IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 38, No. 1, March, 2020, pp. 131-136
Journal homepage: http://iieta.org/journals/ijht

Heat Transfer Characterization of Test Rooms with Six Different Roofs

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https://doi.org/10.18280/ijht.380114

Received: 12 July 2019
Accepted: 25 January 2020

Keywords:
building heat transfer, building envelope, built environment, cooling load, energy efficiency in buildings

ABSTRACT

Six test rooms each with different roof type (RCC roof; galvanized iron sheet roof; lawn over RCC roof; wet-sand bed over RCC roof; clay tile roof and thatched roof) under summer weather conditions are studied to analyze and quantify the role of roof element in reducing solar gain. The study also addresses the effects of roofing element on the test room temperatures. Results have shown that, lawn over the RCC roof could be the best choice among the considered. On the other hand, clay tile roof and thatched roof are found to be better than RCC roof as far as heat gain is considered. It is also observed that, clay tile roof providing better breathing effects as compared to thatched roof.

1. INTRODUCTION

Energy crisis is a common problem all over the world. 20% - 40% of energy consumption is based on buildings and materials used for the buildings [1-3]. The energy consumed by the buildings are either for lighting or for heating, ventilation and air condition (HVAC). Present work mainly addresses the latter, in particular, cooling load. Summer is unbearable in tropical regions as it causes an increase in cooling load demands. The major reason for the cooling load is heat transfer through the building envelope, in particular the roof [4-6]. It is observed that around 60% of heat gain is through the roof. Most of the earlier studies report the influence of weather conditions [7, 8], thermo-physical properties of the roof material [9, 10] and radiative properties of the roof surfaces [11, 12] on the thermal environment inside the buildings. It was found that if the diurnal variation in the ambient air temperature is more than 10K, then the thermal mass of the roof will have significant effect on the built environment conditions [12]. Based on the thermal mass, the roof material could either be of high thermal inertia or lower thermal inertia. Good thermal insulators will have adverse effects during night time [13]. On the other hand, roofs with high reflectance that are popularly called as cool roofs eventually shows decrease in their performance as they are subjected to dust, corrosion etc. [14]. High reflectance of the roof reduces solar gain during the day time, but it also reduces heat loss from inside to outside during night time. Apart from this, many researchers proposed different passive cooling techniques and each of them have their own pros and cons. Roof gardens over real buildings have been extensively studied [15-18] which revealed that cooling load can be significantly reduced. But the studies could not quantify the effect of lawn on cooling load. In hot and arid regions, having roof gardens or roof ponds is not feasible. In such cases, use of clay tile roof or thatched roof can be better options. But there is a lack of study on such roofs. In order to choose an optimum roof type that suits these crouching heats, it is necessary to know the effect on inside air temperature among varied roofs; an effective passive way to achieve better thermal comfort inside the buildings. On the other hand, it is important to analyze the modes of heat transfer inside a room as it could be useful to improve the thermal environment of the room. This paper presents the experimental analysis of six different types of roofs that include RCC, GI sheet, lawn over RCC, wet sand bed over RCC, clay tile, and thatched roofs in having attained subsequent inside air temperatures. This comparative analysis of the heat transfers among roofs is first of its kind which could be of interest to researchers, engineers, policy makers and individuals suggesting the best suitable roof for housing depending on the local weather conditions. These experiments were setup to see how the inner surface temperatures between the roof and floor get affected due to different roofing elements.

2. DETAILS OF EXPERIMENTAL SET UP

Six test rooms were built and the thermo-physical properties of the materials used in construction are tabulated in Table 1. Use of scaled building models in the thermal environment analysis were in practice for several decades as reported by Yoon et al. [19, 20]. On the other hand, there are numerous literary proofs of the analysis on (a) wind effects [21], (b) solar power utilization [22] and (c) thermal performance in comfort potential of low-rise or shallow buildings [23]. Similarly, Nahar et. al. [24], reported the analysis of different passive cooling techniques for RCC roof for which the authors used small test structures. The authors mentioned the use of GI sheets as side walls which can mask the role of roof as the thermal conductivity of RCC roof which is considerably small as compared to that of GI sheet.

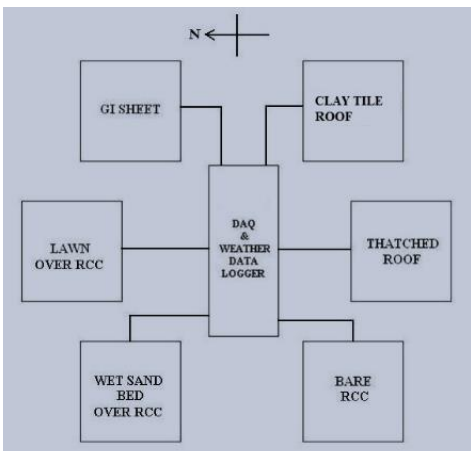
In the present work shallow enclosures were considered for the roof characterization studies. T-type thermocouples were used for temperature measurements in the test rooms. The Agilent data acquisition system was used for recording temperatures from thermocouples. Pyranometer and thermo-hygrometer were used for measuring solar radiation, ambient air temperature and humidity. The test rooms were built over the terrace of a building ensuring direct sunlight and no shade upon the test rooms between 9:00 hrs till 17:00 hrs as shown in Figure 1(a) and (b). The schematic of the experimental set-up is shown in Figure 2(a). The locations of thermocouples in the test rooms are shown in Figure 3.

Four test rooms of size 100 cm X 100 cm X 30 cm size were covered with RCC roof, GI sheet roof, lawn over RCC roof and wet-sand bed over RCC roof respectively. The other two rooms had tiled roof and thatched roof with one side slope. The slope was 30º with smaller height being 30 cm. The details of the geometry are given in Figure 4. It should be noted that all the test rooms had side walls made of thermocol material and the bottom slab was RCC slab of size 1m X 1m X 0.15m with its outer surface insulated using thermocol. All the side walls and outer surface of the bottom slab were essentially made adiabatic where the heat transfer was negligible when compared with that through the roof in order to see the effect of roof on the inside temperature. Ambient temperature and solar radiation were measured in the same location where the test rooms were built.

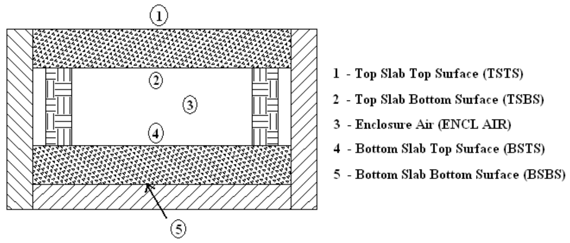
(a) (b)

Figure 1. (a) Test rooms as numbered in the picture - (1) bare RCC roof, (2) thatched roof, (3) clay tile roof, (4) GI sheet roof, (5) lawn over RCC roof, (6) wet sand bed over RCC roof, and, (7) data acquisition; (b) photo taken while building the test rooms

The author used a few abbreviations for the important parts of the setup that might appear often further in the paper. Following are the abbreviations used: (a) top surface of the top slab – TSTS, (b) bottom surface of the top slab – TSBS, (c) enclosure air – ENCL AIR, (d) top surface of the bottom slab – BSTS, and, (e) bottom surface of the bottom slab – BSBS. The abbreviations were also listed in Figure 2(b).



(a)

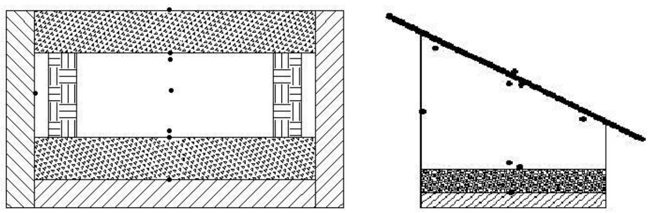


(b)

Figure 2. (a) Experimental set-up plan - Schematic view and (b) abbreviations used in the present paper

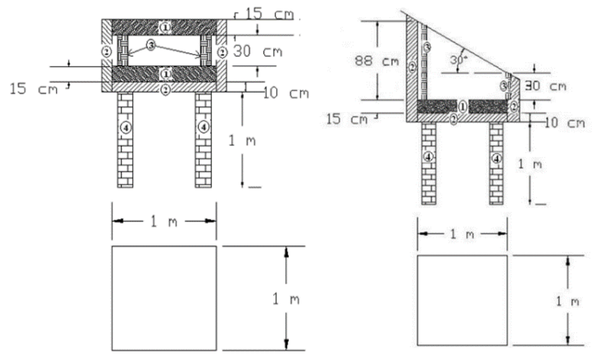
Table 1. Thermophysical properties of important materials used in the test rooms

Material	Thermal conductivity (W/m-K)	Density (kg/m^3)	Specific heat (J/kg-K)
Concrete	1.3	2300	900
GI sheet	5-60	7900	400
Clay tiles	0.85	1900	840
Thatch	0.1	120-230	1800
Thermocol	0.1 – 0.2	25	1000



(a) (b)

Figure 3. Thermocouple locations in test rooms with (a) bare RCC roof and, (b) thatched roof



(a) (b)

Figure 4. Basic geometry details and materials used in the test room. Parts numbered in the figures denote materials used. 1-RCC slab, 2-Thermocol (Expanded Poly Styrene), 3-Wooden supports and 4-Columns made of concrete blocks supporting whole test room

3. RESULTS AND DISCUSSION

Nowadays, over 29% of buildings in India have RCC roofs [3]. Hence the test room with bare RCC roof is assumed as the control in the present study. Details of weather conditions on the experimental days are furnished in Figure 5. The temperature variations recorded in all the six test rooms are as shown in Figures 6 to 11. The details of the abbreviations used are given in Figure 2(b).

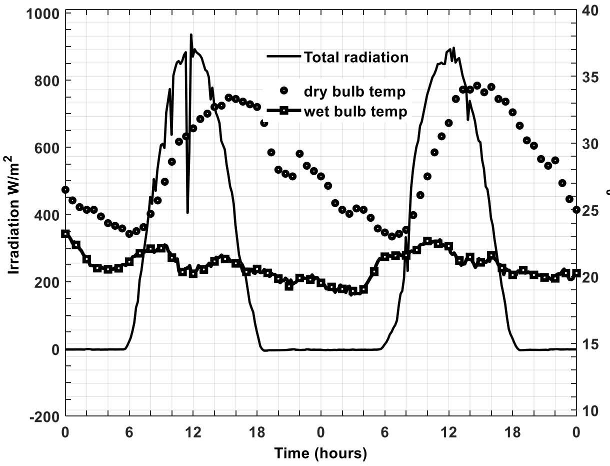


Figure 5. Solar radiation, dry bulb and wet bulb temperature as observed on May 20-21, 2012

The test rooms were essentially enclosures in the present experiments to avoid ventilation effects and to completely capture roof effects. In case of the test room with bare RCC roof represented in Figure 6, high thermal inertia of RCC caused a delay of around two hours between the T_{TSTS} and T_{TSBS} peaking. $T_{ENCL\ AIR}$ peaked around 5:30pm. In case of GI sheet roof it was different as shown in Figure 7. Thermal mass of 0.75 mm thick GI sheet was 127 times lower than that of 150 mm thick RCC slab. The test room with GI sheet roof responded quickly to the changes in the weather conditions. Negligible delay in enclosure inside temperatures can be observed in this case. Maximum T_{TSTS}, T_{TSBS} and $T_{ENCL\ AIR}$ were higher that can be observed in case of RCC roof. But the minimum of the same temperature values was lower than the RCC roof.

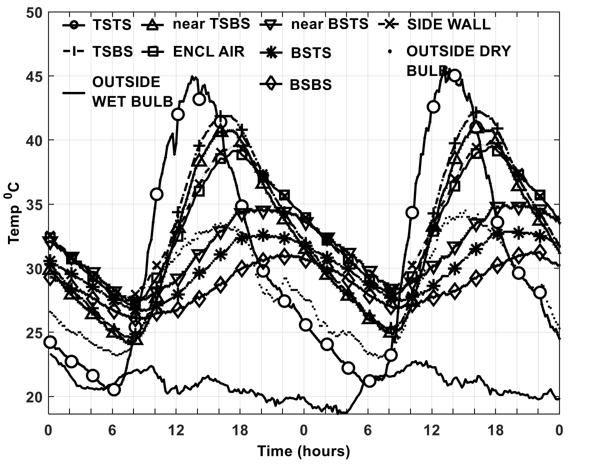


Figure 6. Temperature variations with time – test room with bare RCC roof

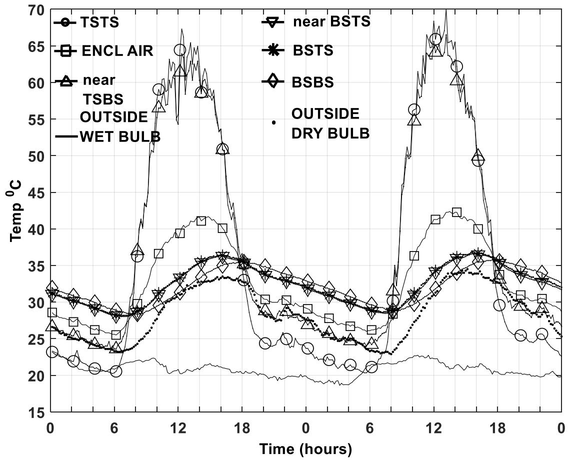


Figure 7. Temperature variations with time – test room with GI sheet roof

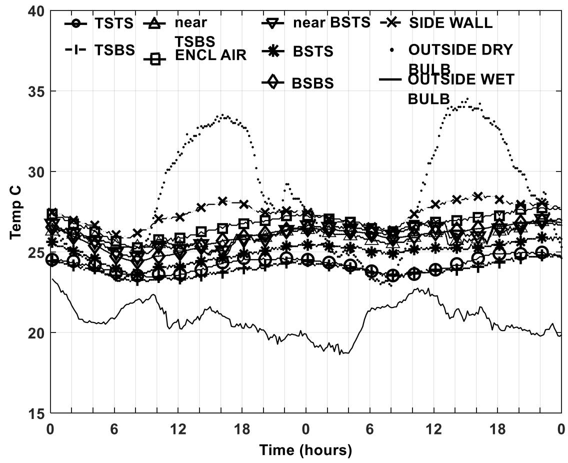


Figure 8. Temperature variations with time – test room with lawn over RCC roof

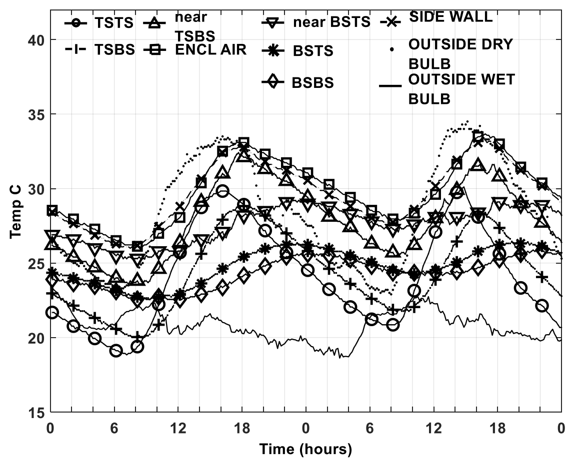


Figure 9. Temperature variations with time – test room with wet-sand bed over RCC roof

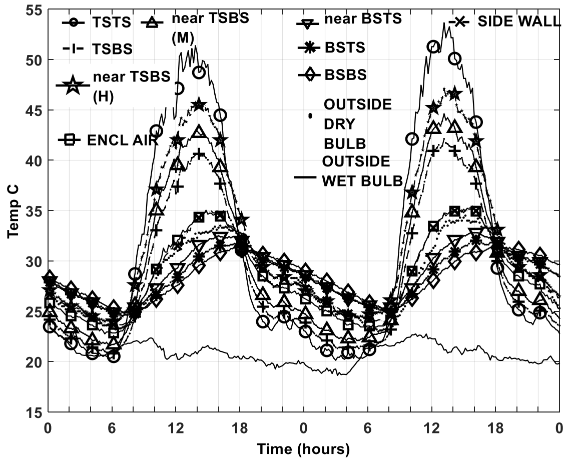


Figure 10. Temperature variations with time – test room with clay tile roof

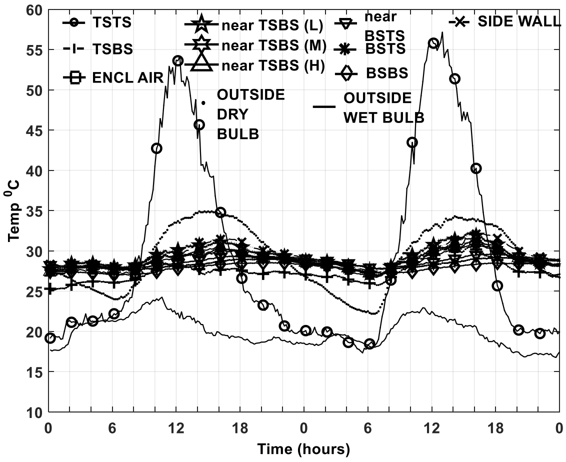


Figure 11. Temperature variations with time – test room with thatch roof

The test room set ups with lawn and wet-sand beds over RCC roofs could provide the details of additional effects of evapo-transpiration [17, 18] and evaporation [25], respectively. In the case of lawn over RCC, range of variation in the temperatures reduced significantly as referred in Figure 8. This is because of evapo-transpiration and additional thermal mass of soil. Wet-sand bed could also reduce the temperatures. But the range of variation is relatively higher as compared to the lawn case as shown in Figure 9.

Both evaporation and additional wet-sand thermal mass cause reduction in temperature variation. It should be noted that the weight of the sand used is approximately 3.5 times less than that of soil used in case of lawn. The height of soil-stone-brick bed of the lawn was about 18 cms and the height of sand bed was 5 cms. Both lawn and sand were watered everyday between 7 am and 8 am. $T_{ENCL\ AIR}$ was found to be higher in case of wet-sand bed than in case of lawn. In both the cases, heat transfers through the side walls were considerable though they were made of thermocol. As the roof was receiving cooling effect due to lawn and wet sand, the side walls downplayed. Due to this, $T_{ENCL\ AIR}$ was found to be higher than both top slab and bottom slab temperatures. From the study, it looked like the thermal performance of wet sand bed can be improved by increasing its thermal mass. But at this point, lawn over RCC roof seems to be better than wet-sand bed over RCC roof. In both these cases, it was observed that RCC roofs have lowest temperature which is due to the fact that lawn or wet-sand bed are placed above the top slab.

Test rooms with clay tile roof and thatched roof had 30^o slopes. Arrangement of tiles in case of the clay tile roof was such that the gaps between the tiles allowed air flow but not the rain water to get inside the test room. Whereas in case of thatched roof, it was porous in nature which could allow both water and air to pass through it. However, the slope of the roof could prevent the rain water getting inside the test room. Clay tiles have relatively high thermal conductivity and high thermal mass when compared to thatch. $T_{ENCL\ AIR}$ in case of the clay tile roof was more or less same as that of $T_{ambient}$ throughout the day as shown in Figure 10. It was noted that T_{TSBS} was much higher than $T_{ENCL\ AIR}$ which shows that the breathing action was very effective in the test room with clay tile roof. T_{TSBS} and $T_{ENCL\ AIR}$ were almost same in case of thatched roof as referred in Figure 11. During the day time, thatched roof $T_{ENCL\ AIR}$ was much lower than $T_{ambient}$ but it was reversed in the night time. This shows that breathing effects in case of thatch are less as compared to that in case of clay tile roof.

Roof outer surfaces attained lowest temperature during early morning in all the cases. It was observed that T_{TSTS} was much lower than $T_{ambient}$ and was almost close to T_{wet} which is due to the fact that the TSTS loses heat to sky by radiation. But in case of wet-sand bed, though the RCC roof surface was not exposed to the sky, both T_{TSTS} and T_{TSBS} are found to be lower than T_{wet}. This issue has remained unclear and hence further investigations are required.

Assuming the air inside the test rooms as a lumped mass, heat content inside the test room can be given as a product of mass of air (m_{air}), specific heat of air (C_{pair}) and $T_{ENCL\ AIR}$. In the present analysis, test room with bare RCC roof has been assumed as control. In order to see the effectiveness of the considered roofs, the heat content inside the test rooms (test rooms other than that with bare RCC roof) are compared with the test room with bare RCC roof using Eq. (1) given below.

$$\frac{\left(\boldsymbol{m_{air} X\, C_{p_{air}} X\, T_{ENCL\, AIR}}\right)_{avg_X} - \left(\boldsymbol{m_{air} X\, C_{p_{air}} X\, T_{ENCL\, AIR}}\right)_{avg_{RCC}}}{\left(\boldsymbol{m_{air} X\, C_{p_{air}} X\, T_{ENCL\, AIR}}\right)_{avg_{RCC}}} \tag{1}$$

where, X represents test room other than that with bare RCC roof.

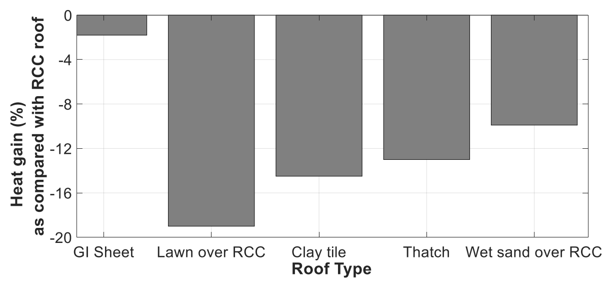


Figure 12. Percentage of average heat content per day in different test rooms as compared to that with bare RCC roof

Figure 12 shows the average percentage of heat gain or loss based on Eq. 1 in a given day. The experiments were carried out in a warm tropic region close to the equator. Hence, the current observations could be true for all such similar regions. It can be seen that lawn over RCC roof can reduce 19% of heat content inside the test room as compared to that in case of the bare RCC roof. On the other hand, wet-sand bed over RCC roof is showing a 10% reduction in a given day but it should be noted that the thermal mass of wet-sand bed much be lower than when compared to lawn soil. Clay tile roof and thatch roof are also showing approximately 14.5% and 13% reduction in heat content inside the test rooms respectively. In case of thatched roof, during night time, $T_{ENCL\ AIR}$ is higher than $T_{ambient}$ which can be reduced by implementing night ventilation techniques.

4. CONCLUSIONS

The proposed research approach can help us in quantifying the thermal performance of a roof. The same idea can be used in analyzing the role of side walls as well. Following are the important outcomes of the present work.

• Lawn over RCC is found to be the best choice among the tested six roof elements but it needs heavy maintenance. Thermal performance of wet-sand bed over RCC roof can still be improved as the sand bed does not demand heavy maintenance. From the present work, it can be concluded that lawn over RCC roof can reduce cooling load by 19% and the same with wet-sand bed over RCC roof reduce cooling load by 10%.

• Though RCC slab surface, in case of wet-sand bed was not exposed to open sky, the temperatures are found to be lower than the wet bulb temperature during early morning and the issue is unanswered in the present study.

• Breathing effects are stronger in case of clay tile roof as compared to that of thatch roof.

• Clay tile roof and thatched roof are found to be better than bare RCC roof with 13%-14.5% reduced cooling load.

• Coupling night ventilation techniques in case of thatched roof can make it better than clay tile roof.

ACKNOWLEDGMENT

This research was partially supported by Center for infrastructure, Sustainable Transportation & Urban Planning (CiSTUP), IISc. The researcher is immensely grateful to Jaywant H Arakeri (Professor, IISc-Bangalore) and K R Sreenivas (Professor, JNCASR-Bangalore) for their comments on an earlier version of the manuscript. Researcher is solely responsible for any errors if found and should not tarnish the reputations of these esteemed persons.

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