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Feasibility Study of Free Cooling and Heating for a Small Residential Building at Bhuj, Gujarat, India

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ABSTRACT

In this study, the viability of passive cooling in residential spaces within the temperate climate of Kutch is examined using standardized adaptive comfort criteria. Ventilation-based free-cooling is identified as an energy-efficient cooling method. To maintain comfortable room temperatures and reduce energy consumption for mechanical ventilation, variable airflow rates are necessary when using ventilation for cooling. Consequently, free-cooling relies on the availability of cooling potential and appropriate airflow control mechanisms. The research focuses on the effectiveness of night ventilation techniques in the hot-dry climate of Bhuj, Kutch, for residential buildings. The study evaluates the impact of various natural ventilation approaches on the indoor thermal environment of Bhuj homes, using data from a comprehensive field experiment. Thermal performance measurements were taken from a corner terrace house in Bhuj to determine the efficiency of free cooling ventilation as a passive cooling strategy. The experiment compared four configurations: no ventilation, full ventilation, daytime ventilation, and night-time ventilation. The findings indicate that night ventilation offers improved thermal comfort for residents in Bhuj, Kutch, and has a significant impact on the results.

Keywords: Free Cooling; Passive Cooling; Night Ventilation; Direct Air Free Cooling; Ventilation.

1. Introduction

India is a highly populous country, with a current population of approximately 1.39 billion people, making it the second-most populous country in the world after China. Its population accounts for about 17.7% of the global population, indicating the country's significant demographic weight. According to population projections, India is expected to surpass China's population by 2023, becoming the most populous country in the world. This is a significant demographic shift that is expected to have far-reaching implications for India's economic, social, power energy consumption and political development in the coming years [1]. In India, there is a strong correlation between energy usage, economic development, and population expansion [2]. In India, the energy-intensive sectors can be broadly classified into three primary groups: namely, the industrial sector, the transportation sector, and the remaining sectors. Amongst these, agriculture and construction are two of the most energy-intensive sectors that fall under the "others" category. Furthermore, buildings require energy to power various appliances that cater to human convenience and comfort. As depicted in Figure-1, a substantial 45% of the total energy consumption in India is attributed to maintaining optimal thermal conditions in residential buildings [2].

Recently, there has been a growing body of literature on the topic of energy conservation in buildings by means of passive cooling technologies. These publications have shown that passive cooling has the potential to substantially decrease energy usage in buildings in the near future. Even if a building lacks air conditioning, its ventilation system can provide cooling during the summer months. Passive cooling techniques, such as night ventilation, use the cool night air to lower indoor temperatures by cooling the structural components. A fan is used in the ventilation system to ensure that enough cooling occurs at night by drawing in ambient air. There are two other methods of free cooling in addition to night ventilation. The first is an open-loop air circuit, which brings in ambient air when the outside temperature is comfortable. The second involves storing cool energy from the ambient air at night in a storage device to be used during the day to cool the building. Phase Change Materials (PCMs) are the best option for energy storage because of their high storage density and isothermal behaviours. Evaluate the feasibility of using the aforementioned free cooling methods in the chosen location. Extensive research has been conducted to assess the cooling capabilities of night ventilation methods and free cooling technologies that do not require thermal storage.

In order to assess the effectiveness of night ventilation and create a simple model for building management systems, Pfafferott et al. [3] conducted experiments in an office building using both mechanical and free night ventilation. Parys et al. [4] explored the possibility of passively cooling buildings using manual window operation during daytime in Belgium's temperate climate. Waqas and Kumar [5] studied the thermal performance of latent heat storage for free cooling in hot, dry climates. Rajagopal et al [6] investigated free cooling potential and suitable technologies for different seasons in Bangalore, India. In Malaysia's hot and humid climate, Kubota, Chyee, and Ahmad [7] examined the effectiveness of night ventilation in residential buildings, finding it provided better thermal comfort than other strategies. Carrilho da Grac et al. [8] used numerical simulations to evaluate day and night ventilation in six-story apartment buildings in Beijing and Shanghai, with night ventilation proving more effective. Shaviv et al. [9] studied the impact of thermal mass and night ventilation on maximum indoor air temperature in Israel during summer, suggesting a daily air temperature range greater than 6°C for an effective 3°C reduction in peak temperatures.

Blondeau et al. [10] found that night ventilation could decrease diurnal indoor air temperature by 1.5 to 2°C, even with an average daily air temperature range of only 8.4°C. Kubota et al. [11] discovered that daytime ventilation lowered indoor air temperature by 1.5°C, while night ventilation resulted in a 2.5°C reduction compared to no ventilation. These findings indicate that natural ventilation strategies can improve indoor thermal comfort and reduce energy consumption in hot-humid climates like Malaysia. Kolokotsa et al. [12] demonstrated that night ventilation can effectively reduce indoor temperatures in hot and humid climates, with its effectiveness depending on factors such as building design, ventilation rates, and outdoor temperature and humidity levels.

This paper investigates the effectiveness of direct air free cooling techniques at night for concrete roof houses (townhouses) in Kutch, a hot and dry climate region. This study aims to investigate the feasibility and effectiveness of direct air free cooling at night in the Kutch region. An experiment was conducted in a room located in Mankuva, Bhuj, with temperature measurements taken both inside and outside the experimental room to assess the climatic conditions influencing night ventilation. The climate in this city is tropical, hot, and dry, with three distinct seasons: summer, monsoon, and winter. Summer months, from April to June, experience daytime temperatures between 34 and 42°C and night-time temperatures between 26 and 30°C. Even during the hottest months, nights tend to be cool.

The focus of this study is on direct air free cooling, which aims to remove heat from facilities using cold outside air. The temperature difference between indoor and outdoor environments determines the cooling capacity. Night ventilation in this city may provide a reasonable cooling effect when compared to the daily air temperature range. Houses in this region are typically constructed from heavy materials like bricks and concrete, which have high thermal mass.

In this study, we evaluate the effects of various ventilation strategies, such as night ventilation, daytime ventilation, no ventilation, and full-day ventilation, to determine their impact on indoor temperatures and thermal comfort.

2. Climatic Zones of India – An Overview

India, a tropical country, has various climate zones categorized into five groups: hot-dry, warm-humid, composite, temperate/moderate, and cold [13]. Approximately 45% of major Indian cities experience warm and humid climate zones, as shown in Figure-2, with extreme summer and winter conditions in the northern regions. In contrast, southern and coastal areas have a warm climate throughout the year. Table-1 summarizes the annual average maximum and minimum temperatures for each zone. In hot and dry zones, the maximum daytime temperature ranges from 40°C to 45°C, while the maximum night-time temperature varies between 20°C and 30°C.

The Indian Meteorological Department (IMD) identifies six distinct weather seasons in India: winter/cold (January and February), pre-monsoon/summer (March, April, and May), south-west monsoon/summer monsoon (June, July, August, and September), and post-monsoon/northeast monsoon (October, November, and December) [14]. Kutch's climate is hot and dry, making free cooling a viable option for improving thermal comfort and reducing energy consumption.

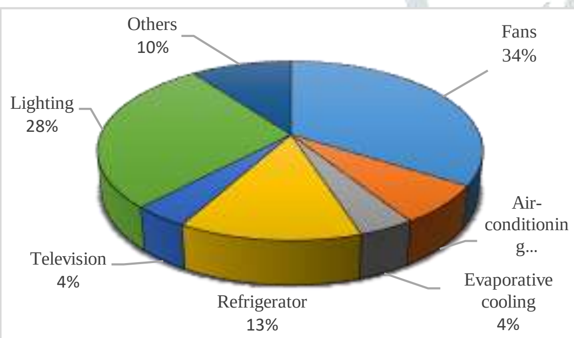


Figure-1 Energy consumption pattern in Indian residential buildings. [2]

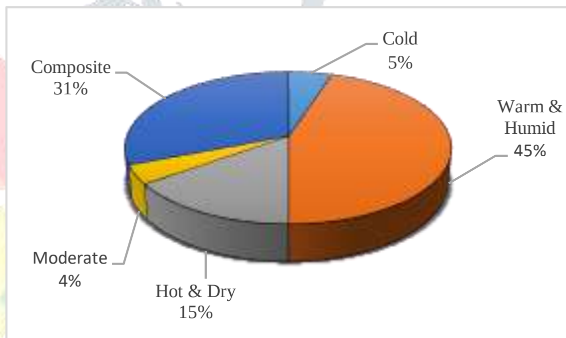


Figure-2. Climate zones of India. [13]

Table 1 Different climatic zones of India.

Climatic Zones	Cities	Description	Summer		Winter		Diurnal Variation (°C)	Average Maximum/ Minimum Temperature (°C)
			Day (°C)	Night (°C)	Day (°C)	Night (°C)		
Hot &Dry	Jaipur/Rajasthan, Madhya Pradesh, Central Maharashtra, Ahmedabad, Kutch etc.	High temperature. Low humidity. High/Intense solar radiation. Clear sky.	40-45	20-30	5-25	0-10	15-20	32/19
Warm & Humid	Chennai, Mumbai, Kerala, Coastal parts of Orissa, etc.	Moderate temperature. Moderate humidity during day and high humidity during night. Diffused solar radiation if cloud cover is high, Intense/Direct solar radiation in cloudless days.	30-35	25-30	25-30	20-25	5-8	33/24
Temperate	Bangalore, Goa and Deccan parts	Moderate temperature. Moderate humidity.	30-34	17-24	27-33	16-18	8-13	29/19

		Clear sky.						
Cold	Jammu & Kashmir, Ladakh, Sikkim, Himachal Pradesh	Low temperature during winter and moderate temperature during summer. High solar radiation during sunny/cold days. Low humidity in cold/sunny days, high humidity in cold/cloudy days.	(17-24)/ (20-30)	(4-11)/ (17-21)	4-8	-3-4	15-25	20/7
Composite	New Delhi, Punjab, Uttar Pradesh, Bihar, Jharkhand, etc.	High temperature during summer and low temperature during winter. Low humidity during summer and low humidity during winter. High solar radiation.	32-43	27-32	10-25	4-10	22	31/19

3. Need for Passive Cooling Technologies

Approximately 30% of India's overall electricity usage is attributed to residential and commercial structures, with residential buildings accounting for 22% and commercial establishments contributing 8% [15]. In order to successfully employ passive cooling methods, it is essential to have a thorough understanding of the region's climatic conditions and to fine-tune crucial elements using suitable automation controls. By adopting this strategy, it is possible to either completely or partially replace traditional air conditioning systems in a variety of building types, resulting in significant energy conservation and enhanced environmental sustainability.

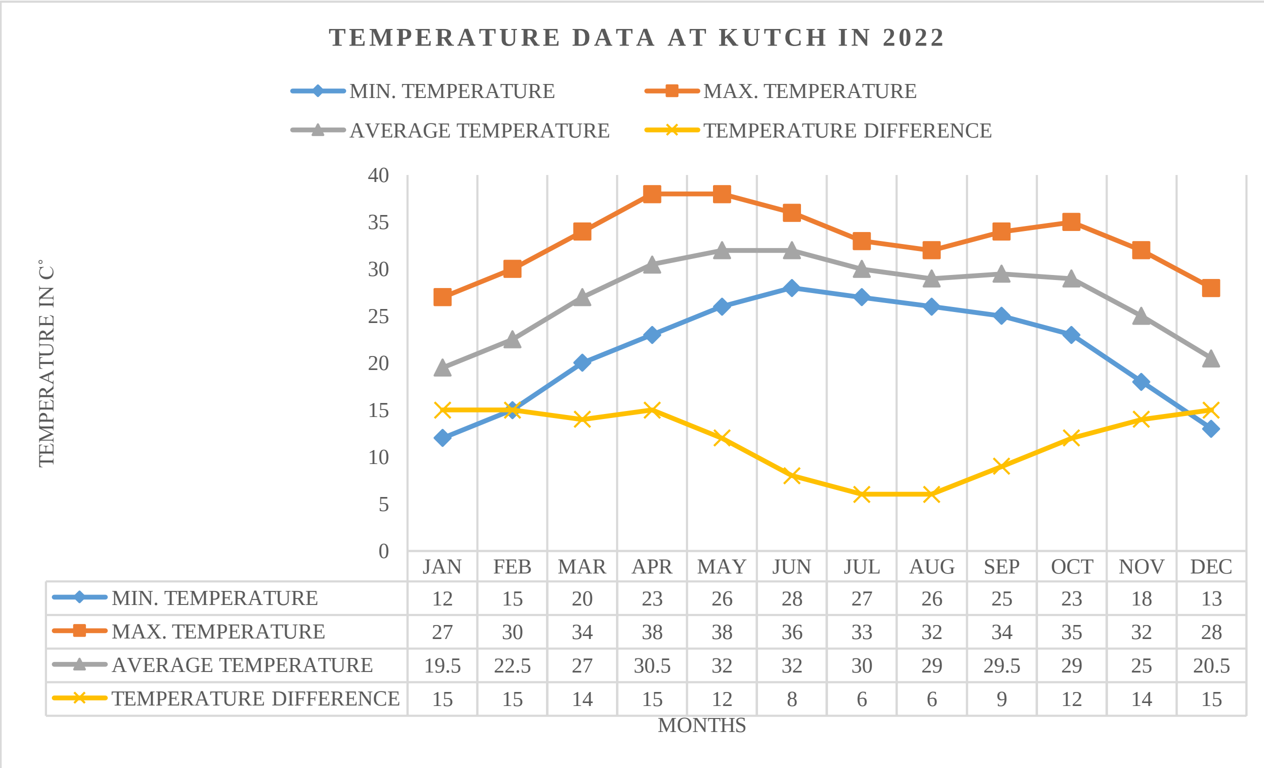
4. Outline of Field Experiment

4.1 Location and Climate

During the field measurements conducted from November, 2022, to April, 2023, researchers collected data on temperature and other relevant factors in a single-story house located in Mankuva, Bhuj, Kutch, India. This data collection aimed to better understand the indoor thermal conditions and the effectiveness of various passive cooling strategies in the region.

Figure-3, which shows the monthly mean air temperature for the entire year of 2022, provides valuable insights into the local climate and its variations throughout the year. This information is crucial for designing and implementing effective passive cooling techniques tailored to the specific climate conditions of the area. The study established comfort temperatures for the room, considering 25°C as the ideal temperature during summer months and 22°C during winter months. These comfort temperatures serve as benchmarks for evaluating the performance of passive cooling strategies and determining their effectiveness in maintaining thermal comfort for occupants.

By analysing the collected data and comparing it to the established comfort temperatures, researchers can identify the most effective passive cooling techniques for the region and provide recommendations for their implementation in residential and commercial buildings. This knowledge can contribute to reducing energy consumption, improving indoor thermal comfort, and promoting sustainable building practices in the area.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MIN. TEMPERATURE	12	15	20	23	26	28	27	26	25	23	18	13
MAX. TEMPERATURE	27	30	34	38	38	36	33	32	34	35	32	28
AVERAGE TEMPERATURE	19.5	22.5	27	30.5	32	32	30	29	29.5	29	25	20.5
TEMPERATURE DIFFERENCE	15	15	14	15	12	8	6	6	9	12	14	15

Figure 3 Monthly Temperature data in 2022 at Kutch

4.2 Evaluation of Required Cooling Load by Using (CLTD/SCL/CLF) Method.

In order to attain optimal indoor thermal comfort, it is imperative to accurately compute the cooling load utilizing the CLTD/SCL/CLF methodology, which is an abbreviation for Cooling Load Temperature Difference, Solar Cooling Load, and Cooling Load Factor. This comprehensive approach considers the entire cooling load, amounting to 1134.64 watts, which encompasses all sources of heat gain within an edifice. These sources include heat emanating from the roof, walls, occupants (accounting for both sensible and latent heat), lighting, ventilation (sensible and latent heat), and various appliances.

To ascertain air velocity, an anemometer was employed as a measurement instrument. It was estimated that the velocity of air ingress through the window is approximately 35 to 40% of the external air velocity at the apex of the building. Based on these findings, the essential supply airflow was determined to be 0.16m^3⁄s, with a requisite mass flow rate of 0.192kg⁄s.

In order to achieve the target airflow of 1.6m^3⁄s, the window dimensions were meticulously calculated through a series of mathematical computations. The finalized window design features an area of 0.38m^2, ensuring the proper airflow is sustained for optimal indoor thermal comfort and efficient cooling performance.

4.3 Ventilation Strategies.

The study delves into four distinct ventilation techniques: the absence of ventilation (full ventilation), continuous ventilation (full day ventilation), and ventilation during daytime hours (daytime ventilation), and ventilation during night-time hours (night-time ventilation). These methods focus on regulating airflow through windows, with daytime ventilation occurring between 8:00 and 20:00, and night-time ventilation taking place between 20:00 and 8:00. To enhance air movement within the room, a ventilation fan was installed, while ceiling fans were operated or turned off as needed during the data collection phase. The door's position, either open or closed, was also adjusted according to the specific ventilation strategy being examined.

To ensure a comprehensive analysis, each ventilation approach was evaluated across different months, taking into account any potential changes in weather conditions and their impact on the effectiveness of the strategies. Table-2 presents an in-depth description of the individual investigation techniques, outlining the specifics of each approach and the conditions under which they were tested. This information provides valuable insights into the various ventilation methods and their potential benefits for optimizing indoor air quality and comfort.

Table 2 Detailed information on the investigated room

Variable	Value
Level	First
Orientation	East
Floor area (m^2)	11.2
[illegible]	[illegible]

Table 3 Details of ventilation modes and strategies.

Ventilation Strategy	Window Operation	
	Day (8:00–20:00)	Night (20:00–8:00)
without ventilation	Closed	Closed
full ventilation	Open	Open
day ventilation	Open	Closed
night ventilation	Closed	Open

4.4 Investigated Room Experimental Setup

The room under consideration spans an area of approximately 11.2 m^2 and has a vertical clearance of 3 m. As shown in Figure-4, the house's floor plan reveals an extended window situated on one side of the room and experimental setup. The structure, built in 2003, consists of a sturdy reinforced concrete frame accompanied by brick walls, providing durability and stability. Both the ground and upper floors are equipped with reinforced concrete slabs, ensuring a robust foundation.

Despite the solid construction, it is important to note that the house lacks insulation against heat in both the roof and walls, which may impact energy efficiency and indoor comfort. To provide a deeper understanding of the room's features and construction materials, Table-3 contains detailed information about the specific room being investigated. Additionally, Table-4 enumerates the various materials employed in constructing different components of the house, offering insight into the overall building composition.

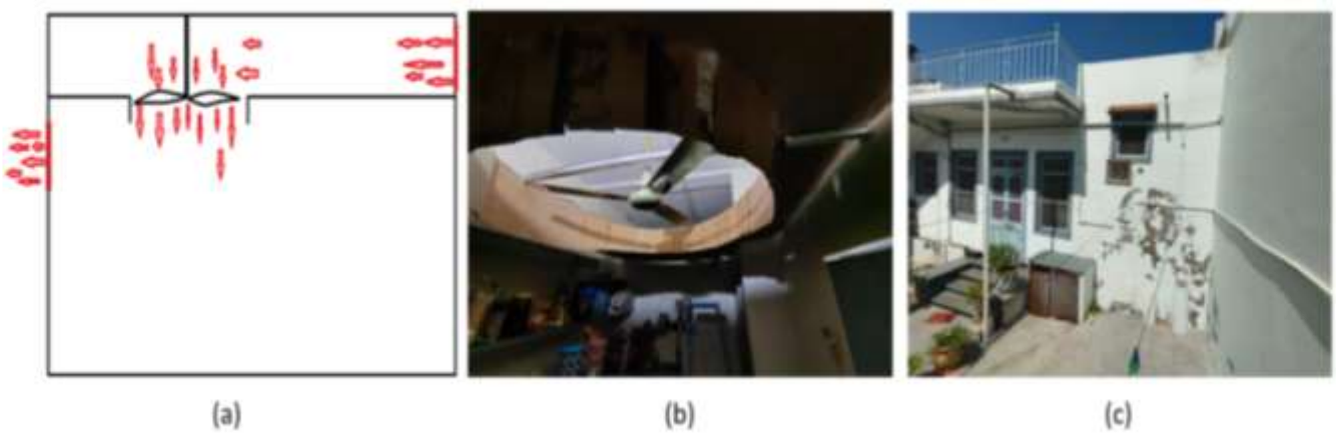


Figure 4 Experimental Setup Images of the investigated room. a) Experimental setup outline, b) Experimental setup, c) window positioning.

Table 4 Building materials used in investigated house.

Component	Material	U-value W/ (m^2 K)]
Door	Solid hard wood panel door	0.64
Ceiling	150-mm thick reinforced concrete slab with 12-mm cement plaster	1.23
Wall material	225-mm think brick wall with 12.5-mm thick cement plaster on both sides	2.13
Floor material	150-mm thick reinforced concrete slab	1.03

4.5 Measurement Setup

The study involved measuring both indoor air temperature (Ti) and outdoor air temperature (To), as depicted in Figure-5, which shows the location and nature of the climatic parameter measurements conducted within the house under investigation. To capture an accurate representation of the thermal environment below the ceiling, measurements were taken at 30-minute intervals.

The data collected from these measurements provides valuable insights into the indoor and outdoor temperature conditions and their potential impact on the effectiveness of the various ventilation strategies being tested. By analysing the temperature and velocity data, researchers can gain a better understanding of the thermal environment within the room and how it is affected by different ventilation approaches. This information can be used to optimize indoor comfort and energy efficiency, leading to improved sustainability and reduced energy consumption.

Figure 4 Equipment setup for Indoor and outdoor measurement. a) Outdoor Temperature recorder, b) Anemometer, c) Indoor Temperature recorder,

4.6 Instruments Used in Experiment

The researchers used an Elitech RC-5 temperature sensor with an accuracy of ±0.5°C to measure the temperature during the field measurements. They also employed an anemometer to collect velocity data. Before taking measurements, each instrument was calibrated to ensure accuracy, and its consistency was verified. Additionally, an exhaust fan was used for forced ventilation during the measurements.

Table -5 provides more details about the instruments used in the field measurements, including their specifications and accuracy. Figure-6 shows the instruments used in the field measurements, providing a visual representation of the equipment used to collect data on temperature and velocity.

The use of calibrated instruments with high accuracy is crucial for obtaining reliable data and ensuring the validity of the study's findings. By using appropriate instruments and calibration procedures, the researchers were able to collect accurate and consistent data on temperature and velocity, which are essential for evaluating the effectiveness of passive cooling strategies in the region.

Table 5 List of instruments used; Ti, To = temperature at indoor and outdoor, Vi, Vo = air velocity at indoor and outdoor

Space	Instrument	Parameters	Accuracy and Range
Indoor	Temperature Recorder Elitech RC-5 Data Logger	Ti	± 0.5 °C [-30 °C– 70 °C]
	Digital Anemometer AVM - 03	*Vi*	± 3% Of Reading [0 - 45 M/S]
	Exhaust Fan		Sweep-230mm, 2600 RPM,[0 - 8 M/S]
Outdoor	Temperature Recorder Elitech Rc-5 Data Logger	To	± 0.5 °C [-30 °C– 70 °C]
	Digital Anemometer AVM - 03	*Vo*	± 3% Of Reading [0 - 45 M/S]

Figure 5 Instruments used in the field measurements. a) Temperature recorder, b) Anemometer, c) Exhaust Fan

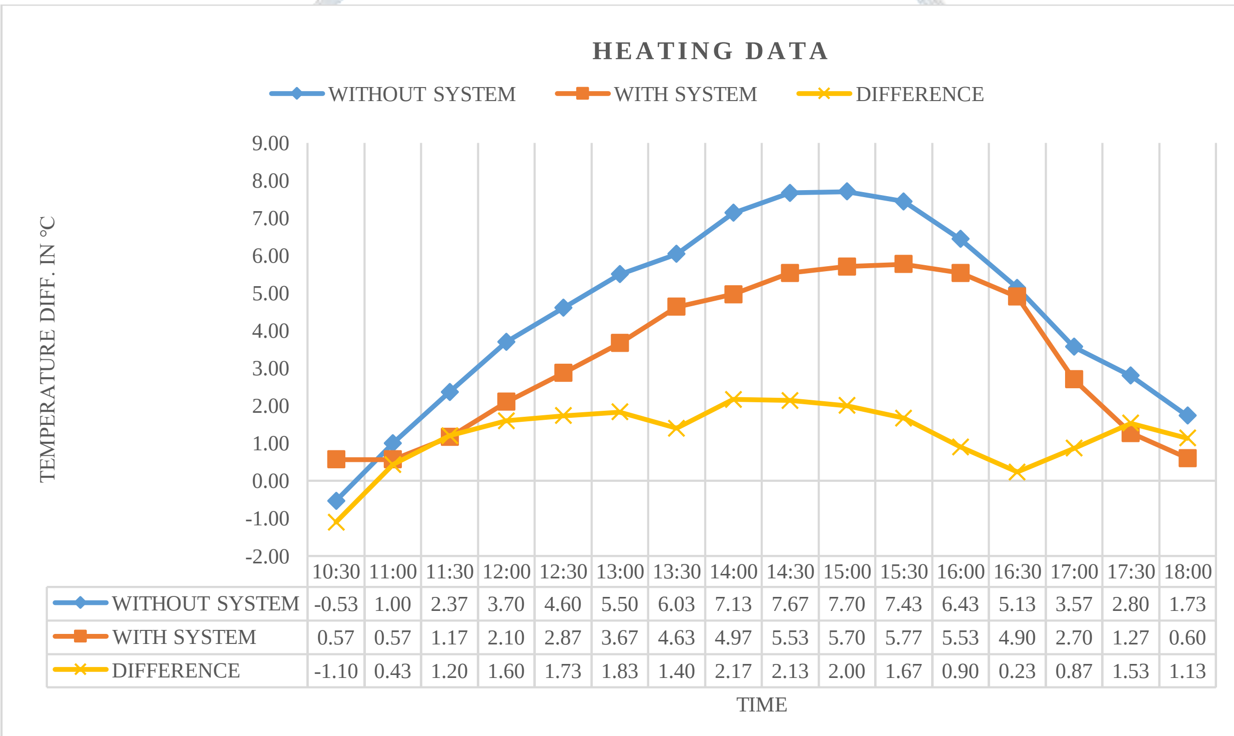
5. Results and Discussion

To reiterate, according to Blondeau et al. [10], night ventilation can decrease air temperature by 1.5 to 2 degrees, even when the daily temperature range is only 8.5 degrees. This study is relevant in areas where there is a significant temperature difference between indoor and outdoor temperatures. The 2022 weather data for Kutch, displayed in Figure -3, shows that the temperature difference between day and night is larger from October to May. These months are more suitable for direct air-free cooling. However, heating is needed from November to February instead of cooling.

Temperature readings were collected in a room with and without a heating system, as illustrated in Figure -7. The datasets were compared by calculating the mean, median, and standard deviation, and a line graph was used for visualization. The data demonstrates that the heating system is more effective in maintaining a consistent temperature, with a 26.4% improvement in the mean temperature difference.

The effectiveness of the heating system may be influenced by factors such as the efficiency of the specific heating system, the insulation of the room, and external weather conditions. However, based on the provided data, the heating system proves to be an efficient solution for temperature regulation. The heating system that circulates outside air is a cost-effective option compared to a system without heating, as it offers a comfortable environment without increasing energy consumption or operational costs.

The data analysis provides valuable information for homeowners, businesses, and building managers when considering the installation or upgrade of heating systems. The heating system's ability to maintain a consistent temperature can help prevent significant temperature fluctuations that may cause discomfort or negatively impact productivity. The energy consumption and cost of operation are the same for both systems, emphasizing the efficiency of the heating system as a cost-effective solution for temperature regulation.



	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00
WITHOUT SYSTEM	-0.53	1.00	2.37	3.70	4.60	5.50	6.03	7.13	7.67	7.70	7.43	6.43	5.13	3.57	2.80	1.73
WITH SYSTEM	0.57	0.57	1.17	2.10	2.87	3.67	4.63	4.97	5.53	5.70	5.77	5.53	4.90	2.70	1.27	0.60
DIFFERENCE	-1.10	0.43	1.20	1.60	1.73	1.83	1.40	2.17	2.13	2.00	1.67	0.90	0.23	0.87	1.53	1.13

Figure 6 December and January Heating data

The heating system is more effective in increasing room temperature compared to not having a heating system, with an approximate effectiveness of 1.24 °C. The heating system that circulates outside air is an efficient solution for maintaining a consistent and stable temperature in a room, providing a comfortable environment without increasing energy consumption or operational costs. The standard deviation, range, and mean temperature difference comparisons further support the decision to invest in a heating system that circulates outside air.

We are now examining the data from March, which presents a figure-8 line graph illustrating the temperature difference versus time. This analysis aims to assess the performance of a direct air passive free cooling system in sustaining a stable temperature gap between the ambient temperature and the room temperature throughout March. The data set includes temperature difference readings recorded at 30-minute intervals from 18:00 to 8:00, comparing a room equipped with a cooling system to one without it. This detailed evaluation helps us understand the effectiveness of the cooling system in maintaining a consistent temperature difference.

In order to evaluate the data's distribution, the standard deviation was computed. A smaller standard deviation signifies that the data points are more concentrated around the average, whereas a larger standard deviation implies a greater dispersion of data points. The standard deviation for the room with the cooling system is 1.63, while for the room without the cooling system, it is 1.71. The marginally lower standard deviation for the room with the cooling system indicates a more uniform temperature difference when the cooling system is operational. The data's range was calculated to identify the difference between the highest and lowest values. A smaller range signifies less data dispersion, while a larger range indicates more data spread. The range for the room with the cooling system is 8.55, and for the room without the cooling system, it is 8.75. The slightly smaller range for the room with the cooling system suggests a more stable temperature difference when the cooling system is utilized.

To evaluate the cooling system's effectiveness, the average temperature differences for both data sets were compared. The average temperature difference for the room with the cooling system is -1.30, while for the room without the cooling system, it is -3.31. The cooling system is 60.66% more effective in maintaining a consistent temperature difference compared to the room without a cooling system, indicating a significant improvement in temperature regulation.

To determine the average temperature difference between the room with the cooling system and the room without it, the following calculation was performed:

Temperature difference = -3.31 - (-1.30) = -2.01

On average, the temperature is 2°C lower with the cooling system compared to the room without it.

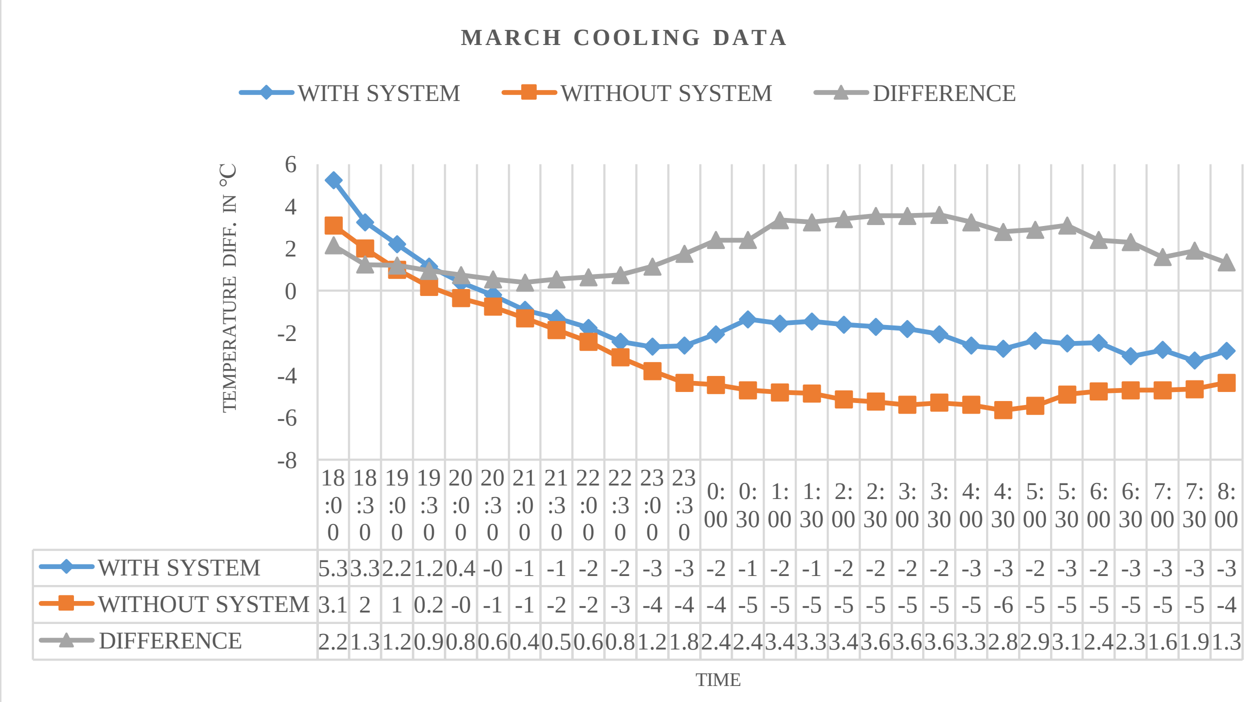


Figure 7 March cooling data

In summary, the cooling system offers a more consistent and stable temperature difference compared to the room without a cooling system, as demonstrated by the lower standard deviation and range. The cooling system is 60.66% more effective in maintaining a consistent temperature difference and results in an average temperature that is 2 degrees lower than the room without a cooling system. Given that energy consumption and cost are the same for both systems, the direct air passive free cooling approach is an energy-efficient and cost-effective solution for temperature regulation.

We are currently analyzing April's data, which features a figure-9 line graph depicting the temperature difference versus time. This evaluation aims to determine the effectiveness of a direct air passive free cooling system in maintaining a consistent temperature gap between the ambient temperature and room temperature throughout April. The study's objective was to compare the performance of three distinct cooling systems in sustaining a comfortable room temperature. The systems examined included a cooling system with a fan, a cooling system without a fan, and no cooling system. Temperature difference data, calculated as atmospheric temperature minus room temperature, was collected every 30 minutes from 6:00 PM to 8:00 AM. The analysis focused on standard deviation, range, and average temperature differences to assess each cooling system's effectiveness.

Standard deviation measures the dispersion or spread of a dataset. A lower standard deviation means data points are closer to the mean, while a higher standard deviation indicates more spread out data points. In this study, the standard deviations for the three cooling systems were calculated as follows: with fan cooling system, 2.47; without fan cooling system, 2.29; and no cooling system, 1.43. The cooling system without a fan showed a slightly lower variation in temperature difference compared to the one with a fan, suggesting it maintains a more consistent temperature difference. The no cooling system had the lowest standard deviation, indicating the least variation in temperature difference. However, it's important to note that the no cooling system doesn't provide active cooling.

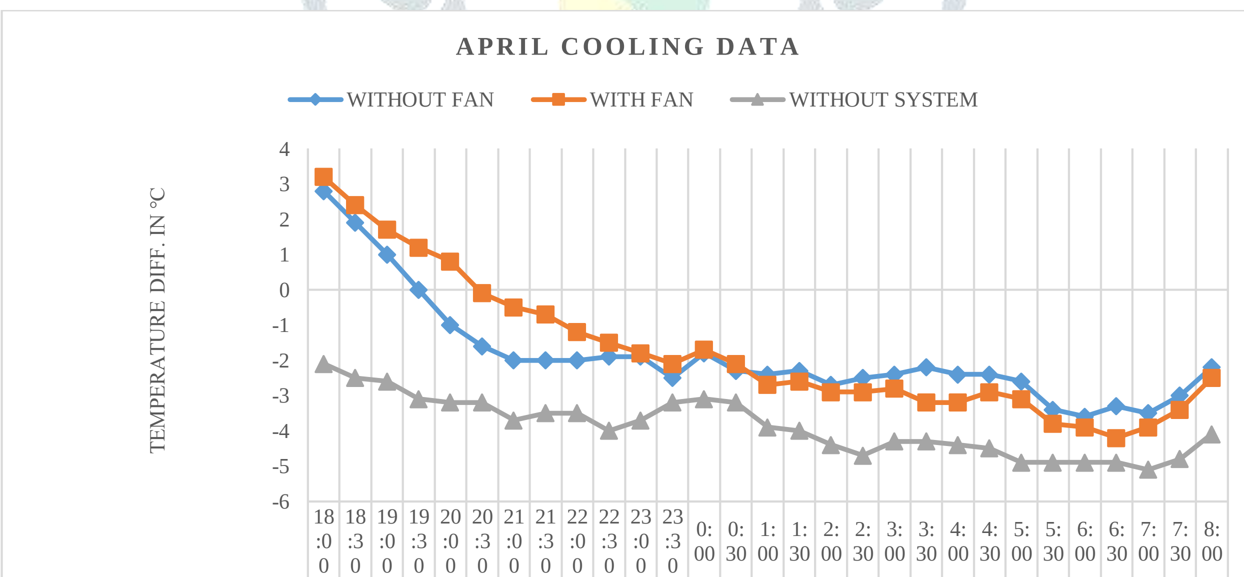
The range represents the difference between the maximum and minimum values in a dataset. A smaller range indicates more closely grouped data points, while a larger range signifies a wider spread. The ranges for the three cooling systems were calculated as follows: with fan cooling system, 7.4; without fan cooling system, 6.6; and no cooling system, 3.0. Similar to the standard deviation results, the cooling system without a fan had a smaller range compared to the one with a fan, suggesting it maintains a more consistent temperature difference. The no cooling system had the smallest range but didn't provide active cooling.

The average temperature differences for the three cooling systems were calculated to determine their effectiveness in maintaining a comfortable room temperature. The results were as follows: with fan cooling system, -1.34; without fan cooling system, -1.17; and no cooling system, -3.84. The cooling system with a fan was approximately 65.1% more effective compared to the no cooling system. The cooling system without a fan was slightly more effective than the one with a fan, with an effectiveness of 69.5% compared to the no cooling system.

To further comprehend the cooling systems' effectiveness, the temperature differences between the cooling systems and the no cooling system were calculated:

With fan: 2.50°C lower than the no cooling system

Without fan: 2.67°C lower than the no cooling system



	18:00	18:30	19:00	19:30	20:00	20:30	21:00	21:30	22:00	22:30	23:00	23:30	0:00	0:30	1:00
WITHOUT FAN	2.8	1.9	1	0	-1	-2	-2	-2	-2	-2	-2	-3	-2	-2	-2
WITH FAN	3.2	2.4	1.7	1.2	0.8	-0	-1	-1	-1	-2	-2	-2	-2	-2	-3
WITHOUT SYSTEM	-2	-3	-3	-3	-3	-3	-4	-4	-4	-4	-4	-3	-3	-3	-4

	1:30	2:00	2:30	3:00	3:30	4:00	4:30	5:00	5:30	6:00	6:30	7:00	7:30	8:00
WITHOUT FAN	-2	-3	-3	-2	-2	-2	-2	-3	-3	-4	-3	-4	-3	-2
WITH FAN	-3	-3	-3	-3	-3	-3	-3	-3	-4	-4	-4	-4	-3	-3
WITHOUT SYSTEM	-4	-4	-5	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5	-4

TIME

Figure 8 April cooling data

The cooling system with a fan reduced the temperature by 2.50°C compared to the no cooling system, while the cooling system without a fan reduced the temperature by 2.67°C. The cooling system without a fan was slightly more effective in lowering the temperature than the one with a fan.

In conclusion, given that energy consumption and operational costs are the same for all three systems, the cooling system without a fan is a better choice for maintaining a more consistent temperature difference. However, it's crucial to consider other factors such as comfort, air circulation, and specific cooling requirements before making a final decision. The cooling system without a fan is slightly more effective than the one with a fan, but the difference is not significant. The no cooling system, while having the lowest standard deviation and range, doesn't provide active cooling and isn't suitable for maintaining a comfortable room temperature.

6. Conclusion

Finally, we will synthesize our findings to draw conclusions about the overall effectiveness and benefits of direct air free cooling systems. This will involve a discussion of the key factors that contribute to the system's performance, as well as recommendations for future research and development in this area. By providing a thorough analysis of our experimental results, we aim to contribute to the growing body of knowledge on direct air free cooling and its potential for improving indoor comfort, reducing energy consumption, and promoting sustainable building practices.

For December and January Heating System

- The heating system results in an average temperature that is 1.3℃ higher than the without a heating system.
- The heating system demonstrates a 26.4% improvement in mean temperature difference compared to not having a heating system.

For March Cooling System

- The cooling system results in an average temperature that is 2℃ lower than the room without a cooling system.
- The cooling system shows a 60.66% improvement in maintaining a consistent temperature difference compared to not having a cooling system.
- The cooling system offers a more stable temperature difference, as indicated by the lower standard deviation and range.

For April Cooling System

- The cooling system without a fan maintains a more consistent temperature difference compared to the one with a fan, as shown by lower standard deviation and range.
- The cooling system without a fan reduces the temperature by 2.67°C, slightly more effective than the one with a fan (2.50°C lower than no cooling system).

Overall, the data analysis highlights the effectiveness of heating and cooling systems in maintaining consistent and comfortable room temperatures. The systems offer energy-efficient and cost-effective solutions for temperature regulation, benefiting homeowners, businesses, and building managers. However, specific factors and requirements should be taken into account when selecting the most suitable system for a particular scenario.

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