Radiative and Radiative/Evaporative Passive Cooling Systems for a Hot Humid Climate – Maracaibo

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ABSTRACT: Maracaibo has a hot humid climate with maximum annual average temperatures of 32°C to 34°C and corresponding minimum relative humidity of 50% to 60%. The maximum average relative humidity is always over 90%. Its temperature and relative humidity vary slightly throughout the year; the average mean temperatures and relative humidity are 27°C to 28.6°C and 70% to 80% respectively, with temperature amplitudes of 7°C to 9°C. The annual precipitation is about 500 mm and its daily global radiation is over 5 KWh/m²/Day. Such a climate presents a serious challenge for passive cooling. Experiments were conducted to measure the performance in Maracaibo of two passive cooling systems in test cells with roof ponds. One system uses nocturnal radiation and evaporation and the other system uses only nocturnal radiation as a cooling source. Based on the experimental data, formulas were developed that predict the indoor maximum, average and minimum temperatures of the test cells cooled by the two systems. These experiments have demonstrated that even in the climate of Maracaibo there is a potential for passive cooling, at least of single storey buildings that have a roof structure that can accommodate a roof pond.

Conference Topic: 2 Design strategies and tools
Keywords: Passive cooling, temperature prediction, hot humid climate

INTRODUCTION

The study of Passive Cooling systems (PCS) started in Maracaibo in1978, after a visit of B. Givoni as invited professor at the School of Architecture of the University of the Zulia, resulting a line of investigation on natural cooling of buildings. The nocturnal radiative cooling was the first strategy to evaluate in this climate, theoretically, very far from the ideal conditions for an efficient operation.

After some years of experimental research, using small test cells [1], E. González [2] prepared an experimental platform to study PCS on a real scale. He conducted extensive monitoring program in 1996 and 1997 of systems based on evaporative cooling, nocturnal radiative cooling and combined radiative and evaporative cooling. These experiments were carried to characterize the thermal performance and to determine the Mean Cooling Potential (MCP) of each system under the hot and humid climatic conditions of Maracaibo. The higher MCP values, of the two systems presented in this paper, ranging between 21.3 and 27.8 W/m², were observed in Radiative/Evaporative system in the January series. These values represent daily averages of removed energy from 510 to 667 Wh/m²d. In the August series of the same system the MCP values were between 14.7 W/m² and 22.9 W/m², with an average value of 19.2 W/m². These differences showed the effect of climatic conditions. A significant reduction of MCP with respect to that of the previous cases was observed in Radiant cooling system, where the MCP was of 16 W/m², with values between 14.7 W/m² and 17.2 W/m².

A way to generalize the results is by numeric simulation of the systems under different climatic conditions, once validated the models [3]. This procedure has among one of its limitations requiring very detailed information of the dimensions and characteristic of components and construction materials.

Another way to generalize results is developing equations, to predict the indoor temperatures, based on measured data obtained in the monitored systems. It was demonstrated by Givoni [4] that the characteristic temperatures of a building (Tmax, Tagv and Tmin) can be calculated based only on the outdoors averages temperatures. Givoni has developed formulas to predict the internal temperatures in unoccupied buildings [4] and also in occupied buildings [5] [6]. In those studies buildings were naturally ventilated.

In this paper the results of application of this methodology to develop predictive equations for buildings with two different PCS in Maracaibo, are presented.
2. THE EXPERIMENTAL SETUP

2.1 Experimental platform and test cells

This study is based on measurements carried out in an experimental platform composed of two test cells designed to evaluate the thermal performance of passive cooling systems (Fig. 1). The test cells are theoretically identical. Only the roof is different. Both have an interior surface of 9 m² (3m x 3m) and a height of 2.45 m. They have features typical of a local construction. Their structure, in reinforced concrete (beams, columns and flooring), and their partitions in hollow bricks of 0.15 cm. of thickness, covered of mortar of sand and cement on the two faces, represent the traditional building characteristics. The cells constructive plans and thermo-physical properties of materials are described in [2]. The global transmittance (UAg) of the reference cell was experimentally determined and his value is 73.6 W/K.

![Figure 1: Experimental and Reference test cells.](image)

The cells access is made of double door to limits infiltration and reduces heat gain by conduction. The cells also have two windows, one on the north facade and the other one on the south facade. These windows of aluminium and glass were closed and covered by panels of polystyrene of 10 cm of thickness, during the periods of tests.

The test cells are built directly on soil. In this way they are in the same conditions that the traditional dwellings. This condition represents a continuous heat gain by conduction through the floor because the soil temperature is higher than that of the experimental cell indoor air. The temperature of the soil was measured to 1 meter deep.

2.2 Roofs of the reference and experimental cells.

The roof of the reference cell was conceived like an insulating element; its objective being to limit the heat transfer through the roof. This roof is composed of layers of: 1.2 cm of fibrocement, 25 cm of polystyrene, 5 cm of mortar and 0.3 cm of asphaltic coat with a very reflective outside surface (painted in white colour). This conditions guarantee negligible fluxes of energy through the roof (UA = 1.24W/K).

The roof of the experimental cell is a water pond made of galvanized metallic sheet of 1.2 mm thick, covered with two polystyrene folding panels, covered with fibre glass and painted white. A 0.25 m airspace separate the water surface from the insulating panels. Description of the experimental roof pond for each PCS is presented in section 3.

3. DESCRIPTIONS OF THE PASSIVE COOLING SYSTEMS AND MONITORING CONDITIONS.

During the monitored series the reference cell preserve the same physical and operative features which have already been described in section 2; it has never been modified. It constitutes an invariable reference point in relation to temperatures of the experimental cell. The experimental cell also preserved the same physical and operative features in each case. Only some roof pond characteristics are changed to accommodate to particular objectives of the studied PCS.

3.1 Radiative/Evaporative Passive Cooling System

In this system the roof is constituted of a full metallic pond filled with water until a height of 10 cm. (± 961 lts). The pond is protected during the day with two folding insulating panels (3.2 m x 1.6 m x 0.05m) of polystyrene recovered with fibre glass and painted of white colour. Panels are fixed to a metallic structure on which are arranged four pulleys and two counterweights to facilitate the operation of opening and closing. The free water surface in the pond is exposed during the night by opening (19:00 h) the roof to the sky and closing (07:00 h) it during the day. Water is in direct contact with air over it and with the metallic sheet of the container to its bottom part. The water in the pond is cooled by radiation during the night and by evaporation all day long. Heat gain in the water is reduced by isolating from solar radiation and natural ventilation during the day.

The Radiative/Evaporative system has been monitored during two extreme climatic conditions. A first set of measurements was carry out during the month of August (13 to 28) 1996; local period characterized by high temperature and humidity, weak wind speeds, partly to fully overcast sky and medium rainfall. The second set of measurements was made during the month of January (14 to 27) 1997; it is necessary to underline that the month of January corresponds to one of the three months of lower temperature and relative humidity of the year, with clear sky, trade winds and without rainfall. Figures 2 and 3 shows the outdoor, indoor reference cell and indoor experimental cell temperatures evolution of four days of each monitored period.
surface. The evaporation was eliminated by putting over the water a fine polyethylene film. In that way the water roof pond is cooled only by long wave radiation at night, where the pond is open. The roof remains closed between 07:00 h to 19:00 h. The roof pond has been filled up to 15 cm as in the first system.

The Radiant system was monitored during a period of 10 days from March 23 to April 1, 1997. Figure 4 show the outdoor, indoor reference cell and indoor experimental cell temperatures evolution of four days of this experimental series.

4. MATHEMATICAL MODELING OF THE COOLING SYSTEMS

4.1 Procedure of Development of the Formulas

In developing formulas for predicting the indoor daily maximum, average, and minimum temperatures of the test cells, the first issue, with respect to each one of these indoor parameters, is to find out what parameter of the outdoor climate could best serve as a basis for prediction. This means analysis of the patterns of the relationship between the daily outdoor maximum, average and minimum temperatures, as a set, and the indoor temperature parameter of interest. This analysis can be performed visually by plotting the indoor parameter of interest over the background of the outdoor daily maximum, average and minimum temperatures. Once this pattern is observed it is a relatively simple matter to express it in a formula.

The indoor parameter of interest, e.g. the maximum temperature, is plotted over the background of the climate data, so that the fine details of the relationship between it and the various climate parameters could be observed. This procedure is illustrated in the stages of development of the indoor maximum temperature of the experimental test cell cooled by nocturnal radiation (Fig. 5).

The formulas for the indoor maximum, average and minimum of the experimental cell will be discussed first, for the two passive cooling systems: radiant cooling and combined radiant/evaporative cooling. The formulas for the reference cell will be discussed later.

4.2 Radiant Cooling

Figure 5 shows the indoor maximum of the experimental cell with radiant cooling, with the background of the outdoor maximum, average and minimum temperatures.

During the two monitored series the experimental and reference cells remains closed all the time. The windows were protected and closed by sheets of polystyrene of 10 cm. of thickness, adjusted very strongly in front of the windows, in order to eliminate the direct flux of solar radiation inside the cells and to reduce air infiltration.

3.2 Radiative Passive Cooling System

In this case the roof pond configuration is the same as in the previous case but with a "dry" water
Consequently, the formula for the indoor maximum was developed on the basis of the outdoor average.

Close inspection of the relationship between the indoor maximum and the outdoor average in figure 5 shows that the average elevation of the indoor maximum above the outdoor average is 1.8 K. It can also be observed that the daily changes in the indoor maximum are smaller than the daily changes in the outdoor average. To quantify this relationship the daily changes in the indoor maximum were expressed as a function of the daily changes of the outdoor average; as can be seen in figure 6.

\[
y = 0.5204x + 2E-16
\]

\[R^2 = 0.6334\]

The regression line has a slope of 0.5204. Consequently, the initial formula predicting the indoor maximum of the test cell cooled by nocturnal radiation, \(T_{\text{inMax}}\), is:

\[T_{\text{inMax}} = GT_{\text{avg}} + 1.8 + 0.5204(T_{\text{avg}} - GT_{\text{avg}})\]

The correlation coefficient with the initial formula was 0.7959.

4.3 Effect of Cloudiness

With nocturnal radiant cooling it can be assumed that heat loss would increase as the sky, during the night time, is clearer. However, no data on the sky cloudiness was available.

Generally, with clearer sky the temperature drop, from the previous day's maximum to the following minimum, is larger. Therefore, this temperature drop was used as a proxy for night cloudiness.

The differences between the measured and the computed (by the initial formula) indoor maximums (Deviations) were expressed as a function of the night temperature drop, \(TD\), as is seen in figure 7.

\[\text{Deviations} = 1.1 - 0.1847*TD\]

This expression is added to the initial formula to give:

\[T_{\text{inMax}} = GT_{\text{avg}} + 1.8 + 0.5204(T_{\text{avg}} - GT_{\text{avg}}) + (1.1 - 0.1847*TD)\]

The correlation coefficient with the final formula was 0.8867. The largest difference between the measured and the computed maximums is -0.2 K, and the average difference is 0.08 K.

Figure 8 shows the measured and the computed indoor maximum temperatures over the background of the outdoor maximums and minimums.
4.4 Indoor Average and Minimum Temperature

The development of the formulas for the indoor average and minimum temperatures had followed the same procedure of the maximum. The effects of the rate of daily changes in the outdoor temperatures and the effect of the nocturnal temperature drop were tested following the same procedure.

The formula for the average indoor temperature is:

\[ T_{\text{inAvg}} = G_T^{\text{avg}} + 0.2 + 0.2741 \times (T_{\text{avg}} - G_T^{\text{avg}}) + (1.2 - 0.2103 \times TD). \]

With correlation coefficient of 0.7058.

The formula for the minimum indoor temperature is:

\[ T_{\text{inMin}} = G_T^{\text{min}} + 1.3 + 0.4406 \times (T_{\text{min}} - G_T^{\text{min}}) + (0.85 - 0.1395 \times TD). \]

With correlation coefficient of 0.8593.

Figure 9 shows the measured and the computed indoor maximum, average and minimum temperatures, of the cell cooled by nocturnal radiation, over the background of the outdoor maximum and minimum.

4.5 Radiant/Evaporative Nocturnal Cooling

As mentioned, combined Radiative/evaporative cooling was tested in two series: August 1996 and January 1997. The analysis procedure will be described in developing the formula for the indoor maximum.

Figure 10 shows the indoor maximum of the experimental cell with the background of the outdoor maximum, average and minimum temperatures. It can be seen that also in this case the pattern of the indoor maximum follows, with the following modifications, that of the outdoor average.

In August the outdoor temperature, \( G_T^{\text{avg}} = 29.5 \), was higher than in January, 27.5. The average elevation of the indoor maximum above the outdoor average was 1 K in August and 0.7 K in January. In other studies (Givoni and Vecchia, 2001 [5]) it was demonstrated that this elevation is affected by the average season's temperature, \( G_T^{\text{avg}} \).

The relationship between \( G_T^{\text{avg}} \) and the indoor maximum, \( \Delta T \), elevation in the present study could be expressed as:

\[ \Delta T = 0.1453 \times G_T^{\text{avg}} - 3.3. \]

It can also be observed in figure 9 that the rate of daily changes in the indoor maximum are slightly higher than the daily changes in the outdoor average.

These two observations have resulted in the following formula, with a correlation coefficient of 0.9363.

\[ T_{\text{inMax}} = G_T^{\text{avg}} + (0.1453 \times G_T^{\text{avg}} - 3.3) + 1.0856 \times (T_{\text{avg}} - G_T^{\text{avg}}). \]

4.6 Effect of Humidity Ratio

As the cooling process in these series occurs partly by evaporation it was of interest to check the effect of the humidity ratio on the elevation of the indoor maximum above the outdoor average. The relationship between these parameters is shown in figure 11.

Although some elevation of the indoor temperature occurs with higher humidity ratio the R2 value is very small (0.066). Thus the direct effect seems to be insignificant.

\[ y = 0.0679x - 0.3563 \]

\[ R^2 = 0.066 \]

Figure 11: Humidity ratio and indoor maximum elevation above outdoor average.

Figure 12 shows the measured and the computed indoor maximum temperatures over the background of the outdoor maximums and minimums.

An additional check of the effect of the humidity ratio, after development of the above formula, was performed.

The residual effect of the humidity ratio is its effect on the differences between the measured and the computed indoor maximums (by the above formula).
This effect is shown in figure 13. No such effect was evident from the data.

Figure 12: Measured and the computed indoor maximum temperatures with Radiant/Evaporative cooling.

Figure 13: Residual effect of Humidity Ratio.

Thus, it seems from the experimental data that the humidity ratio didn’t have a significant effect on the performance of the radiant/evaporative cooling system.

Following the same procedure, formulas were developed also for the indoor average and the indoor minimum temperatures:

For the indoor average:
\[ T_{inAvg} = T_{avg} - (4.4 - 0.1322 \times T_{avg}) - 0.2985 \times (T_{avg} - T_{GTavg}) \]

For the indoor minimum:
\[ T_{inMin} = T_{min} + (1.3026 \times T_{min} - 31.9) - 0.5706 \times (T_{min} - T_{GTmin}) \]

Figure 14 shows the indoor average and minimum of the experimental cell with Radiant/Evaporative cooling, with the background of the outdoor maximum and minimum temperatures.

Figure 14: Measured and computed indoor average and minimum temperatures with Radiant/Evaporative cooling.

CONCLUSION

The experiments discussed in this paper have demonstrated that even under the very humid climate of Maracaibo there is a potential for passive cooling of buildings.

REFERENCES