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Original Article

Thermal Comfort Study of Roof Shapes and Materials in Jaisalmer, India

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***Abstract* -** *Heat gain through building envelopes has been a big issue all over the world, particularly in hot and dry regions. Since low-rise buildings are typically found in hot, arid climates, the roofs always admit the majority of heat. Traditionally, roof forms were designed according to the site context and climatic conditions, ensuring containment of the heat gain through them. However, the ability to build different types of roofs in nearly every place is possible, yet its unavailability can be attributed to a number of problems, including the constraints of skilled labour and construction technologies. It is challenging even to experiment with materials under similar conditions. This research looks at several kinds of roof shapes and materials that are typically used for habitats in hot and dry climatic regions. The availability of these shapes and materials is subjective as well. Therefore, the best possible options were selected and transformed into models suitable for simulation study, and a local climate file was fed into these models. The simulation study was conducted for a typical year cycle on each model, and the results were recorded. The instances from Rajasthan's city of Jaisalmer were examined using TRNSYS, as it is a dependable tool for measuring human comfort and transferring energy. The results were transformed into percentages representing the degree of comfort attained for every kind of roof. The higher the percent of the result, the better will be the performance of the roof shape vis-à-vis the attainment of thermal comfort. It is found that within the scope of roof shapes and materials studied under the purview of this paper, Gable roofs combined with Slate material have the best thermal performance values for the region of Jaisalmer, India. Considering shapes and materials individually, the Gable roof shape is the best-performing shape with an average score of 76.01%, and Timber is the best-performing material with an average score of 74.01%.*

***Keywords* -** *Gable Roof, Slate, Timber, Hot and dry climate, Jaisalmer, TRNSYS.*

1. Introduction

A significant portion of all sectors' energy consumption is currently accounted for by the building industry [1]. There are two methods to use this energy: operationally and through embodied energy. Operational energy consumption is far higher than embodied energy, according to the LCA analysis [2]. Buildings should be designed to be able to regulate their internal thermal comfort in order to reduce the operational cost post occupancy. Although means of controlling indoor temperature exist, they are all active means and energy exhaustive in nature. Therefore, passive means of controlling indoor temperature are needed to gain thermal comfort without spending energy. For this, making a building envelope that aids in minimizing heat gain from solar radiation is a straightforward strategy.

A building's walls, roof, and openings make up its envelope, and typically, low-rise buildings are constructed in regions with hot and dry climates as there are usually no high-rise buildings in these low-rise neighbourhoods. The Indian state of Rajasthan's city of Jaisalmer and its environs serve as a prime illustration. Furthermore, while high-rise buildings use more energy, low-rise is the only option available in rural and semi-urban locations. As a result, low-rise buildings make up the majority of erected structures, and their roofs ingress the majority of heat gain in hot and dry climatic regions. However, because of its practicality and convenience of construction, roofs are often flat in design combined with a unique collection of locally available materials. Heat-mitigating techniques and easily installed natural materials are typically employed in these regions. These materials maintain the structures' temperature lower than the external environment because of their high thermal capacity (mass). In order to create thermal comfort conditions inside spaces while utilising minimal active energy sources, a variety of materials and techniques with different shapes have been used in both traditional and modern constructions. It is also critical to remember that operational energy, which makes up the majority of the energy consumed in a building over its lifetime, is active energy. This suggests that both non-renewable and renewable sources are used in its generation. Even while the share of renewable sources is still lower, the energy produced by non-renewable sources contributes to pollution and the depletion of fossil fuels, which negatively impacts both human health and the health of the planet.

The value of roof shapes and materials in a building and how they contribute to lowering heat gain and fostering comfortable living environments for occupants are discussed in the study. Their shapes' geometry and thermal characteristics, including transmittance, resistance, mass, and time lag, are also taken into consideration.

2. Research Gap

There are studies covering heat gain and temperature control through roof shapes. Similarly, studies covering materials and their impact in terms of heat transfer through them. In theory and practice, they have been evaluated individually, and their results have been validated. However a single study covering all aspects of roof shapes and materials and their combined impact has not been found. Some studies do cover both aspects, but their sample sizes and material/shape selections are very limited. Usually based on availability or popularity or vernacular or a combination of either or all aspects.

However a broader study covering more shapes and materials and their various combinations would not only help explore new options but give more accessibility to the construction industry. As already mentioned, the study is simulation-based, therefore, industry players can utilize the various combinations and achieve results which may be scalable and market-ready. To summarize, the study covers a major research gap between theory and industry by providing simulation results for more options of roofs available, which can be beneficial for the general public and industry at large.

3. Roof Shapes

Any building's thermal performance, especially in hot and dry climates, can be largely impacted by its roof's shape [3]. This happens due to the fact that roofs are the major source of heat gain through solar radiation and can raise the indoor temperature of the building [4]. Various roof shapes offer distinct advantages in reducing heat buildup and improving energy efficiency [5]. Here, we explore some roof shapes and their heat reduction capabilities in hot and dry climates:

Flat roofs are a popular choice in hot and dry climates due to their simplicity and cost-effectiveness [6]. They offer opportunities for the installation of reflective coatings or cool roofing materials, which can help reduce solar heat absorption and lower indoor temperatures. Flat roofs can also accommodate rooftop gardens or green roofs, providing additional insulation and reducing heat transfer through the building envelope.

Dome roofs are characterized by their curved or hemispherical shape, offering unique advantages in hot and dry climates [7]. The curvature of dome roofs helps distribute solar heat more evenly, reducing the formation of hot spots and minimizing heat transfer into the building's interior [8-10]. Dome roofs can also incorporate skylights or clerestory windows strategically positioned to maximize natural daylighting while minimizing direct sunlight penetration.

Gable roofs consist of two sloping planes that meet at a ridge, forming a triangular shape at each end. While gable roofs can be effective in shedding rainwater, they may also be ideal for hot and dry climates due to their geometry [11]. Incorporating gable vents or installing a ridge vent can help improve airflow and reduce heat buildup in the attic or ceiling space.

Hip roofs feature slopes on all four sides, offering advantages in hot and dry climates by promoting natural ventilation and heat dissipation. The inclined slopes allow hot air to rise and escape through ridge vents or other openings, facilitating airflow and reducing heat buildup in the attic or ceiling space. Additionally, hip roofs provide ample opportunities for shading, as the overhanging eaves can help block direct sunlight from entering the building's interior.

In conclusion, selecting the appropriate roof shape is crucial for optimizing thermal performance and reducing heat buildup in hot and dry climatic regions. The roof shapes considered for study in this research are listed below:

- Semi Circular dome
- Gable Roof
- Segmental dome
- Onion Dome
- Hip Roof

4. Roof Materials

Various roof materials offer different levels of heat reduction capability, as well as unique properties that impact their suitability for specific environments [12]. The study covers a variety of roof materials and their heat reduction capabilities in hot and dry climates. These are mentioned below:

Glass roofs, while aesthetically pleasing and abundant natural light admitters, can also lead to significant heat gain, especially in hot and dry climates. Without appropriate shading or low-emissivity coatings, glass roofs may allow solar heat to penetrate indoors, increasing cooling demands [13].

Ferrocement roofs are durable, lightweight, and possess good thermal insulation properties. Their relatively low thermal conductivity helps to reduce heat transfer into the building's interior, contributing to comfortable indoor temperatures in hot and dry climates [14, 15].

Table 1. Roof material's specifications (Sources: SP41, research papers mentioned below, and TRNSYS)

Sr. No.	Materials Name	Conductivity	Capacity	Density	Source	U Value	R-Value
		kJ/hmk	kJ/kg.K	kg/m3		$W/m^2.K$	$m^2.K/W$
1	Glass	2.88	1	2500	SP41	4.30	0.23
2	Ferrocement	0.7956	2.1	1457.89	SP41	1.96	0.51
3	Slate	6.192	0.84	2750	SP41	4.38	0.23
4	Terracotta	2.87	0.88	1892	Koumbem, W.N.D., Ouédraogo, I., Ilboudo, W.D.A. and Kieno, P.F. (2021)	4.62	0.22
5	Timber	0.2592	1.68	480	SP41	0.64	1.56
6	Stone	5	1	2000	TRNSYS	4.13	0.24
7	Asphalt Shingles	1.98	0.837	1900	TRNSYS	4.12	0.24
8	Fiber Tiles	1.8	0.84	1950	TRNSYS	4.00	0.25
9	Polycarbonate	0.24	0.84	1200	TRNSYS	1.84	0.54
10	Cavity Blocks	2.9232	0.837	1618	TRNSYS	3.41	0.29
11	Rubber	0.72	6	1100	TRNSYS	1.26	0.79

Slate roofs are known for their durability, fire resistance, and natural cooling properties. Slate's dense composition and dark colour can help absorb and dissipate heat, reducing solar heat gain and maintaining cooler indoor environments [16-18].

Terracotta roofs are popular in hot and dry climates due to their thermal mass properties and natural cooling benefits [19]. Terracotta has high thermal inertia, which controls the temperature indoors as it absorbs and releases heat slowly [20]. This also elevates the energy efficiency of a building [21, 22].

Timber roofs, while aesthetically pleasing, are also suitable choice for hot and dry climates and have been used traditionally as a choice of building material [23, 24]. Even without proper insulation and ventilation, timber roofs contribute to a reduction in heat gain and thermal discomfort [25].

Stone roofs, such as those made from limestone, offer excellent durability and thermal mass properties. Their natural cooling abilities help mitigate heat transfer into the building, maintaining comfortable indoor temperatures in hot and dry climates [26].

Asphalt Shingles are commonly used in roofing due to their affordability and ease of installation. While they may absorb some heat, for hot and dry climatic regions, reflective coating-based or light-coloured asphalt shingles can help improve efficiency and reduce heat gain. Fiber Tiles, made from a mixture of fiberglass and asphalt, offer good durability and weather resistance. Light-coloured fibre tiles with reflective coatings can help reduce heat absorption and contribute to heat reduction in hot and dry climates [27-31].

Polyurethane foam roofing systems provide excellent insulation properties and can help reduce heat transfer into the building's interior [32, 33]. When properly installed and coated with reflective materials, polyurethane roofs can significantly contribute to heat reduction and energy efficiency in hot and dry climates [34].

Cavity Blocks, commonly used in construction for their thermal insulation properties, can also be utilized in roofing systems. Similarly, hollow roofs can also be built cast in situ. When integrated into roof assemblies, cavities can help reduce heat transfer, enhancing the building's thermal performance in hot and dry climates [35]. Rubber roofing materials, such as EPDM (ethylene propylene diene monomer), offer good durability and weather resistance. Light-coloured rubber roofs with reflective coatings can help minimize heat absorption and contribute to heat reduction in hot and dry climates [36].

While materials like terracotta, slate, and ferrocement offer inherent thermal mass properties and natural cooling benefits, others, like glass, may require additional measures to mitigate heat gain. By considering factors such as thermal conductivity, reflectivity, and insulation properties, we can select roof materials that promote comfortable indoor environments in hot and dry climates. A comprehensive list of roof materials considered for this study are:

- Glass
- Ferrocement
- Slate
- Terracotta
- Timber
- Stone
- Asphalt shingles
- Fiber tiles
- Polyurethane

- Cavity blocks
- Rubber

5. Heat Exchange Mechanism

Heat exchange mechanisms are fundamental processes through which thermal energy is transferred between systems. There are three primary mechanisms of heat transfer: conduction, convection, and radiation.

5.1. Conduction

Conduction is the transfer of heat through direct contact between materials. In this process, heat moves from a region of higher temperature to a lower temperature as faster-moving particles collide with slower-moving particles, transferring kinetic energy. This mechanism is prevalent in solids, where molecules are closely packed, allowing efficient energy transfer without the movement of the material itself. The rate of heat transfer by conduction can be described mathematically using Fourier's law as per Equation (1), which states that the heat transfer rate *Q* is proportional to the temperature difference and the area through which heat is being transferred, divided by the thickness of the material:

$$Q = \frac{K.A.(T_{hot} - T_{cold})}{d} \tag{1}$$

Where, K is the thermal conductivity of the material, A is the area, T_{hot} and T_{cold} are the temperatures of the hot and cold regions, respectively, and *d* is the thickness of the material [37, 41].

5.2. Convection

Convection involves the transfer of heat by the movement of fluids (liquids or gases). This mechanism can occur in two forms: natural convection, driven by buoyancy forces due to density differences caused by temperature variations, and forced convection, which occurs when an external force (like a fan or pump) moves the fluid. In convection, warmer, less dense fluid rises while cooler, denser fluid sinks, creating a circulation that facilitates heat transfer. The efficiency of convection can be influenced by factors such as fluid velocity and temperature gradients [37, 40].

5.3. Radiation

Radiation is the transfer of heat in the form of electromagnetic waves. Unlike conduction and convection, radiation does not require a medium; it can occur in a vacuum. All objects emit thermal radiation based on their temperature, and this energy can be absorbed by other objects, increasing their thermal energy. The Stefan-Boltzmann law in Equation (2) describes the power radiated by a black body in terms of its temperature:

$$P = \sigma A\, T^4 \tag{2}$$

Where *P* is the power radiated, *A* is the surface area, *T* is the absolute temperature in Kelvin, and σ is the Stefan-Boltzmann constant [37, 40].

5.4. Summary

In summary, the mechanisms of heat exchange—conduction, convection, and radiation—are essential for understanding thermal energy transfer in various applications, from engineering systems like heat exchangers to natural processes in the environment. Each mechanism operates under distinct principles, contributing to the overall efficiency of heat transfer in different contexts [38-40].

6. Behavioral Adaptation

Behavioral adaptation in buildings refers to the strategies occupants employ to enhance comfort and energy efficiency in response to environmental conditions. This concept is particularly relevant as buildings face challenges from climate change, necessitating both structural and behavioral modifications. Thermal Comfort Management is an important adaptation strategy implemented in buildings. When occupants often adjust their behaviors to maintain thermal comfort. This can include actions such as opening windows to facilitate natural ventilation or adjusting heating and cooling systems based on outdoor temperatures. Such adaptations can significantly impact energy consumption and indoor climate quality [42, 44]. Another important aspect is integration with structural adaptations. While behavioral adaptations are essential, they often work best in conjunction with structural adaptations (hard adaptations) like improved insulation or energy-efficient envelopes, including roofs. This combined approach maximizes the thermal efficiency of buildings [42, 43]. Overall, behavioral adaptation plays a vital role in how buildings can remain thermally comfortable and energy-efficient in the face of changing environmental conditions. By promoting adaptive behaviors among occupants, buildings can enhance their sustainability and comfort.

7. Science of Thermal Comfort

Thermal comfort in buildings is a critical aspect of architectural design and HVAC (heating, ventilation, and air conditioning) systems, influencing occupant satisfaction, productivity, and overall well-being. Understanding the science behind thermal comfort involves examining various environmental and personal factors, as well as the systems designed to regulate these conditions.

7.1. Definition and Importance of Thermal Comfort

Thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment. It is influenced by a combination of factors, including air temperature, humidity, air velocity, and radiant temperature, as well as personal factors like clothing and metabolic heat production [45].

The importance of thermal comfort lies in its direct impact on occupants' mood and productivity; optimal thermal conditions can enhance cognitive function and reduce health risks associated with discomfort [45, 48].

7.2. Factors Influencing Thermal Comfort

7.2.1. Environmental Factors

Air Temperature

The dry bulb temperature is a primary measure, affecting how warm or cool a space feels.

Relative Humidity

High humidity can hinder the body's ability to cool itself through evaporation, making temperatures feel warmer than they are.

Air Velocity

The movement of air can enhance cooling effects, particularly in warmer environments.

Mean Radiant Temperature (MRT)

This represents the average temperature of all surrounding surfaces and is crucial for assessing thermal comfort, as it significantly influences how warmth or coolness is perceived [45, 47].

7.2.2. Personal Factors

Clothing Insulation

The type and amount of clothing worn affects heat exchange between the body and the environment.

Metabolic Rate

Physical activity levels influence the amount of heat produced by the body, affecting comfort levels [47, 48].

7.3. Models of Thermal Comfort

The Predicted Mean Vote (PMV) model and the adaptive model are two widely recognized frameworks for assessing thermal comfort. The PMV model is based on heat balance principles and is applicable in controlled environments, while the adaptive model considers how occupants adjust their behavior in response to changing conditions, making it suitable for naturally ventilated spaces.

7.4. Achieving Thermal Comfort in Building Design

To ensure thermal comfort, several strategies can be implemented:

7.4.1 Effective HVAC System

Systems should be designed to manage not only temperature but also humidity and air quality. Radiant heating and cooling systems can be particularly effective as they regulate MRT without directly affecting air temperature [47, 48].

7.4.2. Minimizing Air Leakage

Proper sealing of building envelopes prevents unwanted air exchange that can disrupt thermal conditions [47].

7.4.3 User Control

Allowing occupants to control aspects of their environment, such as thermostats and operable windows, can enhance perceived comfort levels [47, 48].

7.4.4. Simulation and Modeling

Engineering simulation tools can help predict and optimize thermal comfort during the design phase, allowing for adjustments based on various parameters [45, 46].

7.5. Conclusion

Thermal comfort is a multifaceted concept that plays a vital role in building design and occupant satisfaction. But in this paper, we do not focus on any active means of thermal comfort like HVAC, etc. Also, factors like clothing, etc are not included, and neither is metabolic rate. The study covers only passive means through building envelopes,

8. Climate Chambers

Climate chambers, also known as environmental chambers or constant climate chambers, are enclosures used to test the effects of specified environmental conditions on materials, products, and devices. They can simulate various conditions, such as:

- Extreme temperatures
- Sudden temperature variations (thermal shock)
- Moisture or relative humidity
- Vibrations
- Radiation
- Corrosion
- Rain
- UV exposure
- Vacuum

Key features of climate chambers include:

- Precise control and monitoring of temperature and humidity
- Homogeneous distribution of climate conditions
- Programmable cycling through specified sequences of conditions
- Viewing ports or video feeds for visual inspection
- Reach-in access for handling test samples
- Computer programmability and networking capabilities

Climate chambers are used to determine the thermal performance and parameters of various building materials. The data generated by them is used to create specifications files which are used to simulate their functioning.

9. Adaptive Model

The adaptive model for thermal comfort in buildings is a framework that recognizes the influence of outdoor climate conditions on indoor thermal comfort, particularly in naturally ventilated spaces.

This model has been integrated into standards such as ASHRAE Standard 55, which guides the design and operation of buildings without mechanical cooling systems.

9.1. Key Aspects of the Adaptive Comfort Model

9.1.1 Foundation and Development

The adaptive comfort model was developed through extensive research analyzing over 21,000 data sets from thermal comfort studies in 160 buildings worldwide.

This research demonstrated that occupants in naturally ventilated buildings accept a wider range of indoor temperatures compared to those in mechanically cooled environments. This acceptance is attributed to behavioral and psychological adaptations to outdoor conditions [49].

9.1.2. Thermal Comfort Definition

Thermal comfort is defined as a state of mind that expresses satisfaction with the thermal environment. The adaptive model posits that factors such as access to environmental controls and past thermal experiences significantly influence occupants' thermal preferences and expectations [50].

9.1.3. Application of the Model

The model is particularly relevant for buildings with operable windows where occupants can adjust their environment.

It allows for a more flexible approach to indoor temperature settings, which can lead to energy savings and improved occupant satisfaction.

The ASHRAE 55-2010 standard introduced the concept of using the mean outdoor temperature as a basis for determining acceptable indoor temperatures [49].

9.1.4. Categories of Adaptation

The adaptive model encompasses three types of adaptations:

- Behavioral Adaptation: Changes in occupant behavior in response to thermal conditions.
- Physiological Adaptation: The body's natural responses to temperature variations.
- Psychological Adaptation: Changes in perception and expectations regarding comfort based on previous experiences.

9.1.5. Implementation and Standards

The adaptive model has been adopted in various building standards globally, including the European EN 15251 standard, which allows for its application in mixed-mode buildings. However, the ASHRAE standard specifically applies to buildings without mechanical cooling systems [50].

In summary, the adaptive model for thermal comfort provides a robust framework for understanding and improving occupant satisfaction in naturally ventilated buildings, promoting energy efficiency and comfort through a flexible approach to temperature regulation.

10. Literature Review

Comprehensive literature regarding roof shapes and roof materials was conducted.

B. Su et al. (2009) studied that roof thermal design is crucial for achieving indoor thermal comfort in naturally ventilated tropical houses, considering both daytime and night-time thermal performance [51].

BerkÖz (1977) in his study compared flat roofs with gable and sloping roofs to find out their heat gain quotient for hot and dry climates. He concludes that the gable roof's performance is the best among all the typologies and is appropriate for hot and dry climates [11]. Runsheng (2003) et al. compared flat roofs with curved roofs and concluded that curved roofs perform better than flat roofs and can curb heat gain annually more than flat ones [52]. Ventilated roofs can improve thermal performance by adjusting cavity ventilation, roof slope, solar radiation intensity, cavity size and shape, and panel profiles, resulting in better cooling effects (Lee et al., 2009) [53].

Vahdaneh et al. (2016) concluded through a study that a double-dome roof in Kashan, Iran, provides comfortable conditions with lower energy consumption and better thermal performance on hot and cool days due to its reduced heat transfer and increased radiation absorption [54]. A study by Soleimani et al. (2018) conveyed that the integration of roof vents in geodesic-type dome buildings improves ventilation and thermal comfort in hot climates [55]. Ali et al. (2023), in their study on energy efficiency in dome structures, conclude that a combination of traditional shapes and modern materials can be very efficient for reducing heat gain and achieving thermal comfort indoors [56]. Also, the study found that domed-shaped structures exhibit better efficacy in controlling indoor temperatures, with increased temperatures during colder months and decreased temperatures during hotter months compared to alternative structures.

Asadi et al. (2015) stated that using recycled broken and waste glass cullets in the production of asphalt shingles can help mitigate heat island effects and reduce building energy consumption by increasing their reflectivity [13].

Ramirez (2014) et al., in their study of coconut-ferrocement roofing systems, conveys that it can enhance the time lag by 40% in comparison to the traditional roof [14]. Iburahim (2017) et al. conducted a study to test the thermal performance of ferrocement panels on roofs, and the result conveyed that it can be helpful in reducing indoor temperature by up to 15°C [15].

Lucy (2013), in her dissertation thesis on the thermal improvement of traditional building fabric using slate, conveyed that slate can be efficient on any surface for the provision of thermal comfort indoors [16]. Labus (2019) et al., in a similar study, derive the fact that slates have a high thermal anisotropy coefficient [17]. Eynde (2021), in his study of the usage of slate as a roofing material and its thermal performance, concludes that roof slates are the worst thermal conductors among natural stones and can be great insulators [18].

Pisello (2015) et al., in their study on the thermal performance of clay tiles through simulation, found out that clay tiles are better performers than generic roof materials [19]. Sirimanna (2016) et al. experimented with 3 roof materials and concluded that the best material was clay tile for thermal performance [20]. Rahmani (2022) et al. proved that terracotta has good thermal behavior with respect to materials like concrete which are typically used in roofs [21]. In a study conducted by Fathima et al. (2022), it was observed that rammed earth houses have the best thermal performance in a hot and semi-arid climate due to their high thermal mass and optimal thermal comfort [22].

Timber has been traditionally categorized as a material which is thermally comfortable for both hot and cold climatic conditions. Research by Dewsbury (2015) et al. [23], Fernandes (2020) et al. [24], and Caniato (2021) et al. [25], among others, provide support to the facts stated above.

Jayesh et al. (2023) state that traditional Jaisalmer limestone is an effective and efficient material for outdoor thermal comfort in hot and dry regions like Jaisalmer, with traditional limestone showing positive results [26].

Roma et al. (2008) concluded that roofing tiles reinforced with vegetable fiber are acceptable as substitutes for asbestos-cement sheets in hot and dry climates [28]. In a study conducted by Tonoli et al. (2011), it was found that sisal fiber-cement roofing tiles provide better thermal performance at room temperature (25°C) and better protection against radiation at 60°C compared to asbestos-cement sheets and ceramic tiles [29].

Michels et al. (2020) in his study found that all the fiber cement roof tiles tested by the team had lower thermal gain than the reference traditional roof, with reductions of 55% for white tiles, 67% with a radiant barrier, and 70% with conventional thermal insulation [30]. Joshima et. al. (2021) in their study stated that Mangalore pattern tiles exhibit better thermal performance on RCC sloping roofs due to their low conductivity, diffusivity, and slightly corrugated profile [31].

Al-Sanea (2002) concluded that polyurethane insulation on roofs reduces heat-transfer load to less than one-quarter in hot and dry climates like Riyadh [33]. According to Piselli et. al. (2019) the combination of cool polyurethane-based membrane and PCMs with suitable melting temperature range significantly reduces roof surface temperatures and heat flux through the roof in both Mediterranean and Hot desert climate conditions [34].

Navarro et al. (2010), in a study, convey that a combination of recycled polyethylene and ground tire rubber improves the thermal and rheological properties of modified bitumen blends, making them more suitable for roofing applications [36].

11. Research Methodology

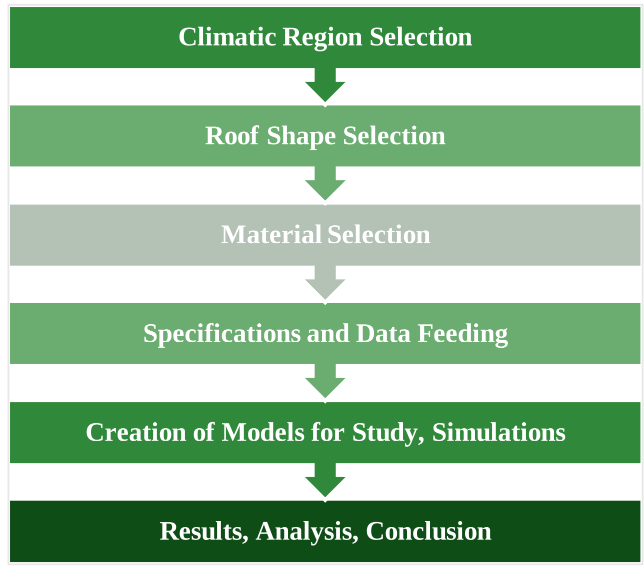

Fig. 1 Flow chart of the research methodology

Source: Author

The research methodology followed the stages beginning with climatic region selection, roof shape selection, material selection, specifications and data feeding, creation of models for study, simulation, and ending with results, analysis, and conclusion.

12. TRNSYS

This study anticipates that the simulation will yield the ideal roof structure, integrating forms, techniques, and materials to reduce heat transmission and lower indoor air temperature. As a result, the software/tool TRNSYS was selected for heat transfer simulation. Being based on algorithm modelling, it is not only best suited for research and scientific work but also the most dependable tool for these kinds of simulations. This tool's accuracy in producing results has led to its implementation in numerous research projects. TRNSYS was the simulation tool used in the studies by Jonas (2019) et al. [57] and Vera-García (2022) et al. [58]. The outcomes of these simulations were validated by physical modelling. It was found that simulation results and physical model results were consistent. TRNSYS has also received validation from ASHRAE.

13. Experiment

As already mentioned, the software of choice for the experiment was TRNSYS. The objective of the study was to achieve thermal comfort indoors using a combination of roof shapes and materials. The region chosen for study was Jaisalmer, India, which falls under the category of hot and dry climate. To achieve the desired thermal comfort conditions, clause 11.1.3 was chosen, which states that "thermal comfort conditions can be assumed to be achieved if a project attains the comfort standards of NBC 2005 or ASHRAE 55 or Indian Adaptive Comfort (IAC) Model". A building in a composite climate, hot and dry climate and moderate climate should achieve thermal comfort conditions as per the above standards for 90% or more duration in the occupied state and in a warm and humid climate for 60% or more in the occupied state to be called thermally comfortable building. As the study focuses on hot and dry climates, there was a need to take into account the 90% criteria. Also, being residential in function, its occupancy can be very varied, and no particular standard occupancy hours will be considered. Therefore, it may be assumed that over and above the percentage of thermal comfort achieved through simulation, thermal comfort may be imparted through active means. This also confines the capabilities of passive means of thermal comfort achievement. The simulation worked on four components:

Thermal Comfort Conditions: When the body heat equilibrium can be maintained by a person with comfort at normal temperature. Criteria 11 of GRIHA v2015 incorporates the thermal comfort conditions inside a building for naturally ventilated spaces. It should also be compliant with ASHRAE or NBC 2005 requirements.

Table 1. Wind speeds requirement in thermally comfortable conditions

Dry bulb Temperature (deg C)	Relative Humidity (%)						
	30	40	50	60	70	80	90
28	*	*	*	*	*	*	*
29	*	*	*	*	*	0.06	0.19
30	*	*	*	0.06	0.24	0.53	0.85
31	*	0.06	0.24	0.53	1.04	1.47	2.10
32	0.20	0.46	0.94	1.59	2.26	3.04	**
33	0.77	1.36	2.12	3.00	**	**	**
34	1.85	2.72	**	**	**	**	**
35	3.20	**	**	**	**	**	**
* none ** higher than those acceptable in practice							

Source: Author

Weather Data: it was chosen for the region of Jaisalmer, India, and its weather data file was obtained from the TRNSYS database.

Standard Conditions: For a basic room in a hot, dry area, a standard model was created. The Indian city of Jaisalmer was selected for the study. It is located in an arid or hot, dry climate zone. The room's measurements remained at 4.0 by 3.0 meters, with a 3.0-meter high roof. Table 3 lists the built structure's specs and specifics. The simulation ran for a duration of one year, or 8,760 hours, from January 1 to December 31. For the study, the simulation included both DBT and RH. Thermal comfort conditions were later incorporated into the software in accordance with ASHRAE Section 55. Following the creation of 11 material models and 5 distinct forms, the data was loaded into TRNBUILD, which produced a comfort level hourly database as per ASHRAE standards. The outcome was 0 for discomfort and 1 for comfortable condition. The sum was determined for each model that represented a distinct material using an Excel sheet. This produced a percentage that represented the comfort factor of each model. The user will be more comfortable with a higher proportion.

Table 2. Standard conditions for the simulation

Criterion	Description
Simulation Area	Complete Built Structure
Thickness of Wall	230 mm
Power (Lights)	8 W/m^2
Power (Equipment)	10 W/m^2
Rate of Ventilation	6 fresh air changes hourly
Rate of Occupancy	365 days, 24 hours a day
Total Time of Occupancy	8760 hours
Standard of Thermal Comfort	NBC 2005
Size of Room	4000 mm x 3000 mm
Thickness of Roof	Covered top layer and 120 mm thickness
Specification of Wall	The base material is clay brick. External and Internal covering plaster is made of cement, and sand is 12 mm thick.
Wall Openings	Window of size 1200 mm x 1000 mm and Door of size 2100 mm x 1000 mm
Openings Overhangs	1000 mm x 1500 mm on each opening

Source: Author

Models for Simulation: A total of 11 materials and 5 shapes were considered for the simulation study. This gave a total of 55 models that were to be simulated. Table 4 gives a pre-simulation sheet used for filling the post simulation data.

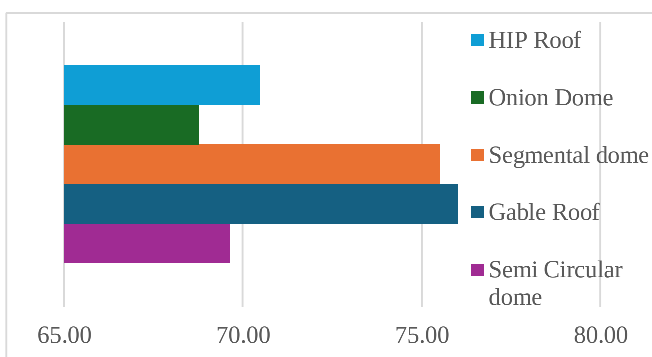

Fig. 2 Average results of roof shapes

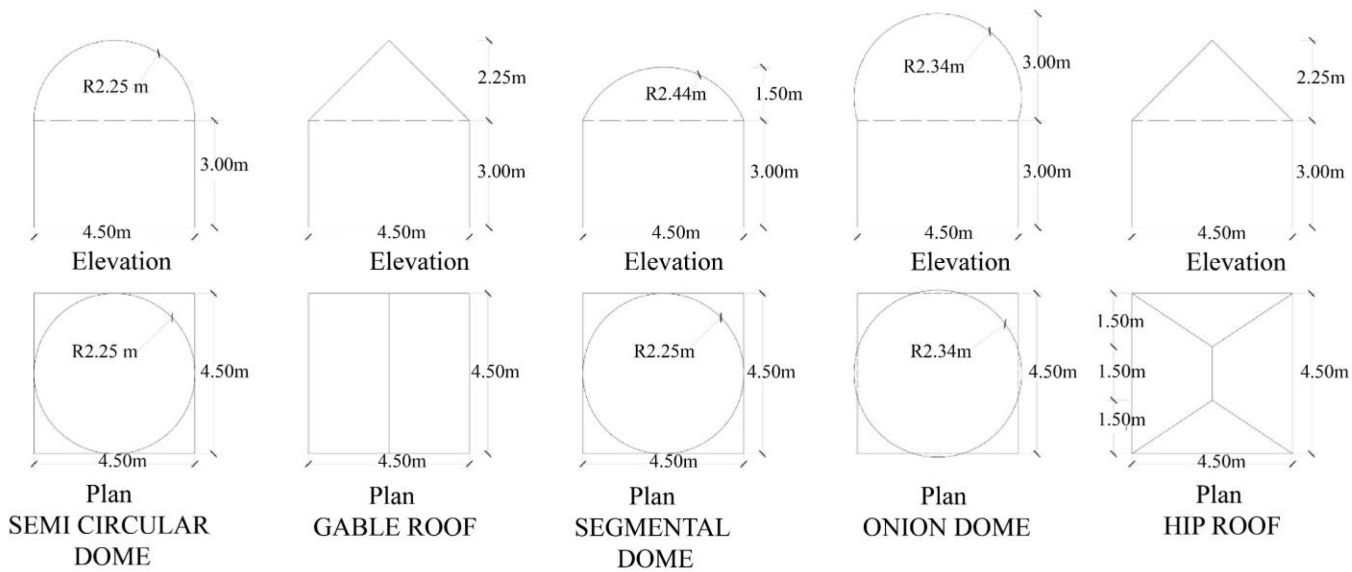

Fig. 3 Roof shapes and their geometry

Source: Author

14. Findings and Analysis

The final results were recorded as percentages for the 55 models which were simulated annually. The outcome communicated that the comfort level was directly proportionate to the percentage achieved in each result i.e. higher comfort level can be achieved if the result percentage is higher. The results are in a tabular form for each roof shape vis-à-vis its material.

Table 3. Sheet for filling simulation results

S. NO.	ROOF TYPOLOGY	Glass	Ferrocement	Slate	Terracotta	Timber	Stone	Asphalt Shingles	Fiber Tiles	Polyurethane	Cavity Blocks	Rubber	Average Value of Results
1	Semi Circular Dome												
2	Gable Roof												
3	Segmental Dome												
4	Onion Dome												
5	HIP Roof												
Average Value of Results													

Source: Author

The highest percentage recorded was 77.23%, which was for a gable roof built using slate, whereas the lowest percentage was 66.67% for an onion dome built using slate. It was surprising to observe that similar materials performed differently with different shapes. This also emphasized the fact that roof shapes play a major role in deciding the thermal comfort conditions in any building. Considering individual shape results, the gable roof had an average result of 76.01% across all materials, whereas at 68.77% onion dome’s thermal comfort performance was the lowest. An analysis of this conveys that the best and lowest-performing roof combinations are logically working.

In the chart below, a comparison of the average results of all the roof shapes is displayed. As mentioned above, a gable roof has the overall best performance in terms of thermal comfort across all roof shapes studied in this paper. The segmental dome is a close second, followed by the hip roof, semicircular dome and onion dome. While gable and segmental dome roofs are very close in terms of results, there is a substantial gap between these two and the other three. Overall, the range of average results for roof shapes falls between 68.77% to 76.01%.

In terms of roof material, timber had an average score of 74.01%, although individually, it was not the best-performing roof material, that being slate. At the same time, terracotta was the lowest performer among materials at an average percentage of 71.19%. The chart below shows the average results of all the roof materials covered in this study. It clearly indicates that timber performs exceptionally well with all roof shapes, and rubber is a close second.

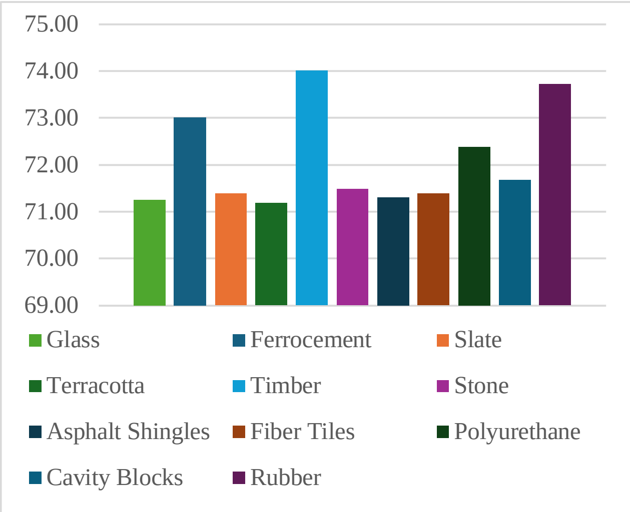

Fig. 4 Average results of roof materials

Ferrocement and polyurethane are third and fourth in the order, and including the first two, these four materials are close in terms of results to each other. The remaining seven materials are in the following order: cavity blocks, stone, slate, fiber tiles, asphalt shingles, glass and terracotta. All these seven materials perform very similarly in terms of thermal comfort and fall very close to one another. Overall, the range of average results for roof materials falls between 71.19% to 74.01%.

Traditionally, for hot and dry climatic conditions, roof shapes with more surface area, i.e. dome or spherical shapes, have been preferred, whereas this study denotes that a gable roof is a better performer than the other two cases. A probable reason behind it could be that the conditions studied in previous cases may have been during the day time when solar radiation is high. This denotes that the thermal comfort evaluation has been partially done without considering the nighttime and/or seasons with lesser sunshine or heat. Similarly, materials like slate have not been a material of choice for hot and dry climatic conditions.

However, the study defies that and establishes it as a material with good thermal performance. Although, very much like the vernacular practices define, timber has performed as the single best material for heat mitigation with all shapes. The study also indicates that the studied roof materials play a lesser role in the thermal performance of the roof as compared to the studied roof shapes, atleast till this point. Henceforth, the geometry of the roof should be the first touch point in terms of thermal comfort and is more important than the material used. The table below combines all the results in a tabular format.

Table 4. Final simulation results

S. No.	Name	Roof Typology	Glass	Ferrocement	Slate	Terracotta	Timber	Stone	Asphalt Shingles	Fiber Tiles	Polyurethane	Cavity Blocks	Rubber	AVERAGE VALUE OF RESULTS
1	Type 1	Semi Circular dome	67.73	71.42	67.60	67.66	74.38	67.91	68.03	68.22	70.95	68.76	73.21	**69.62**
2	Type 2	Gable Roof	76.80	75.78	77.23	76.75	73.90	77.00	76.47	76.43	74.76	76.27	74.77	**76.01**
3	Type 3	Segmental dome	76.31	75.17	76.85	76.30	72.97	76.56	76.07	75.94	74.10	75.90	74.22	**75.49**
4	Type 4	Onion Dome	66.78	70.37	66.67	66.70	74.06	67.00	67.08	67.26	70.25	67.77	72.56	**68.77**
5	Type 5	HIP Roof	68.65	72.32	68.62	68.53	74.74	68.96	68.92	69.08	71.89	69.69	73.87	**70.48**
AVERAGE VALUE OF RESULTS			**71.26**	**73.01**	**71.39**	**71.19**	**74.01**	**71.49**	**71.31**	**71.38**	**72.39**	**71.68**	**73.73**	

LEGEND			
(red)	BEST PERFORMERS	(light)	70.00% - 74.99%
(orange)	75.00% & Above	(yellow)	65.00% - 69.99%

Table 5. Best performers

Roof shape	Performance (%)	Roof material	Performance (%)	Combination of shape and material	Performance (%)
Gable roof	76.01	Timber	74.01	Gable roof and slate	77.23

The cells highlighted in red are the best performers in any category. Table 6 summarizes the best performers.

Also, the results are bifurcated in terms of thermal performance achieved. The results in orange-colored cells indicate either material and/or shape and/or combinations of both, wherein the thermal comfort conditions were more than 75% of the whole year's duration. Table 7 summarizes the performers above 75% thermal performance.

Table 6. Performers above 75% thermal performance

Roof Shape	Performance (%)	Combination of Shape and Material	Performance (%)
Segmental Dome	75.49	Gable roof and glass	76.80
		Gable roof and ferrocement	75.78
		Gable roof and terracotta	76.75
		Gable roof and stone	77.00
		Gable roof and asphalt shingles	76.47
		Gable roof and fiber tiles	76.43
		Gable roof and cavity blocks	76.27
		Segmental dome and glass	76.31
		Segmental dome and ferrocement	75.17
		Segmental dome and slate	76.85
		Segmental dome and terracotta	76.30
		Segmental dome and stone	76.56
		Segmental dome and asphalt shingles	76.07
		Segmental dome and fiber tiles	75.94
		Segmental dome and cavity blocks	75.90

Table 8 categorizes the results falling between 70.00% and 75.00%. These were the third-best results in the lot and hence can be considered as the next best combinations in terms of shapes and/or materials and/or both. Interestingly, barring one, all the other roof materials fall under this category. This implies that materials may not be the best performers in terms of achieving thermal comfort through roofs. Still they might be a very important component for the same. It is, therefore, considerable that both shapes and materials strongly influence the thermal performance of roofs, unlike what was assumed earlier.

Table 7. Performers between 70.00% to 75.00%

Roof Shape	Performance (%)	Roof Material	Performance (%)
Hip roof	70.48	Glass	71.26
		Ferrocement	73.01
		Slate	71.39
		Terracotta	71.19
		Stone	71.49
		Asphalt shingles	71.31
		Fiber tiles	71.38
		Polyurethane	72.39
		Cavity blocks	71.68
		Rubber	73.73

Table 8. Performers between 70.00% to 75.00%

Combination of Shape and Material	Performance (%)
Semicircular dome with ferrocement	71.42
Semicircular dome with timber	74.38
Semicircular dome with polyurethane	70.95
Semicircular dome with rubber	73.21
Gable roof with timber	73.90
Gable roof with polyurethane	74.76
Gable roof with rubber	74.77
Segmental dome with timber	72.97
Segmental dome with polyurethane	74.10
Segmental dome with rubber	74.22
Onion dome with ferrocement	70.37
Onion dome with timber	74.06
Onion dome with polyurethane	70.25
Onion dome with rubber	70.56
Hip roof with ferrocement	72.32
Hip roof with timber	74.74
Hip roof with polyurethane	71.89
Hip roof with rubber	73.87

The cells highlighted in yellow are the lowest performers and henceforth, their thermal performance is of the lowest level among the materials and shapes studied. These shapes and/or combinations imply that they should be avoided or atleast prioritized at the very end in case of thermal comfort achievement. Their performance percentage was below 70% annually. The table below summarizes the lowest performers among the shapes and/or combinations studied in this paper. Interestingly, no single material's performance has been below 70% but shapes and/or combinations do fall below this criteria. Also, it must be noted that the lowest combination performance is 66.67%, i.e. in any case, any single shape and/or material and/or combination of both performs well for more than 2/3 part of the year.

Table 9. Performers between 65.00% to 70.00%

Roof shape	Performance (%)
Semicircular dome	69.62
Onion dome	68.77

Table 10. Performers between 65.00% to 70.00%

Combination of shape and material	Performance (%)
Semicircular dome with glass	67.73
Semicircular dome with slate	67.60
Semicircular dome with terracotta	67.66
Semicircular dome with stone	67.91
Semicircular dome with asphalt shingles	68.03
Semicircular dome with fiber tiles	68.22
Semicircular dome with cavity blocks	68.76
Onion dome with glass	66.78
Onion dome with slate	66.67
Onion dome with terracotta	66.70
Onion dome with stone	67.00
Onion dome with asphalt shingles	67.08
Onion dome with fiber tiles	67.26
Onion dome with cavity blocks	67.77
Hip roof with glass	68.65
Hip roof with slate	68.62
Hip roof with terracotta	68.53
Hip roof with stone	68.96
Hip roof with asphalt shingles	68.92
Hip roof with fiber tiles	69.08
Hip roof with cavity blocks	69.69

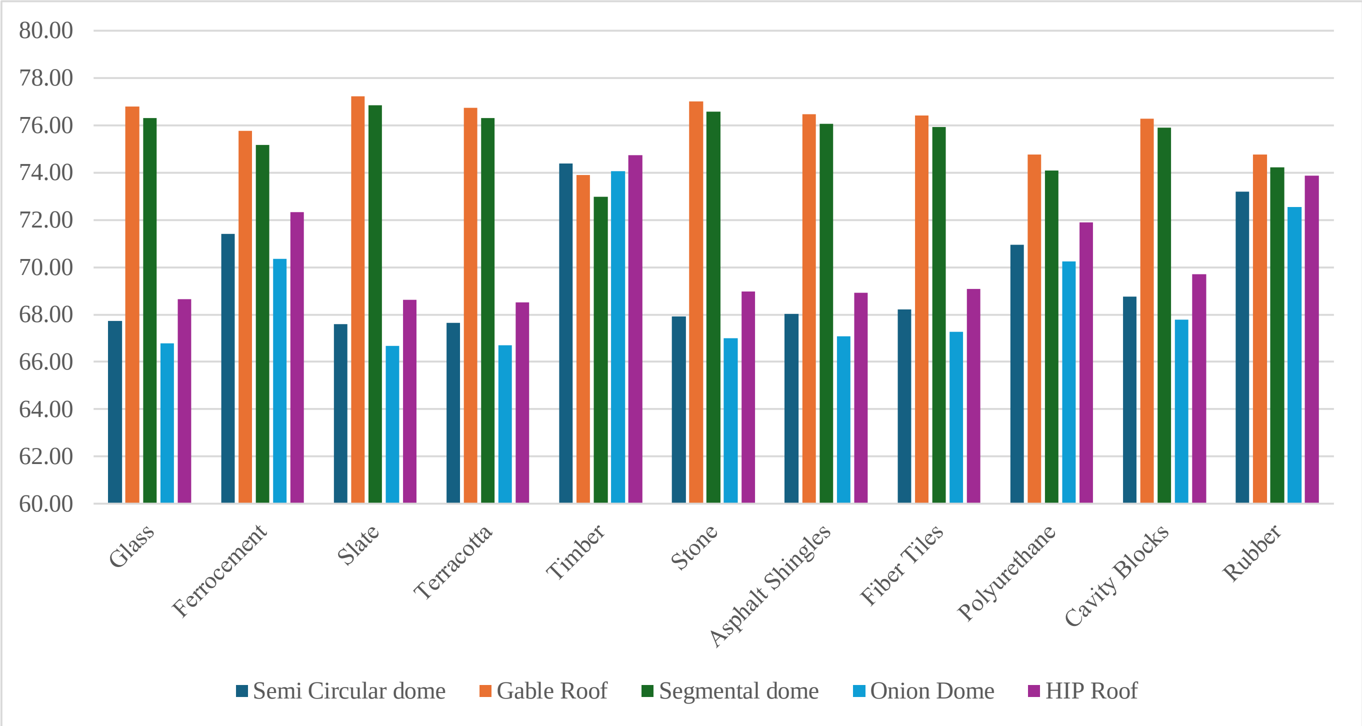

Fig. 5 Results shown in a graphical manner

15. Conclusion

Out of the 55 results that the simulation yielded, 16 had thermal comfort levels above 75%, 18 had thermal comfort levels between 70% and 75%, and the remaining 21 had thermal comfort levels below 70%. There was an overall difference of 10.56%, ranging from 66.67% to 77.23%. The results of the simulations are suggestive of the choice of shapes and materials being hot and dry climatic region appropriate. Hence, they can provide good indoor thermal comfort. Many new material categories and more intricate computer-generated designs are still missing from this study, despite the fact that the shapes and materials extensively used in study and practice are simulated and examined for hot and dry region. It should be mentioned, however, that the simulation results are the outcome of the annual thermal comfort study and not only for the summer season. Therefore, the comfort level attained extends to the winter months as well as the summer and other seasons. The coziness extends to the evenings as well as the days.

15.1. Discussion

The work done uses state of the art software and simulation tools. TRNSYS is an industry leader in simulations and its results are validated by multiple research and industries. Already a lot of work is done on the roofs and their thermal comfort, but it considers only a single parameter of either shape or material. Even in a few cases of combination of shape and material, the choice of either is limited, and not all materials are combined with all shapes. Though factors like availability, cost, ease of construction, etc., are considered in other studies for their limitations, they cannot be a valid reason. Today, technology and infrastructure have made it possible for all shapes combined with any material to be constructed. Factors like availability and costing, etc., can also be managed. Therefore, the research work done in this paper is a step ahead of all the works done and covers a comprehensive combination of shapes and materials. At the same time, this study covers annual simulation, whereas most of the studies focus only on the daytime data in summer, i.e. the peak season. But, if we consider any building, it has a possibility of year-round occupancy. The region considered for this study is also an important parameter. The city of Jaisalmer and its surroundings are apt for hot and dry climatic study as they fall in semi – arid category. Nevertheless, not many studies cover the region especially with respect to buildings study. Therefore, even the best state-of-the-art studies do not cover the complete picture of thermal comfort as covered by this study.

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