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Experimental Investigation of Thermal Assessment of Smart Passive Cooling System

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Abstract. Energy consumption in conventional domestic housing in Oman is quite high due to cost-intensive mechanical air conditioning systems. For the climate conditions in Oman, it is expected that energy conservation using a smart passive cool roof will be valuable and significant. This paper presents the thermal assessment and energy efficiency of a novel forced convective evaporative cooling system with a radiation reflector. The results revealed that the proposed smart passive cool system can reduce the indoor air temperature of the building models, with the highest reduction in the room and roof surface temperature of 13.07ºC (36.7%) and 66.42°C (75.7%), respectively. This is due to its ability to inhibit solar radiation and dissipate heat by evaporation, forced convection due to the dynamic behaviour of air in the air ventilation between primary and secondary roofs, and nocturnal radiation. The research has conclusively demonstrated that the smart passive cool system may significantly lower the energy consumption of residential and commercial buildings.

Introduction

Residential buildings are the largest energy consumers in the Sultanate of Oman, accounting for 69.1% of total consumption in the 2018 annual electricity report [1]. The increase in energy consumption in residential buildings is principally attributable to the heavy use of air conditioning systems due to high solar radiation throughout the year. The depletion of oil supplies and falling fuel prices, resulting in an increase in electrical energy costs, necessitates a concentrated effort to reduce energy use. In such cases, green energy or passive cooling systems can significantly decrease heat leakage into buildings and lower energy consumption.

Many investigations have been undertaken to explore the effectiveness of a passive cool roof since Fracastoro et al. [2] investigated the possibility of minimizing heat gain in dwellings by employing under-roof cavities in 1997. In 2002, the French Scientific and Technical Centre for Building Research [3] took measurements on a number of experimental passive cool roofs. Evaporative cooling utilizes the effect of evaporation as the natural heat dissipater. Sensible heat inleak from surroundings has been utilized as latent heat needed to dry out the water. Nagano [4] compared the efficiency of evaporative cooling with a conventional mortar concrete roof and observed that evaporative cooling can reduce the top surface heat by 8.63°C. Erens [5] & San Jose Alonso et al.[6] observed that direct evaporative cooling produces low air conditioning expenses.

Khedari et al. [7] investigated free convection in a roof thermal panel experimentally. In 2007, Chang et al. [8] performed an experimental evaluation of the energy savings gained by adding a thermal insulation barrier in a double-skin roof. Based on a research of the thermo-fluid dynamic behaviour of the air within the ventilated roof and heat fluxes through ventilated roofs, Gagliano et al. [9] reported in 2012 that roof ventilation can significantly reduce heat fluxes (up to 50%) during the summer season. In 2001, Hirunlabh et al. [10] studied several performance characteristics as a function of solar radiation for various roof pitch degrees. Villi et al. [11] establish correlations to characterize airflow and heat transport events in the ventilation cavity. Ciampi et al. [12], and Medved [13] discovered that a ventilated roof maintains the inner shell temperature closer to ambient, minimizing the impact of solar radiation on the building. The reduction of heat in a leak into an attic through metal deck roofing in industrial buildings was studied by Ming ChianYew et.al [14]. The study reveals the effect of cavity ventilation, solar powered fans and thermal reflective coating on the thermal performance of buildings. A maximum reduction of 15ºC attic air temperature was obtained compared to a normal roof. The improved performance is because of integration of reflective coating, moving air cavity (MAC) with solar powered fans and reflection of sunlight and circulate the hot air efficiently. Jorge L. Alvarado [15], USA, used commercially available materials such as aluminium 1100 and galvanized steel as radiation reflectors; and polyurethane, polystyrene, polyethylene, and an air gap were used as insulation. Experimental results showed that the radiation reflector shape as well as the material selection of each passive cooling system led to reductions in heat conduction between 65 and 88%. Anna Laura Pisello [16], 2014, Italy, have used traditional roof brick tiles for passive cooling. Results showed that during summer the high reflection tiles are that able to decrease the average external roof surface temperature by more than 10°C and the indoor operative temperature by more than 3 °C. Several studies have been conducted in various regions in order to produce novel and energy efficient passive cool roofing [17-21].

High ambient temperature in arid regions raises the indoor and exterior temperature levels of residential and commercial structures, accelerating the use of energy-intensive and costly mechanical air-conditioning systems. The novelty of the present study is to assess and compare the thermal performance of a smart passive cool system (forced convective evaporative cooling with radiation reflector) with a conventional system. It also quantifies those advantages in terms of heat flow changes in the field.

Materials and Methods

Two symmetrical scaled laboratory test models were used to study the thermal performance of smart passive cool roof. One of them is a reference roof with aluminium sheet of thickness 2 mm that has no additional roof materials on top of it. It is used to compare the room air and roof slab temperatures. The second model is a smart passive cool system that has a roof with aluminum radiation reflector and evaporator cooling system separated by an air gap of 10 cm between them. Evaporator cooling system has cooling fans connected in series with a diaphragm pump for water circulation.

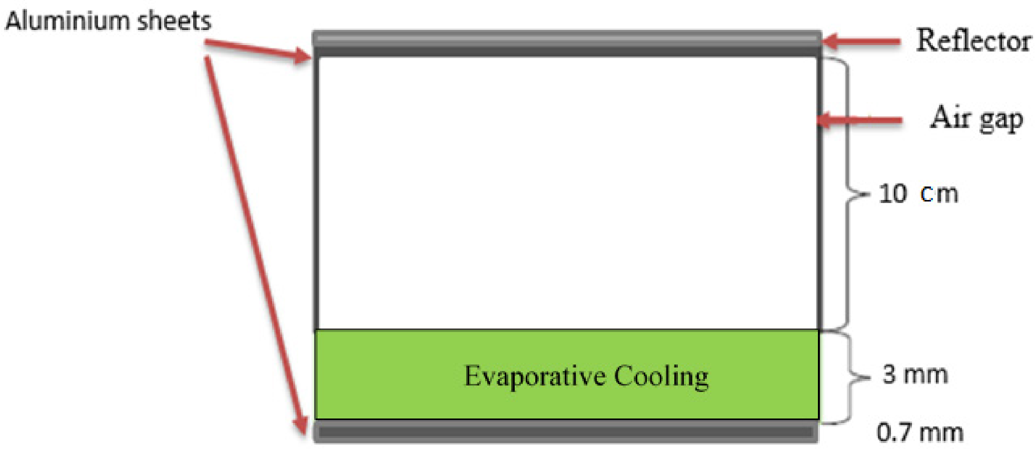
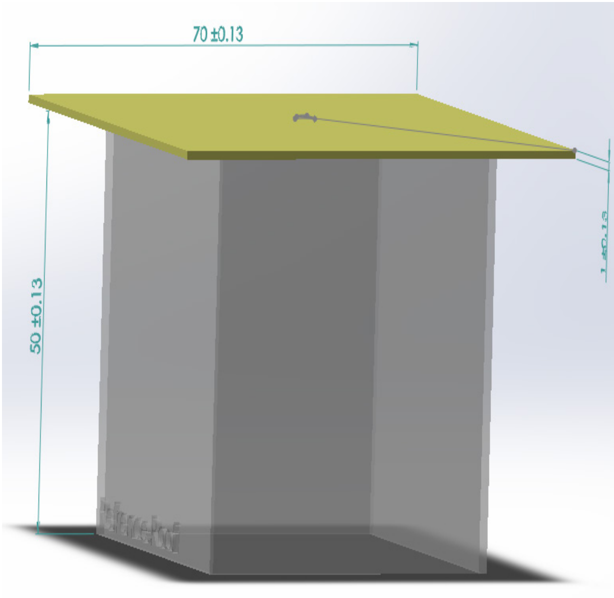


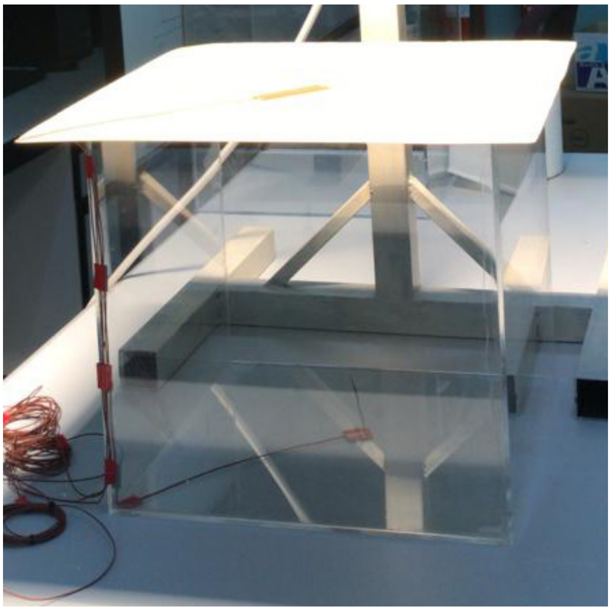
Fig.1 Schematic of the Experimental Set up

Heat Transfer Mechanisms. There are three types of heat transfer mechanisms taking place in a smart passive cool roof system as shown in Fig.1. First stage cooling is reflection of solar radiation by the external surface of aluminium reflector. In the second stage of heat transfer process, evaporative cooling with forced convection due to the dynamic flow of air in the ventilation take place. The final stage of heat in leak is conduction through the top surface of the roofing layer. The heat in leak into the smart passive cool room is effectively reduced by a combination of radiation reflector, dynamic air ventilation and evaporative cooling technique as shown in experimental set-up.

Conventional Reference system. The walls of the reference laboratory model (50 cm x 50 cm x 50 cm) was fabricated by acrylic resin thermal insulator to avoid any lateral heat conduction through the walls and to ensure that the heat transfer will take place only through the roofs as shown in Fig.2. Aluminium sheet with a thickness of 2 mm was fixed at the top of the model as roof. Thermocouples are fixed at various points to measure room air and roof surface temperatures.

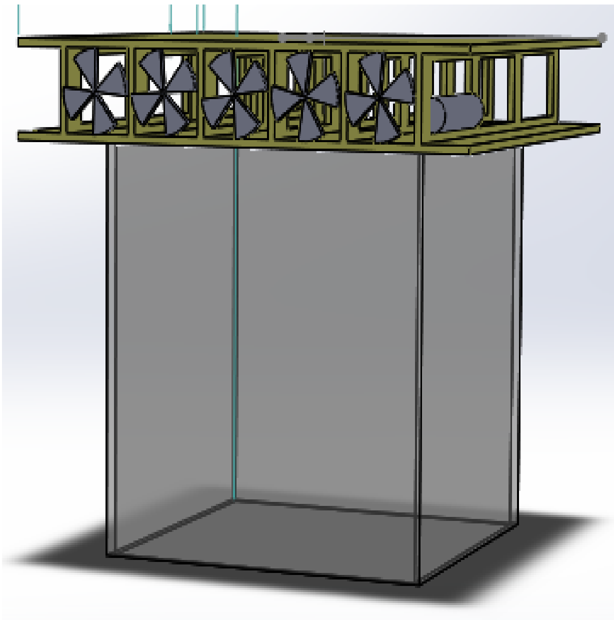


(a) Model

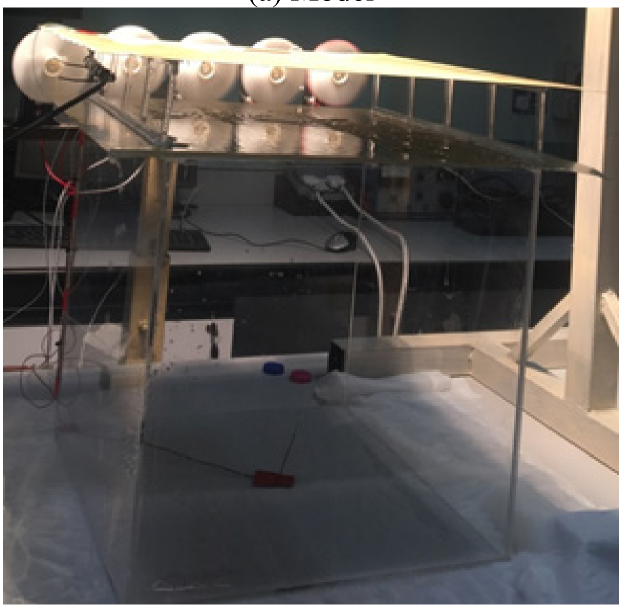


(b) Manufactured system

Fig.2 Reference roof System



(a) Model



(b) Fabricated system

Fig.3 Smart Passive cool Roof

Smart Passive Cool Roof System (Forced Convective Evaporative Cooling-Radiation Reflector Passive Cool System). In a smart passive cool system, two aluminium metal sheets with an air gap of 10 cm between them were used to enhance the convective cooling process as shown in Fig.3. Specially made channels were used to fix the metal plates with the required air ventilation. The experimental model consists of water ejectors fixed between the metallic roofs to spray water to obtain evaporative cooling. Water jets sprayed through the nozzle will absorb sensible heat load from the roof and utilize it as latent heat to get evaporated. The majority of heat from the roof will be taken away by evaporative cooling. A series of cooling fans (five) are fixed in the air ventilation (10 cm) to improve the heat transfer rate by forced convection. Presence of dynamic air in the ventilation reduces heat in leak. In addition, radiation reflector fixed on top of the system improves the cooling rate by radiation reflection. Thermocouples are fixed at various points to measure room air and roof surface temperatures.

Materials. The various layers of the passive cool model are shown in Table 1.

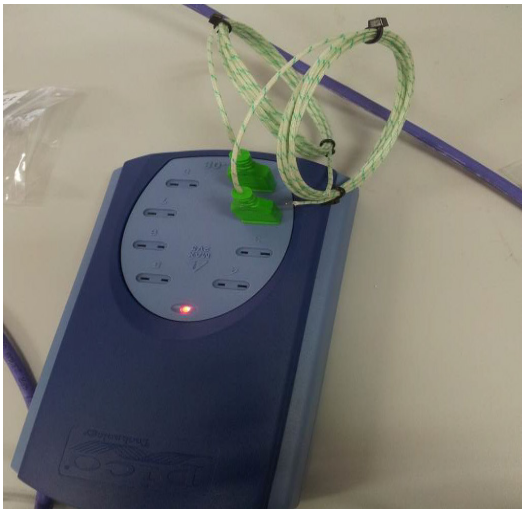
Table 1 Material Specifications

Material	Thickness (cm)	Thermal conductivity (W/ m°k)
Acrylic Resin	0.5	0.19
Aluminium radiation reflector	0.2	221
Air ventilation	10	26

Instruments. Table.2 shows the specifications of the temperature data recorder and Type T thermocouples installed (Fig.4) to measure the indoor air and the roof surface temperatures. The data were recorded every 5 minutes for 120 minutes in both the reference and passive cool system models.

Table 2. Data logger and Thermocouple specifications

Type	Type T, exposed type, PTFE insulated	Model	TC-08
Sensitivity	40 µV/°C, 1°C over the range -200°C to 400°C	Channels	Eight
Tip diameter	1.5 mm	Range of measurement	–270 to +1820 °C
Tip temperature	–75°C to +350 °C	Resolution	0.025°C



(a) Data logger

(b) Type T thermocouple

Fig.4 Instruments for measuring the temperature

Results and Discussions

Type T thermocouples fixed in the middle of the symmetrical test models were used to measure room air temperature. The sensors fixed on the interior roof surface were used to measure roof surface temperature. These sensors are connected to the temperature data logger and temperatures were recorded with a computer assisted system continuously for 120 minutes. The two halogen lamps of 1500 W were used to heat the reference and passive cool roofs artificially in the laboratory.

Thermal Performance of Conventional Reference System. The room air and interior roof surface temperature profile of reference system is shown in Fig.5. The room air temperature increased gradually from 21ºC to 30ºC in first 27 minutes and then increased slightly from 30 to 120 minutes. The interior surface temperature increased sharply in first 9 minutes from 22ºC to 78ºC and then gradually increased from 9 to 30 minutes. The indoor temperature recorded after 45, 90 and 120 minutes were 32.9ºC, 35.11ºC and 35.29ºC respectively.

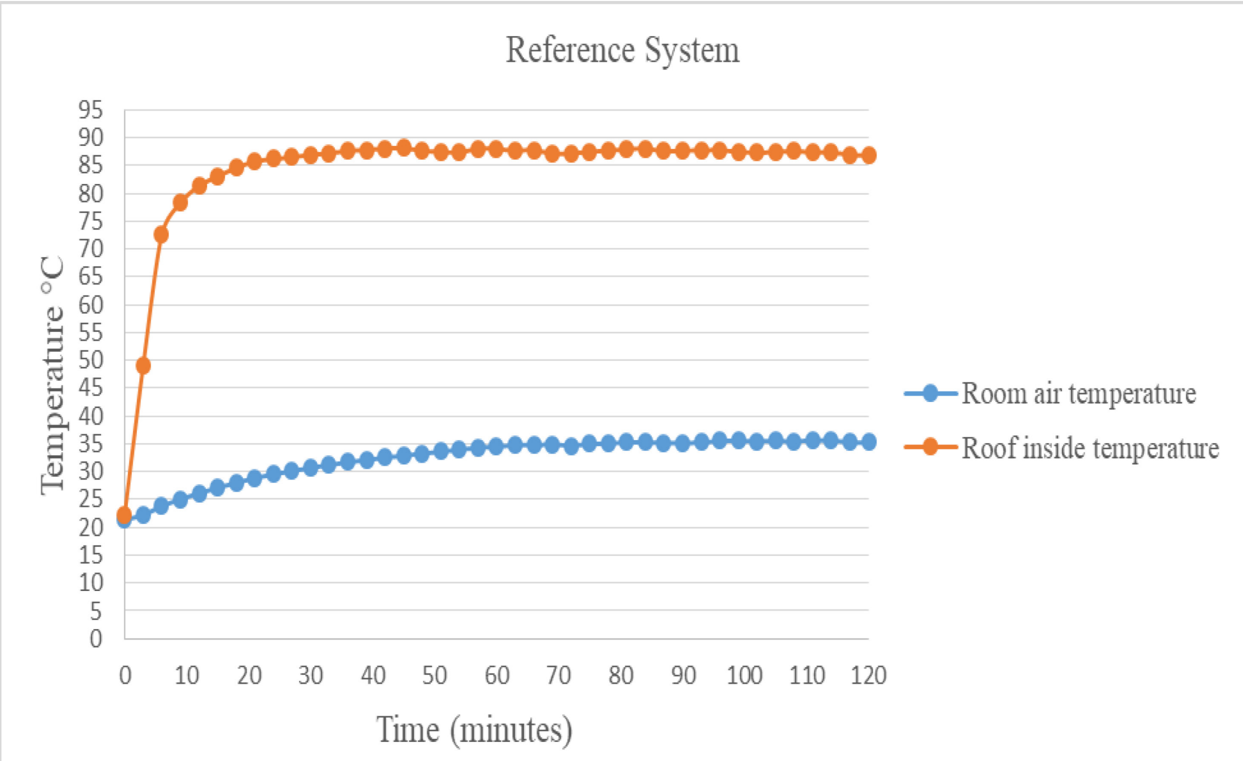


Fig.5 Temperature profile of reference roof

Thermal Performance of smart passive cool roof system. The passive cool room has significantly lower temperature peaks as shown in Fig.6. The roof surface temperature increased gradually from 22.18ºC to 42.57ºC in the first 21 minutes and raised slightly from 21 to 120 minutes. There was only a minor increase in room air temperature. The indoor air and roof surface temperature obtained after 120 minutes of operation were 22.38ºC and 41.82ºC respectively.

Comparison of Reference and Smart Passive Cool Roof Systems - Room Air Temperature. Compared to a reference room, the smart passive cool room has significantly lower temperature peaks as shown in Fig.7. The room air temperature of reference system increased steadily from 21.37ºC to 32.9ºC in the first 45 minutes and then increased slowly about 0.1 to 0.8 ºC in every 5 minutes until 120 minutes. Whereas room air temperature of the smart passive cool roof increased very slowly and marginally from 21.58 ºC to 22.81ºC in the first 45 minutes and afterwards remained almost constant from 45 to 120 minutes. It indicates that the passive cool room's indoor temperature was significantly lower than that of a standard reference roof. The maximum reduction in room air temperature of smart passive cool roof system in comparison to a conventional reference roof was observed to be 13.01ºC (36.7%) as shown in Fig.8. The difference in temperature is due to to the improved evaporative cooling, exploiting dynamic nature of air ventilation and radiation reflector. The roofing system stops the incoming heat flux using the dynamic air in the ventilated channel which is cooled by means of water evaporation (latent heat) and also due to the radiation reflection by aluminium reflector at the top layer.

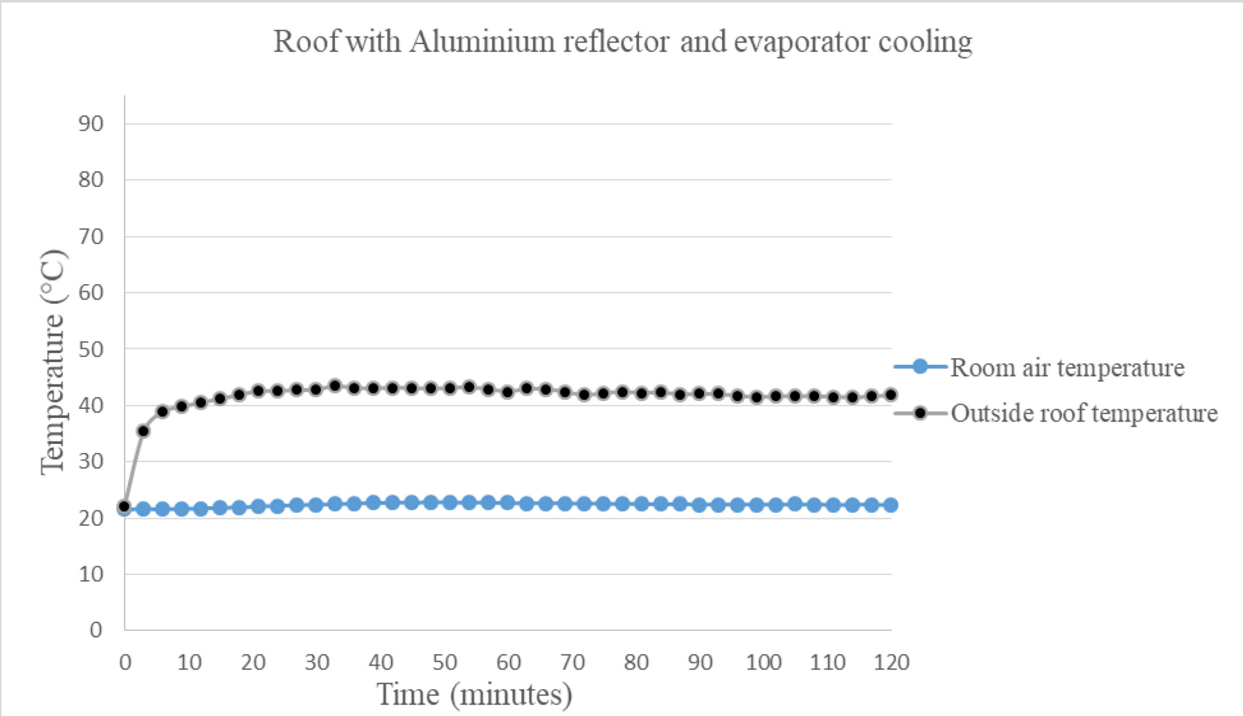


Fig.6 Temperature profile of smart passive cool roof

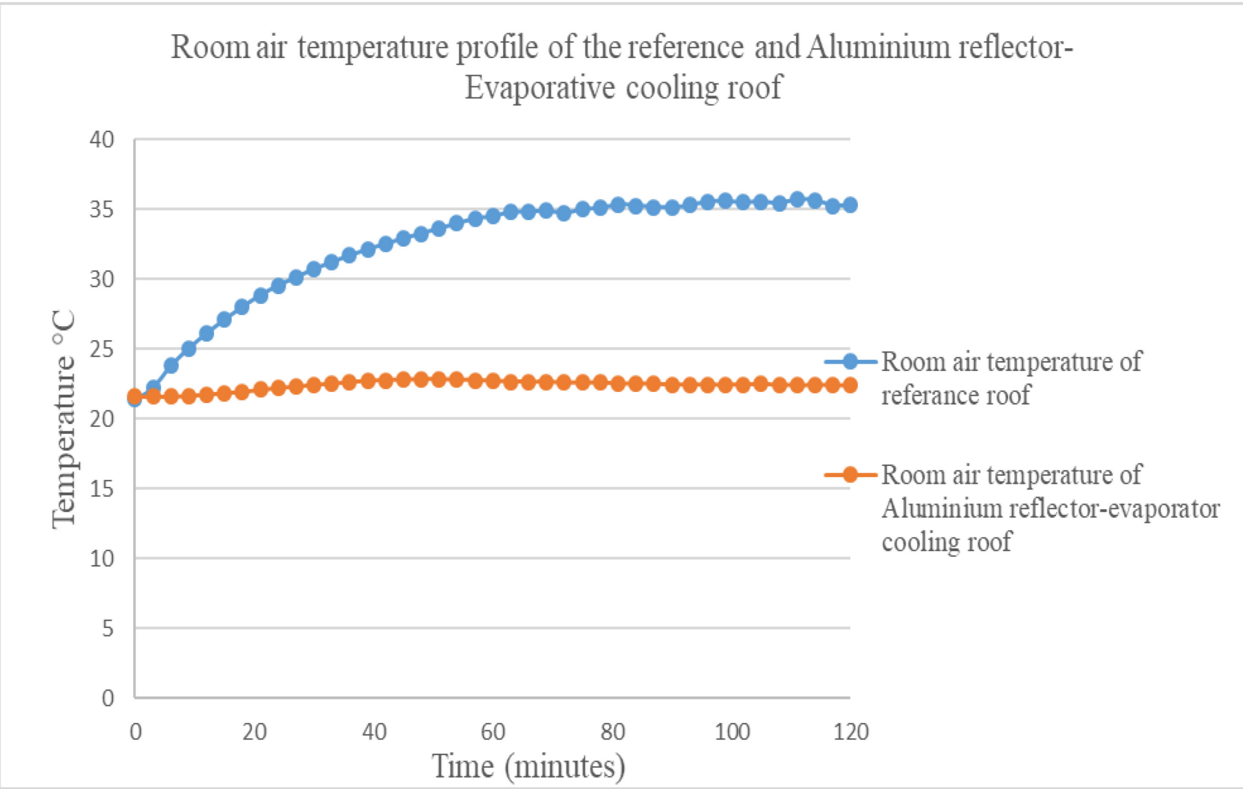


Fig.7 Room air temperature profile of reference and passive cool roofs

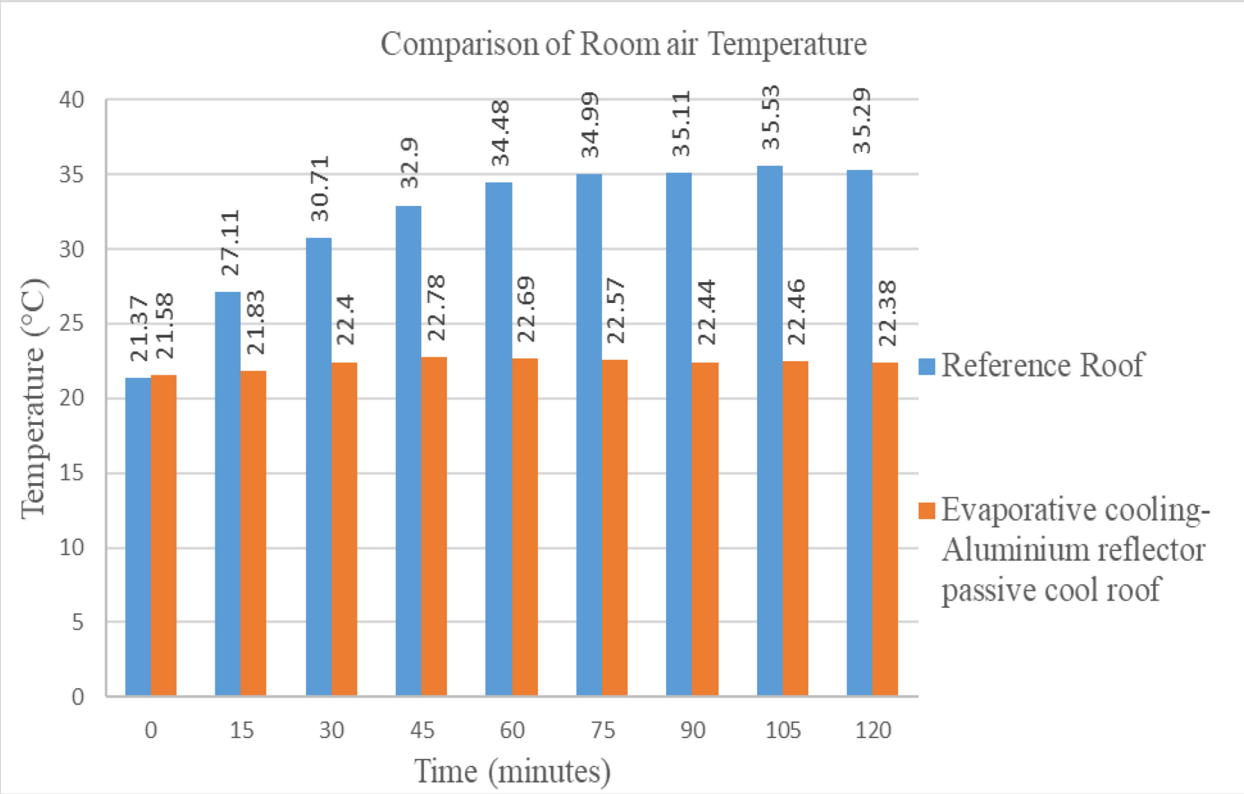


Fig.8 Room air temperature reduction between reference and smart passive cool roof

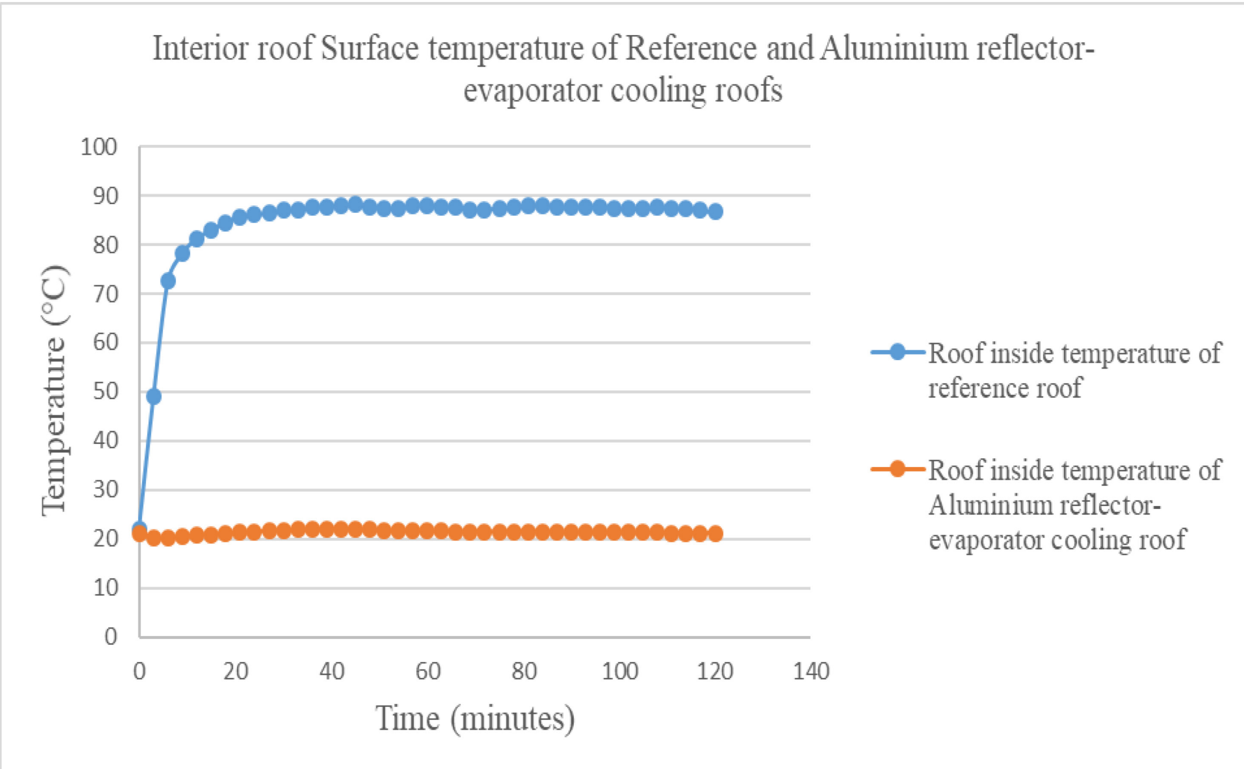


Fig.9 Interior Roof Surface temperature profile of reference and smart passive cool roof

Comparison of Reference and Smart Passive Cool Roof Systems Interior Roof Surface Temperature. When compared to a typical reference room, the passive cool room has significantly lower roof surface temperature peaks as shown in Fig.9. The roof surface temperature of reference roof increased significantly from 22°C to 85°C in the first 21 minutes. Regardless, the aluminium reflector - evaporator passive cool system stayed stable all the time with a marginal fluctuation in temperature and the data after 60 and 120 minutes were 21.64ºC and 21.2ºC respectively. The maximum reduction of 66.59ºC (75.7%) has been observed in interior roof temperature of smart passive cool roof in comparison with a normal reference roof as shown in Fig.10.

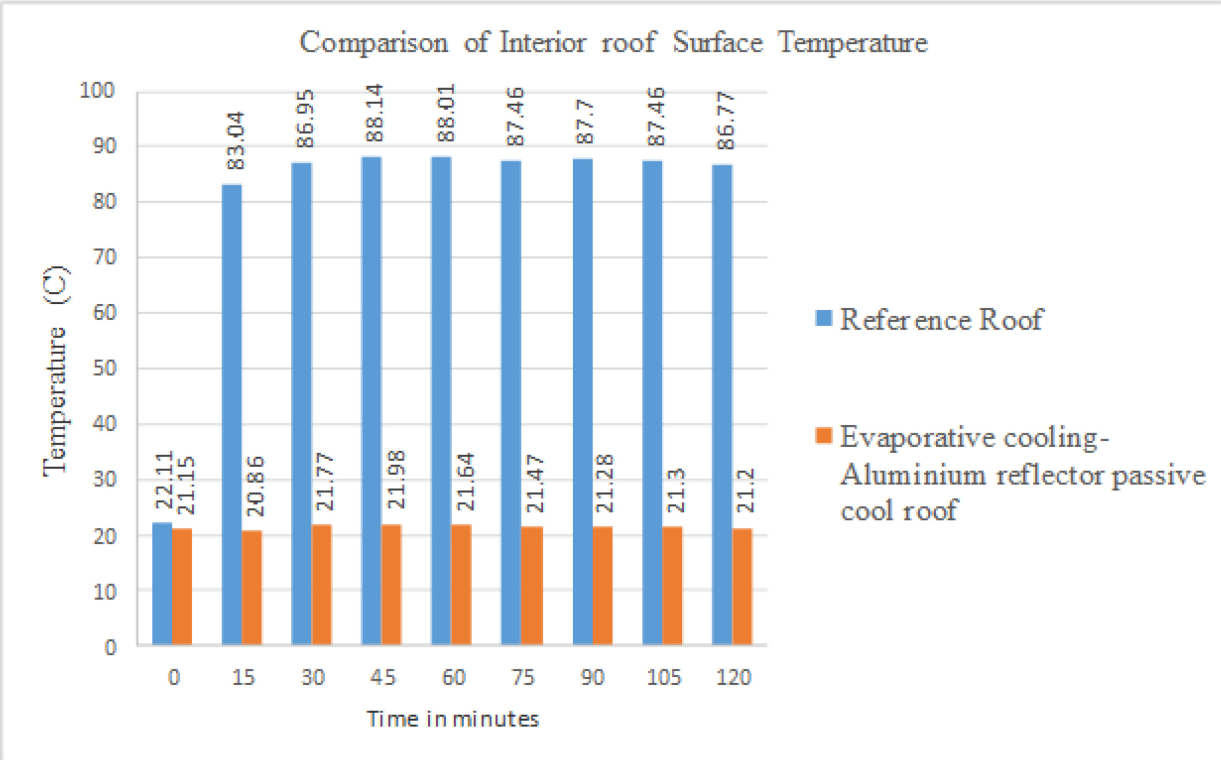


Fig.10 Interior roof surface temperature reduction between reference and smart passive cool roof

Conclusions

The present study focuses on the thermal assessment of a smart, innovative passive cooling system and its impact on cooling potential. It has been established that the smart passive cooling system showed much lower temperature peaks than the normal reference roof. The resulting maximum reduction in room air and interior roof surface temperature after 120 minutes of operation were 13.07ºC (36.7%) and 66.42°C (75.7%), respectively. The efficiency of a smart passive cool roof (evaporative cooling system with forced convection and radiation reflector) has been demonstrated convincingly through the laboratory test models. It can be used as an energy-saving technique and provide comfort conditions in Oman villas to reduce the indoor temperature of the buildings and save energy in terms of air conditioning.

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