THERMAL PERFORMANCE USING RADIANT BARRIER AND PHASE CHANGE MATERIAL IN ROOFS

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ABSTRACT: Buildings are large consumers of energy worldwide, responsible for roughly 40% of the world's primary energy consumption. This paper analyzes the thermal performance of two passive roof construction technologies as a means of improving the indoor thermal conditions under summer conditions. Three identical Test Cell Structures (TCS) were constructed in eastern Kansas. All the TCSs were calibrated and two types of roofing technologies, Radiant Barrier (RB) and Phase Change Material (PCM) were individually applied to a TCS and their performance in terms of indoor air temperature reduction was compared. A one-way analysis of variance (ANOVA) was calculated for the study. The experimental results show that the thermal performance of RB obtained the best thermal improvement. TCS equipped with RB registered indoor air temperature 1.6 °C (2.9 °F) lower than the control test structure.

KEYWORDS: Thermal performance; Passive roofs, Energy; Test cell structures

INTRODUCTION

The issue of energy consumption in various sectors of life, especially in buildings, has become a fundamental concern for all countries. Buildings in most countries are responsible for large amounts of energy consumption, for both space cooling and heating. Undeniably, space cooling loads due to solar gains represent about half of the global space cooling loads for residential and non-residential buildings (Datta, 2001). Residential energy consumption represents a substantial proportion of total global energy consumption. The percentage of residential houses using air conditioning has increased, reaching 80% in 2000 attributed to the continuous rise in urban population and air temperature year after year (Aixing, 2002). The use of mechanical and electrical systems in buildings is necessary to ensure a suitable internal environment for the occupants, especially in the hot summer. Use of these systems has led to an increase in the rate of energy consumption in buildings.

The roof represents the most important component of the building envelope. It is highly subjected to solar radiation and other environmental modifications, and hence it influences the thermal performance of the buildings. Larger amounts of heat gain and loss are attributed to roofs, principally in buildings with large roof areas (Sadineni, Madala, & Boehm, 2011). The energy efficiency of a building depends on the thermal envelope, specifically the thermal behavior of roofs (Silva, Gomes, & Silva, 2016). Even though the building enclosure components are in contact with the environmental conditions, the roof experiences the highest temperature swings (Haider Mohamed, Chang, & Alshayeb, 2015). Heat gain through the roof is a major part of the space cooling load for a single-story building during the cooling season (Hosseini & Akbari, 2015). A study shows that indoor temperatures inside buildings are above comfort levels during the summer period due to the fact that 50% of the heat loads in the buildings come from the roof (Nahar, Sharma, & Purohit, 1999). The way that solar radiation is affecting space cooling load in buildings could be impacted by the properties of external and internal roof technologies (Kokogiannakis, Tuohy, & Darkwa, 2012). Therefore, controlling temperature gains, as a passive strategy, are required in most of the cases.

Several experimental studies have been carried out using passive roof technologies (Haider Mohamed & Chang, 2016). All these aim to reduce and/or control thermal gain through direct radiation. Among them are Radiant Barrier (RB) and Phase Change Material (PCM). The performance of these passive roof technologies has been individually investigated. Review of literature didn't find any previous studies that looked at the aforementioned technologies under the same settings and conditions. This study intends to determine the most effective technique that will reduce the heat transmission via roof system. Consequently, the goal of this research is to put forward passive solutions that can contribute to increasing the thermal performance by minimizing indoor air temperature and heat gain. These technologies have received considerable attention because of their potential to reduce radiant heat transfer across vented spaces between roofs and ceilings of buildings (Haider Mohamed, Lee, & Chang, 2016). RBs consist of a highly reflective material that reflects radiant heat rather than absorbing it. Most often, RBs are aluminium foil laminates or metalized synthetic films sheets. A study showed that radiant barriers contribute to a reduction of heat transfer rate in attics when compared to attics without radiant barriers. The percent of reduction varied from approximately 6–7.7% (Haider Mohamed et al., 2015). (Asadi & Hassan, 2014) showed that RBs could reduce energy loads from 8% to 25% depending on the climatic conditions. Michels conducted an experiment measuring different samples and the results showed that a 70% reduction in heat flux to the inside of the residence on the day of higher solar radiation can be obtained by using RBs (Michels, Lamberts, & Güths, 2008).

PCM is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. PCMs are used on building interiors to reduce the absorption of solar energy. Reduced solar energy absorption results in lower interior temperatures and consequently, less heat flow across the building envelope, and reduced mechanical requirements to maintain air-conditioned space. PCMs represent an innovative and relatively inexpensive technique to reduce building energy requirements for space cooling (Cabeza et al., 2007). reported that the PCM can reduce the peak temperatures up to 1°C (1.8°F) as well as the electrical energy consumption was reduced by as much as 15%. An experiment was performed with a PCM roof panel compared to a reference room without the PCM panel. The results showed that the PCM panel on the roof narrowed the indoor air temperature swings, and better suit for all seasons (Pasupathy & Velraj, 2008).

1.0 Methodology

1.1. Experimental setup

This experimental study seeks to evaluate the thermal performance of two passive roof construction technologies as a means of improving the indoor thermal conditions under summer conditions. The study site, which was located at the Center for Design Research in Lawrence, Kansas, was selected for its orientation and unobstructed solar access as shown in (Fig. 1).

Figure 1: The identical test cell structures on site

Each TCS was 1.14 m (3.74 ft) x 1.14m (3.74 ft) x 1.42 m (4.65 ft) and faced south. All the TCSs were tested simultaneously under the same orientation and weather conditions. All sides are made of one layer of ISO 95□ GL Woodfiber Composite 0.05m (2 in) thick and two layers of Oriented Strand Board (OSB) 0.01m (0.4 in) thick. The external layer of OSB was finished with white paint. The roof assemblies were built of 0.1 m (4 in) thick cast concrete over the test structures, 0.01m (0.4 in) bitumen, 0.06m (2.36 in) clean soil and 0.05m (1.96 in) thick concrete tiles. The plan of the TCS is shown in (Fig. 2). The roof was slightly sloped for drainage. The roof was the only envelope parameter that changed among the TCSs.

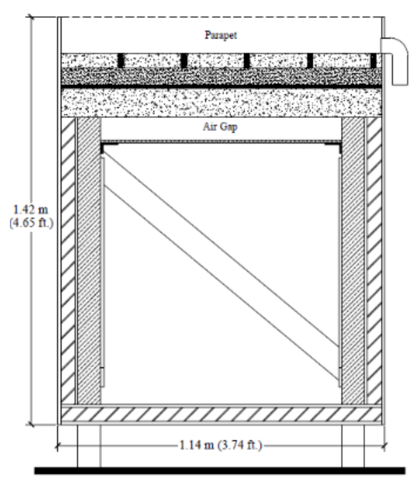

Figure 2: Test cell structure section

1.2. Monitoring system

A 15 channel HOBO U30 data logger equipped with thermocouples was used for data acquisition. The thermocouples were installed in multiple locations of each TCS to monitor temperature. Data were recorded every 5 minutes and averaged hourly, which minimized the effects caused by sudden changes in outdoor and/or indoor conditions such as wind speed and passing clouds. The meteorological parameters (solar radiation, air temperature and relative humidity) were obtained with a weather station positioned near the TCSs. The external parameter registered by the system was the surface temperature of roofs. The locations of the sensors are presented in (Fig. 3) and the specifications of the sensors are shown in (Table 1).

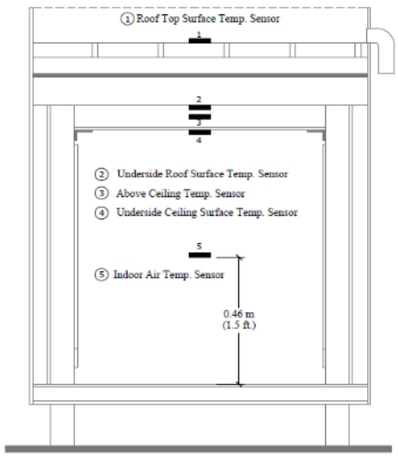

Figure 3: Sensor placement

Table 1: Manufacturer specifications for the loggers and sensors

Data Logger	**Operating Range**	**Sensor Inputs**
Onset HOBO U30	-40 to 60°C (-40 to 140°F)	15
Sensors	**Operating Range**	**Accuracy**
Onset S-TMB-M0X	-40°C to 100°C (-40°F to 212°F)	±0.2°C (±0.36°F)
Onset RH Smart	0-100% RH	±2.5% to ±3.5%
Onset Solar Radiation	0 to 1280 W/m2	±10 W/m²
Onset Wind Speed	0 to 76 m/s (0 to 170 mph)	±1.1 m/s (2.4 mph)

1.3. Calibration phase

Calibration tests were performed to verify the thermal performance of the experimental bed before applying any treatment. The calibration was initiated on July 17, 2015 at 12:00 a.m. and ended on August 1, 2015 at 11:55 p.m. The maximum recorded value of solar radiation was 918 W/m² (291 Btu/hr.ft²) and the maximum air temperature was 37.4°C (99.3°F). July 24, 2015 was selected as it had the highest maximum of ambient temperatures throughout the day, which represents the warmest day during this phase of the study, as shown in (Table 2).

Table 2: Weather conditions for July 24, 2015

Solar Radiation W/m² (Btu/hr.ft²)	**Ambient Temp. °C (°F)**	**Max °C (°F)**	**Min °C (°F)**	**ΔT °C (°F)**
918 (291)	30.2 (86.4)	37.4 (99.3)	23.8 (74.8)	13.6 (24.5)

1.4. Retrofit phase

The local climate of the experimental site is generally hot and humid. Measurements were taken between August 6, 2015 at 12:00 am, and August 18, 2015 at 11:55 p.m. The preliminary results, under such conditions, indicated that the average temperature inside the STCs exceeds 25 °C (77 °F). The materials examined during this stage were applied only to the roofs, since the focus of this work was roofs. One TCS was kept as a Basecase (BC), control unit without any treatment, and the proposed modifications were applied to the other TCSs. The passive modifications were introduced to the roof of the modified TCSs as follows:

- *Radiant Barrier (RB) underside the roof*:

By placing a radiant barrier on the underside of the roof, thermal heat that conducts through the roofing material is reduced, hence, lowering the indoor temperature. Radiant Shield having thermal emittance of 0.03, which consists of two layers of aluminum foil laminated to a layer of woven polyethylene, was installed between the underside of the roof and above the roof ceiling, see (Fig. 4).

Figure 4: Installation of radiant barrier (RB)

- *Phase Change Material (PCM) over the ceiling*

PCM works by increasing the thermal mass of a building, increasing the time it takes for the structure of a building to warm up or cool down. The melting temperatures of PCMs employed in building heat storage systems for passive heating and cooling vary starting from 17 °C (62.6 °F). This study used PCM with a melting temperature of 27 °C (80.6 °F) over the ceiling of the model under consideration based on the PCM manufacturer's recommendation, see (Fig. 5).

Figure 5: Installation of PCM

The weather data showed the average ambient temperatures varying between 16.61 °C (61.89 °F) during the night and 34.36 °C (93.85 °F) during the day with an average of 25.67 °C (78.20 °F). That is, an average temperature difference of 17.76 °C (31.96 °F) between day and night was recorded. The maximum recorded value of solar radiation was 891.6 W/m² (282.6 Btu/hr.ft²). August 7th was one of the hottest days in the data collection period and was selected to evaluate peak influences of materials under investigation on indoor air temperature for all TCSs. More details for the weather condition are presented in Table 3.

Table 3: Weather conditions for August 7, 2015

Solar Radiation W/m² (Btu/hr.ft²)	Ambient Temp. °C (°F)	Max °C (°F)	Min °C (°F)	ΔT °C (°F)
875.6 (277.6)	27.7 (81.8)	34.4 (94)	21.8 (71.2)	12.6 (22.6)

2.0. Results and discussion

2.1. Calibration phase

The thermal performance of the TCSs was compared and recorded as reference .The temperature inside all TCSs was continuously measured at the center of each TCS. The average value of all measurements was plotted against the time of day to show the nature of air temperature variation inside the TCSs. The indoor air temperatures were recorded as shown in (Fig. 6). The recorded data showed that the indoor air temperature for all TCSs varying between 35.2 °C (95.3 °F) during the day and 22.7 °C (72.8 °F) during the night. That is, an average temperature difference of 12.5 °C (22.5 °F) between day and night was recorded.

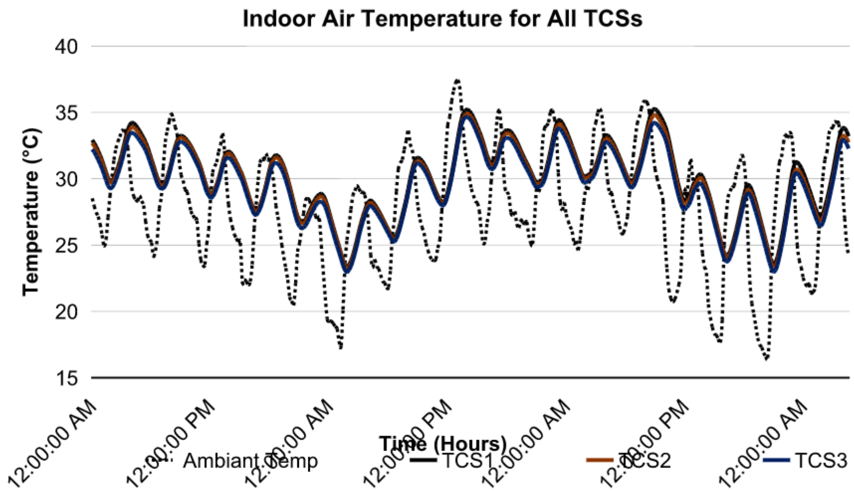

Figure 6: Variations in the ambient temperatures inside TCSs

The pattern shows a constant difference in temperature for all the TCS. That means the average indoor air temperatures are close to each other. The comparison explains that indoor air temperature was considered identical and acceptable for all the TCSs since the maximum difference of 0.5 °C (0.9 °F) was recorded.

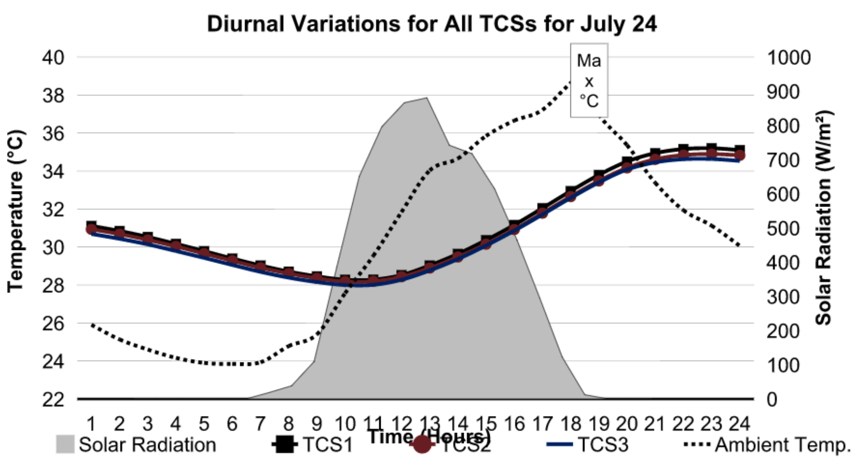

Figure 7: Average hourly indoor air temperatures recorded during July 25 measure period

The indoor air temperature for the all TCSs plotted against ambient temperature are reported in (Fig. 7). The average indoor air temperatures were between 31.1°C (87.9°F) and 30.8°C (87.4°F). An average temperature difference of 0.3 °C (0.5 °F) between all indoor air temperatures for all TCSs was registered. A one-way analysis of variance (ANOVA) was conducted as a powerful statistical method using SPSS to evaluate and compare the relationship between the indoor air temperatures for all TCSs. The indoor air temperature was used as a dependent variable to evaluate the performance of each TCS and also to investigate whether there is a statistically significant difference between them. The omnibus hypothesis for our data of interest assume that there is no significant difference between the indoor air temperature means for the TCSs while the alternative assumes there is a significant difference. The ANOVA results showed that there is no statistically significant difference between indoor air temperature means for TCS1 (M= 31.1; SD= 2.5), TCS2 (M=30.9; SD= 2.4) and TCS3 (M= 30.8; SD= 2.4). The strength of the relationship, as assessed by n^2, was not strong, with the TCS factor accounting for 0.4% of the variance of the indoor air temperature.

2.2. Retrofit phase

2.2.1. Thermal performance of Radiant Barrier underside the roof (TCS2)

The variation of indoor air temperature inside the BC and indoor air temperature inside the TCS2 for August 7th are presented in (Fig. 8). The results indicate that application of a radiant barrier shield reduces radiant heat transfer across the space which it faces. The drop in the average air temperature inside the TCS2 as compared to the BC was 1°C (1.8°F). The maximum indoor air temperature of TCS2 was reduced by 1.6 °C (2.9 °F) as compared to the BC. The thermal performance of the TCS2 demonstrates that the average indoor air temperature is dependent on application of the Radiant Barrier Technology.

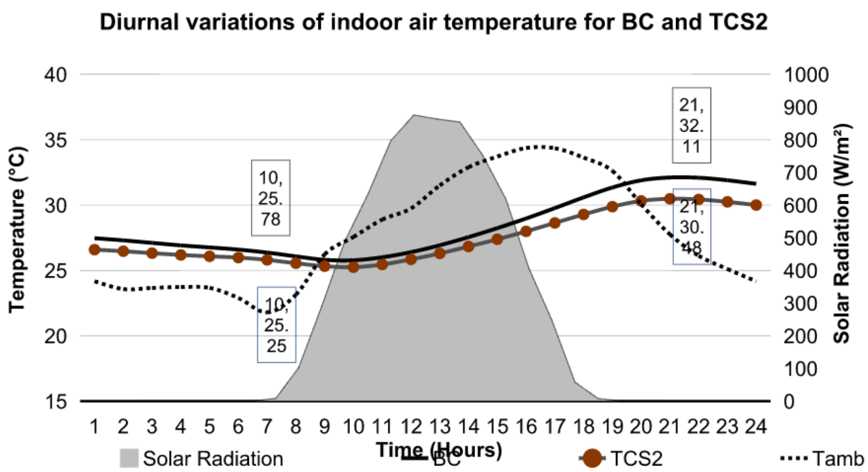

Figure 8: Average hourly indoor air temperatures recorded during August 7 measure period

The ANOVA outputs indicated a statistically insignificant difference between indoor air temperature means for BC (M=28.3; SD=2.3) and TCS2 (M=27.4; SD=1.9), $F(1, 46) = 2.4$, $p=0.1$. The strength of the relationship, as assessed by n^2, was not strong, with the TSCs factor accounting for 5 % of the variance of the indoor air temperature.

2.2.2. Thermal performance of Phase Change Material over the ceiling (TCS3)

The variation of indoor air temperature inside the BC and indoor air temperature inside the TCS3 for August 7th are presented in Figure 9. As seen, the average indoor air temperature of TCS3 was reduced by only 0.9 °C (1.6 °F) compared to the BC. The maximum indoor air temperature of the TCS3 was 1.2 °C (2.2 °F) lower than that of the BC, while the minimum of the TCS3 was reduced by 0.5 (0.9). The ANOVA outputs reported that there is a statistically insignificant difference between indoor air temperature means for BC (M=28.4; SD=2.4) and TCS (M=27.5; SD=2.1), $F(1, 46) = 1.8$, $p=0.1$. The strength of the relationship, as assessed by n^2, was not strong, with the TCSs factor accounting for 3.9% of the variance of the indoor air temperature.

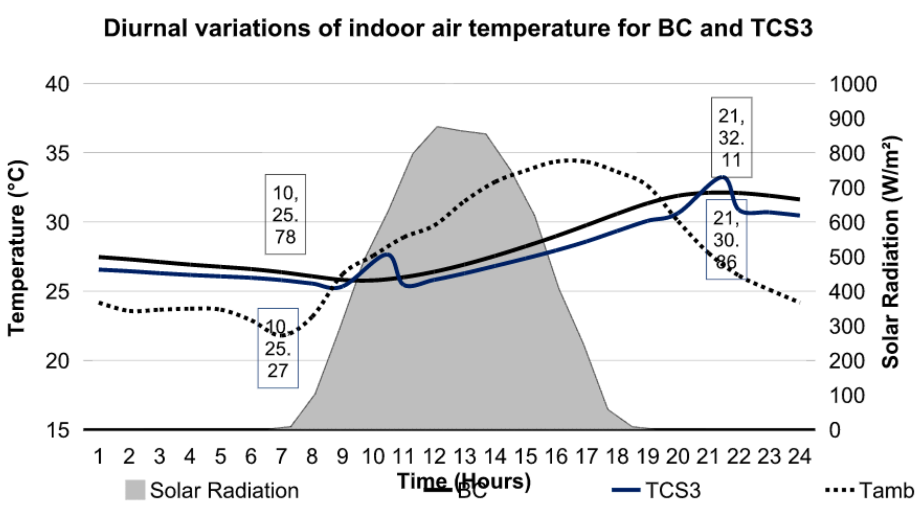

Figure 9: Average hourly indoor air temperatures recorded during August 7 measure period

CONCLUSION

This paper analyzes the thermal performance of two passive roof construction technologies using three identical Test Cell Structures (TCSs) as a means of improving the indoor thermal conditions under summer conditions. All the TCSs were calibrated and two types of roofing technologies, Radiant Barrier (RB) and Phase Change Material (PCM) were individually applied to a TCS and their performance in terms of indoor air temperature reduction were compared. The thermal performance of the radiant barrier was 1°C (1.8°F) lower than the indoor air temperature for the BC. The phase change material showed only 0.9 °C (1.6 °F) reduction in indoor air temperature. A general conclusion is that the investigated technologies can be arranged in descending order according to their performance as radiant barrier and then phase change material. This study arises from the need to put forward passive solutions that can contribute to reducing energy use and improving building thermal performance by minimizing indoor air temperature and heat gain.

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