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Thermal Performance of Composite Roof Structures with Insulating Layers in Non-Conditioned Buildings for Hot-Dry Climate

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Abstract*: The roof configurations with an insulating layer and their impact on hourly floating temperature analyzed in a hot-dry climate context. A predefined computer program using a modified Fourier admittance method utilized as the primary research. The thermal performance of ten composite roof structures evaluated to obtain optimal roof structure for hot-dry climate, Jodhpur. Nine composite roof structures with an insulation layer and one without insulation layer as the base case were analyzed for the summer months (April-September). The utilization of roof thermal insulation showed a significant influence on the overall thermal performance of roofs. It also revealed that minimum temperature variation found about 8.8 ^{0}C for the composite roof structure of Reinforced Cement Concrete (RCC) with foam concrete insulation (i.e., RF-5) with thicknesses 150 mm and 140 mm respectively. The analysis assessed that composite roof structure with an insulating layer is a useful technique to reduced indoor temperature in non-conditioned buildings of hot-dry climate.

Keywords: Fourier admittance method, Heat Gain, Hot-dry climate, Thermal comfort, Simulation.

I. INTRODUCTION

The energy consumption in buildings accounts for about 40% of total world energy, and residential and commercial sectors of buildings consume 60 % of the world's electricity. Buildings have become the primary source of global greenhouse gases emissions due to the use of an air conditioning system [1].The building generally uses most of the energy is an air-conditioning and ventilation system in hot climates. Heat transmission by conduction through roofs and walls characterizes the significant component of the entire thermal load. The amount of energy utilized in the air-conditioning process directly linked to the buildings thermal load [2].In developing countries, worldwide buildings require the best thermal comfort for the occupants with the lowest energy consumption and greenhouse gas emissions. Therefore, the objective of achieving high energy efficiency is critical, and one of the cost-effective strategies is thermal insulation of building envelope [3]. Roof contributes tremendously to building heat gain compared to walls because it exposed to the sun throughout the day. Heat through the roof can be reduced by applying thermal insulation on the roof or installing insulation under the attic roof. Thermal insulation of roofs is an inexpensive method to save energy and to improve the comfort level [4].

In hot-dry climates, the buildings built with bricks, stones, cement, and flat roofs constructed of sandstone slabs and steel girders. This climate characterized by high temperatures, low humidity, less rainfall, and intense solar radiation in summer. The mean monthly temperature and relative humidity are 30 ^{0}C and 55 %, respectively. In the summer, temperature varies from 40-45 ^{0}C with diurnal variation 15-20 ^{0}C, which leads to uncomfortable conditions. To maintain thermal comfort for buildings in the summer period is a big concern in these regions [5]. India is a tropical country that received an average annual solar insolation between 4-7 kWh/m^2. It leads to a higher temperature and higher cooling energy consumption in the buildings during the day time operation of summer. Roofs received maximum solar radiation among all building envelopes, so energy efficient roof plays a vital role in reducing the energy consumption of buildings in the hot climate. There are three solutions to reduce the heat transfer into the buildings, i.e., roof insulation, cool roof, and radiant barriers. Roof insulation is conventional and widely used in India also it reduces the effectiveness of passive strategies and reduces indoor thermal comfort [6]. The thermal insulation is one of the most valuable techniques in achieving energy conservation in buildings. It also helps to reduce building energy use (heating and cooling of space) and to maintain a required indoor thermal comfort for occupants. The most common thermal insulations used are fiberglass, wood wool, mineral wool, rock wool polyethylene, polyurethane, and polystyrene [7]. In this paper, the study based on a modified Fourier admittance method to see the influence of the different roof structures with an insulating layer and prediction for hourly floating temperature for the non-conditioning building of hot-dry climate, Jodhpur. The study represented a comparative analysis in terms of minimum hourly floating room temperature for the selection of the roof configuration for six months (April-September) including summer season

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II. ANALYSIS

A. Admittance Method

The matrix equation related to temperature and energy cycle expressed as [8].

$$\begin{bmatrix} T_0 \\ Q_0 \end{bmatrix} = \begin{bmatrix} A & B \\ D & A \end{bmatrix} \begin{bmatrix} T_i \\ Q_i \end{bmatrix} \quad (1)$$

where, T_0 and Q_0 represents the temperature and heat flux at the two surfaces of the slab. The matrix elements in equation (1) defined as

$$A = \cosh(1 + j)\emptyset \quad (2)$$

$$B = \frac{L}{K(1+j)\emptyset} \sinh(1 + j)\, \emptyset \quad (3)$$

$$D = \frac{K(1+J)\emptyset}{L} \sinh(1 + j)\, \emptyset \quad (4)$$

where, $\emptyset = \left(\frac{\pi L^2 \rho C}{24K}\right)^{1/2}$

L, K, ρ and C, the thickness, thermal conductivity, density and specific heat of the roof slab respectively. Symbol j indicates the unit imaginary number $\sqrt{-1}$.

B. Fourier Method

For the analysis of all time dependent functions i.e. ambient temperature, room temperature and solar radiation etc. have been resented in terms of Fourier series as [9]

$$f(t) = \sum_{-x}^{+x} f_n \exp(in\omega t) \quad (5)$$

The heat flux transmitted through the roof expressed as

$$Q = A_R \sum_{-x}^{+x} \frac{S_n\left(T_{rn} + \frac{\alpha_i I_{i\omega n}}{h_i}\right) - \left(T_{an} + \frac{\alpha_o I_{on}}{h_o}\right)}{Q_n} \times \exp(in\omega t) + A_R \sum_{-x}^{+x} (\alpha_i I_{i\omega n}) \exp(in\omega t) \quad (6)$$

where S_n and Q_n dependent on thermo-physical properties of roof materials and A_R is the area of the roof slab.

$$M_\tau \frac{d}{dt} = \sum_{-x}^{+x} T_{y=a,R,W} \exp(in\omega t) = \sum \dot{Q}_i \quad (7)$$

where, M_τ is the thermal mass of the room air and $\dot{Q}_i$ is a heat gain due to the infiltration from ambient into room.

The solution of equation (7) governs different harmonics of the room air temperature and same can be combined together to give hourly floating room temperature i.e.

$$T_r(t) = \sum_{-x}^{+x} T_{y=a,R,W} \exp(in\omega t) \quad (8)$$

III. RESULT AND DISCUSSION

The requirement of thermal comfort in buildings is a primary need in buildings specially located in hot-dry climatic zones. The presence of intense solar radiation and higher variation in surrounding temperature caused discomfort levels in non-conditioning buildings during the summer. The need for air-conditioning systems enhanced in building constructed with conventional roofs. Thus the simulation study carried out for different roof structures with one layer of insulating materials and its impact on hourly floating indoor temperature investigated.

A typical room of a non-conditioned building was selected for simulation with roof area 48.75 m^2. The room has two windows (size 1.05 m^2 each) facing east and west and door (size 2.0 m^2) assumed to be located on the east side. The height of the ceiling was 2.70 m. The studied model indicated in Fig. 1.

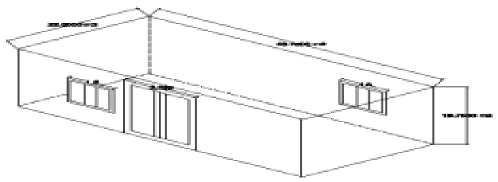


Fig.1 Schematic of the room model

The dimensions of building envelopes represented in Table I and for the investigation, ten different types of roof configurations with the insulation layer selected.

Table I: Dimensions of building envelopes

S. No.	Details	Dimensions [L × W] (m)	Area (m^2)
1	Roof	7.5 × 6.5	48.75
2	East and West Wall	6.3 × 3.1	19.53
3	South and North Wall	5.5 × 4.1	22.55
4	East and West Window	1.5 × 1.0	1.50
5	Door	2.2 × 1.0	2.20

Thermal performance evaluated and impact in terms of indoor temperature in a hot-dry climate. In ten roof configurations, eight roof structures with insulation and two roof structures without insulation taken for simulation. The allocated notations and details of different roof configurations described in Table II. The thermo-physical properties of all components of the walls and roofs used in the simulation given in Table III. Simulation performed in the summer season (April to September) of Jodhpur, India. The climatic parameter i. e. mean monthly radiation and the ambient temperature of Jodhpur (26.2° N, 73.0° E) have shown in Fig. 2.

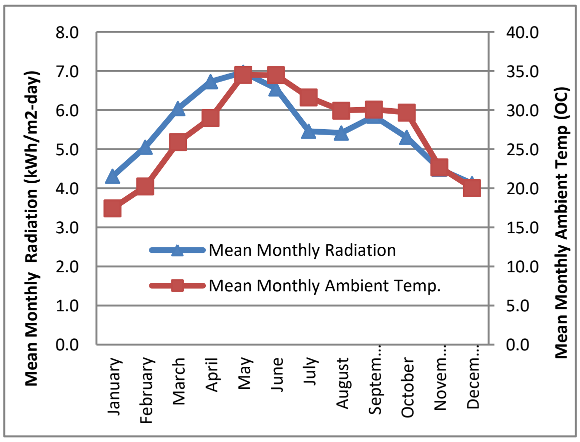


Fig. 2 Climatic parameters for Jodhpur

Table II: Details of different configuration of roofs and walls

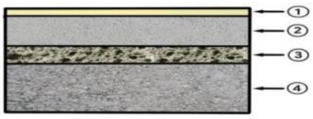
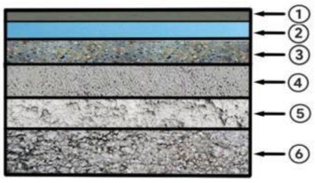
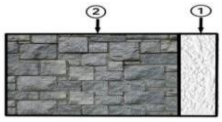
S. No.	Composite Structure	Material detail & layer dimension
1	Base Case 	1. Lime Concrete 100-150 mm) 2. Plaster (15 mm) 3. Stone (110 mm)
2	RF-1 	1. Elastospray insulation (50 mm) 2. RCC (120 mm)
3	RF-2 	1. PUF insulation (50 mm) 2. RCC (150 mm)
4	RF-3 	1. Expanded Polyurethane Insulation (70 mm) 2. RCC (150 mm)
5	RF-4 	1. Fiber Glass Insulation (80 mm) 2. RCC (150 mm
6	RF-5 	1. Foam Concrete Insulation (140 mm) 2. RCC (150 mm
7	RF-6 	1. Concrete (100 mm) 2. Interior Plaster (20 mm)
8	RF-7 	1. Concrete (100 mm) 2. Glass Wool (20 mm) 3. Plaster (20 mm
9	RF-8 	1. Polyurethane Hard form plastics (14 mm) 2. Cement Mortar (45 mm) 3. Lightweight aggregate concrete (20 mm) 4. RCC (120 mm)
10	RF-9 	1. Coil waterproof layer (2 mm) 2. Extruded polystyrene board (14 mm) 3. Fine stone concrete (20 mm) 4. Cement mortal (20 mm) 5. Lime, Cement, Sand and Mortar (25 mm) 6. RCC (110 mm)
11	Walls 	1. Plaster (150 mm) 2. Stone (450 mm)

Table III: Thermo-physical properties of roofs and walls materials investigated [10, 11, 12, 13].

Details	Materials	Thermal conductivity (k) (W/m K)	Specific Heat ($J/kg^{O}C$)	Density kg/m^3
Base Case	Lime concrete	0.73	880	1646
	Plaster	0.72	840	1762
	Stone	1.80	800	2240
RF-1	Elastospray Insulation	0.023	1080	43.8
	RCC	1.28	1130	2300
RF-2	PUF Insulation	0.027	820	32.0
	RCC	1.28	1130	2300
RF-3	Expanded polystyrene Insulation	0.038	1130	16
	RCC	1.28	1130	2300
RF-4	Fiber Insulation	0.040	1000	16
	RCC	1.28	1130	2300
RF-5	Foam Concrete Insulation	0.070	920	320
	RCC	1.28	1130	2300
RF-6	Concrete	1.37	840	2076
	Interior Plaster	0.70	840	2078
RF-7	Concrete	1.37	840	2076
	Glass wool	0.038	700	24
	Interior Plaster	0.70	840	2078
RF-8	Polyurethane hard foam plastics	0.025	1380	40
	Cement Mortar	0.93	1051	1800
	Lightweight aggregate concrete	0.89	600	1600
	RCC	0.59	1220	2500
RF-9	Coil waterproof layer	0.175	1465	600
	Extruded polystyrene board	0.030	1386	30
	Fine Stone Concrete	1.74	920	2500

	Cement Mortar	0.93	1050	1800
	Lime, cement, sand and mortar	0.87	1050	1700
	RCC	0.59	1220	2500
Walls	Stone	1.80	800	2240
	Plaster	0.72	840	1762

A computer simulation carried out for different configurations for ten roof structures, i.e., Base Case, RF-1, RF-2, RF-3, RF-4, RF-5, RF-6, RF-, RC-8 and RF-9. The study evaluated hourly floating room temperature for six months (April-September) and its variation for twenty-four hours cycle period, as shown in Fig. 3 to Fig. 8.

Fig. 3 and Fig. 4 represent hourly floating room temperature for all roof structures in the month of April and May. Variation in maximum and minimum temperature for roof structure 6 (RF-6) was noted as 12.3^{0}C and 11.8^{0}C respectively. Roof structure 5 (RF-5) gave best performance with maximum and minimum temperature variation of 4.3^{0}C and 4.0^{0}C for April and May respectively.

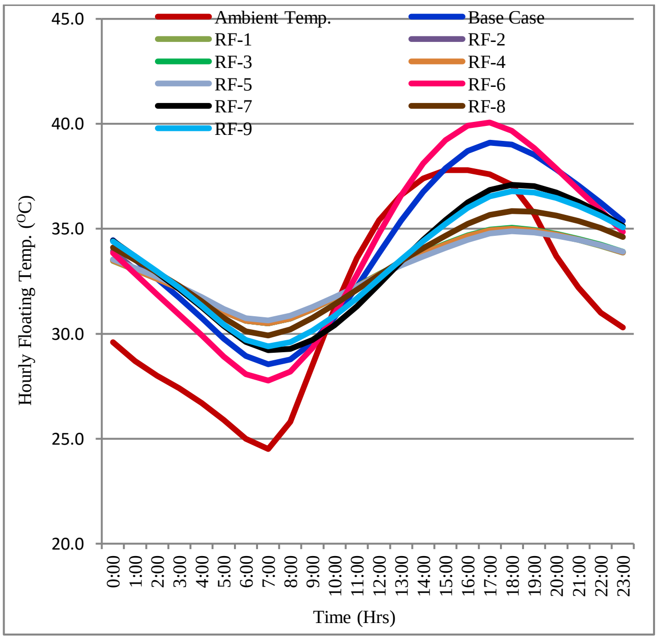


Fig. 3 Hourly floating room temperature in April

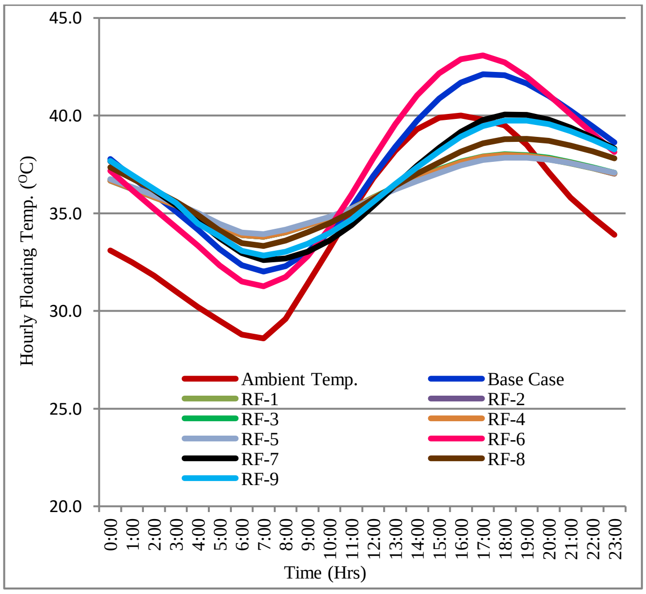


Fig. 4 Hourly floating room temperature in May

Likewise, in the month of June the hourly floating room temperature for structure RF-6 and RF-5 were 9.7^{0}C and 3.1^{0}C respectively. In this month all roofs structure, performed better compared to month of April and May except base roof, which, performed was noted much similar to RF-6 with the temperature variation about 8.2^{0}C.The rate of heat transfer from environment is higher in both structures due to the lack of insulation layer(See Fig. 5).

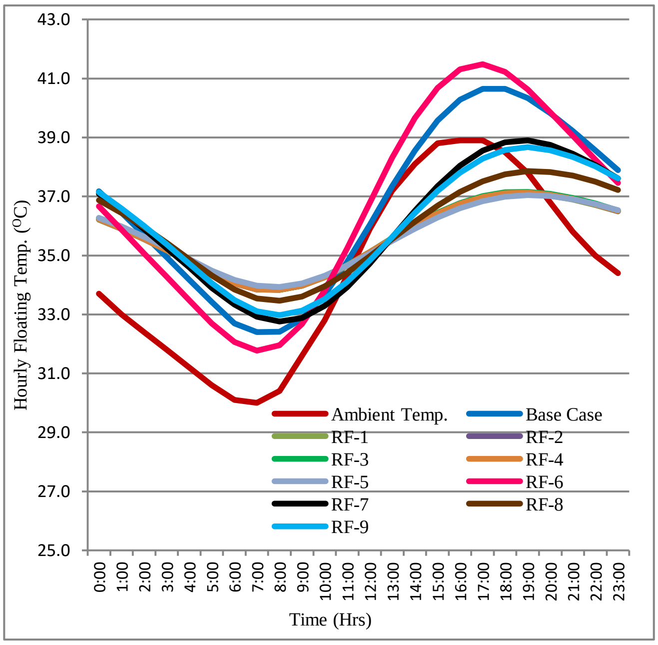


Fig. 5 Hourly floating room temperature in May

Similarly, in July temperature variation in all roof structure was quite less as compared to May and June, except RF-6 and Base roof (See Fig. 6). It may be due to lower intensity of the solar isolation and outdoor temperature.

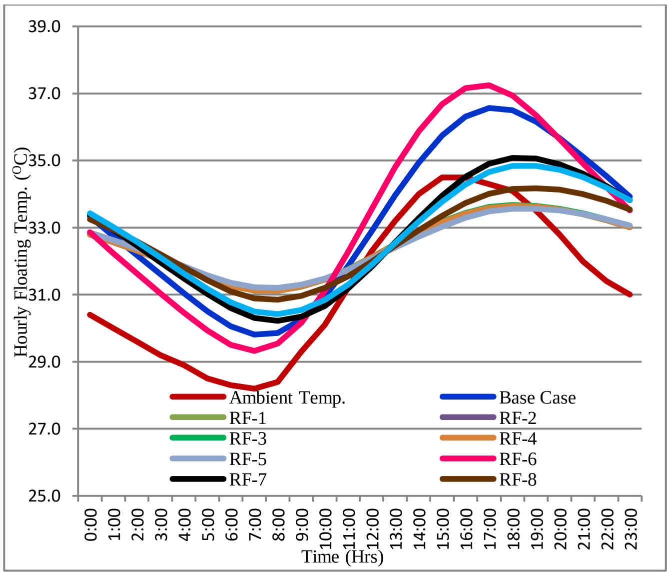


Fig. 6 Hourly floating room temperature in July

The maximum and minimum temperature fluctuation (7.6 ^{0}C and 2.2 ^{0}C) was achieved for RF-6 and RF-5 in the month of August (See .7). Close look of figure 2.16 reflect that other roofs performance was quite brilliantly in this month except base case with the temperature variation about 6.5 ^{0}C.In September,RF-5 performed well with minimum hourly floating temperature of 2.7 ^{0}C (See Fig. 8). Not much improvement was observed for roof structures Base roof and RF-6.

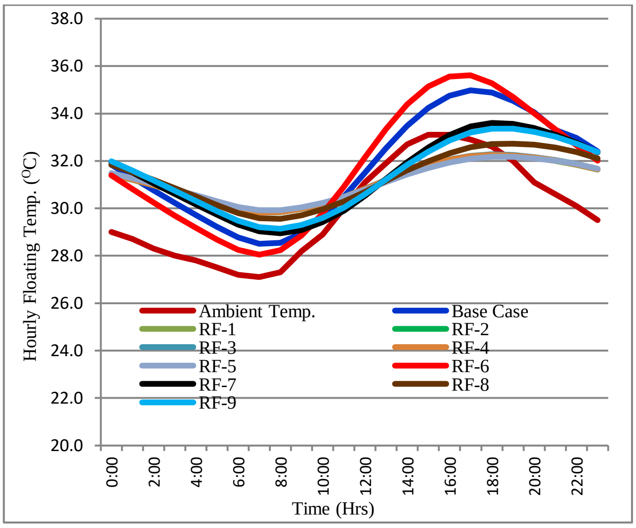


Fig. 7 Hourly floating room temperature in August

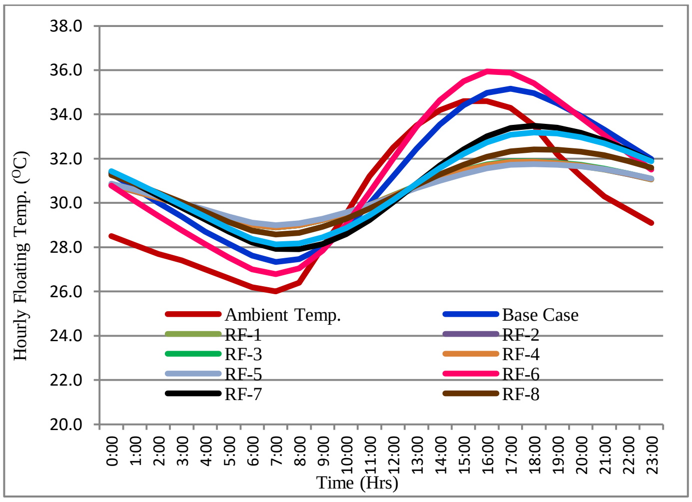


Fig. 8 Hourly floating room temperature in September

Month wise performance in terms of maximum and minimum hourly floating indoor temperature of all roof structure for Hot-dry climate (Jodhpur) is shown in Table IV.

Table- IV: Maximum and minimum room temperatures (^{0}C) in all roofs structures (April-September) for hot-dry climate, Jodhpur

S. No.	Details	April			May			June			July			August			September		
		T_{Max}	T_{Min}	ΔT	T_{Max}	T_{Min}	ΔT	T_{Max}	T_{Min}	ΔT	T_{Max}	T_{Min}	ΔT	T_{Max}	T_{Min}	ΔT	T_{Max}	T_{Min}	ΔT
1	Base Case	39.1	28.6	10.6	42.1	32.0	10.1	40.7	32.4	8.3	36.6	29.8	6.8	35.0	28.5	6.5	35.2	27.3	7.8
2	RF-1	35.0	30.5	4.5	38.0	33.8	4.2	37.1	33.8	3.3	33.6	31.1	2.5	32.2	29.8	2.4	31.8	28.9	2.9
3	RF-2	35.0	30.5	4.5	38.0	33.8	4.2	37.1	33.8	3.3	33.7	31.1	2.5	32.3	29.8	2.4	31.9	28.9	3.0
4	RF-3	35.1	30.5	4.6	38.0	33.8	4.2	37.2	33.8	3.3	33.7	31.1	2.6	32.3	29.8	2.5	31.9	28.9	3.0
5	RF-4	35.0	30.5	4.5	38.0	33.8	4.2	37.1	33.8	3.3	33.7	31.1	2.5	32.3	28.8	3.4	31.9	28.9	3.0
6	RF-5	34.9	30.6	4.3	37.9	33.9	3.9	37.1	33.9	3.1	33.6	31.2	2.4	32.2	29.9	2.3	31.8	28.9	2.9
7	RF-6	40.1	27.8	12.3	43.1	31.3	11.8	41.3	31.8	9.5	37.3	29.3	7.9	35.6	28.0	7.6	35.9	26.8	9.2
8	RF-7	37.1	29.2	7.9	40.1	32.6	7.4	38.9	32.8	6.1	35.1	30.2	4.9	33.6	29.0	4.7	33.5	27.9	5.6
9	RF-8	35.9	29.9	5.9	38.8	33.3	5.5	37.9	33.5	4.4	34.2	30.9	3.3	32.7	29.6	3.2	32.4	25.6	6.9
10	RF-9	36.8	29.4	7.4	39.8	32.8	6.9	38.7	33.0	5.7	34.8	30.4	4.4	33.4	29.1	4.2	33.2	28.1	5.1

IV. CONCLUSION

The following conclusions can be drawn from the study

1. Roof structure -5 (Reinforced cement concrete (RCC) with foam concrete insulation), should be preferred for composite and hot-dry climates for non-conditioning buildings.
2. Roof structures, RF-5, RF-4, are the best roofs in achieving minimum hourly floating room temperature. However, roof structures, RF-6, and Base case exhibited the worst performance.
3. Roof structures with insulation (50-150 mm) are a useful technique for reducing indoor room temperatures and maintain thermal comfort in non-conditioning buildings in composite and hot-dry climates.

4. The hot-dry climatic zones have solar isolation and high variations in diurnal temperature due to hot wind movement in summer. So roof structures with insulating layers are a significant technique for reducing indoor temperature and maintaining thermal comfort in non-conditioning buildings in hot-dry climate.

Although this analysis was carried out specifically for roofs situated in New Delhi, composite climatic zone and Jodhpur, hot-dry climates, however, results could be adapted and implemented successfully in other regions where the construction technique is similar.

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ABBREVIATION

PUF: Poly Urethane Foam

RCC: Reinforced Cement Concrete

NOMENCLATURE

A_R	Room area, m^2
C_R	Specific heat of room air, J/kg^0C
h	Convective heat transfer coefficient, $W/m^{2\,0}C$
I	Intensity of solar radiation, W/m^2
k	Thermal conductivity, W/m^0C
L	Thickness of roof slab, m
M_τ	Thermal Mass of room air
Q_i	Heat flux at the inner surface of roof slab, W/m^2
$\dot{Q}_i$	Heat gain, W
T_i	Temperature of inner surface of roof slab, ^0C
T_o	Temperature of outer surface of roof slab, ^0C
T_{an}	n^{th} harmonic factor of Fourier series for ambient temperature, ^0C
T_R	Room air temperature, ^0C
T_{Rn}	n^{th} harmonic factor in Fourier series for room air temperature, ^0C
x_i	Thickness of the roof slab of i^{th} component, m
α_i	Absorptivity of inner surface of roof slab
α_0	Absorptivity of outer surface of roof slab
ρ	Density of air, kg/m^3
ω	Frequency (2π/time period)

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