temperature conditions are kept lower than outdoors. Considering that in those regions outdoor temperature fluctuations are small and humidity is normally high [21,32,9], the use of direct evaporative cooling can increase indoor humidity, not being an effective solution to improve indoor comfort. Permanent cross ventilation is the usual recommendation, as a means of enhancing direct skin evaporation and removing excess heat input and also of ensuring structural cooling [21]. In such climates, primarily ventilated buildings with low thermal mass should be employed. Although examples of light weight constructions are broadly seen in vernacular architecture in hot-humid regions, by means of permanent, daytime cross ventilation it is not possible to lower the indoor temperatures below outdoors. The indoor maximum can be close to the outdoor maximum and normally even higher due to internal heat gains. In most cases, resulting indoor conditions will lie above the human thermal comfort range.

Maracaibo (latitude 10° 34′ N, longitude 71°44′ W, elevation 66 m above sea level) has a hot-humid climate type. Climatic data for 30 years (1951–1980), gathered at the local meteorological station (meteorological normals based on data of two stations operated by the Venezuelan Air Force, airport *Grano de Oro* and *Aeropuerto de Maracaibo "Caujarito"*), show that there is little variation of air temperatures and humidities throughout the year with daily averages of 26.5–28.6 °C and 73–77%, respectively.

The use of an evaporative cooling system for the hot-humid conditions of Maracaibo may at first glance seem inadequate. Indeed, in such location, direct evaporative cooling systems may

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increase indoor humidity and thus not be very effective. González (1997) [14] shows that, in turn, indirect evaporative cooling systems can be used to cool parts of the building structure without generating extra moisture internally. This has later been tested experimentally for Maracaibo [3]. Two effects take place in the case of indirect evaporative cooling: structural cooling and placement of the evaporative panels outside the inhabited space.

The driving force of evaporative cooling systems is the process of evaporation, which is the phase change of water from liquid to vapor. 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 given by Givoni [37], 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, which is 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 possibilities of employing a passive evaporative cooling system, several of which have been reported in the literature for the last five decades such as roof ponds with or without moveable insulation ([5,7,16,19,20,23,28–31,35,36], roof ponds with shading elements [34,35,25]) natural draft cooling towers [1,6,24], among other systems, which have been implemented in diverse climatic conditions.

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. Based on this principle, an indirect evaporative passive cooling system (IEPCS) was conceived for an experimental one storey house in Maracaibo, Venezuela.

In this study, we briefly describe the experimental dwelling and investigate its applicability to diverse Brazilian climatic regions with the aim of improving indoor thermal comfort. The thermal behavior of the dwelling's passive cooling system is estimated for different locations by means of predictive formulas developed in previous studies from experimental data [11,22]. The rationale behind the development and use of predictive formulas has been discussed by Givoni (1999) [10]; such formulas have the advantage of allowing building designers to have a first assessment of a given passive system's applicability in climate regions different from the original one, i.e. where experimental data were generated. In regard of the passive system discussed in this paper, the authors have evaluated in a previous study its adequacy to a different climatic region, which was more favorable to an improved performance [22]. For that, the approach was based on the use of predictive formulas, which were applied to a hot-dry summer period in Sede Boqer, Israel. Results were considered to be consistent and relevant to assess the IEPCS performance under arid conditions.

The analysis presented in this paper is based on results obtained from predictive formulas where the input variables are meteorological data from a database of 411 Brazilian locations (TMY data). Four cities are also analyzed in a more detailed way: two hot-humid, coastal cities and two semiarid locations. The IEPCS efficiency was assessed in terms of its potential in lowering indoor temperature, relative to outdoors, as well as with respect to the sum of degree-days[1] above the upper limit of the adaptive thermal comfort, i.e. cooling degree-days, in each location.

[1] Degree-days/year in this work is the algebraic sum of the difference between the maximum temperature and the upper limit of the comfort zone for every day of the year.

2. Building with IEPCS

The design of the original dwelling which contains the IEPCS results from a long-term research project involving the design, construction and evaluation of a bioclimatic housing prototype named *Vivienda Bioclimática Prototipo* (VBP-1), which was built in Maracaibo, Venezuela, sponsored by the private sector and the *Universidad del Zulia* (LUZ). The research project had the primal purpose to apply knowledge based in materials science, bioclimatic design and passive cooling systems for designing a bioclimatic, solar passive low-cost house [15].

VBP-1 is sited on a plot 12.6 m × 20 m with its main façade towards west. Total built area is 87 m^2 consisting of a living room with cooking facilities and dining space, two bedrooms, toilet with separated bathroom and an independent office (located at the west façade), which can be used by the family as a local store or office (*tienda*). An internal courtyard is also adopted in the south façade. Table 1 presents the thermo-physical characteristics of VBP-1 (Fig. 1).

The bedroom area is covered by the IEPCS (Figures), which is comprised of a metallic ceiling/water tank system 3–4 cm thick over concrete slabs. As roof element, insulated (1 cm thick EPS), high reflectance metallic sheets are used. The water surface is forced ventilated by fans in order to enhance evaporation, although fans were operated intermittently.

Since the passive system was not expected to be fully capable of ensuring comfort conditions in the presence of significant internal heat gains under Maracaibo's climatic conditions, the rationale was that the IEPCS should only be implemented in the bedroom area. In other words, in terms of the thermal zoning of the experimental dwelling, particularly the rooms with a lower heat generation, where a higher performance of the IEPCS would be expected, were provided with the system. For the heat

Table 1
Building envelope thermo-physical characteristics of the VBP-1.

Layer	Conductivity (W/mK)	Density (kg/m^3)	Specific heat (J/kgK)
External walls (from inside to outside)			
20 mm Plaster	0.698	1800	1005
150 mm Hollow concrete block	0.499	$\rho Cp = 3.272*10^6$	
20 mm Plaster	0.698	1800	1005
Internal walls (from inside to outside)			
20 mm Plaster	0.698	1800	1005
150 mm Hollow concrete block	0.499	$\rho Cp = 3.272*10^6$	
20 mm Plaster	0.698	1800	1005
Floor (from inside to outside)			
50 mm Cement and sand	0.53	1570	1000
120 mm Poured concrete	1.75	2300	920
Roof (from inside to outside)			
Prefabricated concrete beam	1.75	2300	920
3 mm Steel sheet	46	7900	454
0.2 mm Polyethylene foil	0.33	1526	1645
30–40 mm Water	0.582	1000	4187
300–900 mm Ventilated air layer	0.026	1.223	1063
0.2 mm Polyethylene foil	0.33	1526	1645
200–300 mm Ventilated air layer	0.026	1.223	1063
10 mm Polystyrene sheet	0.036	41	1500
0.8 mm Galvanized steel sheet P white	46	7900	454
Openings	Net area (m^2)	U-value (W/m^2 K)	Solar transmittance (%)
2 One glass tilt Windows	2.80	5.73	80
2 Plywood doors	3.20	2.09	0