International Journal of Renewable Energy Technology Research
Vol. 2, No. 6, June 2013, PP: 170 -180, ISSN: 2325-3924 (Online)
Available online at www.ijretr.org

Research article

Full scale experimental studies of a passive cooling roof in hot arid areas

H. Bencheikh[1]

[1] Laboratoire de genie civil Amar telidji university Laghouat Algeria

+213 663369396 +213 29920067

E-mail: h.bencheikh@mail.lagh-univ.dz

Abstract

A full scale Evapo-reflective roof for Arid climates have been developed. The proposed roof design is composed of a concrete ceiling over which lies a bed of rocks in a water pool. Over this bed is an air gap separated from the external environment by an aluminum plate. The upper surface of this plate is painted with a white titanium-based pigment to increase reflection of a radiation to a maximum during the day. At night, the temperature of the aluminum sheet falls below the temperature of the rock bed mixed with water. Water vapor inside the roof condenses and falls by gravity. This heat pipe effect carries heat outwards and cold inwards. Heat exchange is improved by radiation between two humid internal surfaces. The efficiency of this cooling system is studied using finite difference method. Numerical calculations performed for different external temperatures and solar radiation show that the cooling produced by such a system is significant. As a result of this, the mean air temperature in the room may be kept a few degrees above the minimum nocturnal outdoor temperature throughout the day. However, the maximum indoor air temperature was observed at sunset. This could further be lowered by allowing ventilation of the building in the evening.

A full scale experimental study of passive cooling roof was carried out for a typical summer day of June for Laghouat in Algeria. The proposed roof design is composed of a concrete ceiling over which lies a bed of rocks in a water pool. Over this bed is an air gap separated from the external environment by an aluminum plate. The upper surface of this plate is painted with a white titanium-based pigment to increase the radiation reflection process during daytime. Several passive modifications have been introduced to the roof in order to reduce indoor air temperature in hot climates. An experimental investigation, employing passive procedure, has been carried out to study the possibility of reducing air temperature in buildings. The results show that the air temperature can decrease with a range from 6 to 10°K. This decrease can further be lowered by 2 to 3°C if night natural ventilation of buildings is allowed.

Keywords: Evaporative cooling, Evapo-reflective roof, hot dry climate, Night ventilation, dynamic model

---

Introduction

In hot climates such as southern Algeria, excessive heat is the major problem that causes human thermal discomfort. Space cooling is therefore the most desirable factor for the inhabitants. Various examples of dwellings responsive to climatic constraints were found in vernacular architecture throughout the world. Compact cellular layout with minimum external surface exposure to the sun, whitewash surfaces to reduce absorptivity, blind external facades, courtyards, vegetation to provide humidity and shade, heavy buildings with high thermal capacity materials are common passive features in most hot arid climates such M'Zab settlements in southern Algeria, Egypt and Iran [1-4]. Wind towers for cooling ventilation are well known in Iranian and Middle East architecture, which along with cooling of the air by water evaporation kept the building comfortable in hot periods [5]. Underground Buildings have the advantage of large thermal capacity storage of the earth. They are used in Matmata in Tunisia and Cappadocia in central Turkey [2].

In recent years several investigations were performed and showed that there can be multiple solutions to the excessive heat problem. Popular is cooling ventilation using a solar chimney [2, 6, 7]. The results showed that cooling ventilation using a solar chimney can reduce internal temperatures of buildings. Shading devices (overhangs and verandas) to reduce summer solar radiation are also investigated and useful depths of these shading elements for various orientations in continental climates were defined [8].

Space cooling can also be achieved by improving of the performance of roofs. This is because the roofs are the most exposed surfaces to direct solar radiation and can cause excessive heat gain in hot periods.

Some efforts were made by investigators to improve the roof thermal performance. The use of low emissive material in the attic of a roof reduced the underside ceiling surface temperature which lowered the room air temperature [9]. Evaporative cooling approach for passive cooling of buildings in hot arid climates has also become an attractive subject of investigation for many researchers. The relative advantage of evaporative cooling in relation to many other approaches (cavity wall, insulation, white wash and large exposure orientations, vegetable pergola shading, roof with removable canvas, water film , soil humid grass and roof with white pots cover) were demonstrated by [10, 11].

The reduction of heat gain through the roofs using evaporative cooling systems was extensively investigated on open roof pond [18, 19], on water spraying over the roof, moving water layer over the roof, thin water film and roofs with wetted gunny bags [12-17]. Chandra and Chandra [12] have developed a periodic heat transfer model to study the effects of evaporative cooling using water spray and variable ventilation on the temperature control of a non-air-conditioned building. The influence of evaporative cooling over the roof as compared to bare roof case and intermittent ventilation as compared to the continuous or no-ventilation case have been assessed for controlling the indoor air temperature. It was found that the effectiveness of the evaporative cooling can be improved by conscious choice of the rate and duration controls the inside air temperature significantly. It was concluded that a combination of evaporative cooling and variable ventilation can make the internal environment of a building more comfortable. Chandra et al. [13] presented a theoretical assessment of three roof cooling systems for a non air conditioned building, and showed that the maximum cooling is achieved by water spray over the roof. But the roof pond system with stationary water is more effective in stabilizing the fluctuations of indoor temperature.

The present study suggests an improved roof design by combining the advantages of previous described cooling techniques (water ponds, low emissive surfaces) and inserted rocks of high thermal capacity materials. The resulting design can be more advantageous and effective than other systems for reducing heat during daytime and storing coolness at night. High thermal capacity materials (rocks bed) will delay the entry of daytime heat into the building by such a period that it reached the interior during the evening when it is least bothersome or often welcome. The roof is composed of a concrete ceiling and a flat aluminum plate separated with air space partially filled with rocks inserted in small quantity of water. The system is closed to prevent water vapor skipping outside. A schematic diagram of the model design is shown in figure 1.

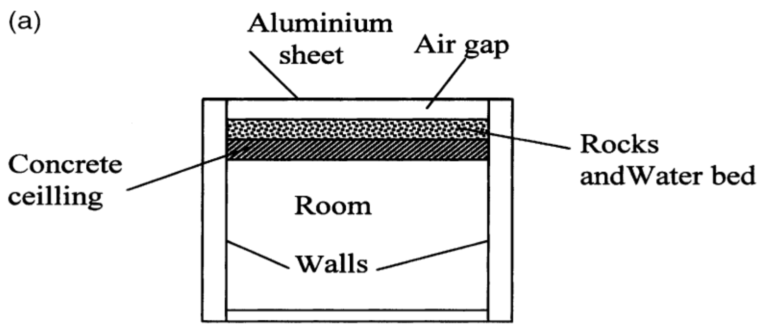

Figure 1: (a) Room with cooling roof system

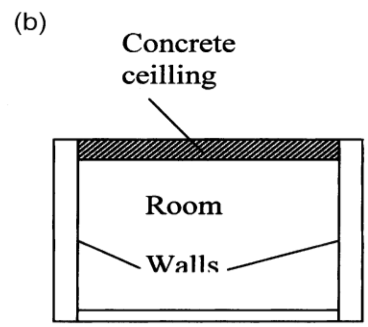

Figure 2: (b) Room without cooling roof syste

Table1. Material properties

Material	Density Kg/m^3	Specific heat (j/kg °k)	Conductivity (w/m°k)
Concrete slab	2400	1080	1.8
Rocks	2600	800	2.3
Water	1000	4175	0.613
Aluminum	1.22	1008	0.026
Concrete slab	2750	936	204

2. Mathematical model

The basic configuration of the model considered here are shown in figure 1. It is a cubic room with 3m high and 3m wide. South wall is provided with a window and the North one is provided with a door. Physical properties of materials used for the roof are presented in table 1.

The purpose of the present mathematical model is to determine the inside air temperature at each time step as a function of outside air temperature, solar radiation and heat due to ventilation. The solution is based on the inside heat balance at each time step, the method of lagging with zone capacitance uses information from previous time steps to predict system response and update the zone temperature at the current time. 15 minutes is used as a time step (the shorter the time step the smaller the error). The simulation was done for the described model for two highest temperature summer days. The model situated in Algeria (Laghouat, latitude +33.46°, longitude +2.56° and elevation 767 m). The simulated day was the 26 of July, the maximum and the minimum temperature were respectively 42.7°, 24.5°.

2.1 Inside air heat balance equation

The heat balance for the inside room air may be formulated as follows:

$$C_{ai}\frac{dT_{ai}}{dt} = Q_{\text{int}} + Q_{ci} + Q_{v} \qquad (1)$$

$C_{ai}\frac{dT_{ai}}{dt} =$: The heat stored in the inside air $C_{ai} = m_{ai}.c_{ai}$

Q_{int} : Heat exchange by convection in the inside;

$$Q_{\text{int}} = \sum_{i=1}^{i=n} Q_{\text{int}\,i} \text{ (w)}$$

Q_{ci} : Heat exchange by convection between aid and other surfaces

$$Q_{ci} = \sum_{i=1}^{i=n} h_i A_i (T_{si} - T_{ai}) \text{ (w)} \qquad (2)$$

Q_v : Heat exchange by ventilations and infiltration

$$Q_v = m_{ae}.c_{ae}.(T_{ae} - T_{ai}) \quad \text{(w)} \qquad (3)$$

The derivative term $\frac{dT_{ai}}{dt}$ can be expressed by finite differences approximations as follow;

$$\frac{dT_{ai}}{dt} = (T_{ai}^{t} - T_{ai}^{t-\partial t})\frac{1}{\partial t} \qquad (4)$$

From the above equations the inside air temperature;

$$T_{ai}^{t} = \frac{\sum Q_i^t + \left[\frac{C_{ai}}{\partial t}T_{ai} + \sum A_i h_i T_{si} + m_{ae}c_{ae}T_{ae}\right]^{t-\partial t}}{\frac{C_{ai}}{\partial t} + \left[\sum A_i h_i + m_{ae}c_{ae}\right]} \qquad (5)$$

2.2 Surface temperatures

To calculate the internal surface temperatures T_{si}^{t}, , at each time step t, as function of outside conditions, finite deference equations based on heat balance at each node were used, which allows for temperature determination at any point of interest. The first step is to select these points, by subdividing the medium into a number of small regions represented by reference points called nodes. In our case, we considered the heat flow in one direction in plan elements (walls, roof and floor) composed of deferent materials, so each layer of these material is divided into small regions and represented by nodes. Clarke suggested that three nodes per homogeneous element and a 1 h time step, in building applications are consistent with acceptable accuracy [20]. The temperature for each single node at time t is evaluated using heat balance equations.

The heat exchange between internal slab nodes is modeled using Fourier's one dimensional heat conduction equation [21]

$$\frac{dT}{dt} = \frac{d\lambda}{\rho c}\frac{d^2T}{dx^2} \quad (6)$$

This equation can be solved numerically [21] by dividing the element into layers of thickness dx called nodes, making a heat balance for each node. The boundary condition for the inside surface nodes in contact with room air may be given by:

$$\frac{\lambda \partial T_{si}}{\partial x} = h_i(T_{si} - T_{ai}) \quad (7)$$

The boundary condition for the outside surface nodes in contact with outside air may be formulated using the following equation:

$$\frac{\lambda \partial T_{se}}{\partial x} = h_e(T_{se} - T_{ao}) \quad (8)$$

The upper roof surface exchanges heat with the outside air by convection and by radiation to the sky. According to [23], a horizontal surface with emissivity ε_r and absolute temperature Tr, produces a net radiative cooling rate Qr, where;

$$Q_r = A\sigma\varepsilon_r\left(T_r^4 - T_{sky}^4\right) \quad (9)$$

Where

$$T_{sky} = \varepsilon_{sky}^{1/4} T_{ae}, \ \varepsilon_{sky} = 0.741 + 0.0062 T_{dp}$$

σ is the Stefan–Boltzman constant

Tdp is the surface dew point temperature in ° C. It was computed as a function of the ambient temperature (Tae) and the relative humidity (RH), using the expression by Murray [24]:

$$T_{dp} = 237.3\frac{\ln RH + a \cdot b}{(a - \ln RH) + a \cdot b} \quad (10)$$

The heat exchange by convection for outside horizontal surface is given by:

$$Q_c = Ah_{ce}(T_r - T_{ae}) \quad (11)$$

The heat exchange between the lower aluminum surface and the upper rock bed surface is by radiation, convection and evaporation. Following equations reported in [25], we may write the following.

Heat exchange by radiation is given by:

$$Q_r = Ah_r E_{wr,al}(T_{wr} - T_{al}) \quad (12)$$

Heat exchange by convection is given by:

$$Q_c = Ah_{c,wr,al}(T_{wr} - T_{al}) \quad (13)$$

Heat exchange by evaporation and condensation is given by:

(14)

$$Q_{evp} = 6.3 \times 10^{-3}[P_{vs}(T_{wr}) - P_{vs}(T_{al})] \cdot L \cdot h_{c,wr,al}$$

Where L is the latent heat of evaporation at an average temperature, which is equal to 2350 kJ/kg and Pvs is the saturated vapor pressure in kPa at temperature T in °C. For the temperature range

$$20 \leq T \leq 80\ ^{\circ}\mathrm{C}$$

The following polynomial gives acceptable results [25]:

$$P_{vs}(T) = -16.037 + 1.8974T - 0.0699T^2 + 0.0012T^3 - 5.8511 \times 10^{-6}\ T^4 \tag{15}$$

In modeling the floor elements the earth temperature at 60 cm of depth below the floor is considered constant and equal to the daily average temperature of the region [2]. In the above equations the number of the unknowns is greater than the number of equations; these equations were solved by proposing the initial inside air temperature at start time t. This initial temperature Tai (t) will not be correct and it is necessary to simulate the model with the same daily repetition of air temperature and solar radiation until the temperature of each node returns to the same value at the same time in each day simulation. At this point the building is in thermal harmony with the environment.

3. Experimental measurements

The experimental set-up consisted of two identical test cells (A) and (B), a cubic room with 3m high and 3m wide. South wall is provided with a window and the North one is provided with a door. The experimental cell (B) was the basic reference unit. The roof was constructed of simple aluminum sheet painted white.

4. Temperature measurements

Air temperatures outside the room were measured using weather stations installed near the laboratory, far from the test cell by 150m. The temperature at different positions under the roof level has been measured by copper constant thermocouples connected to digital thermometer. Thermocouples fixed under the roof surface the end of the thermocouples were enveloped in thin aluminum paper to reflect the radiation from the surrounding interior surfaces.The readings of all thermocouples have been averaged to give the average temperature.

5. Results and discussion

Figures 3 shows the calculated and measured inside and outside air temperature in test cell (A) with cooling system, without nocturnal natural ventilation. When the maximum outside temperature was 39 °C the maximum measured and calculated temperatures were respectively 36°C and 35°C, the minimum ones were 27°C and 29°C. The maximum inside air temperature accrued at 19.00PM when the outside one was 32°C, at this time natural ventilation was associate. Figure 4 shows the calculated and measured inside and outside air temperature in cell (A) with cooling system, with nocturnal natural ventilation. The ventilation lower the inside air temperature by 3 to 4°C.

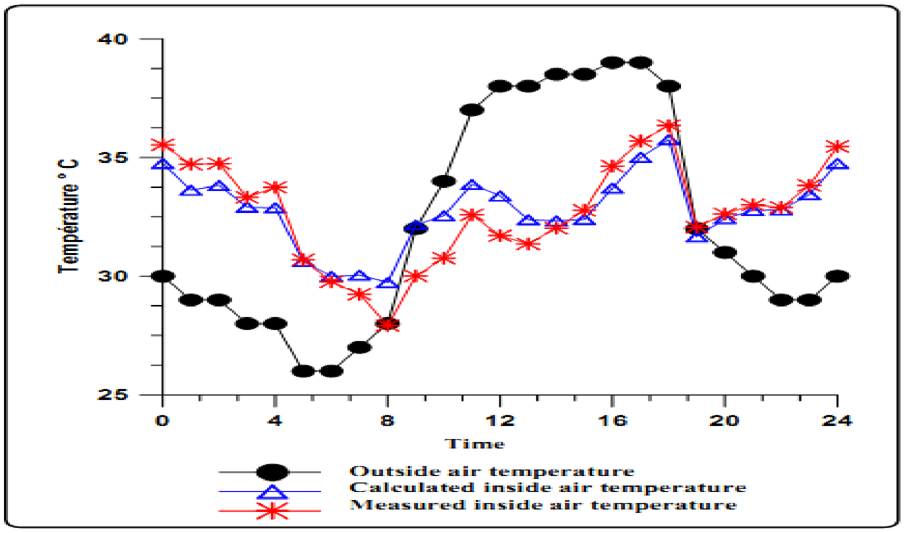

Figure 3: Calculated and measured temperature in test cell (A) without night natural ventilation

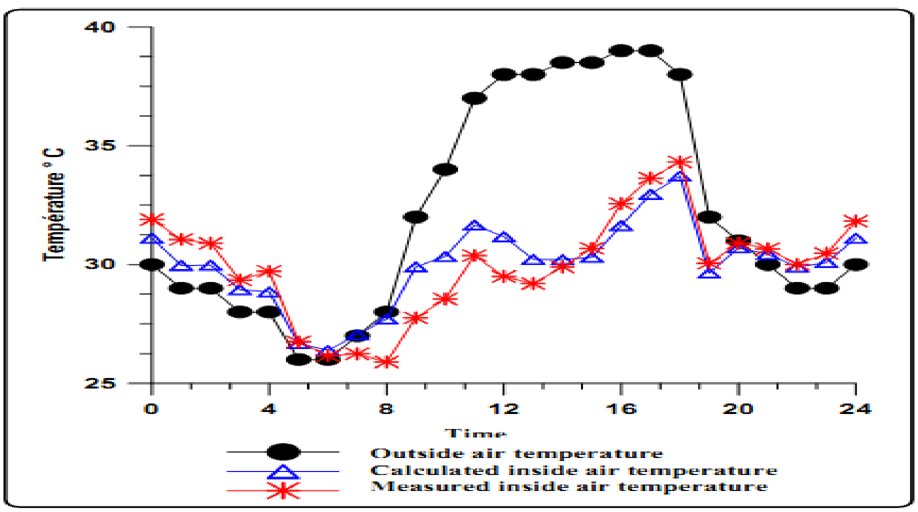

Figure 4: Calculated and measured temperature in test cell (A) with night natural ventilation

Figure 5 and 6 show the calculated and measured inside and outside air temperature in test cell (B) without cooling system, with and without nocturnal natural ventilation. The calculated and measured inside air temperature in figure 5 present no differences whoever in figure 6 the two graphs present small differences during ventilation period due to the uncertainty in wind speed which variable from hour to another.

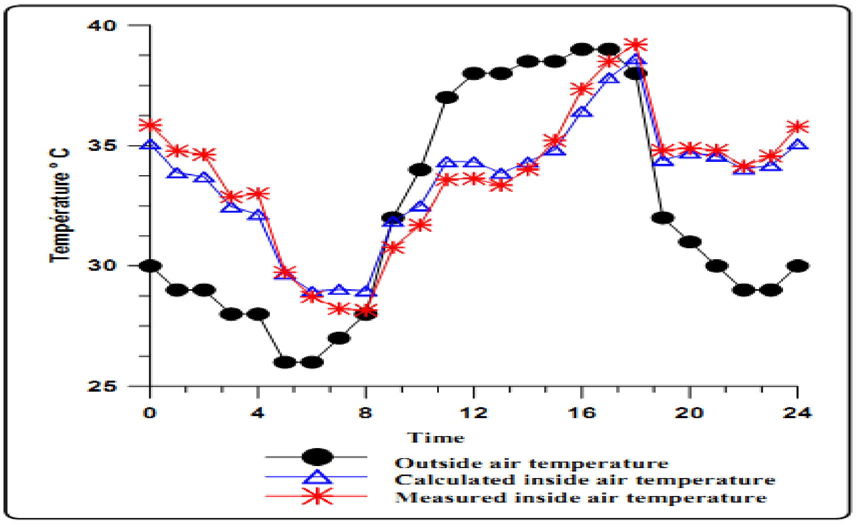

Figure 5: Calculated and measured temperature in test cell (B) without night natural ventilation

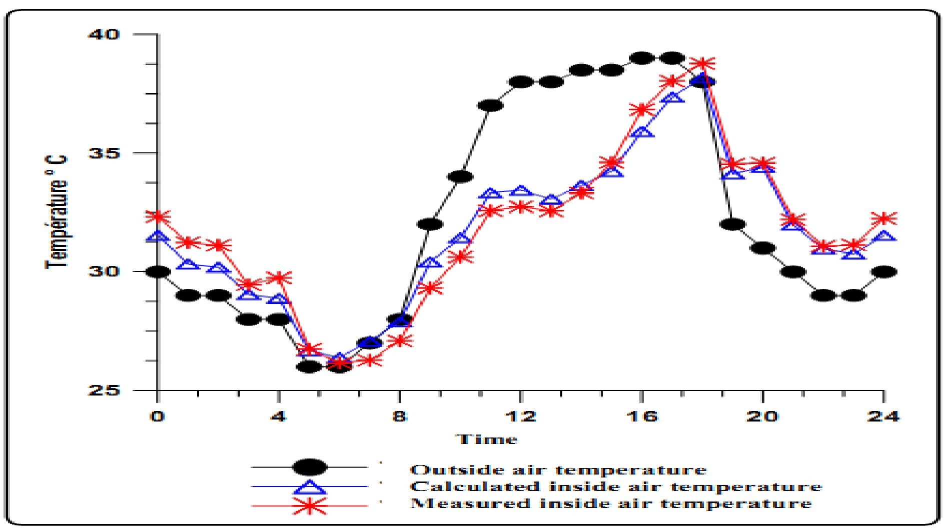

Figure 6: Calculated and measured temperature in test cell (B) with night natural ventilation

Fig.7. shows a comparison of room air temperatures with cooling roof system and with bare roof without room night natural ventilation. It can be seen from this figure that the evaporative reflective roof can reduce the internal room air temperatures during the day up to 10 °C in comparison to the air temperatures for a bare roof over the room. Fig.7. is the comparison of room air temperatures with cooling roof system and with bare roof when room night natural ventilation is allowed. The ventilation was allowed from 8 pm till 9 am, a period when the outside air temperature is relatively low. This can significantly improve cooling of room air temperatures, as shown in Fig. 8.

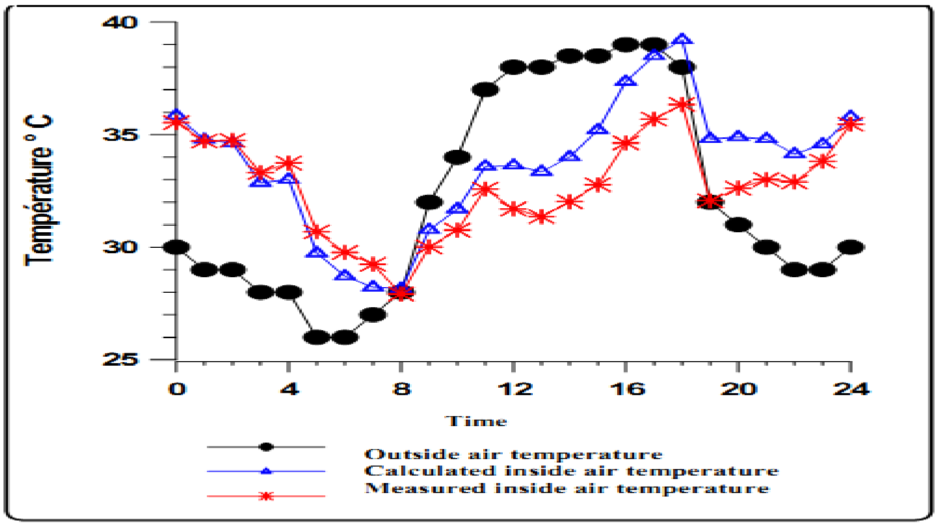

Figure 7: Comparison of room air temperatures, test cell (A) and (B) without night natural ventilation.

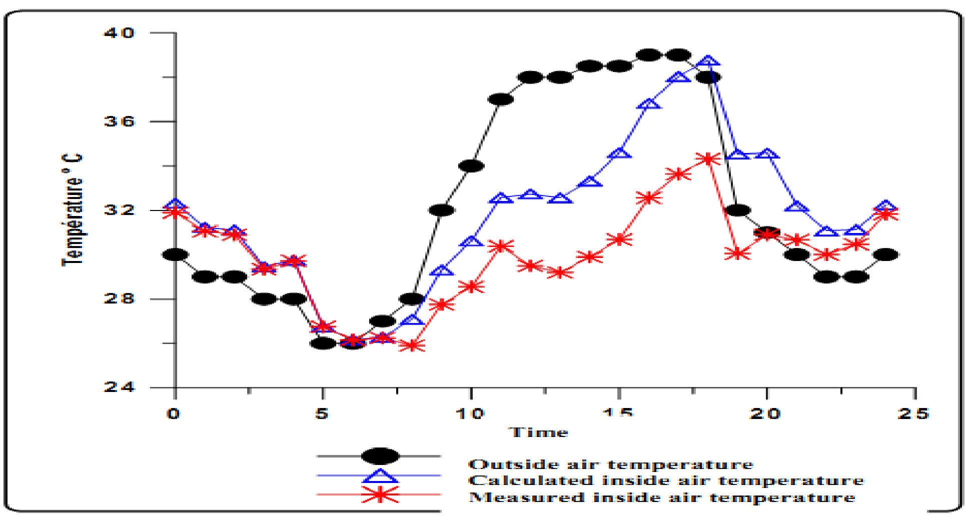

Figure 8: Comparison of room air temperatures, test cell (A) and (B) with night natural ventilation

6. Conclusion

In comparison between calculated and measured inside air temperatures in cell (B) without cooling system, without nocturnal natural ventilation, the two temperatures have almost the same values , however the calculated and measured ones in the same cell with nocturnal natural ventilation, present a small difference between calculated and measured temperatures during ventilation period as shown in figure 8, that due to wind speed variations during night time, which was in calculations usually considered constant value.

Measured and calculated temperature in cell (A) with cooling system, with and without nocturnal natural ventilation, presents a small differences in two periods time, from 6.00 Am till 1500Pm and form midnight till 4.00 Am which correspond to the evaporations and condensations periods. The differences were due to that the quantities of water vapor and condensate water were not exactly well known.

Under hot arid conditions a full scale test cell for an evaporative reflective roof used to improve space cooling in buildings has been tested. The experimental results examined the effectiveness of such a roof cooling system in comparison to a bare roof. The results showed that cooling inside buildings can be improved by the application of such a cooling design. It was also seen that combining evaporative reflective roof with night ventilation increases such cooling more significantly.

Nomenclature

C_{ai} specific heat of inside air (J kg^{-1} K^{-1})

C_{ae} specific heat of outside air (J kg^{-1} K^{-1}) E surface emissivity

I total solar radiation (W m^{-2})

I_j long wave radiation (W m^{-2})

h_{ci} inside convection heat transfer coefficient (W m^{-2} K^{-1})

h_r radiation heat transfer coefficient (W m^{-2} K^{-1})

$h_{c,wr,al}$ convection heat transfer coefficient between the rock bed and aluminum (W m^{-2} K^{-1})

P_{vs} saturated vapor pressure (kPa)

T_{al} aluminum outside surface temperature (˚C)

T_{ao} solar temperature

T_{wr} rock bed upper surface temperature (˚C)

References

[1] Bouchair A. Dupagne A. Building traditions of Mzab facing the challenges of re-shaping of its built form and society. Building and Environment, 38;1:1345–1364.

[2] Bouchair A. Solar induced ventilation in the Algerian and similar climates. PhD thesis. UK: University of Leeds; 1989.

[3] Golany G. Housing in arid lands: design and applications. London: The Architectural Press; 1980.

[4] Evans M. Housing, climate and comfort. London: The Architectural Press; 1980.

[5] Bahadori MN. Passive cooling systems in Iranian architecture. Scientific American 1978;238:144–54.

[6] Bouchair A. Solar chimney for promoting cooling ventilation in southern Algeria. Building Services Engineering Research and Technology 1994.

[7] Bouchair A, Fitzgerald D, Tinker JA. Passive solar induced ventilation. Alternative energy sources VIII. Proceedings of the Miami International Conference on Alternative Energy Sources (1987: Miami Beach, Florida). Solar energy fundamental and applications, vol. 1. New York, USA: Hemisphere Publishing Corporation; 1989.

[8] Pour-Deihimi S. Control of sunshine in buildings by fixed shading in continental climates. PhD the- sis. Leeds university; 1984.

[9] R. Lambert. Heat transfer through roofs of low cost Brazilian houses. PhD thesis. UK: University of Leeds; 1988.

[10] Verma R, Bansal NK, Garg HP. The comparative performance of different approaches to passive cooling. Building and Environment 1986;21(N2):65–9.

[11] Nayak JK, Srivastava A, Singh U, Sodha MS. The relative performance of different approaches to passive cooling of roofs. Building and Environment 1982;17(2):145–61.

[12] Chandra S, Chandra S. Temperature control in a building with evaporative cooling and variable ventilation. Solar energy 1983;30(4):381–7.

[13] Chandra S, Kaushik SC, Bansal PK. Thermal performance of a non-air-conditioned building for passive solar air-conditioning: evaluation of roof cooling systems. Energy and buildings 1985;8:51–69.

[14] Nahar NM, Sharma P, Purohit MM. Performance of different passive techniques for cooling of buildings in arid regions. Building and Environment 2003;38:109–16.

[15] Runsheng T, Etzion Y, Erell E. Experimental studies on a novel roof pond configuration for the cooling of buildings. Building and Environment 2003;28:1513–22.

[16] Sodha MS, Kharty AK, Malik MAS. Reduction of heat flux through a roof by water film. Solar Energy 1978;20:189.

[17] Sodha MS, Srivastava A, Kumar A, Tiwari GN. Heating and cooling of a building by flow of water over the roof. Applied Energy 1980;7(1):229.

[18] Sodha MS, Kumar A, Singh U, Srivastava A, Tiwari GN. Experimental validation of thermal model of open roof pond. Building and Environment 1981;16(2):93.

[19] Sodha MS, Singh U, Tiwari GN. Periodic theory of an open roof pond. Applied Energy1980;7(4):307.

[20] Clarke AJ. Energy simulation in building design. Bristol: Adam Hilger; 1985.

[21] Kreith F. Principles of heat transfer. New York: Index Educational Publishers; 1985.

[22] CIBSE guide. Vol. A. London: Chartered Institution of Building Services Engineers; 1986.

[23] Berdahl P, Fromberg R. The thermal radiance of clear skies. Solar Energy 1982;29(4):299–314.

[24] Murray FW. The computation of saturated vapour pressure. Journal of Applied Meteorology 1967;6:203–4.

[25] Sfeir AA, Guarracino G. Inge´nerie des systeme solaires applications a` l'habitat. Technique et doc- umentation; 1981.