Journal of Green Engineering (JGE)

Volume-11, Issue-1, January 2021

Straw Bale Installation on the Roof Top Green Projects Effects in the Indoor Building Temperature: Case Study Peshawar, Pakistan

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Abstract

Study aim to improve the indoor building thermal comfort environment by using straw bale on the roof top promoting green construction projects. Experimentally field temperature of the residential building in Peshawer, city of Pakistan was collected for July 2019 and January2020 which has the highest and lowest temperature of the year further experimental temperature data is compared and validated using CFD modeling. CFD simulation was used to determine the effect of straw bale thermal insulator material on the roof top. Findings indicated that the experimental temperature shows 2nd January has the lowest temperature and 11th July has the highest and predicated validated temperature result shows similar findings with slightly difference of less than 20%. Straw bale utilization shows temperature reduces in the summer and increase in the winter inside the building but did not meet the ASHARE standard -55 recommended comfort zone temperatures values. This study concluded that straw bale did not effectively helpful to use in the Peshawar city for the thermal comfort in residential building. In the line,

Journal of Green Engineering, Vol. 11_1, 122-140.

more studies have recommended to use other natural and recycled thermal insulator materials and compare the result. The placement of thermal insulator material in buildings is essential has to consider in the future studies.

Keywords: Thermal Insulator, Green construction Projects, Peshawar Pakistan, CFD Simulation, Straw bale, Roof top.

1 Introduction

Globally, occupants demand for higher thermal comfort has increased the number of heating and air-conditioning systems installed in buildings. Buildings account for about 40% of the global energy consumption and contribute over 30% of the carbon dioxide (CO^2) emissions [1]. A considerable amount of this energy is consumed in buildings via heating, cooling and dehumidifying to provide thermal comfort. The energy condition is becoming harsh to the countries facing challenge of environmental change impact and energy crises. In the context of Pakistan the weather condition is important to understand. Pakistan lies in the temperate zone. The climate is generally arid, characterized by hot summers and cold winters and wide variations between extremes of temperature at given locations. Pakistan has are three seasons winter (November to March is cold but dry) summer, (April to July extremely hot weather) and the Moon soon season (July –August) heavy rainfall occurred [2]. In the past, people of Peshawar constructed building using natural raw materials such as mud bricks stones and wood also leaves or trees for roofs and soil for floor. These natural materials helped to keep comfortable atmosphere inside the building. However, urbanization had leaded the city for contemporary building constructions using concrete and composite materials which do not have similar thermal characteristics as with traditional construction materials. Building materials has high correlation with indoor temperature in winter and summer. The objective of this study is to improve the indoor thermal environment in residential buildings in Peshawar by keeping the building's indoor air within a comfortable range of temperatures through using of roof thermal insulation and without the need of mechanical systems.

2 Literature Review

2.1 Khyber Pakhtunkhwa (KP)

Climate Change Impacts in Khyber Pakhtunkhwa (KP) province of Pakistan, a topographically diverse province situated in the northwest region of Pakistan. The northern region of the Khyber Pakhtunkhwa (KP) comprises the Himalayan and Karakoram mountains where southern parts are plains lands. Northern part of the province has the cold weather with heavy rainfall with lowest temperature and the south parts of the KP has extreme dry cold to hotter summer and moderate rainfall. South part of the KP experience two extreme climate very hot to very cold and monsoon [3]. The weather in summer is hot throughout the day, temperatures can reach up to 50°C during the day [2-3]. Study of global climate risk indexed 2020 [4] reported the most affected countries in the period of 1999-2018 among Pakistan is ranked on 5th most affected country. Despite, negligible contribution to global warming Pakistan is highly climate change affected countries due to large scale deforestation, rapid and unmanaged urbanization and inactive neglected environmental ministry. Recently, science has closely found linked between increasing temperature /heat waves and climate change [5].

The thermal discomfort of the occupants in the buildings has documented in several studies [6–8]. Apart from the highly vulnerable to the climate change country is facing heavy shortage of electric power generation. The country power generation and consumption data indicated big difference where consumption has increased 11% compare to last decades [9]. Unplanned urbanization and ineffective strategies for improving thermal comfort in the buildings are among the reason occupants greatly effect with discomfort especially in the summer where temperature is on the highest. Therefore, researchers are seeking alternative modern material suited with the modern construction design to provide thermal comfort especially countries like Pakistan facing climate and power cries same time. In the past the problem was address using less conductive or bad conductive materials such as wood, grass or leaves etc which is no longer in the use of modern buildings system.

In the modern buildings most of the buildings materials are good conductive of heat which increase thermal conductivity of the building in the result occupants suffered with discomfort in the winter and summer. Modern buildings are equipped with mechanical systems for the controlling of indoor temperature. In this context, improving thermal comfort and at the same time minimizing the energy consumption can be achieved in many ways, including proper insulation of the building envelop [10].

To achieve the target of creating a better indoor thermal environment and at the same time minimizing building energy consumption, there are great efforts have been made in improving the construction and design of building envelopes to help in controlling the indoor temperatures without the need of mechanical systems. In the daylight heat transfer occurs through roofs and walls of the building by the conduction process where buildings elements and materials absorb solar heat energy. Solar radiation hits dominantly the roof of the building longer hours with highest solar intensity absorb high solar radiation compare to the vertical walls of the buildings [11]. Building roof top particular are the most important envelope component for reducing energy consumption because main thermal load in building comes from the roof [10-12]. Thermal insulation of roofs is one of the most effective strategies for achieving energy conservation and thermal comfort for cold winters and warm summers in a composite climate. Thermal insulation reduces unwanted heat loss or gain and hence decreases the energy demands of heating and cooling systems [13-16]. Less thermal conductive material is always suggested alternative and additionally added materials in the construction elements to reduce the heat transfer effect or increase thermal comfort in the building [17][28][29]. Straw bales significantly reduce solar heat effect using as a building material [18]. Previously conducted studies has highlighted the notable effect of straw bales utilization in the buildings and encouraging results been achieved. This study aims to use straw bale as a composite material in the building construction on the roof top for the green construction engineering to reduce the thermal effect in the indoor of the building.

3 Methodology

3.1 Study Location

Peshawar city of Pakistan has chronic weather condition in summer and winter, thus study has selected Peshawar city, where most of the year weather is dry and out of the comfort zone for the occupants in the contemporary design houses. On the other side electricity consumption in the area has drastically increased.

3.2 Structure Selection

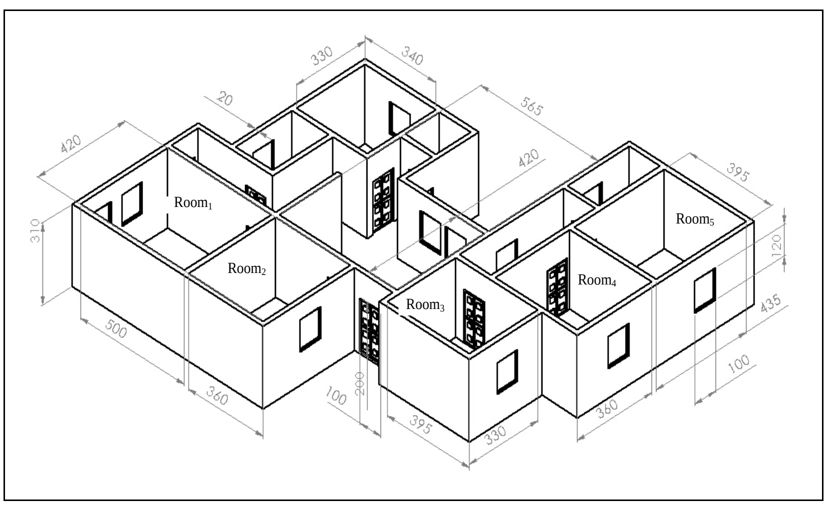


Figure 1 Sketch of the Residential building in Peshawar

Most commonly practicing residential building structures in the Peshawar, city consists of reinforced concrete, cement block, cement-mortar plaster and has a modern architectural style. The sketch of selected residential building for this study is shown in Figure 1. This building consists of five rooms. The total built - up area of the building is 420 m^2 with a height is 3.5 m.

3.3 Field Temperature Measurement

The highest and lowest temperature in the whole year is July and January in Peshawar city [3] So the temperature data of July 19 and January 20 has collected. Internal and external temperature of the buildings were measured using hot wire anemometer data logger and HOBO series data logger measuring instruments were used during the field temperature data collection. The hot wire anemometer data logger was used to measure the temperature inside the building, while the HOBO series data logger was used to measure the temperature of the outside surface of the building.

The temperature data was recorded from 26 points within the structure internal and external surface as shown in Figure 3. In the room five (5) points P1-P5 has allocated to collect temperature as shown in the **Figure 2**. The air temperature at these points was measured at the height of 1.1 m from the ground level. The chosen height level is based on ASHRAE Standard-5 [23]. The measured data at these points were used to evaluate the effectiveness of the current roofing system as well as to validate the 3D CFD model of the building. The other points are located at the outside surface of the building (roof, vertical walls, windows and doors), namely P6 to P26 respectively shown in Figure 3. The measurements at these points were taken at the central area of each surface. The measured data at these points were used for specifying the boundary conditions of the developed 3D CFD model of the building. The measured locations and the usage of measured data are summarized in Table 1.

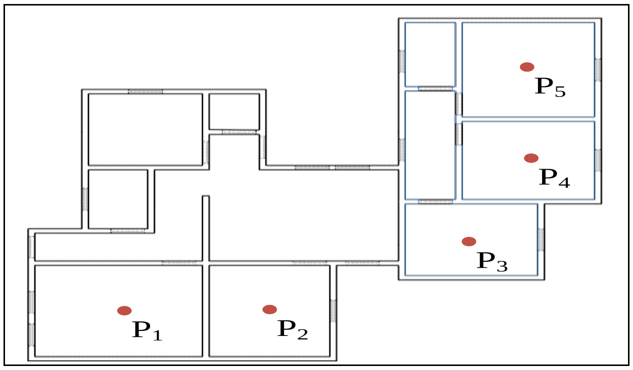


Figure 2 Locations of Temperature and Air in the Room

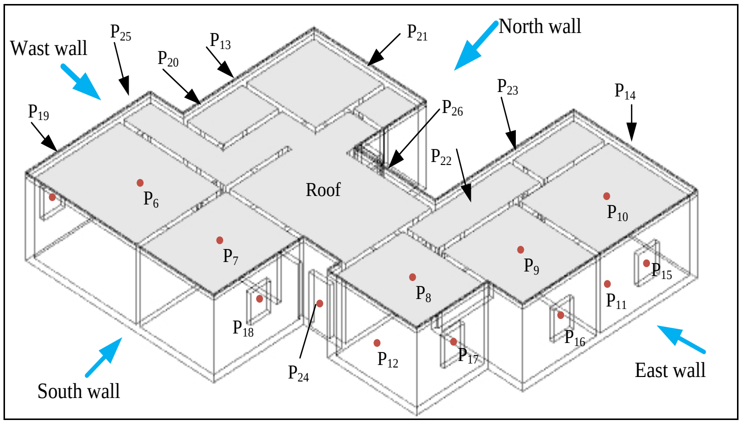


Figure 3 Outside Surface of Roof, Vertical Wall, Windows and Doors: 26 Points

Table 1 Location and Points of Field Measurement

Location	No. of Point	Measurement Purpose		
		Evaluation	Boundary condition	Validation
Inside rooms	5 (P_1 to P_5)	Yes	-	Yes
Outside roof surface	5 (P_6 to P_{10})	-	Yes	-
Outside vertical walls	4 (P_{11} to P_{14})	-	Yes	-
Windows	9 (P_{15} to P_{23})	-	Yes	-
Doors	3 (P_{24} to P_{26})	-	Yes	-

3.4 Selection of Thermal Insulator

Roofs are highly susceptible to solar radiation and other environmental changes, thereby, influencing the internal temperature conditions for the occupants[19]. The roof plays vital role in the thermal performance of the building [20]. Therefore, a good thermal insulation is required for the roof of the building to reduce the heat gain inside the building [21]. Selecting an appropriate thermal insulation material depends mainly on thermal properties of the materials among thermal conductivity of the material. This study has considered two important parameter for the selection of thermal insulator materials should natural or recycled material and must available locally in Peshawar city with the lowest cost possible. This study has focused on the straw bale thermal insulator having following properties shown in Table 2.

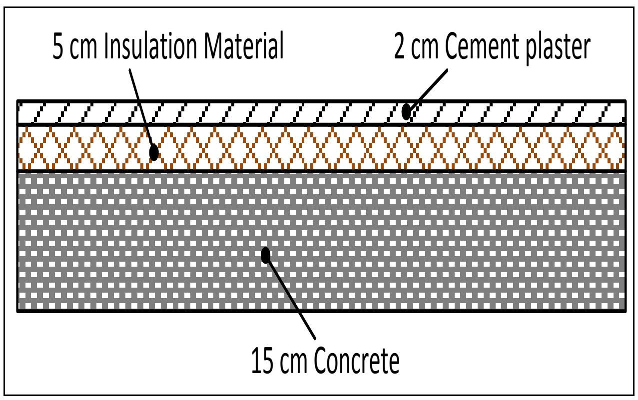
Table 2 Properties of the Selected Thermal Insulation Materials

Natural materials	Density (kg /m^3)	Thermal conductivity (W/m.K)	Specific heat (kJ/kg.K)	Type of material	Available in Peshawar
Straw bale	100	0.0525	0.6	Natural	✓

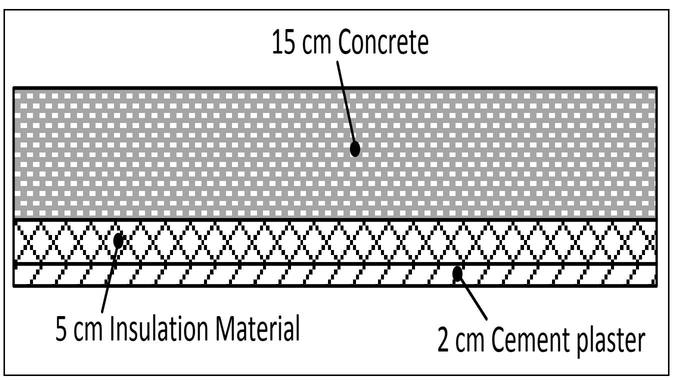
3.5 Configuration of Thermal Insulator

The configuration of thermal insultors plays an important role in the dynamic thermal behavior of the roof. Straw bale insultor were configured in the following manner shown in the Figure 4 (a-d)

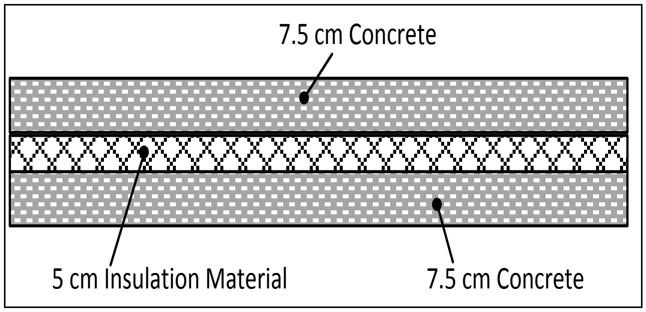
- Insulation at the outer roof surface
- Insulation at the inner roof surface
- Insulation at the middle of the roof
- Insulation is distributed within the roof structure



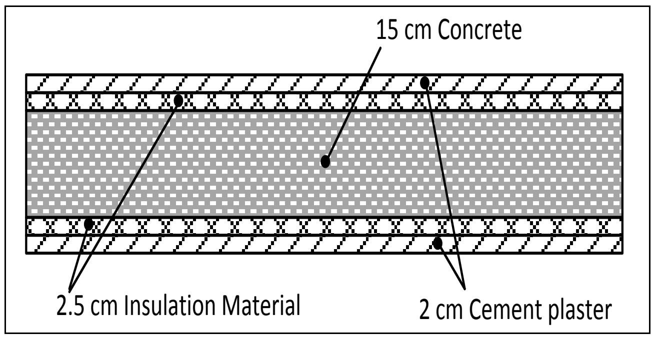
(a) Insulation at the Outer Roof Surface



(b) Insulation at the Outer Roof Surface



(c) Insulation in the Middle of the Roof



(d) Insulation is Distributed within the Roof Structure

Figure 4 Location of Thermal Insulation Materials at the roof (a) Outer (b) Inner (c) Middle and (d) Distributed

As a pilot examination to determine the potential of the thermal insulation materials in improving the thermal comfort in residential buildings in peshawar. Initially, the straw bale insulation material installed in the outer surface of the roof was simulated using CFD. Baseline two models were designed for summer and winter and additionally two models were designed by installaiton of 5cm thick straw bale insulator at the outer surfaceof the roof for two season. These two models have the same 3D geometry, mesh and material characteristics, but they differ in the boundary conditions; as boundary conditions are different for summer and winter. Daily average temperature, thermal amplitude, time lag and period of comfort were determined.

4 Results and Analysis

4.1 Field Data Temperature Evoluation

The temperature measurements were recorded inside five rooms during July 2019 and January 2020 for the whole day and daily average temperature is shown in the Figure 5 for July and Figure 6 for January.

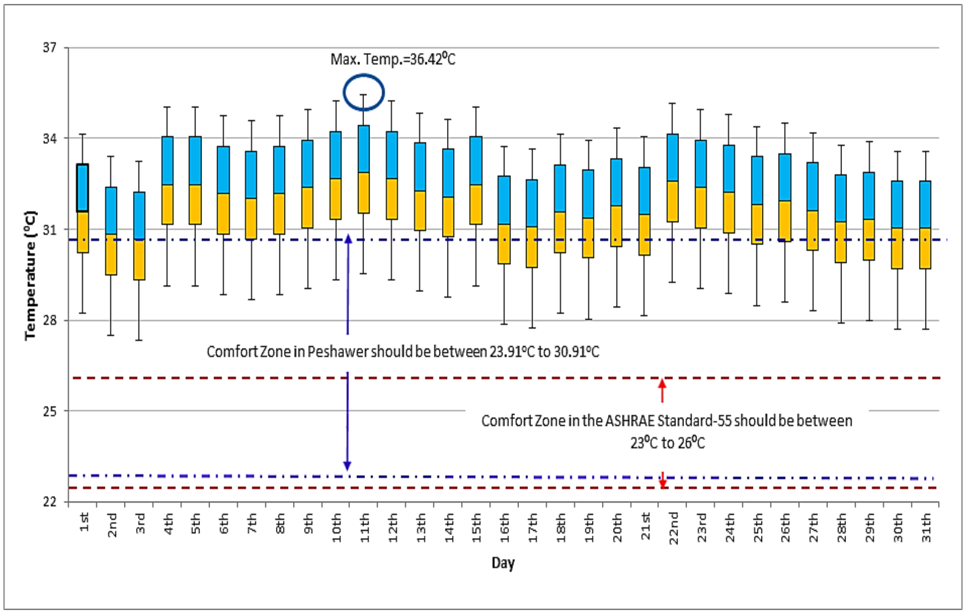


Figure 5 Temperature Measurements Inside Room throughout the Month of July, 2019

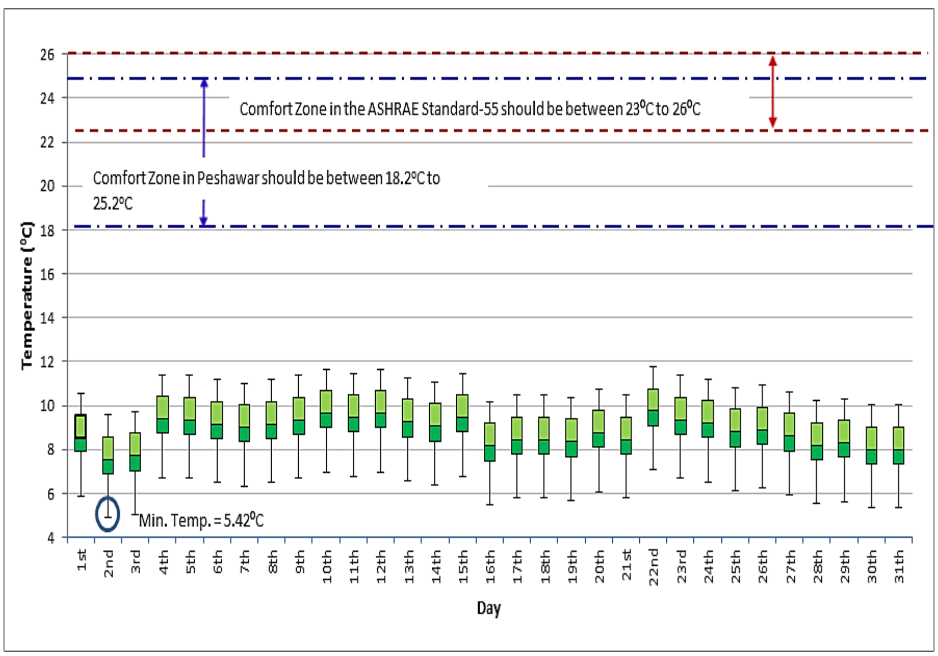


Figure 6 Temperature Measurement Inside Room throughout the Months of January 2020

Figure 5 indicated that the highest average temperature recorded in the room 5 on the 11th day of July 2019 conversely lowest daily temperature is recorded in the room -1 on the second day (2nd) of the month January 2020 as shown in the Figure 6. Room-5 is exposed to the solar radiation from all the directions from the roof, the northern and eastern walls. Where Room-1 is located on the western side that is exposed to low solar radiation, as well as it has walls shared with the adjacent buildings. Temperatures at most hours of the day during July were higher than the recommended thermal comfort range. Likely temperature in the January also found lower than the thermal comfort range. The recommended daily average temperature in summer is 23-26 ^{o}C and in the winter 18.2-25.2 Celsius. The comfort zone in Peshawar zone should between 29-30 ^{o}C. This indicates that the condition inside the rooms is not quite comfortable to the occupants. Thus, it can be concluded that current roofing system is an ineffective.

4.2 CFD Model Simulation

A CFD (Ansys Mesh-R16 software) method was used to develop a 3D model to predict the temperatures inside the building. A simplified 3D geometry of the building as shown in the Figure 7 was constructed using Solid work at the actual dimension practicing in Peshawar. The building has an overall size of length, L = 27 m, width, W = 15 m and height, H = 3.5 m. The building has 3 doors and 13 windows on the outside vertical wall. The doors dimensions are 1.2 m width and 2.0 m height, while the dimensions of windows are 1.2 m width and 1.4 m height.

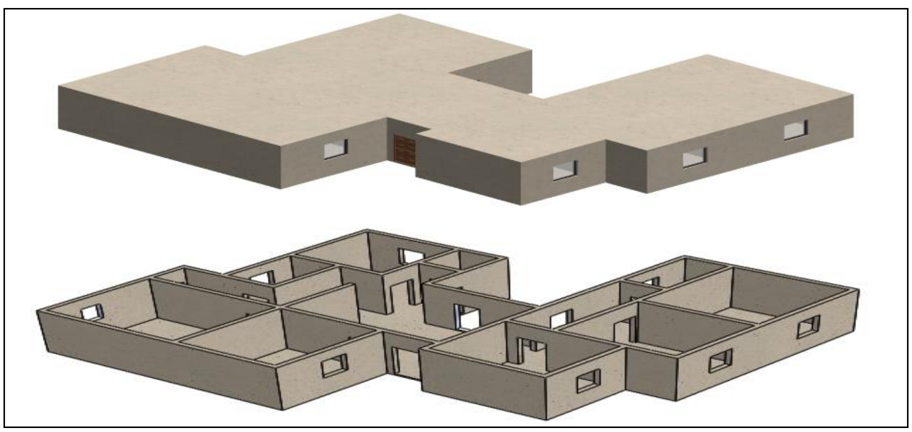


Figure 7 Simplified CFD model of the building

Ansys (Mesh-R16) unstructured cutcell grids model was adopted to predict the temperature in the building. Qualitative grid verification was performed by GIT using different grid sizes to determine the effect of the grid size on the results [21]. The GIT was started from coarse (default) size to finer size, elements size of 1,000,610 and 6,142,164, respectively. Figure 8 and Figure 9 represented the result of the predicted temperature similar with measured. The comparison result shows similar temperature distribution in 5 rooms with slightly difference.

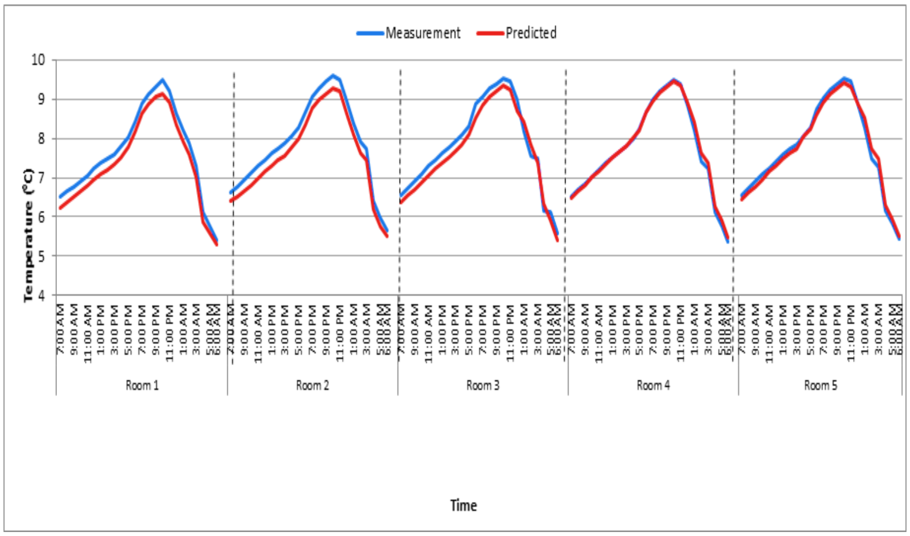


Figure 8 Measured Temperature Verses Predicted Temperature in January 2020

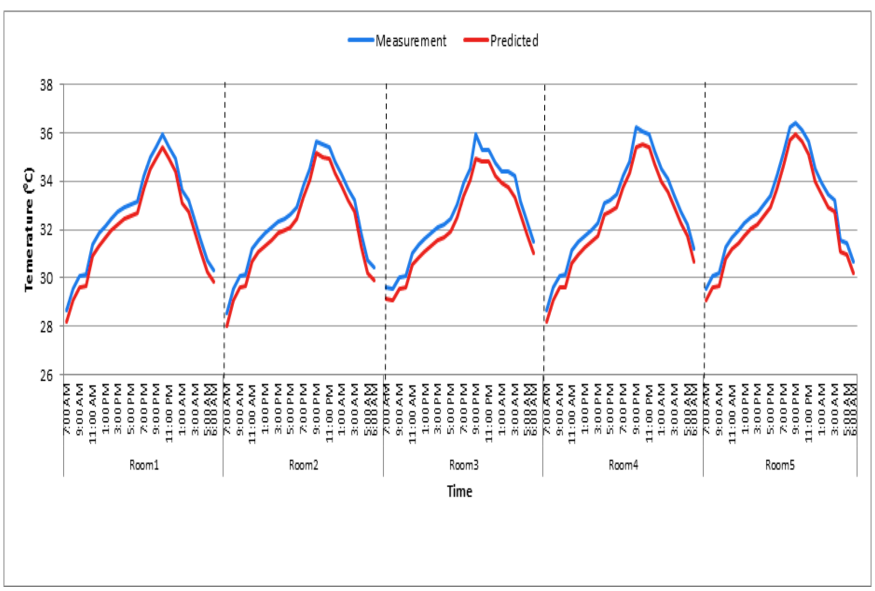


Figure 9 Measured Temperature Verses Predicted Temperature in July 2019

4.3 Effect of the Installation of Straw Bale Thermal Insulation Material on the Roof Top

A 5 cm thick straw bale insulation material was placed at the top of the roof in order to investigate the effect of indoor building temperature. The effect was quantified by developing a 3D model for the building with thermally insulated roof using straw bale material. Experimental/Field data collection is compared with the CFD model simulation as shown in the above Figure 8 and 9. Room-1and Room-5 was selected for comparison, as those have the highest and the lowest temperatures respectively. If temperatures in these particular rooms are improved, then perhaps the same improvement could be achieved for other rooms.

The calculated comparison factors (daily average temperature, thermal amplitude, time lag and period of comfort) for the summer and winter are summarized in Figure 10 and Figure 11.

To study the effect of the thermal insulation, the percentage change in each factor was calculated between the baseline model and the new developed model of the building with the thermally insulated roof. Generally, the percentage change between any Old value and New value is calculated based on the following equation [23].

$$Percentage \quad Change = \frac{New \quad value \; - Old \quad value}{Old \; value} \times 100 \quad \text{……..} \; (1)$$

Where

Old value represents the value of the factor obtained from the simulation of baseline case,

The new value represents the value of the factor obtained from the simulation of the building with thermally insulated roof.

Table 3 indicated the straw bale effect comparison for summer and winter. Where, in the summer average temperature using baseline 32.47C and with straw bale insulation reduce the temperature to 30.85C, thermal amplitude (Baseline-6.84 and Straw bale insulation 4.43), Time Lag (Base line , 5 and straw bale 8) and period of comfort in summer 5 hours while after straw bale insulation has increase to 12 hours. Conversely Findings shows for the winter as average temperature using baseline 7.37 C and with straw bale insulation reduce the temperature to 6.43C, thermal amplitude (Baseline-3.81 and Straw bale insulation 2.81), Time Lag (Base line 4 and straw bale 7) and period of comfort in winter shows no effect due to not changing the temperature.

Figure 10 indicated slightly improvement in the temperature for the summer in the Room5 which is highly exposed to the sunlight. The figure shows that roof top temperature in the summer is above 45C, where baseline indicated 34 C but after straw bale insulation temperature slightly dropped to the 30C in the summer. The obtained temperature result still does not meet with ASHRAE Standard 55 and literature recommended temperature value for the thermal comfort [24-28].

Table 3 Results of the Comparison Factors for the summer and winter

Season	Factors	Baseline case	With straw bale insulation
Summer	Average temperature (°C)	32.47	30.85
	Thermal amplitude	6.84	4.43
	Time lag (hr)	5	8
	Period of comfort (hr)	5	12
Winter	Average temperature (°C)	7.37	6.43
	Thermal amplitude	3.81	2.81
	Time lag (hr)	4	7
	Period of comfort (hr)	0	0

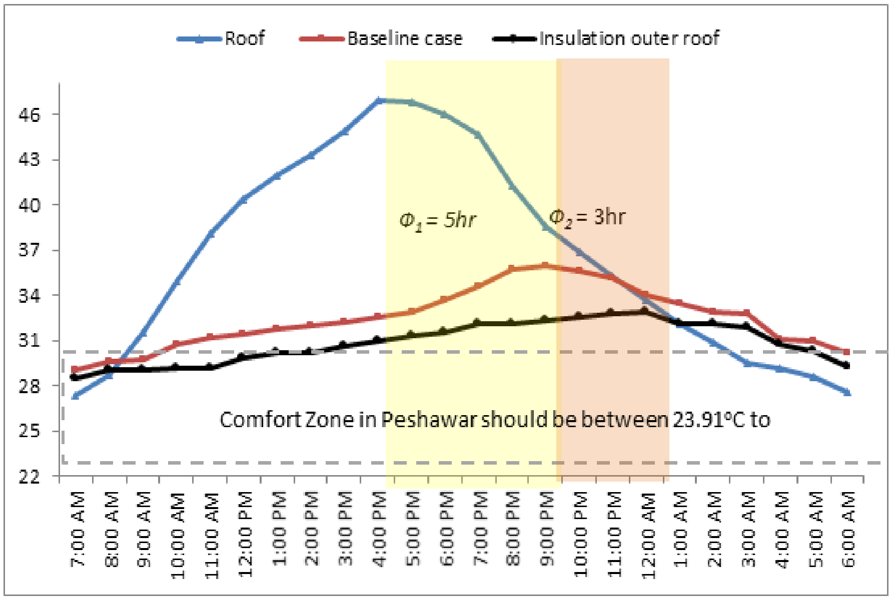


Figure 10 Error! Reference source not found.Straw Bale Effect in summer (Room 5)

Figure 11 shows the indoor temperature for the room -1 which is not exposed to the sunlight and need to improve thermal comfort for the winter.

The result shows that room temperature in the winter should up to the thermal comfort level but it does not happen where roof temperature showing higher than the insulation installed temperature inside room is lower the comfort level. Therefore, the obtained temperature result still does not meet with ASHRAE Standard 55 and literature recommended temperature value for the thermal comfort [24-28].

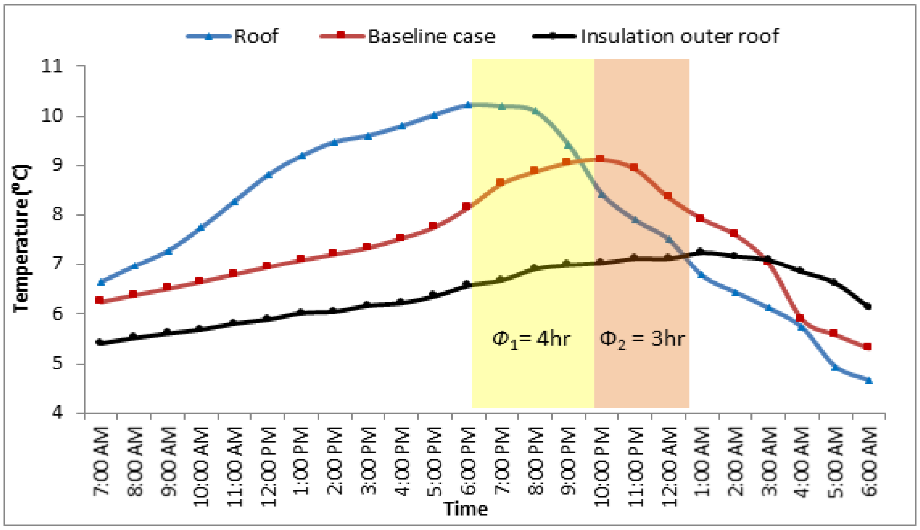


Figure 11 Straw Bale Effect in winter (Room 1)

5 Discussions

Experimental temperature of the 5 room's residential building was measured July 2019 and January 2020 by using digital logger. Study found the 2nd day of January 2020 has the lowest and 11th day of July has the highest indoor room temperature. The experimental collected temperature data is compared and validated with predicted temperature simulation using CFD modelling. The predicted temperature for January and July has almost similarity with slightly difference of less than 20% with experimental data as shown in the figures 8 and 9 above. The predicted and experimental measured temperature data shows that existing roofing system in the residential buildings does not provide comfort as per the ASHRAE Standard-55. To achieve comfort in the residential buildings the indoor temperature should be between 23.91 °C to 30.91 °C for summer and 18.2 °C to 25.2 °C for winter [24-28].

The findings indicated that existing roofing is not providing thermal comfort to the occupants so to achieve the thermal comfort in the buildings straw bale was installed on the roof top.

The effect of straw bale installation was studied by comparing the simulation results of the CFD model including the straw bale with those obtained from the CFD model of the baseline case. The results showes that installing straw bale insulation material on the top of the roof has slight effect on the indoor temperature; it slightly reduced the temperature during summer and slightly increased during winter. However, the temperature was still not in the range specified by the ASHRAE standard-55 and previous studies. To meet with the ASHRAE standard-55 to maintain thermal comfort in the residential building, study has further performed used other types of insulation materials to improve the thermal comfort which is elaborated in another research paper.

6 Conclusion and Recommendations

Pakistan is listed among top most climate change risk indexed countries. Additionally, country has the highest power energy crises and difference between production and consumption where heavy load shedding of 8-10 hours in rural and 3-5 in the urban area causes discomfort among the occupants. During July and January has the highest and lowest temperature in the Peshawar city densely populated and once poorly managed city of the country.

This study conducted simulation based research where straw bale effect on the roof top has monitored and compared. Experimentally, house with 5 rooms exposed to the sunlight from all the directions has taken as a study sample and temperature in July 2019 and January 2020 recorded. Study concluded the average daily highest temperature 36.42 ^{0}C recorded in the room 5 on the 11th day of July 2019 conversely lowest daily temperature 5.42 ^{0}C is recorded in the room 1 on the second day (2nd) of the month January 2020. Room 5 is exposed to the solar radiation from all directions and room 1 is less exposed to the solar radiation.

Study has concluded daily average temperature in July was higher than the recommended thermal comfort range and likely in the January the daily average temperature was lower than thermal comfort range. By the installation of Straw bale thermal insulator material on the roof top has slightly reduce the temperature 30.85 ^{0}C in July and slightly increase in the January but this temperature changes still did not meet with the ASHARE Standard -55 for the comfortable environment in the residential buildings. This study has concluded that straw bale slightly effect thermal temperature of the rooms but cannot achieve the thermal comfort in the buildings. In the line, more studies have recommended to use other natural and recycled thermal insulator materials and compare the result. The placement of thermal insulator material in buildings is essential to promote green construction projects more future studies required.

Conflict of Interest: There is no conflict among the authors.

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