Building and Environment 87 (2015) 265–273

Contents lists available at ScienceDirect

Building and Environment

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

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

Eduardo González Cruz [a, b], Eduardo Krüger [c, *]

[a] Facultad de Arquitectura y Diseño, Universidad del Zulia, Núcleo Técnico de LUZ, Av. Goajira (16) con Calle 67, Maracaibo CP 4011-A-526, Venezuela
[b] Graduate Program in Architecture and Urban Planning of the Federal University of Santa Catarina, Brazil
[c] Programa de Pós-Graduação em Tecnologia/Programa de Pós-Graduação em Engenharia Civil, Departamento de Construção Civil, Universidade Tecnológica Federal do Paraná – UTFPR, Av. Sete de Setembro, 3165, Curitiba, PR CEP. 80230-901, Brazil

ARTICLE INFO

Article history:
Received 17 December 2014
Received in revised form
21 January 2015
Accepted 22 January 2015
Available online 7 February 2015

Keywords:
Passive cooling
Indirect evaporative cooling
Indoor temperature prediction
Thermal comfort

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

* Corresponding author.
E-mail addresses: eduardo.Gonzalez@fad.luz.edu.ve (E. González Cruz), ekruger@etfpr.edu.br (E. Krüger).

http://dx.doi.org/10.1016/j.buildenv.2015.01.020
0360-1323/

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

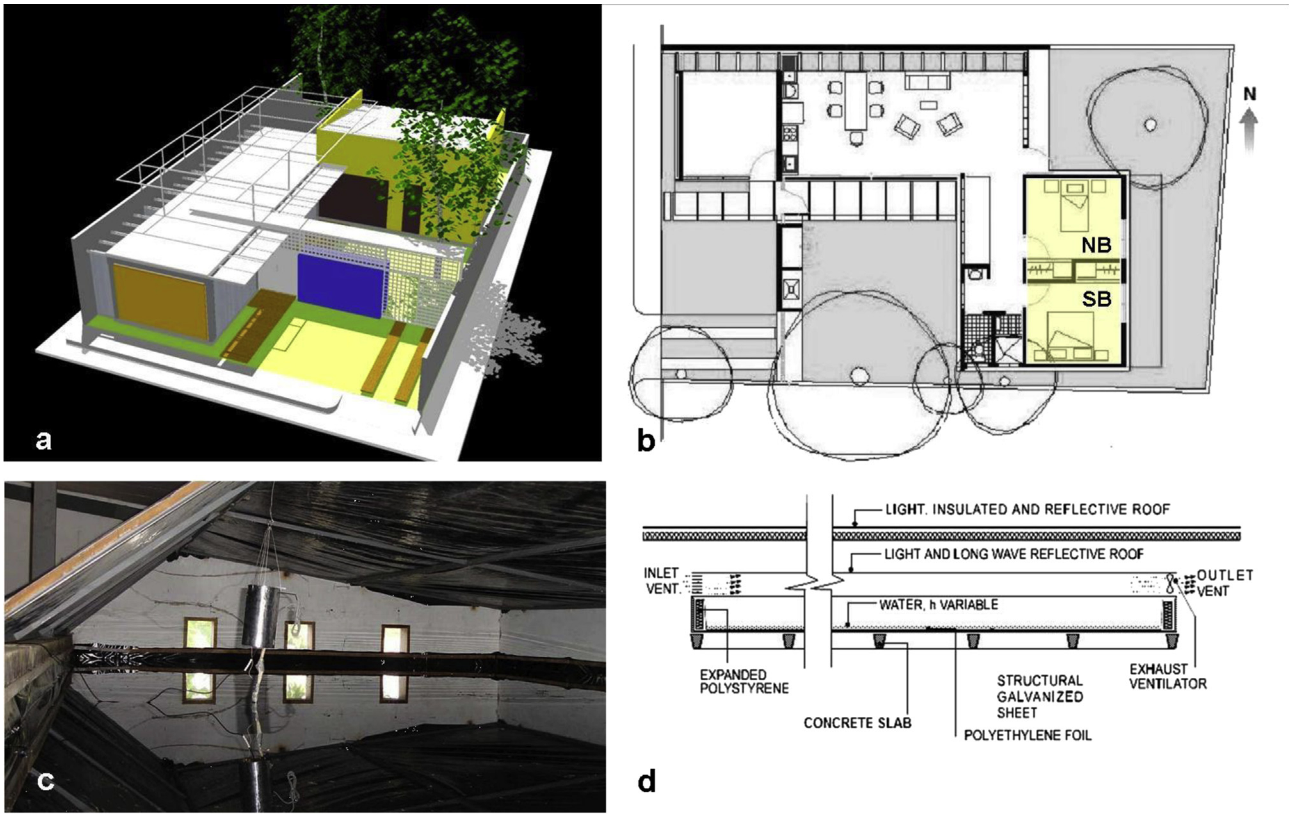


Fig. 1. (a) VBP-1, (b) Floor plan, (c) Water tank and roof details (d) IEPCS.

generating zone of the dwelling (kitchen, living room and, eventually, the office space), other bioclimatic strategies were used: natural ventilation, solar protection and vegetation, so that air and surface temperature profiles were close to those of a shaded condition. These two thermal zones have been clearly defined and separated by a services strip in order to make more efficient the bioclimatic and the passive cooling strategies [15].

The utilization of indirect evaporative cooling systems has been studied under arid conditions [7,8,33] as well in hot-humid climate types, where the potential of the system of reducing indoor average temperatures has been demonstrated [12–14,18,27].

Results from the IEPCS employed in the experimental prototype showed that reductions of the mean daily temperature were around 1 °C; under optimal conditions the drop of the outdoor maximum temperature in the bedroom area reached 2.4 °C. The added thermal mass and heat capacity of the water pond contributed to a lower swing of the indoor temperature within a 24 h-cycle, about a third of that of the outdoors [17].

It should be stressed that the several experimental runs took into account different operation modes of the system, such as with the bedroom area naturally ventilated with and without the IEPCS (no water in the pond area), with and without occupants, with and without nocturnal ventilation among others. Diverse intervening factors (infiltration rates due to ventilation, heat gains due to occupancy etc) were analyzed case by case according to the respective configuration mode. The concept was to evaluate the performance of the system under a given set of conditions for a typical bedroom environment —the variable used for the evaluation was the room temperature, as this variable can be easily compared to existing indoor comfort indices.

2.1. Predicted formulas generated for the IEPCS

Predictive formulas have been developed for the two bedrooms underneath the IEPCS according to the procedures described in Givoni & González (2009), [11] from monitored data gathered throughout a nine-month test period. Data were divided into two sections: a) for the generation of the formulas and b) for their validation. The set of equations developed gives the indoor temperature in the south bedroom (SB) and in the north bedroom (NB) from a first estimate of the water temperature (Pond).

The roof pond above both bedrooms provides the indirect evaporative cooling to the bedrooms underneath. Therefore, a mathematical representation of the temperature of the roof pond was needed as an input in the generation of the formulas of the maximum, average and minimum indoor temperatures. The input variables in the formula representing the average temperature of the roof pond are the average daily air temperature (T_{avg}) and wet-bulb temperature (WBT), the diurnal temperature range (Swing), the availability of water in the pond (Water) and the operation of the fans (Fans). Such formulas as well as the formulas needed for predicting indoor temperature in each bedroom were generated by means of multiple regressions (Table 2). Correlation coefficients between monitored and predicted data ranged 0.85–0.96. The north bedroom was left empty over the monitored period whereas the south bedroom was mostly occupied by two persons at night and for a couple of hours during the day, thus the variable of usage is employed (Use).

3. Methods and materials

By means of the predictive formulas derived for the IEPCS, the expected thermal behavior of the dwelling's passive cooling

Table 2
Predictive formulas for the north and south bedrooms in VBP-1.

Pond		
	$\text{Pond} = 3.67 + 0.6449{*}\text{WBT} + 0.3261{*}T_{avg} - 0.0638{*}\text{Swing} - 1.68{*}\text{Water} - 0.5{*}\text{Fans}$	(1)
South (SB)		
	$\text{Maximum} = -0.15 + 0.1333{*}T_{avg} + 0.6477{*}\text{Pond} + 0.2312{*}\text{RnAvg} + 0.1985{*}\text{Swing} + 0.8{*}\text{Use}$	(2)
	$\text{Average} = -1.0 + 0.1568{*}T_{avg} + 0.5925{*}\text{Pond} + 0.2899{*}\text{RnAvg} + 0.0406{*}\text{Swing} + 0.7{*}\text{Use}$	(3)
	$\text{Minimum} = 1 + 0.5414{*}\text{Pond} + 0.3298{*}\text{RnAvg} + 0.0932{*}T_{min} + 0.41{*}\text{Use} - 0.0668{*}T_{drop}$	(4)
North (NB)		
	$\text{Maximum} = -1.8 + 0.1616{*}T_{avg} + 0.5455{*}\text{Pond} + 0.3732{*}\text{RnAvg} + 0.113{*}\text{Swing}$	(5)
	$\text{Average} = -2.3 + 0.1744{*}T_{avg} + 0.5319{*}\text{Pond} + 0.381{*}\text{RnAvg} + 0.0011{*}\text{Swing}$	(6)
	$\text{Minimum} = 1 + 0.5414{*}\text{Pond} + 0.3298{*}\text{RnAvg} + 0.0932{*}T_{min} + 0.41{*}\text{Use} - 0.0668{*}T_{drop}$	(7)

All temperatures given in Degrees Celsius.
WBT – outdoor daily average wet bulb temperature.
T_{max} – outdoor daily maximum temperature.
T_{avg} – outdoor daily average temperature.
T_{min} – outdoor daily minimum temperature.
RnAvg – running average temperature of three previous days.
Swing – diurnal temperature swing ($T_{max}-T_{min}$).
Pond – pond temperature.
T_{drop} or $T_{max(n-1)}-T_{min}$ – temperature drop from previous outdoor maximum to current minimum.
Use – usage of the bedroom (1 yes or 0 no).
Fans – 0 = no fan; 1 = two fans; 2 = 2 fans.
Water – 0 = no water (dry mode); 1 = with water.

system, in particular for the south and north bedrooms (SB and NB), was estimated using as input variables meteorological data recorded at official meteorological stations over the Brazilian territory. The "raw" meteorological data were transformed into (for the purpose of this study) useful quantities, expressed as WBT, T_{avg}, T_{min}, RnAvg, Swing, T_{drop}, as described above. This was done for 411 Brazilian locations from a database consisting of EPW data files representing the typical meteorological year (TMY) of each location, as shown in Fig. 2 [26].

The reference used for establishing a comfort zone for each location was based on the adaptive comfort method with 90% thermal acceptability (ASHRAE Standard 55-2004 for naturally ventilated buildings, [2,4]). For the starting outdoor conditions, one indicator was obtained from the adaptive comfort referential values, namely the sum of degree-days with indoor maximum temperature in SB and NB above the upper thermal comfort limit; whereas a second indicator is related to the annual daily average and annual maximum wet temperature depression for each location. Obtained results for each location were interpolated for the whole territory by means of *kriging*, thus generating thematic contour maps for a given output variable.

Only temperature predictions for the north bedroom (NB) were used for the more detailed analysis of four selected locations across the Brazilian territory, as such bedroom was left empty throughout the monitoring period, cancelling out thus possible usage effects of the bedroom area. Four locations were analyzed in the north-eastern part of the country, where the winter season is completely absent: two hot-humid, coastal cities (Fortaleza and Natal, local latitude 3.78°S and 5.80°S, respectively) and two semiarid locations (Teresina, lat. 5.05°S, and Petrolina, lat. 9.35°S). 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-hours above the upper limit of the adaptive thermal comfort in each location.

4. Estimated cooling potential of the Iepcs for cities located across the Brazilian territory

The database for 411 cities was used firstly to represent the cooling needs of diverse Brazilian regions, expressed in this case by the cooling degree-days, as well as the potential for using evaporative cooling systems, given by the wet bulb temperature depression. This analysis was done from meteorological data files

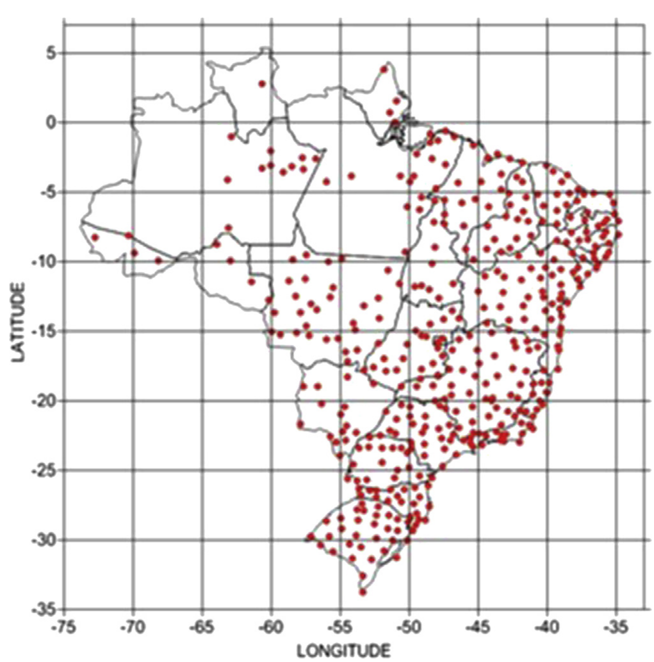


Fig. 2. Spatial distribution of the TMY data files over the Brazilian territory.

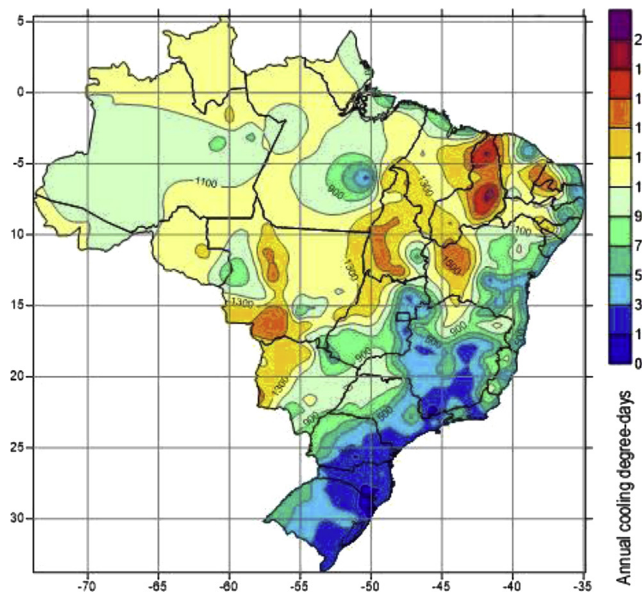


Fig. 3. Annual cooling degree-days – for a base temperature above the upper limit of the adaptive comfort range.

only. After this first appraisal, both the north and the south bedrooms have been evaluated with regard to indoor temperature reductions and to their ability of lowering cooling degree-days as a result from IEPCS implementation. This second analysis used output from the predictive formulas described above.

4.1. Heat discomfort

Fig. 3 presents cooling degree-days per year (shown in contour lines) for the Brazilian territory. Some regions have a low sum of cooling degree-days, below 300 degree-days, normally in more temperate climate zones with a defined summer season. In great part of the country (152 out of 411 cities evaluated), the yearly sum of cooling degree-days surpasses 1000 degree-days, peaking at 2153 degree-days in Picos, PI. There exists thus a strong need for (passive, active or hybrid) cooling in the country.

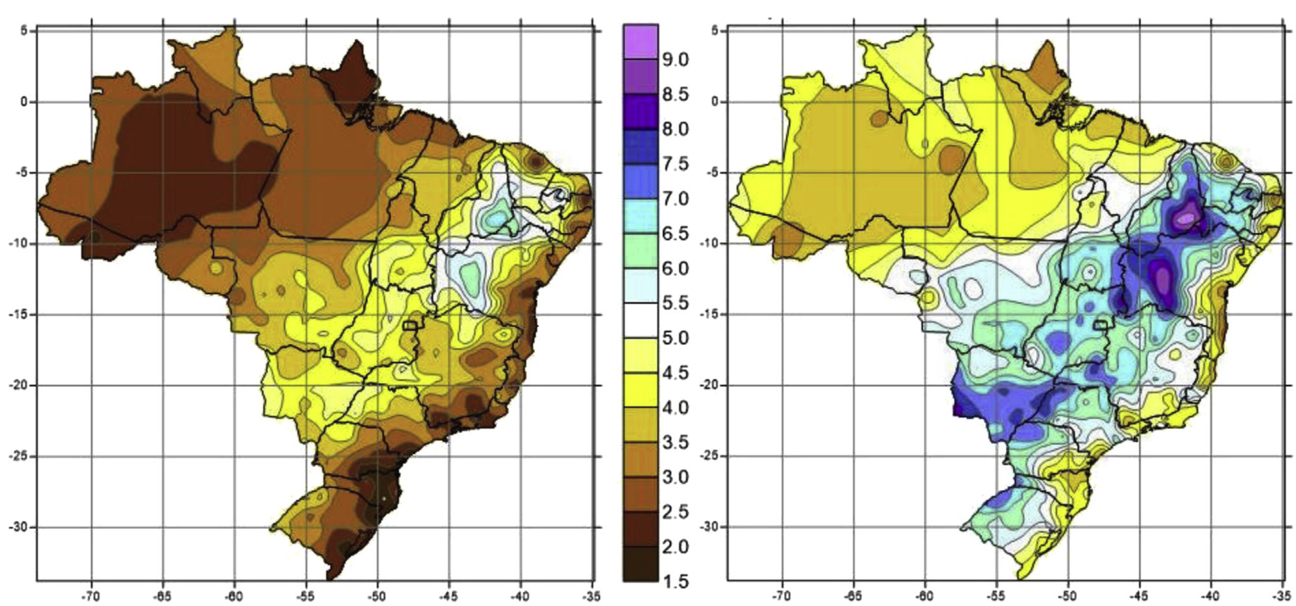
4.2. Evaporative cooling potential

The potential for evaporative cooling in each region of the map is given by the wet bulb temperature depression (DWBT = DBT-WBT) [8]. Annual daily averages are shown alongside the annual maximum DWBT (Fig. 4).

Part of the Amazonian rainforest and coastal regions exhibits a limited potential for evaporative cooling, but more central locations, inclusive of the northeastern semiarid present a high potential for the use of this technique. The maximum DWBT (Fig. 4b) suggests that some regions may have a dry season, when evaporative cooling could be seasonally employed with higher efficiency. Another interesting feature is that there is an overlap between the cooling needs (Fig. 3) and the potential for evaporative cooling (Fig. 4).

4.3. Indoor versus outdoor temperature

The cooling efficiency of the IEPCS can be evaluated in two ways: a) by the ability of the system of reducing indoor temperature relative to outdoors, b) comparatively to a base-case condition, without the evaporative cooling system. Fig. 5 shows the air temperature drop in each bedroom. The south bedroom due to its occupancy has less evident air temperature differences relative to the external conditions. Nevertheless, in such bedroom, reductions in indoor air temperature were found in almost all locations (in 380 cities out of the total of 411); the range of differences was 0.5 °C–1.7 °C. Again, no noticeable effect has been identified in the Amazon region and on the coast, thereby confirming the mean annual DWBT analysis.



(a) (b)

Fig. 4. Annual daily average wet bulb temperature depression DWBT (a) and annual maximum DWBT (b).

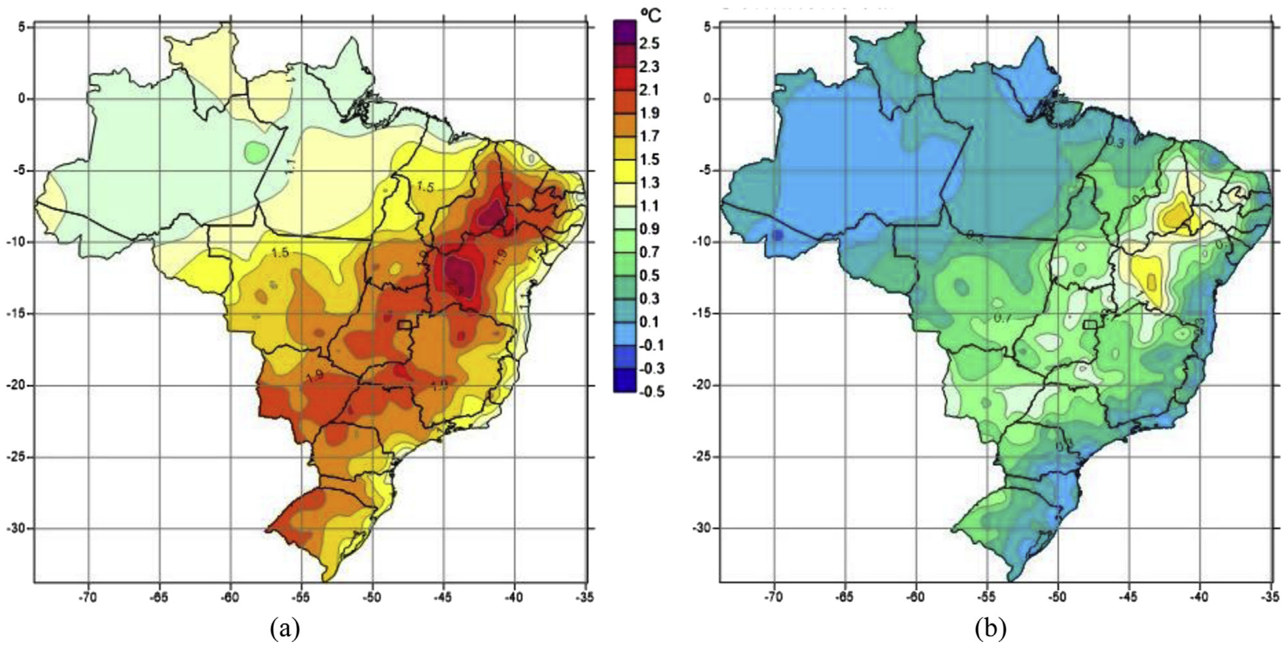


Fig. 5. Difference in indoor temperature relative to outdoors for the a) north bedroom (NB) and b) south bedroom (SB).

In the case of the north bedroom, there is always some reduction of the outdoor air temperature, the greatest differences are for the northeastern semiarid and for the interior of the country.

4.4. Cooling degree-days

Percent decreases in cooling degree-days are shown for both bedrooms (Fig. 6). Such reduction is for NB highly relevant: the IEPCS is responsible for a 100% drop in the cooling degree-days ubiquitously in all the territory. For SB, reductions in cooling degree-days are less pronounced, but also significant (ranging 97–100%), and also somewhat weaker in the Amazon Basin.

5. Performance of the Iepcs for four Brazilian cities

Four selected locations were adopted for temperature predictions for the north bedroom (NB). Those locations belong to the northeastern part of the country. The two semiarid locations (Teresina, lat. 5.05°S, and Petrolina, lat. 9.35°S) exhibit high daily maximum temperatures (Teresina has an annual mean of 34.1 °C

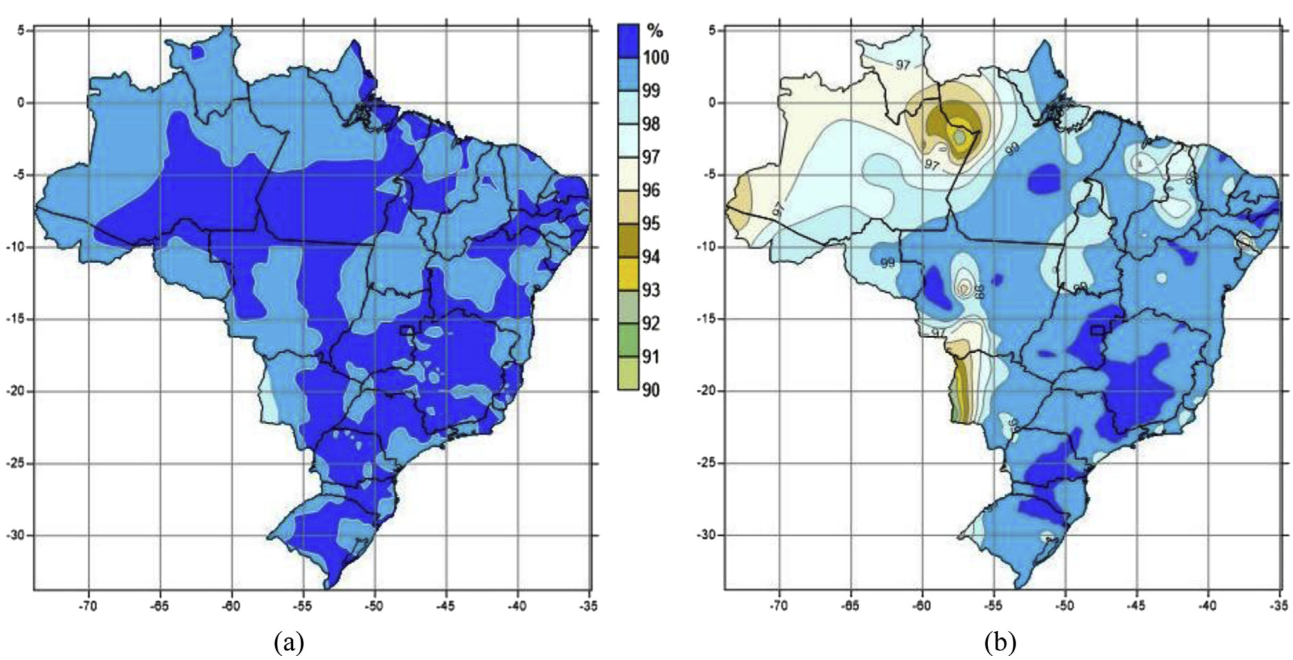
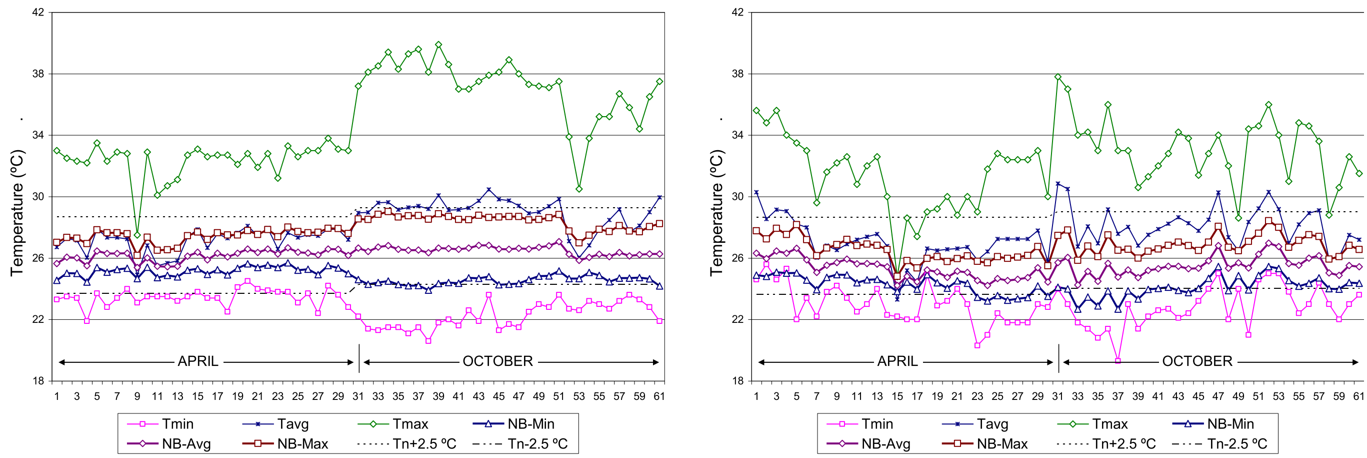


Fig. 6. Percent reductions in cooling degree-days for the a) north bedroom (NB) and b) south bedroom (SB).



a) Teresina b) Petrolina

Fig. 7. Minimum, average and maximum air temperature over the background of outdoor conditions with adaptive comfort range (dotted line), for: a) Teresina, b) Petrolina.

and Petrolina 31.7 °C) and relatively high temperature swings (mean value for Teresina 11.5 °C, for Petrolina 9.7 °C) as well as a high average wet bulb temperature depression (Teresina: mean = 4.8 °C, max = 9.7 °C, Petrolina: mean = 5.8 °C, max = 10.3 °C).

In contrast, two coastal locations were chosen: Fortaleza (3.78°S) and Natal (5.80°S). Both locations also have high ambient temperatures throughout the year, though a bit lower than the semiarid locations, with a similar mean around 30.5 °C. In these locations average daily temperature swing is lower than in the semiarid locations (Fortaleza = 6.2 °C; Natal = 6.6 °C) as well as the mean wet bulb temperature depression (Fortaleza: mean = 3.0 °C, max = 4.8 °C; Natal: mean = 3.8 °C, max = 6.2 °C).

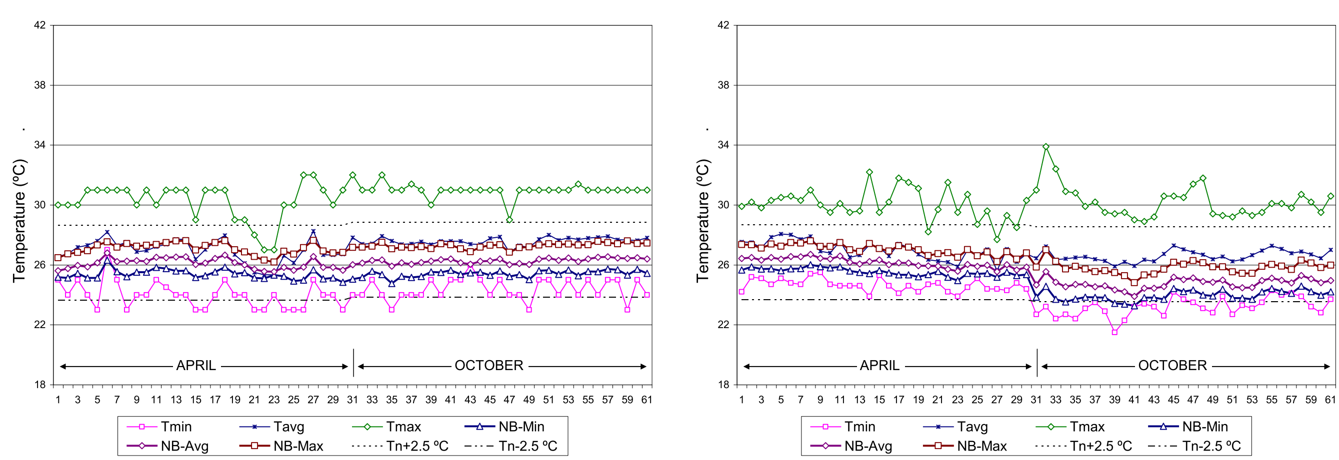
From the point of view of bioclimatic architecture, such local climatic features would require different strategies, with evaporative cooling and the use of thermal mass as relevant strategies for the semiarid locations (the two strategies being part of the IEPCS evaluated). Fortaleza and Natal however do not have evaporative cooling and thermal mass among the recommended bioclimatic strategies, in such locations first and foremost is cross ventilation recommended.

5.1. Thermal performance evaluation

Figs. 7(a–b) and 8(a–b) present for the months of April and October indoor temperatures in the north bedroom (NB) against outdoors. The comfort range is plotted as dotted lines. The cooling efficiency of the IEPCS is given as the direct measure of the reduction of the indoor average temperature relative to outdoors.

In Teresina (Fig. 7a), indoor mean temperatures are on average 1.8 °C lower than outdoors, though the peak difference can reach 4.4 °C. The drop of the outdoor maxima is more significant, on average 6.6 °C, reaching 11 °C on occasion. Correspondingly, a similar drop in the daily temperature swing takes place indoors: from the average of 11.5 °C down to 3.0 °C (yielding a decrement factor of 0.26); this is especially due to the use of thermal mass. Indoor temperatures remain within the adaptive comfort range for the months depicted in the graphs. Petrolina (Fig. 7b) shows a very similar thermal performance, with the same decrement factor, but with less dramatic reductions in indoor temperature.

The coastal cities present a different behavior. Reductions in indoor temperatures are for Fortaleza and Natal less significant: the mean drop is 1.1 and 1.4 °C, respectively, and the maximal drop can



a) Fortaleza b) Natal

Fig. 8. Minimum, average and maximum air temperature over the background of outdoor conditions with adaptive comfort range (dotted line), for: a) Fortaleza, b) Natal.

Table 3
Percentages in thermal comfort/discomfort in the north bedroom (NB) versus outdoor conditions.

		North bedroom			Outdoor conditions		
		NB-max	NB-avg	NB-min	DBT-max	DBT-avg	DBT-min
Teresina	Discomfort	0	1	19	99	16	84
	Comfort	100	99	81	1	84	16
Petrolina	Discomfort	4	18	54	91	18	86
	Comfort	96	82	46	9	82	14
Fortaleza	Discomfort	0	0	0	94	1	21
	Comfort	100	100	100	6	99	79
Natal	Discomfort	0	0	5	94	0	38
	Comfort	100	100	95	6	100	62

reach 3.4 °C in Fortaleza and 4 °C in Natal. Highest performance is reached when outdoor temperature swing is higher. Even though the performance here is lower than in the semiarid locations, comparatively, in Fortaleza and Natal ambient temperature is generally lower and quite close to the adaptive comfort upper limit, so that the IEPCS is able to keep indoor conditions within the comfort range.

The decrement factor, which is the fraction of the indoor temperature swing by the outdoor's is consistent in all cases, on average 0.26.

5.2. Thermal comfort analysis

For the four cities, the comfort range differs only slightly, as the adaptive, climate-related neutral temperature equation was applied to the respective climatic conditions, with the comfort range given for 90% thermal acceptability [2,4]. Thus, the comfort range for Teresina was 23.5–29.4 °C, for Petrolina 22.8–29.2 °C, for Fortaleza 23.5–28.9 °C, and for Natal 23.4–28.9 °C. Table 3 presents percentages of time in indoor thermal comfort/discomfort per year, with respect to daily minimum, average and maximum temperatures.

Outdoor maxima are above the recommended upper comfort limit almost all year round. The maximum outdoor temperature is higher than the upper thermal comfort limit, on average by 5.2 °C in Teresina, peaking at 10.6 °C; 3.0 °C in Petrolina, and up to 12.8 °C higher; 1.8 °C in Fortaleza with a peak of 7.2 °C; and 1.9 °C in Natal, reaching up to 5.7 °C. Indoors, the IEPCS is able to promote thermal comfort by 100% of the time practically in all locations. Except for some instances in Petrolina, thermal discomfort may be present only when indoor temperatures lie below the lower thermal comfort limit, though thermal discomfort due to excess heat is nonexistent. For Teresina, the temperature departure below the comfort range is on average 0.6 °C, for Petrolina 0.9 °C, for Natal, such difference is only 0.2 °C. The rise of the minimum temperatures could however be easily accomplished by increasing the water volume in the pond or slightly changing the thermal mass of the ceiling.

6. Conclusions

The use of predictive formulas was decisive for carrying out this study. The rationale adopted in this case is that the formulas can be adopted for diverse climatic conditions other than the ones where the system was firstly implemented. Thus the process is based on: a) the assessment of the system's performance, b) the generation and validation of predictive formulas and c) the adoption of the generated formulas for other climatic conditions (in the same location, for other times of the year, for other locations). A previous paper looked into the applicability of the formulas developed for the IEPCS in Maracaibo (hot-humid location) under completely different climatic conditions (the arid Negev desert, in Israel) [22]. Presently, another research initiative undertaken by the authors evaluates the applicability of different sets of formulas generated independently for three different climates, but for a same prototype under similar configurations. In the present study we hypothesize that the applicability of such formulas can be extended to the entire Brazilian territory.

From the application of the predictive formulas to the climate database encompassing 411 Brazilian cities, results suggest that the IEPCS can reduce thermal discomfort due to excess heat in 95–100% of the year and in a substantial part of the territory. In the selected locations, the IEPCS has yielded mean temperatures 2.5 °C lower than outdoors. Although our findings could locate the best regions for the applicability of the IEPCS, the system could be applied in diverse Brazilian locations, irrespective of the aridity of the climate, provided that the output is given in terms of promoting thermal comfort indoors; though the ability of reducing indoor temperature is more climate-sensitive.

A more detailed analysis showed that in arid locations, such as Teresina and Petrolina, the IEPCS can lower the average daily temperature somewhat more than in coastal cities in the same latitude range (as Fortaleza and Natal). More significant changes were noticed in the daily maximum temperature in such locations. Considering that the daily temperature swing is strongly related to the aridity of the local climate, whereas hot-humid locations will generally exhibit smaller fluctuations of the daily temperature, though with lower daily maxima, the IEPCS proves to be beneficial for most of the warmer regions of Brazil. Only in extremely humid regions, such as in Amazon basin (with mean daily relative humidity fluctuating between 80 and 90% over the year), the system's yield in reducing indoor temperatures is poor. However, the ability to diminish or even annul annual cooling degree-days is practically ubiquitous in all territory.

Acknowledgments

The Brazilian funding agency CAPES, for the financial support of Prof. Eduardo González Cruz, Visiting Professor at the Graduate Program in Architecture and Urbanism of the Federal University of Santa Catarina.

References

[1] Alvarez S, Sanchez F. Thermally driven cooling and ventilation system (PDEC) [Seville, Spain]. 2000.
[2] ASHRAE Standard 55. Thermal environmental conditions for human occupancy. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers; 2010.
[3] Bravo G, González E. Thermal comfort in naturally ventilated spaces and under indirect evaporative passive cooling conditions in hot–humid climate. Energy Build 2013;63:79–86.
[4] De Dear R, Brager G. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE standard 55. Energy Build 2002;34:549–63.
[5] Fernández-González A. Analysis of the thermal performance and comfort conditions produced by five different passive solar heating strategies in the United States Midwest. Sol Energy 2007;81(5):581–93.
[6] Fisenko SP, Petruchik AI, Solodukhin AD. Evaporative cooling of water in a natural draft cooling tower. Int J Heat Mass Transf 2002;45(23):4683–94.
[7] Givoni B. Experimental studies on radiant and evaporative cooling of roofs. In: Proceedings of the international passive and hybrid cooling conference, Miami Beach. USA: American Section of the International Solar Energy Society; 1981. p. 279–83.
[8] Givoni B. Passive and low-energy cooling of buildings. New York: Van Nostrand Reinhold; 1994.
[9] Givoni B. Climate considerations in building and urban design. New York: ITP; 1997.
[10] Givoni B. Minimum climatic information needed to predict performance of passive buildings in hot climates. In: Proceedings of PLEA conference; 1999. Brisbane, Australia.
[11] Givoni B, González E. Thermal performance of indirect evaporative cooling in a tropical climate. In: Proceedings of the ASES Conference, Buffalo, NY; 2009.

[12] Givoni B. Indoor temperature reduction by passive cooling systems. Sol Energy 2011;85(8):1692–726.
[13] González E. Evaluación de sistemas pasivos de enfriamiento y su aplicación en el diseño de viviendas. Maracaibo, Venezuela: Informe de investigación CONDES, Universidad de Zulia; 1989.
[14] González E. Étude de matériaux et de techniques du bâtiment pour la conception architecturale bioclimatique en climat chaud et humide [PhD thesis]. France: École des Mines des Paris; 1997.
[15] González E, Machado MV, Rodríguez L, León G, Soto MP, Almao N. VBP-1: a sustainable urban house for low-income family in a tropical climate. Cambridge, UK: PLEA 2000; 2000.
[16] González E, Givoni B. Testing and modelling evaporative passive cooling systems for a hot humid climate in Maracaibo. In: Proceedings of ISES 2005-solar world congress; 2005 [Orlando, FL].
[17] González E, Rojas A, Bravo G, Gallardo M, González R, Pérez L, et al. Desempeño térmico de la VBP-1: temperaturas características, factor decremental e retraso térmico. In: Memorias de la 30 Semana Nacional de Energía Solar, ANES 2006, Veracruz, México; 2006.
[18] González-Cruz EM, González-García SI. Estudio experimental sobre el comportamiento térmico de un nuevo tipo de techo-estanque para el enfriamiento pasivo en clima húmedo. Ambiente Construído, Porto Alegre 2013;13(4):149–71.
[19] Hay HR, Yellot IJ. Natural air-conditioning with roof ponds and moveable insulation. ASHRAE Trans 1969;75 [Part I)].
[20] Kharrufa NS, Adil Y. Roof pond cooling of buildings in hot arid climates. Build Environ 2008;43(1):82–9.
[21] Koenigsberger O, Ingersoll T, Mayhew A, Szokolay S. Manual of tropical housing and building. London: Longman; 1974.
[22] Krüger E, González E, Givoni B. Effectiveness of indirect evaporative cooling and thermal mass in a hot arid climate. Build Environ 2010;45:1422–33.
[23] Nahar NM, Sharma P, Purohit MM. Performance of different passive techniques for cooling of buildings in arid regions. Build Environ 2003;38:109–16.
[24] Pearlmutter D, Erell E, Etzion Y. A multi-stage down-draft evaporative cool tower for semi-enclosed spaces: experiments with a water spraying system. Sol Energy 2008;82(5):430–40.
[25] Pearlmutter D, Rosenfeld S. Performance analysis of a simple roof cooling system with irrigated soil and two shading alternatives. Energy Build 2008;40(5):855–64.
[26] Roriz M. Base de dados climáticos de 411 municípios brasileiros. 2013. Available at: http://www.roriz.eng.br/epw_9.html [accessed: 12.04.13].
[27] Sánchez L. Evaluación de un Techo-estanque Como Sistema de Enfriamiento Pasivo en un Clima Cálido Sub-húmedo [MsC thesis]. México: Universidad de Colima; 1993.
[28] Sodha MS, Khatry AK, Malik MAS. Reduction of heat-flux through roof by water film. Sol Energy 1978;20:189–91.
[29] Sodha MS, Singht SP, Kumar A. Thermal performance of a cool-pool system for passive cooling of a non-conditioned building. Build Environ 1985;20(4):233–40.
[30] Spanaki A, Tsoutsos T, Kolokotsa D. On the selection and design of the proper roof pond variant for passive cooling purposes. Renew Sustain Energy Rev 2011;15:3523–33.
[31] Spanaki A, Kolokotsa D, Tsoutsos T, Zacharopoulos I. Assessing the passive cooling effect of the ventilated pond protected with a reflecting layer. Appl Energy 2014;123:273–80.
[32] Szokolay SV. Thermal design of buildings. Canberra: RAIA Education Division; 1987.
[33] Tang R, Etzion Y, Erell E. Experimental studies on a novel roof pond configuration for the cooling of buildings. Renew Energy 2003;28(10):1513–22.
[34] Tang R, Etzion Y. On thermal performance of an improved roof pond for cooling buildings. Build Environ 2004;39:201–9.
[35] Tang R, Etzion Y. Cooling performance of roof ponds with gunny bags floating on water surface as compared with a movable insulation. Renew Energy 2005;30(9):1373–85.
[36] Tiwari GN, Singh U, Sodha MS. Roof cooling by evaporation of water. In: Sodha MS, Mathur SS, Malik MAS, editors. Renewable energy resources. Chichester, UK: Willey; 1984.
[37] Givoni B. Comfort climate analysis and building design guidelines. Energy Build 1992;8:11–23.