TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

THESIS NO: M-101-MSMDE-2024-2026

Thermal Performance Analysis of Paraffin as Phase Change Material

by

Aayush Aryal

(080MSMDE001)

A THESIS
SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND AEROSPACE
ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF SCIENCE IN MECHANICAL SYSTEMS
DESIGN AND ENGINEERING

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

LALITPUR, NEPAL

May 2026

COPYRIGHT

Head of the Department,

Mechanical and Aerospace Engineering,

Pulchowk Campus, Institute of Engineering

Lalitpur, Nepal

TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS
DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled "**Thermal Performance Analysis of Paraffin as Phase Change Material**" submitted by **Aayush Aryal(080MSMDE001)** in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Systems Design and Engineering.

Supervisor: Prof. Dr. Surya Prasad Adhikari
Department of Mechanical and Aerospace Engineering
Pulchowk Campus

External Examiner: Prof. Dr. Hari Prasad Neupane
Department of Mechanical Engineering
Kathmandu University

Committee Chairperson: Asst. Prof. Dr Sudip Bhattarai
Head of the Department
Department of Mechanical and Aerospace Engineering

Date: April 24, 2026

ABSTRACT

Buildings in warm climatic regions often experience significant indoor heat gain due to the use of lightweight roofing materials such as corrugated metal sheets, which absorb and transmit solar radiation. This increases indoor temperatures and the use of energy intensive cooling systems. Phase Change Materials (PCMs) have been investigated as a potential option for passive thermal energy storage because of their capacity to absorb, store and release a significant amount of heat when they undergo a phase change. This research examines the thermal behaviour of the paraffin wax as a phase change material (PCM) incorporated in a model prototype roof.

A small scale experimental setup was designed in which paraffin was placed inside a cavity beneath a metal sheet roof structure. Temperature measurements were taken at three different locations: outer surface, inner surface, and inner ambient air with the help of temperature sensor DS18B20 which were connected to an Arduino based data acquisition system. There were outdoor experiments carried out over several days, taking temperature readings at regular intervals to determine the thermal response of the system with and without paraffin in the natural environment. To simulate external heating under various heating configurations, the external heating experiments were also conducted using electric heating tubes under controlled heating conditions. The results show that the use of paraffin PCM has a significant effect in decreasing the rate of heat transfer through the roof construction by storing the heat energy during the melting process. The findings suggest that paraffin-based PCM systems can effectively enhance passive thermal regulation in building envelopes and have potential applications in improving indoor thermal comfort while reducing dependence on active cooling systems in warm climatic regions.

ACKNOWLEDGEMENTS

I would like to express my sincere and heartfelt gratitude to my thesis supervisor, Professor Surya Prasad Adhikari, PhD, for his constant guidance, encouragement, and support in completing this research work. This research would not have been possible without him. His deep knowledge, useful advice and constructive comments have been of great influence and instrumental throughout the development of this thesis. Without his valuable advice and patient mentorship, it would not have been possible to conclude this research successfully.

My sincere thanks to the Head of Department, Assistant Professor Sudeep Bhattarai for valuable inputs, thoughtful comments and constant encouragement during this research. He has been instrumental in providing the academic environment and resources that we need, to which he is so generous, his efforts are greatly appreciated.

I would like to thank Nepal Academy of Science and Technology (NAST) for providing the research platform, the laboratory facilities and technical supports which were of great importance for the successful completion of this work. I have been privileged to have been granted this opportunity to conduct research at NAST and thankful to all faculty and staff members who have cooperated and assisted me.

I would like to express sincere gratitude to all my teachers and faculty members of the department who helped me in my academic process to build a solid foundation of knowledge and made this research possible. Thanks to all my friends and colleagues who spent time on my ideas, gave new ideas and moral support in the different phases of this work. To everyone who has assisted me in this thesis work in different ways, whether directly or indirectly, I extend my heartfelt appreciation. This work would not have been possible without your collective support.

Finally, I am deeply indebted to my family for their unconditional love and unwavering support. Their constant encouragement has been my greatest source of strength throughout my studies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

T	Temperature
W	Watt
C	Celsius
Q	Heat transfer
P	Power
PCM	Phase Change Material
XRD	X-Ray Diffraction
Cu-Kα	Copper K-alpha
DSC	Differential Scanning Calorimetry
TES	Thermal Energy Storage
NAST	Nepal Academy of Science and Technology

CHAPTER 1: INTRODUCTION

1.1 Background

With the increase in global temperatures and the rising cost of energy, the demand for energy-efficient and sustainable buildings is only growing. Buildings account for a large portion of the overall global energy consumption, especially for the purpose of cooling in hot climatic regions (Cabeza et al., 2011). Heat gain through building envelopes, such as roofs and walls, contributes greatly to indoor thermal discomfort and increases overall energy demand (Kuznik et al., 2011). In most of the hot climatic zones, corrugated metal sheets and lightweight roofing materials are used ,as they are affordable and easy to install. But they also have been problematic for the people and occupants inside. As a result, there is a growing need for passive thermal regulation strategies that can reduce indoor heat gain without the continuous use of active cooling.

Phase Change Materials (PCMs) have gained attention as an effective approach for improving the thermal performance of buildings (Sharma et al., 2009).They have been a effective mean for thermal regulation. PCMs are substances capable of absorbing or releasing large amounts of thermal energy during phase transitions, typically between solid and liquid states. When the surrounding temperature rises to the melting point of a PCM, the material absorbs heat from the environment and undergoes a transition from solid to liquid. Conversely, as the temperature decreases, PCM solidifies and releases the stored latent heat back into the surroundings which also helps in lowering the energy consumed inside. This cyclic process of latent heat storage and release helps to moderate ambient temperature fluctuations, thereby enhancing indoor thermal comfort is one of the primary use cases for using phase change materials in thermal regulation.

In buildings, PCMs can store excess heat when the sun is out, and then gradually release this stored heat as the temperature drops in the evening or at night when the sets. This mechanism stabilizes indoor temperatures, reducing the need for artificial cooling or heating and consequently lowering energy consumption (Zalba et al., 2003). The effectiveness of a PCM depends on several factors, including its latent heat capacity, thermal conductivity, chemical stability, and compatibility with the building envelope materials.

1.1.1 Evolution of Phase Change Materials

The concept of latent heat storage has been and is continuously been explored for several decades. During the 1970s and 1980s, researchers began investigating PCMs primarily for the purpose of solar energy storage (Kenisarin & Mahkamov, 2007) and long strides were made during that period. By the 1990s, the building industry recognized the potential of PCMs for indoor thermal regulation; but the early adoption was limited due to high material costs, leakage problems, and insufficient long-term stability (Zalba et al., 2003). Over time, significant advancements in encapsulation technologies, material stability, and cost-effectiveness have led to renewed interest and usage of integrating PCMs into building systems. The growing global emphasis on green buildings, net-zero energy targets, and sustainable construction practices has also help accelerate the research and development in this area (Tyagi & Buddhi, 2007).

In modern buildings, PCMs are increasingly being utilized for a range of applications, including thermal regulation, peak load shifting, passive cooling, and thermal energy storage in residential, commercial, and industrial structures.But the primary and most effective use case scenario seem to be the use of phase change material in building envelopes.The integration of phase change materials into building envelopes has emerged as a practical and efficient solution for moderating thermal energy transfer across various climate conditions, leveraging the high latent heat storage capacity during phase transitions and further using during the night cycle to thermally regulate the conditions of indoor environment. The global surge in energy demand for space cooling has driven the development of sustainable thermal energy storage (TES) systems that can effectively decouple energy supply from demand (Pomianowski et al., 2013).

Among the various types of PCMs, paraffin wax has been widely studied due to its desirable properties, which includes a suitable melting temperature range, high latent heat of fusion, chemical stability, non-toxicity, and cost-effectiveness (Sharma et al., 2009).These major properties make paraffin stand-out and have been major factor for using paraffin instead of other PCMs which lack these characteristics. Several previous studies have demonstrated that the integration of paraffin-based PCMs in building envelopes can significantly reduce indoor temperature fluctuations (Castell et al., 2010). In composite and hot climates, building envelopes, particularly roofs and walls, serve as the primary sources of heat gain, often leading to elevated indoor temperatures and increased dependence on mechanical cooling systems (Kharbouch et al., 2018). Despite the growing body of research on PCMs in building applications, limited experimental work has specifically focused on the integration of paraffin-based PCMs with lightweight metal roofing systems commonly used in warm climatic regions.Most of the paraffin based research have been based on either laboratory based experiments or advanced building structure; lightweight metal roofing systems are not being explored.This gap in the existing literature motivates the present study, which aims to experimentally investigate the thermal performance of paraffin wax as a phase change material integrated into a prototype metal roof model.

1.2 Problem Statement

In most hot climatic areas, and incase of Nepal in rural parts of Terai belt and lower hilly areas, houses have significant challenges in sustaining thermal comfort during the day time. Most houses rely on passive construction materials like brick masonry, wood walls, metal roofing for maintain the thermal regulation within the thermal comfort range. However it results in, interior temperatures become extremely hot, especially in the afternoon during peak hours, and more energy-intensive cooling equipment like fans and air conditioners being used to maintain the indoor temperature. This is also added upon by the fact that a very large majority of the population does not have access to constant electricity or cannot afford prolonged use of cooling appliances. Passive thermal control thus is a means of using materials that can manage indoor temperatures without energy consumption is a critical necessity. Phase Change Materials (PCMs) have also been quite promising in this regard, since they can absorb, store, and emit heat through phase change.

However, the application of PCMs as a passive method of thermal regulation is not fully exploited in low-cost residential buildings in Nepal. In particular, there is no sufficient experimental study on the thermal performance of paraffin PCMs when used as part of the roofing structure in low-cost residential buildings in Nepal. Most of the research works carried out on the thermal performance of paraffin PCMs have focused on the application of advanced building structures and laboratory-scale analysis, which may not be representative of the application in low-cost residential buildings.

While paraffin PCM has the limitation of low thermal conductivity resulting in low charging/discharging rates(Sharma et al.2009), it concerns whether paraffin can provide meaningful and measurable improvement in indoor thermal comfort when integrated into a corrugated metal roofing system under real and controlled heating conditions. This study addresses this gap by experimentally evaluating the thermal buffering performance of paraffin PCM in a prototype corrugated metal roof model under both outdoor and controlled environment conditions.

1.3 Research Objectives

MAIN OBJECTIVE:

To experimentally evaluate the thermal performance of paraffin as a phase change material (PCM) in a prototype roof structure.

SPECIFIC OBJECTIVES:

- To characterize the physical and thermal properties of paraffin as PCM.
- To design and construct a small-scale prototype roof model with an integrated PCM cavity for experimental data collection.
- To measure the temperature variation across the roof assembly under both outdoor conditions and controlled heating conditions.
- To compare the thermal performance of the PCM-integrated roof with a conventional non-PCM metal roof and assess the effectiveness of paraffin PCM in reducing heat transfer into the interior space.

1.4 Limitations of Research

- Limited daily duration: For the experiment conducted in outdoor environment, the temperature data were recorded only between 9:00 AM and 5:00 PM, covering the daytime heating cycle. Night-time behavior, especially the complete solidification of paraffin and the release of latent heat into the indoor space during the night period, which goes to show PCM's use-case in both day and night, was not monitored. A whole 24 hour analysis done under natural conditions would provide comprehensive understanding.

- Single-season testing: The experiment was conducted over five consecutive days during a single season (characterized by high solar radiation and clear-sky conditions) for outer conditions and 3-days for controlled environment for both type 1 and type 2. The number of days were shorten for controlled environment testings due to common repeatability of the data.The performance of paraffin PCM may differ under other seasonal conditions such as monsoon (low solar radiation, high humidity), post-monsoon, and winter (low ambient temperature, where the PCM may not fully melt).
- Prototype scale: The study was conducted on a small-scale prototype with dimensions of 2 ft × 1.2 ft × 2.5 ft rather than a full-scale residential building. Linear scale was ratioed down to 1:10 for a small-scale metal roofing system. Scaling effects, including the influence of building orientation, wall thermal mass, internal heat gains, and ventilation, were not considered.
- Single PCM configuration: Only one type of paraffin type and one cavity depth (0.5 inch) were tested with no variation in paraffin ratio or paraffin to air cavity ratio. Variations in PCM thickness, melting point and encapsulation method may further influence thermal performance.

CHAPTER 2: LITERATURE REVIEW

The research on phase change materials (PCMs) for building envelopes and thermal energy storage systems have gained significant momentum over the past few decades and is only growing going forward. It has been pushed and driven forward by the goal to reduce load on manual thermal regulation and moving ahead with greener and cost effective approach. The primary objective of this ongoing research has been to identify materials that are cost-effective, readily available, thermally and chemically stable, and environmentally friendly. In composite and hot climates, building envelopes, particularly roofs and walls, serve as the primary sources of heat gain, causing indoor temperatures to rise and increasing the dependence on mechanical cooling systems (Pomianowski et al., 2013).This ultimately causes the cost of energy and dependence on mechanical heating/cooling systems. Among the various solutions explored for mitigating this problem, the integration of Phase Change Materials (PCMs) into building components has emerged as a promising approach, ability to store and release large amounts of thermal energy during phase transitions without significant temperature changes (Zalba et al., 2003).

2.1 Phase Change Materials (PCMs)

Phase change materials (PCMs) are substances that absorb and release substantial amounts of thermal energy during phase transitions process with high latent heat capacity , most commonly between solid and liquid states. This underlying principle of PCM-based thermal energy storage is the utilization of latent heat, which is to store or release heat energy without actually changing the temperature. This distinguishes PCMs from conventional sensible heat storage materials, which in turn need significant temperature change to store equivalent amount of thermal energy.

The thermal energy storage process in PCMs mainly takes place in three stages: heat absorption, heat storage and heat release. During the heat absorption stage, as the surrounding temperature rises and reaches the melting point of the PCM, this causes the PCM to transition from a solid to a liquid state. During this phase transition, PCM absorbs a large amount of thermal energy from the environment without changing the temperature. During this process, breaking of the intermolecular bonds within the solid structure takes place, facilitating the melting process. During the energy storage stage, the absorbed latent heat is stored within the PCM as long as the material remains in its liquid phase. This stored energy can be later be retained for considerable time,which gives PCM the advantage of being used in both day and night time.At day it protects the inner occupants from extreme heat absorbing the heat through metal roofing; while during the night time as the temperature drops rapidly, it's stored heat energy can be used to heat the indoors and prevent temperatures from dropping rapidly. During the heat release stage, the PCM begins to solidify and gradually releases the stored latent heat back into the surroundings. This overall process of PCM helps to stabilize the temperature fluctuations within a closed and limited environment and stable thermal environment during both the day and night cycles.

PCMs are classified into three categories: organic, inorganic, and eutectic phase change materials. Organic PCMs include paraffin waxes and non-paraffin compounds such as fatty acids, fatty alcohols, and polyethylene glycol. Organic PCMs are chemically stable, non-corrosive, exhibit minimal supercooling, and show reliable cycling stability, making it suitable for long-term applications. Paraffin wax which is also the primary component of this report is a organic PCM. Industrial grade PCM were used during the process. Organic PCMs have low thermal conductivity, generally around 0.2 W/m·K, and relatively lower volumetric energy density compared to inorganic alternatives inorganic PCMs, primarily salt hydrates and metallic alloys, have higher latent heat storage capacity (200-300 kJ/kg), and better thermal conductivity. However, they are susceptible to issues such as supercooling, phase segregation, and corrosiveness, which can limit their practical applicability (Pasupathy et al., 2008).These are also a viable options for being used as PCM if these issues were to be addressed. Eutectic PCMs are mixtures of two or more organic and/or inorganic components that melt and solidify congruently at a single, well-defined temperature. Eutectic mixtures offer the flexibility to specify the phase change temperature to certain application requirements, making them particularly useful for building applications where the desired operating temperature range is narrow.

2.2 Evolution and Application of PCMs in Buildings

Over the past decades the global demand for energy has risen extensively due to the urbanization and rapid population growth. This includes demands in energy from all the sectors. The building sector accounts for approximately 36 percent of total energy consumption worldwide, with up to 40 percent of the energy consumed in buildings attributed to cooling loads from air-conditioning systems and heating loads like heaters and air-conditioners. Hence, enhancing the thermal performance of buildings has become a critical strategy for reducing heat transfer into buildings, lowering energy consumption, lowering the use of mechanical means to maintain the thermal comfort within the indoor environment and minimizing greenhouse gas emissions. The integration of phase change materials into building envelope components has emerged as an efficient technique for passively storing thermal energy, reducing thermal transfer through the building envelope, and conserving energy in buildings.

Recent advancements and research in thermal management for buildings show that the application of PCMs can effectively shift peak thermal loads and significantly reduce daily temperature fluctuations within interior spaces. This reduces the need to use mechanical means to maintain thermal comfort within the indoor environment. PCMs also help to time-lag the peak temperature conditions. Unlike conventional sensible heat storage materials, which require a large temperature differential to store energy, PCMs employ latent heat storage and can therefore charge or discharge thermal energy at relatively small temperature changes (Sharma et al., 2009). Over the past several decades, PCMs have been progressively integrated into walls, roofs, ceilings, and floor slabs as passive thermal energy storage systems. With high latent heat storage capacity, they act as a buffer between the outer and indoor temperatures. By absorbing heat during peak solar hours during the day time and releasing it during cooler periods during the night time, PCMs minimize indoor temperature fluctuations, delay peak heat transfer, and improve overall thermal comfort. The effectiveness of PCM integration in building envelopes is largely dependent on three key factors. Firstly, the material properties of the PCM, including its melting temperature, latent heat storage capacity, and thermal conductivity (Sharma et al., 2009). Second, the placement of the PCM within the building envelope significantly affects its performance; common configurations include placement beneath metal roofing, inside wall cavities, or within ceiling panels (Kharbouch et al., 2018). Third, local climate conditions determine the optimal operating parameters; hot, humid, or composite climates demand PCMs with melting points within the comfort range of 20-35°C to maximize heat absorption during the daytime.

Roofs are often the preferred location for PCM integration in tropical and hot climates because they receive the highest intensity of solar radiation than any other building envelope components (Kharbouch et al., 2018).In our experimental prototype too,the placement of PCM was done in the roof section of the structure and placed inside the cavity created. Studies have demonstrated that adding PCM layers behind metal sheets or roofing tiles can delay heat transfer by several hours and lower indoor peak temperatures significantly.(Akeiber et al., 2016) experimentally demonstrated that a newly composed paraffin encapsulated prototype roof structure significantly reduced temperature fluctuations and internal heat flux under hot climatic conditions in Baghdad, Iraq.(Xamán et al., 2020) simulated the thermal performance of a concrete roof with a paraffin wax PCM layer under Mexican weather conditions and found that a 2 cm PCM layer reduced thermal load by up to 57 percent. Brick and masonry walls can also be retrofitted with PCMs through the addition of encapsulated PCM panels in cavity voids or through impregnation of porous bricks, reducing daytime heat gain and improving nighttime thermal comfort. Global studies suggest that well-selected PCMs in building envelopes can reduce indoor temperature swings by 2-5°C and delay peak heat transfer by 1-3 hours, depending on climatic conditions and construction type (Simon et al., 2024). These benefits make PCMs a viable passive thermal regulation option, particularly for regions where energy-intensive air-conditioning is impractical or economically prohibitive.

2.3 Material Properties of Paraffin as a PCM

The material properties, directly related to their thermal performance, stability and usability, are crucial for evaluating PCM for use in buildings. However, the ability of PCM in regulating the indoor temperature of a enclosed surface is not only related to the latent heat storage capacity, but also to other properties such as the melting temperature, thermal conductivity, density, shape stability and cycling stability of the PCM (Sharma et al., 2009).An in-depth evaluation of these properties ensures that the material is able to store enough thermal energy, absorb and release heat in a temperature range as required, and should be thermally stable over many thermal cycles in the building envelope environment (Zalba et al., 2003).

The main reason for the use of paraffin wax as one of the most widely used organic PCMs in buildings is because it has high latent heat of fusion, negligible supercooling on solidification, is chemical stable, non-toxic and non-corrosive, and is affordable (Farid et al., 2004). The paraffin waxes are a series of straight chain hydrocarbons with the general formula of CnH2n+2 and the melting range of these waxes is mainly dependent on the length of the carbon chain (Pasupathy et al., 2008). Commercial paraffin waxes are usually impure with a mixture of isomers and thus have a range of melting temperatures instead of a sharp melting point. The characteristics of the paraffin wax used as PCM in building roof is described in the following subsections:

2.3.1 Density

The density of paraffin wax ranges from 800 to 950 kg/m^3, depending on the specific composition and the number of carbon atoms in the hydrocarbon chain. Its density is specific to the value of 'n' and depends on the length of hydrocarbon of the paraffin used.

2.3.2 Porosity and Shape Stability

Pure paraffin wax is a non-porous material and has zero inherent porosity. In the liquid state, however, paraffin does not have a natural shape stability. Upon undergoing phase change from solid to liquid, paraffin wax changes their shape and structure. Hence, it must be encapsulated or contained within a suitable housing (metal container, aluminium panel, or macro-encapsulation system) to prevent leakage during the melting process (Zalba et al., 2003). Containment is a key criterion when designing building components that incorporate PCM.

2.3.3 Melting and Solidification Temperature

The phase change temperature of paraffin is dependent on the length of the carbon chain in its molecular structure. Commercially available paraffin waxes offer a wide range of melting temperatures, typically between 20°C and 65°C (Farid et al., 2004). In building applications, especially for thermal regulation in warm climatic region, paraffin waxes are chosen in the range of 30-60°C which correspond to the indoor thermal comfort region and the diurnal temperature difference. The choice of melting temperature is very important to ensure proper melting and solidification of the PCM in the diurnal temperature range of the selected site.

2.3.4 Latent Heat of Fusion

For paraffin wax, the latent heat of fusion ranges from 150 kJ/kg to 250 kJ/kg, depending on the purity and composition of the material (Farid et al., 2004). This relatively high latent heat capacity enables paraffin to store substantial amounts of thermal energy within a small volume, making it an effective material for passive thermal energy storage in building applications.

2.3.5 Thermal Conductivity

Thermal conductivity of paraffin wax is 0.2 to 0.25 W/m·K, which is comparatively low as compared with inorganic PCM and the conventional construction materials. This low thermal conductivity is the main drawback of paraffin as a PCM because it will limit how quickly the heat can be absorbed and released during the phase change. Various techniques have been proposed in the literature for enhancing the thermal conductivity, such as the dispersion of high conductivity nano particulates, e.g., carbon nanotubes and graphene, the use of metal foams and fins, and the use of expanded graphite as a thermal conductivity enhancer (Pasupathy et al., 2008). However, the overall thermal performance of paraffin for building envelope applications is found to be satisfactory for passive thermal regulation especially in thin-layer applications and/or in a suitable containment system.

2.3.6 Chemical Stability

Paraffin wax is chemically stable and does not get degraded on repeated thermal cycling within the working range of operating temperature (Sharma et al., 2009). It does not react with common building materials, is non-corrosive and does not generate harmful compounds on phase change. The above properties enable paraffin wax to be incorporated into the building envelope over an extended period of time without degradation of the material or interaction with other building materials (Farid et al., 2004). It is important to note, however, that paraffin is flammable and careful consideration of fire safety is required if it is to be incorporated in building elements.

Property	**Value / Range**
Density	800-950 kg/m³
Porosity	0% (Non-porous)
Shape Stability (Liquid)	None (requires encapsulation)
Melting Temperature Range	20-65°C (Depending on chain of hydro-carbon)
Latent Heat of Fusion	150-250 kJ/kg
Thermal Conductivity	0.2-0.25 W/m·K
Chemical Stability	Chemically stable, non-corrosive
Supercooling	Negligible
Flammability	Flammable (requires precautions)

Table 1:Summary of Key Material Properties of Paraffin Wax as a PCM

CHAPTER 3: METHODOLOGY

This chapter outlines the methodology that will be used to critically evaluate the thermal performance of paraffin wax, as a Phase Change Material (PCM), embedded in a corrugated metal roofing system. This includes an outline of the underlying theory and a discussion on the selection of the appropriate materials. Details will be provided on the development of a prototype, the set-up of the measurement tools and data acquisition protocol, and the procedures to be conducted under outdoor and climatic test conditions.

3.1 Conceptual Framework

The methodology for this research work is demonstrated in a series of sequential steps illustrated in Figure 3.1. A comprehensive search is first performed to review the available literature on phase change materials and their application within thermal comfort and heating and cooling reduction for buildings. The results of the literature review are used to determine a suitable PCM for subsequent testing; an assessment of the PCM's key thermophysical properties then follows. If the properties indicate the PCM has the potential for effective integration into buildings, testing then progresses to the PCM preparation and subsequent experiments; and if not, the material selection process is repeated with alternative candidates until an appropriate material is identified.

After the appropriate material selection, the experimental prototype was designed on a computer-aided design (CAD) software and produced before experimental testing under both outdoor natural environmental and indoor controlled laboratory conditions. The measured temperature data were compared with the available data in the literature and the results validated. Valid results were then concluded and the results reinspected for further improvement if any inconsistency was observed.

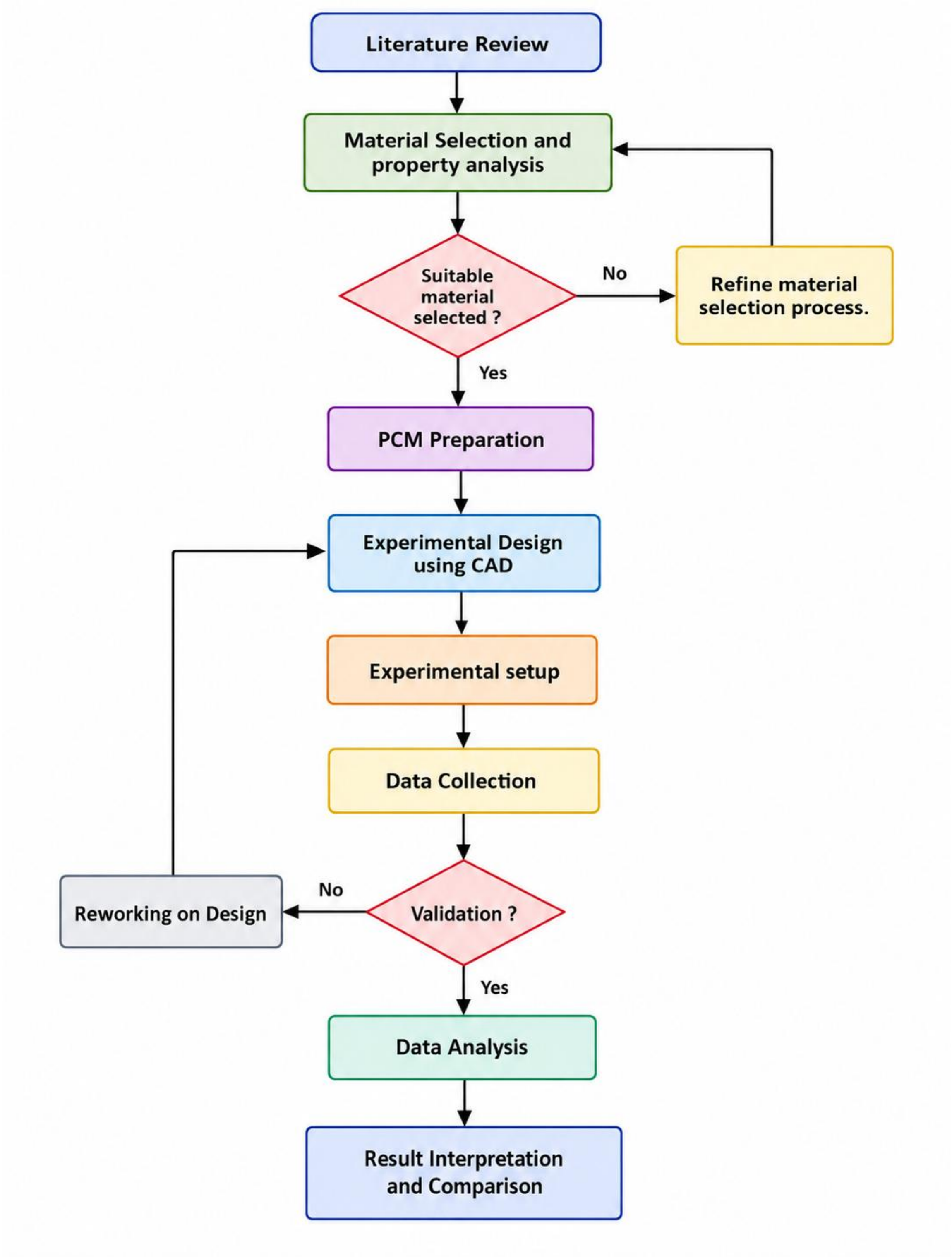


Figure 1:Methodology

3.2 Material Selection and Properties Analysis

The thermal energy storage performance of any phase change material is primarily governed by its thermophysical properties, chemical stability, compatibility with construction materials, cost-effectiveness, and environmental impact (Sharma et al., 2009). In this study, commercial-grade paraffin wax was selected as the PCM for integration into a corrugated metal roofing system. The selection was based on a systematic evaluation of the material against several key criteria, as described in the following subsections.

3.2.1 Selection Criteria

Melting Temperature Range: In terms of passive thermal regulation in residential roofing systems used in warm to hot climatic conditions, the PCM must have a melting point that is equal or greater than the maximum indoor comfort temperature, usually around 30-40 °C for indoor applications or even higher, such as 50-60 °C for roofing applications, where the temperatures of the roofing system will be quite high (Kharbouch et al., 2018). These materials will allow them to absorb extra heat when there is an excess amount of radiation from the sun and release it as the outdoor ambient temperature decreases. Some commercial paraffin waxes have melting points that range from about 20°C to 70°C, allowing them to select one suitable for their thermal application in buildings (Sharma et al., 2009). However, the melting point of the PCM material depends on the intended application; therefore, the melting point should range from 22-28 °C for indoor-air buffering or 50-60 °C for roofing applications, where the PCM will be placed in front of a metallic sheet under the sun.

High Latent Heat of Fusion: Paraffin wax exhibits a relatively high latent heat of fusion, typically in the range of 170-220 kJ/kg (Kenisarin & Mahkamov, 2007). This property enables the material to absorb and store a substantial amount of thermal energy during the melting process without a significant rise in temperature. The high latent heat storage capacity makes paraffin wax an effective medium for thermal energy storage in passive cooling applications, as it can buffer a considerable portion of the solar heat gain through the roof structure (Sharma et al., 2009).

Chemical Stability and Non-Corrosiveness: Paraffin wax demonstrates reliable thermal performance during repeated melting and solidification cycles, with minimal phase segregation(Zalba et al., 2003). It is chemically stable and composed primarily of saturated hydrocarbons. Also, it is non-corrosive to constructive materials.

Non-Toxicity and Local Availability: Paraffin wax is non-toxic, odorless and easily available locally.

Thermal Conductivity Characteristics: Although paraffin wax exhibits excellent latent heat storage characteristics, its thermal conductivity value is quite low, approximately 0.2 W/m·K (Sharma et al., 2009). This act as hinderance. Consequently, the heat transfer efficiency of this material will be lower when compared with other materials whose thermal conductivity value is higher. However, despite its low thermal conductivity, paraffin continues to be extensively applied in latent heat storage applications because of its reliable phase change characteristics, high energy storage capability, and easy usage (Zalba et al., 2003).

Suitability for Corrugated Metal Roofing Systems: Metal sheets with corrugations are used extensively in roofs for domestic houses in Nepal and other developing nations because they are inexpensive and easy to install. However, they have low thermal mass and high thermal conductivity, which enables fast heat penetration from outside into the interior due to excessive solar radiation causing the indoor temperature to rise quickly leading to extensive heating conditions inside. Boobalakrishnan et al. (Boobalakrishnan et al., 2021) demonstrated that the integration of PCM with metal roof buildings can effectively reduce indoor temperatures and improve thermal comfort. In this experiment, adding the PCM layer under the metal roof surface absorbs extra heat during the day by changing from a solid to a liquid state. This significantly slows down the heat penetration process from the outside, thus lowering the interior temperature. When the temperature drops at night, the PCM changes to its solid state and releases the accumulated heat energy.

3.2.2 Material Used

Commercial-grade pure paraffin wax with a melting point in the range of 52-58°C and a latent heat of fusion of approximately 180-210 kJ/kg was selected for this study. The paraffin wax was procured from a local supplier in Nepal. The material was chosen based on its high latent heat, chemical inertness, non-corrosive nature, and established suitability for building thermal applications (Sharma et al., 2009)(Kenisarin & Mahkamov, 2007). The key thermophysical properties of the paraffin wax used in this study are summarized in Table 2.

Property	**Value / Range**
Type	Commercial-grade paraffin wax
Melting Temperature	52-58°C
Latent Heat of Fusion	180-210 kJ/kg
Density	800-950 kg/m³
Thermal Conductivity	≈0.2 W/m·K
Chemical Nature	Saturated hydrocarbons, non-corrosive
Toxicity	Non-toxic, odorless

Table 2:Thermophysical Properties of Paraffin Wax used in this Study

3.2.3 X-Ray Diffraction Analysis of Paraffin Wax

X-ray diffraction (XRD) analysis was performed at Nepal Academy of Science and Technology (NAST) using a Cu-Kα radiation source (wavelength = 1.54060 Å) over a 2θ range of 10° to 90°. The resulting diffraction pattern is presented in Figure 2 in which the XRD pattern shows two sharp and well-defined peaks at approximately $2\theta = 21.4°$ and $2\theta = 23.8°$. These are characteristics of the orthorhombic crystalline structure commonly observed in long-chain n-alkane paraffin waxes. These two peaks correspond to the (110) and (200) crystallographic planes of the paraffin lattice and are consistent with diffraction patterns reported in the literature for crystalline paraffin wax (Sharma et al., 2009; Farid et al., 2004). The sharp and narrow nature of the peaks confirms a high degree of crystallinity in the sample.

The best reference pattern identified during the analysis was PDF 50-2246 corresponds to n-Hexatetracontane ($C_{46}H_{94}$). It is important to note that XRD pattern matching to a particular compound does not mean it is composed of only that compound. It only matches the closest identifying pattern and does not necessarily mean exclusivity of that particular compound or chain of hydrocarbon. To find the exact composition of type of Carbon chain, Differential Scanning Calorimetry (DSC) needed to be done. Commercial grade paraffin wax is a mixture of n-alkanes with varying chain lengths, and the XRD patterns of long-chain n-alkanes in the range of approximately C_{20} to C_{60} produce nearly identical peak positions at $2\theta \approx 21°$ and $2\theta \approx 24°$ because they share the same orthorhombic crystal packing arrangement. This reference pattern simply represents the closest structural match within the database. The actual sample is expected to contain a distribution of hydrocarbon chain lengths centered around the C_{40}-C_{50} range, which is consistent with the measured melting point of 52-58°C reported for the material used in this study. The XRD results therefore confirm that the paraffin wax used in this study possesses the expected crystalline structure of a long-chain n-alkane suitable for latent heat storage applications.

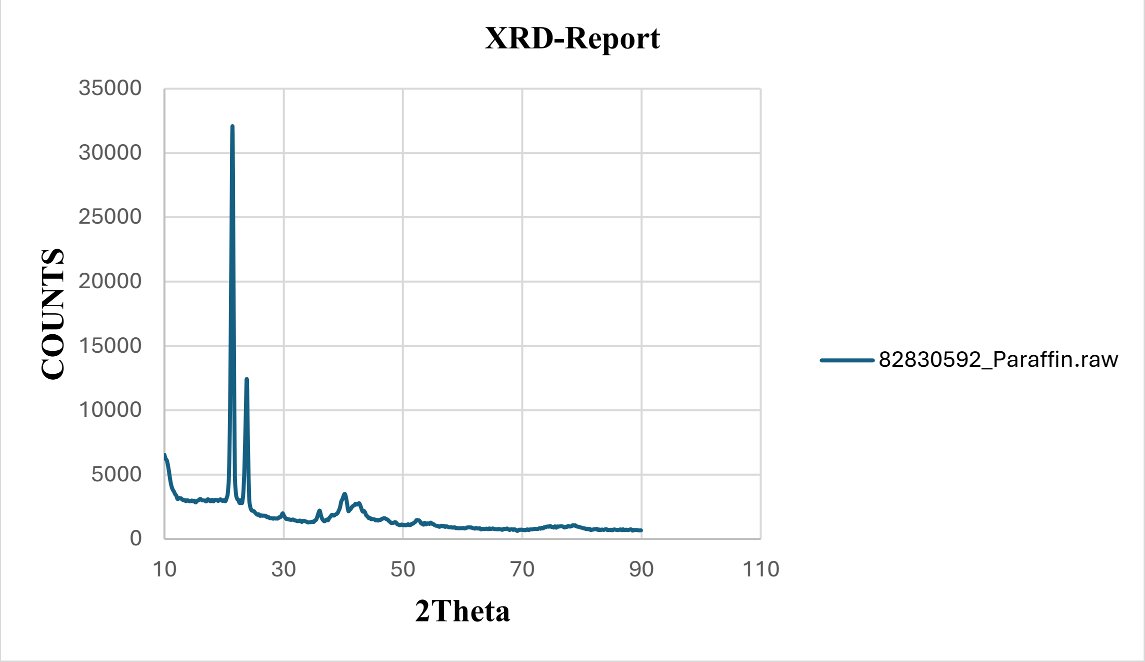


Figure 2:XRD Report

3.3 Experimental Setup and Prototype Design

A small-scale prototype test structure was designed and fabricated to evaluate the thermal behavior of paraffin wax as a phase change material integrated into the metal roof configuration. In the experiment conducted, the overall external dimensions of the prototype structure were 2 ft × 1.2 ft (approximately 610 mm × 366 mm) in plan, with a total height of 2.5 ft (approximately 762 mm). The walls and floor of the structure were constructed from metal sheets to form an enclosed chamber simulating a simplified building interior.

Above the main structure, a rectangular cavity with a depth of 0.5 inch (approximately 12.7 mm) was constructed to serve as the PCM containment chamber.In this chamber,paraffin was initially melted and poured into the cavity,filling the whole cavity with paraffin wax enclosed by metal sheets on all the sides forming a sealed chamber positioned at the roof level. This configuration was intended to simulate a roof-envelope system in which the PCM layer acts as a thermal buffer between the external environment and the interior space.

Figure 3:CAD Design(Side View)

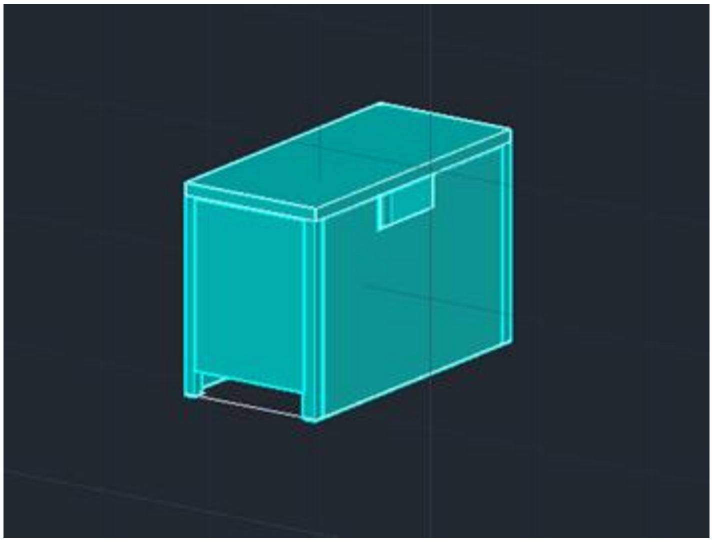


Figure 4:CAD Design(Isometric View)

3.4 Instrumentation and Data Acquisition System

To monitor and record temperature variations within the prototype system at three different points of contact, a digital data acquisition system was assembled using an Arduino UNO microcontroller board and DS18B20 waterproof digital temperature sensors. The DS18B20 is a widely used digital temperature sensor that communicates over a one-wire interface and provides temperature readings with a resolution of ±0.5°C over a measurement range of −55°C to +125°C. These sensors were selected for their accuracy, ease of interfacing with microcontroller-based systems, and suitability for sustained outdoor measurements.

DS18B20 temperature sensors were positioned at different locations within the prototype to capture the thermal behavior; effectively temperature at those points of the system. The first sensor was mounted on the external upper surface of the roof (upper ceiling) to record the surface temperature of the upper surface which was directly exposed to solar radiation or the external heat source. The second sensor was placed on the inner surface below the PCM cavity (lower inner surface temperature) to measure how the temperature is transmitted through the paraffin PCM layer. The third sensor was set up inside of the enclosed area of the prototype (the inner ambient temperature) to measure the inside air temperature in the simulated building interior.

The sensors were connected to the Arduino UNO board programmed to read and log temperature data from all three sensors at defined time intervals. The Arduino board was connected to a computer via a USB interface for real-time data logging and storage.

3.5 Temperature Variation under Outdoor Conditions

The temperature profiles obtained from the outdoor experiment show the variation of upper ceiling temperature, lower inner surface temperature, and inner ambient temperature from 9:00 AM to 5:00 PM.

Data indicates that there was a slow increase in temperature at the top of the ceiling which may have been caused by an increase in solar radiation during the day. The rate of temperature increase at the inner ceiling surface, however, was comparatively low because of the thermal buffering effect of the paraffin PCM layer. In the heating stage, the heat of the PCM material was absorbed, resulting in a slowdown in the process of the heat conduction in the lower part. Furthermore, the difference between the inner ambient temperature and upper surface temperature was smaller than without the presence of the PCM layer, demonstrating good thermal regulation. The tests were conducted outside the building to evaluate the actual working performance of the thermal buffering properties of the paraffin PCM layer.

3.6 Temperature Variation under Controlled Environment

To investigate the thermal response of the PCM system at a higher temperature range, it was subjected to a controlled heating experiment. Every 15 min temperature was measured for a total of 2 hours. The results indicate that the PCM layer absorbed heat in the heating phase, leading to a slower temperature rise rate of the lower inner surface.

Electric heating tubes of 400 W each as an external heat source used in this experiment, were used to simulate the prototype structure exposed to outdoor heat. Two heating configurations were employed to investigate the thermal behavior of the overall system under different heat inputs.

Type 1 Heating Configuration: Two heating tubes with a capacitive power of 400 W were placed along the longer sides of the prototype structure. A heat input of 800 W was obtained using this configuration to replicate heat exposure. Heat Supplying time was 2 hours and total heat supplied is as follows:

$Q = P \times t = (400\times2) \times (3600\times2) = 5.76$ MJ

Type 2 Heating Configuration: Four 400 W capacity heating tubes have been used in type 2 Heating configuration. Two tubes were installed on each of the two longer sides for operation, thus yielding a 1600 W heat input since heating was applied from both sides and not just one. It was supplied heat for a duration of 2 h and total heat supplied is as:

$Q = P \times t = (400\times4) \times (3600\times2) = 11.52$ MJ

Hence, controlled environment testing complements the field experiments by allowing direct comparisons of the thermal performance of PCM systems under controlled, standardized, and repeatable conditions without dependence on weather variability.

3.7 Data Analysis Approach

The temperature data collected from both outdoor and controlled environment experiments were analyzed to evaluate the thermal performance of the paraffin PCM-integrated roof system. The analysis focused on the following parameters: the temperature differential between the outer roof surface and the inner surface beneath the PCM layer, which indicates the heat attenuation capacity of the PCM; the temperature differential between the outer roof surface and the inner ambient air temperature of the enclosed space, which reflects the overall thermal regulation provided by the PCM system; and the variation of temperatures at all three measurement locations, which provides insight into the heat absorption, storage, and release behavior of the paraffin PCM during the cycle. The results obtained from these analyses are presented and discussed in detail in Chapter 4.

3.8 Note on Repeatability and Measurement Error

Each temperature value shown in tables below is the daily measurements taken under nominally identical conditions: five days for the outdoor experiment and three days each of the two controlled-environment experiments for both Type-1 and Type-2 experimental conditions. Temperatures were recorded with DS18B20 digital sensors with a manufacturer-stated accuracy of ± 0.5 °C.

The error percentage column on the right of each table summarises the typical measurement error at every time point. It is computed by combining the day-to-day spread of the replicate readings with the sensor accuracy, and expressing the result as a percentage of the mean temperature. Values fall within roughly 2 % to 6 % across the experiments-controlled-environment tests being the tightest while the outdoor exposure is loosest, as expected from natural meteorological variability. Because the observed temperature reductions (3.4 % to 32.5 %) exceed this measurement error at every time point of measurements, the cooling effect can be directly attributed to the paraffin PCM.

CHAPTER 4: RESULTS AND DISCUSSIONS

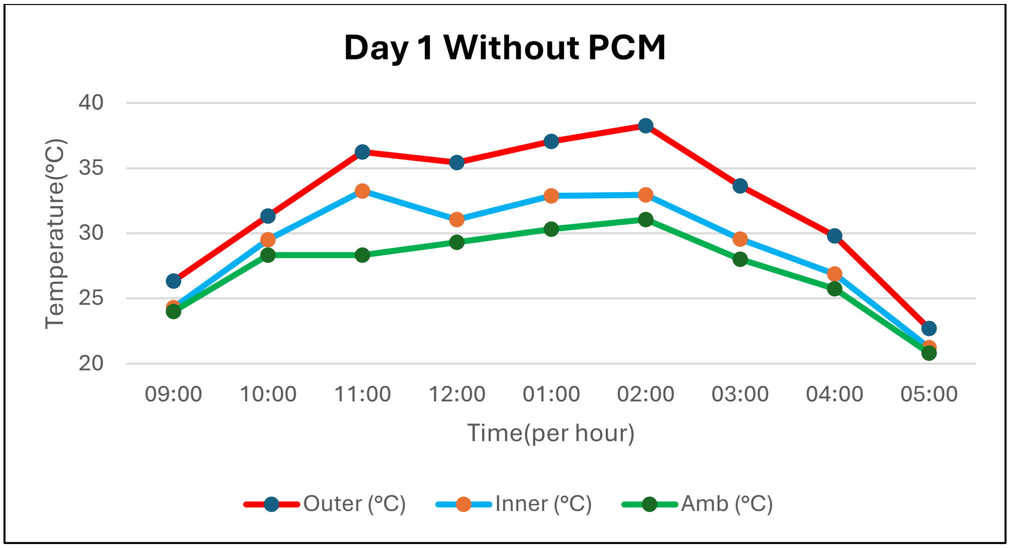
This chapter reports experimental results obtained using the prototype roof model. The results showed the performance of the paraffin-based PCM system as a thermal regulator. Three temperature points were measured: the upper surface of the ceiling (outer surface), the lower inner surface and the inner ambient air inside the closed room (inside air temperature). It is known that PCM in roof systems act as an effective thermal barrier for indoor thermal comfort. Experimental study on similar PCM-integrated roof system showed that Experimental study on a similar PCM-integrated metal roof system showed that the daily average indoor temperature was reduced by 5°C and the peak indoor temperature was reduced by 9.5°C compared to a conventional roof system (Boobalakrishnan et al., 2021).The outdoor test was conducted for a period of five days from 9:00 am to 5:00 pm and temperatures were recorded every 60 minutes.

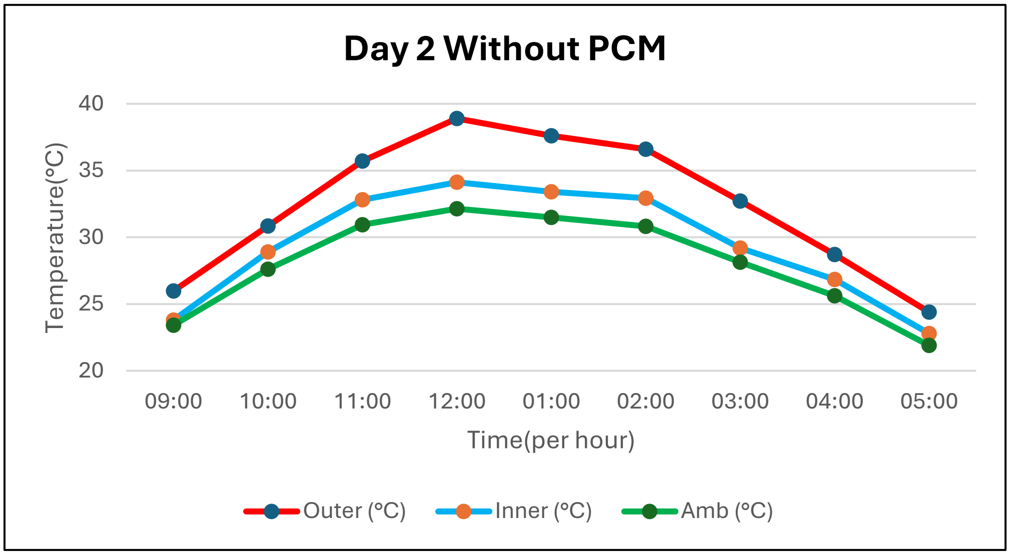
4.1 Temperature Variation of PCM Roof Model for Outdoor Environment

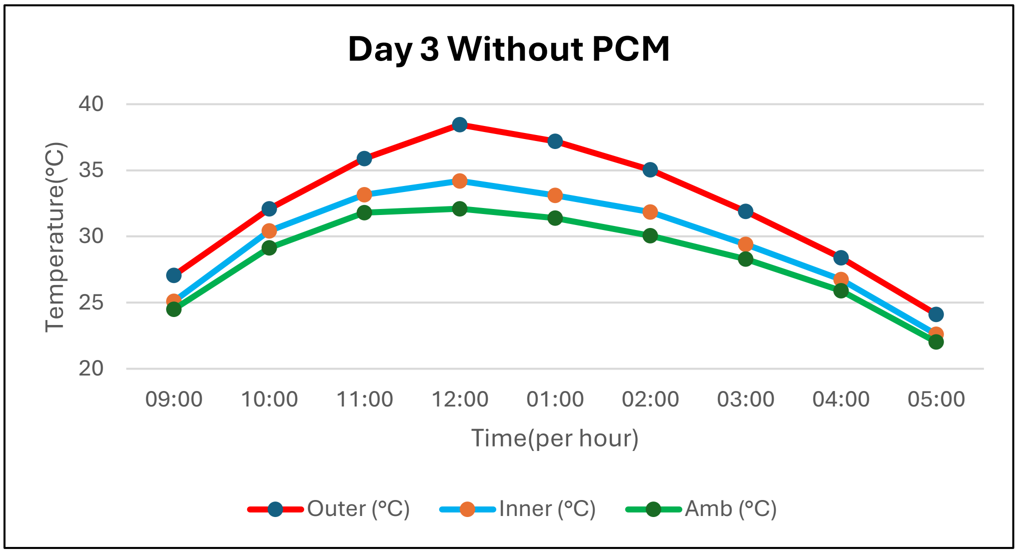
The temperatures were recorded over a period of five days to allow for any change of temperature over the days.

4.1.1 Temperature Variation of PCM Roof Model for outdoor environment without PCM

The following graphs shows the temperature readings from the experiment conducted under outdoor conditions of the roof model without PCM. The corresponding tables of the graphs are in the appendix section of the report. In the absence of a PCM layer, the metal roof allowed solar heat quickly to penetrate to the other side of the roof. As a result, the inner surface of the roof, as well as the air inside the enclosed space, experienced a sharp and dramatic increase in temperature in the middle of the day. Each table is accompanied by a corresponding temperature profile graph. The recorded data are presented below; X-axis shows time per one hour interval of time and Y-axis denotes temperature in degree Celsius.


Day 1 Without PCM
Temperature(°C)
40
35
30
25
20
09:00
10:00
11:00
12:00
01:00
02:00
03:00
04:00
05:00
Time(per hour)
Outer (°C)
Inner (°C)
Amb (°C)


Day 2 Without PCM
Temperature(°C)
40
35
30
25
20
09:00
10:00
11:00
12:00
01:00
02:00
03:00
04:00
05:00
Time(per hour)
Outer (°C)
Inner (°C)
Amb (°C)


Day 3 Without PCM
Temperature(°C)
40
35
30
25
20
09:00
10:00
11:00
12:00
01:00
02:00
03:00
04:00
05:00
Time(per hour)
Outer (°C)
Inner (°C)
Amb (°C)

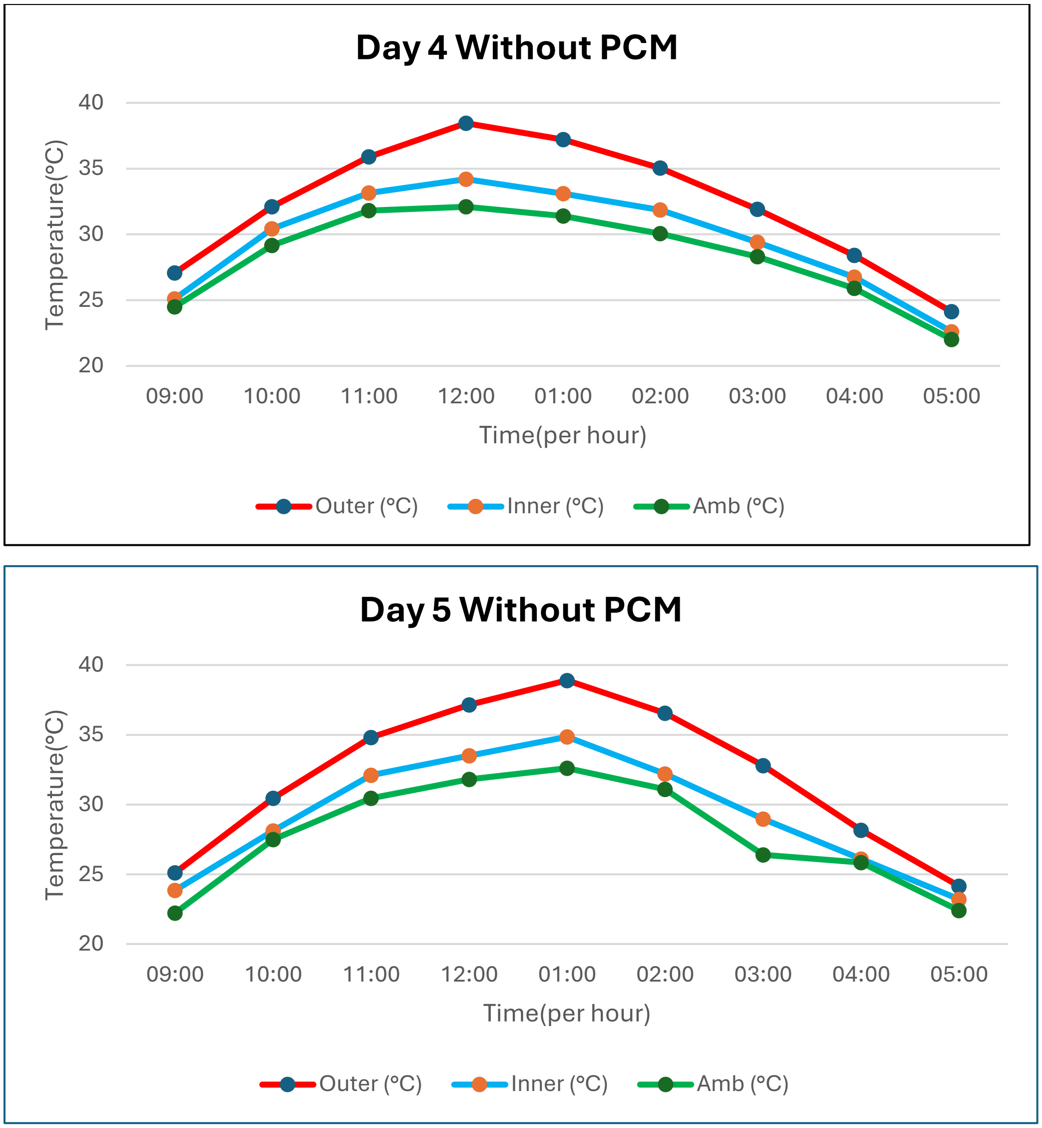


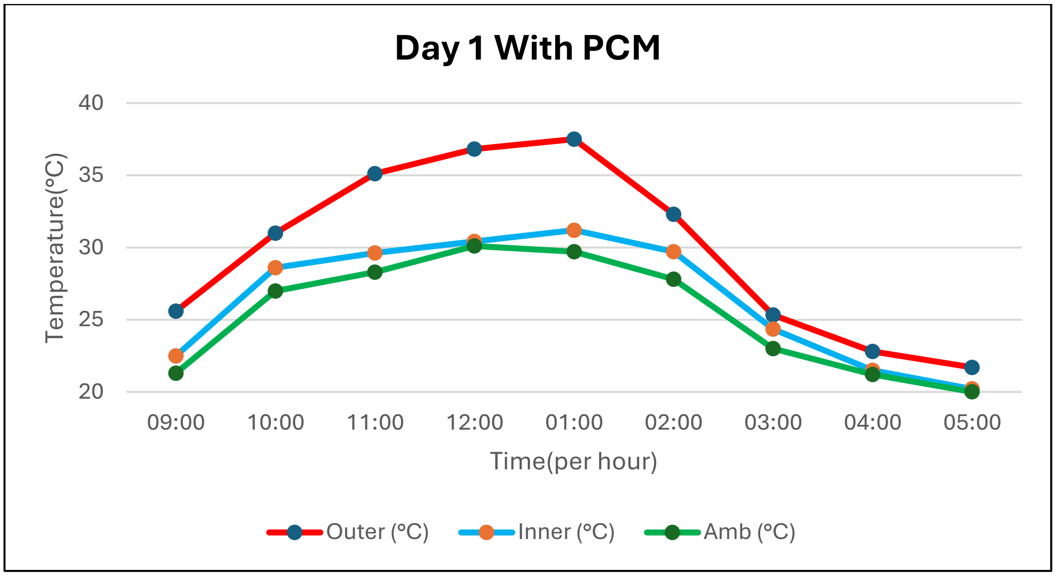
Figure 5:Temperature profile of 5 Days without PCM under outdoor exposure

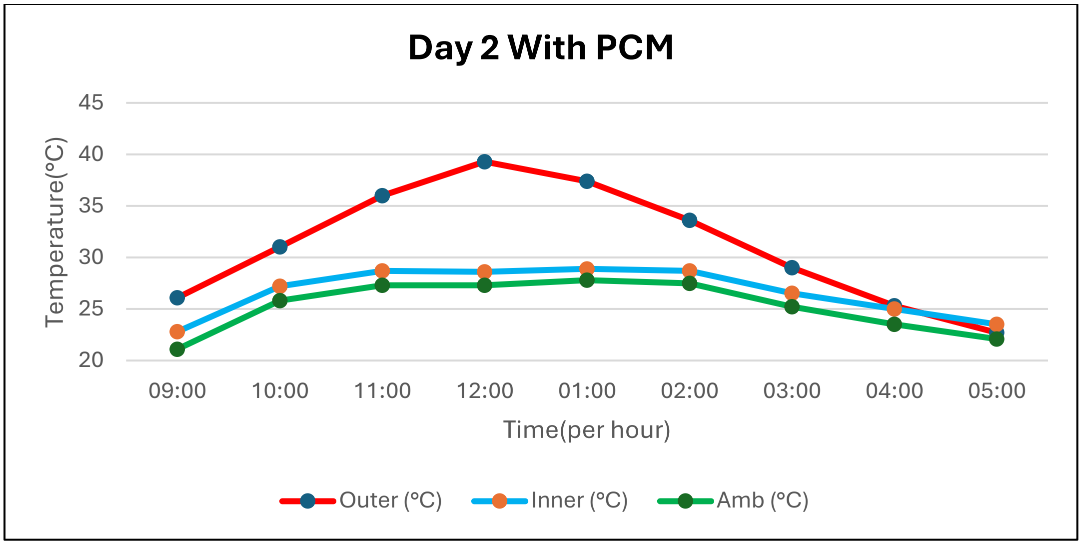
Over the course of the entire five-day period, the thermal performance of the roof without PCM showed a consistently high degree of uniformity. All readings in the morning taken at three different sensor points were in the range from 22°C to 27°C; this was due to moderate conditions during those hours. As solar energy intensity grew, outer surface temperature quickly climbed to 37°C, sometimes even exceeding this number and reaching 38°C to 39°C. The inner surface temperature was also quite high, although lagging slightly behind, showing numbers from 33°C to 35°C. The minimal difference in readings from both sides of the roof is indicative of poor thermal resistance of the material. In other words, no resistance to heat conduction.

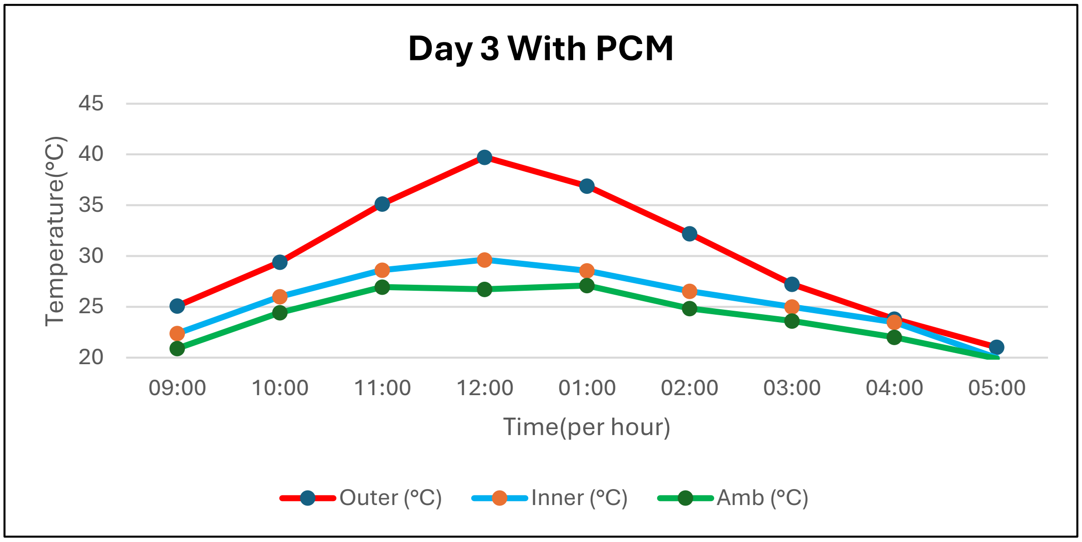
In addition, air temperature inside the cavity reached numbers from 31°C to 33°C during the time when maximum radiation was observed. At 5:00 PM all curves declined steeply, reaching temperatures of less than 23°C. It is easy to see how much temperature varies within a single day. Such dramatic fluctuations are precisely why a metal roof without any insulation would cause problems for residents living in areas where mechanical cooling is not readily available.

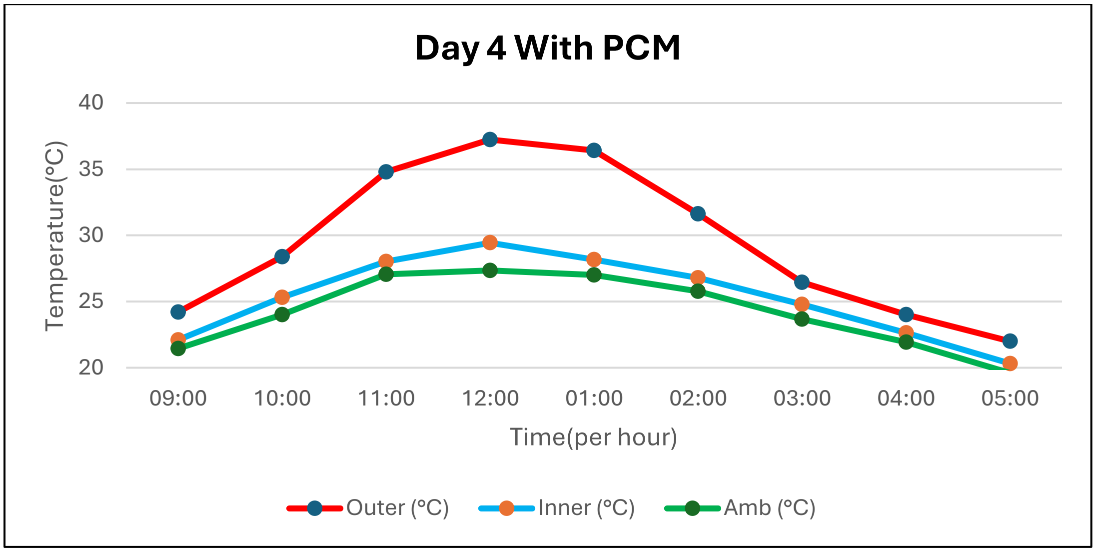
4.1.2 Temperature Variation of PCM Roof Model for outdoor environment with PCM

Following the baseline measurements, paraffin wax was melted and poured into the roof cavity for uniform distribution, where it was allowed to solidify before repeating the outdoor test sequence under comparable weather conditions. The underlying rationale was that the PCM layer, upon absorbing heat during the melting transition, would function as a thermal reservoir-temporarily storing a portion of the incoming solar energy rather than allowing it to pass through to the interior space. The recorded data are presented below; X-axis shows time per one hour interval of time and Y-axis denotes temperature in degree Celsius.




Day 2 With PCM
45
40
35
30
25
20
Temperature(°C)
09:00
10:00
11:00
12:00
01:00
02:00
03:00
04:00
05:00
Time(per hour)
Outer (°C)
Inner (°C)
Amb (°C)


Day 3 With PCM
45
40
35
30
25
20
Temperature(°C)
09:00
10:00
11:00
12:00
01:00
02:00
03:00
04:00
05:00
Time(per hour)
Outer (°C)
Inner (°C)
Amb (°C)


Day 4 With PCM
40
35
30
25
20
Temperature(°C)
09:00
10:00
11:00
12:00
01:00
02:00
03:00
04:00
05:00
Time(per hour)
Outer (°C)
Inner (°C)
Amb (°C)

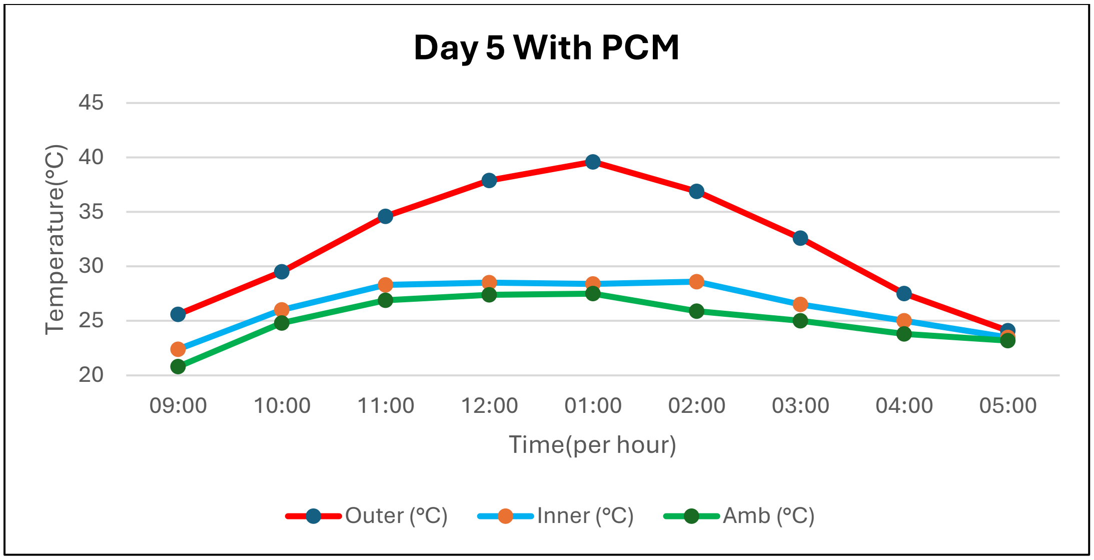


Figure 6:Temperature profile of 5 Days with PCM under outdoor exposure

The introduction of paraffin into the roof cavity produced a distinct shift in the thermal response of the inner surface and the enclosed air space. While the outer surface temperature continued to rise and it didn't seem to be having any major changes in the temperature at its surface in the non-PCM configuration-peaking in the upper thirties on most days; the inner surface remained much cooler, typically reaching maximum values between 28°C and 31°C. This represents a reduction of approximately 3 to 6°C relative to the non-PCM baseline, a margin that is both thermally and practically significant.

In the experiments run and data collected, the temperature profile reveal a more gradual rise at the inner surface compared to the non-PCM case. This dampening effect is attributable to the latent heat absorption occurring within the paraffin layer during its solid-to-liquid phase transition. As the wax melts, it draws thermal energy from the surroundings without permitting a proportional temperature increase on the downstream side of the cavity. The inner ambient air followed a corresponding pattern, stabilizing in the range of 27-30°C instead of climbing into the low thirties. In the late afternoon and early evening, the PCM configuration maintained slightly elevated inner temperatures compared to the bare metal roof.

4.2 Comparative Analysis of Outdoor Results

To isolate the net thermal contribution of the paraffin layer from day-to-day variability in solar irradiance and wind conditions, the temperature data from all five outdoor test days were averaged for each sensor location. The resulting mean curves for the inner surface and inner ambient air are plotted below for both configurations.

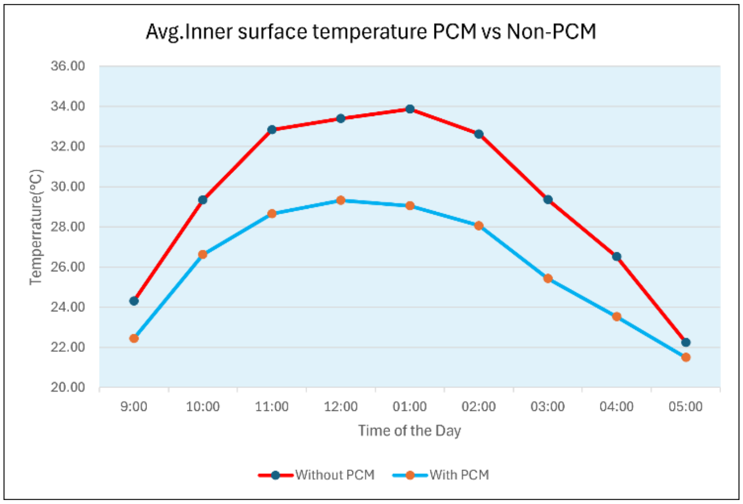


Figure 7:Five-day averaged inner surface temperature - PCM versus non-PCM configuration

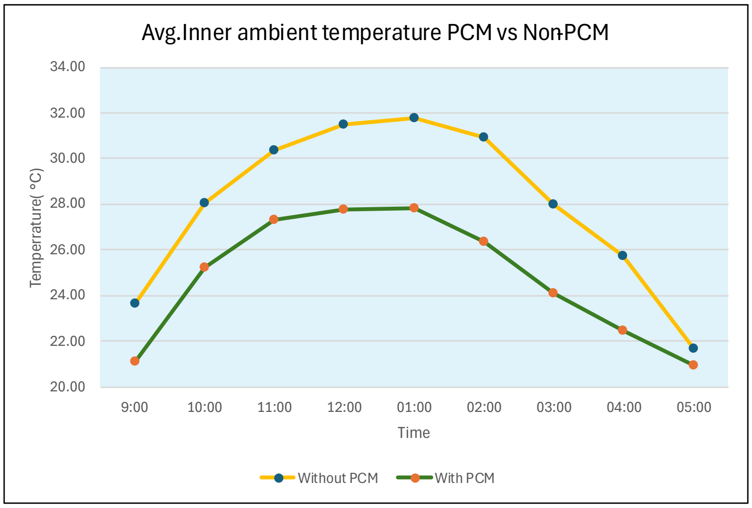


Figure 8:Five-day averaged inner ambient temperature-PCM versus non-PCM configuration

The shaded region between the two curves quantifies the thermal advantage conferred by the PCM during the experiment. At peak hours, the inner surface had an average reduction of 4-5°C, while the interior air was approximately 3-5°C cooler when paraffin was present (Boobalakrishnan et al., 2021). Though these values may appear moderate in isolation, their practical implications are very drastic and greatly influence the thermal comfort of the residents. And it greatly affects the occupants inside. In residential contexts where even basic mechanical cooling is unreliable or unaffordable, a sustained reduction in temperature of this magnitude can shift the indoor environment from distinctly uncomfortable to at least tolerable for longer periods of the afternoon. The data further indicate that the PCM system slightly alters the rate of cooling in the evening, as the solidifying paraffin continues to release stored thermal energy into the interior space.

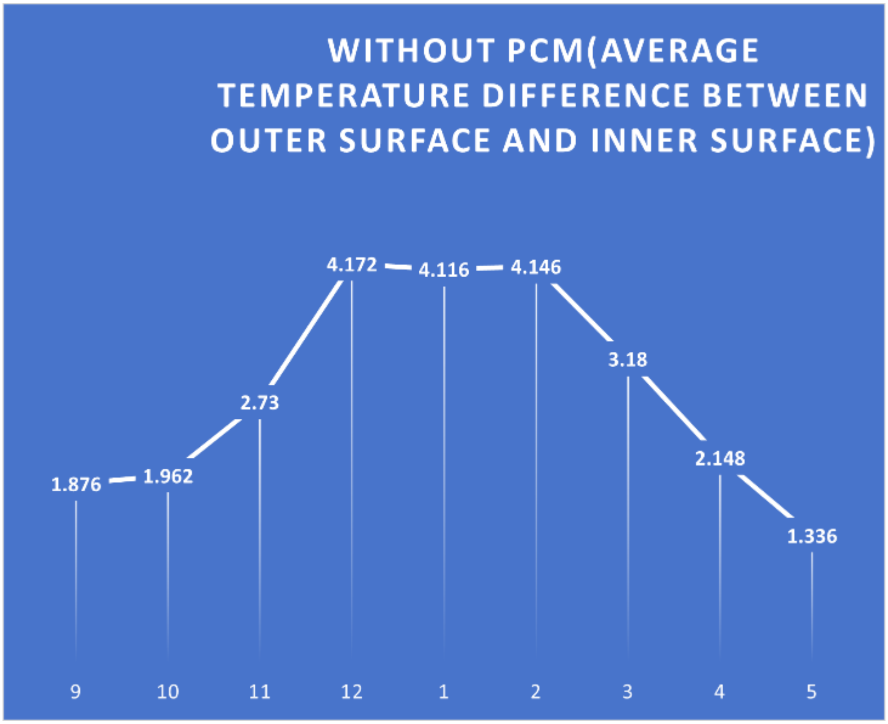


Figure 9:Average Temperature Difference(Without PCM)

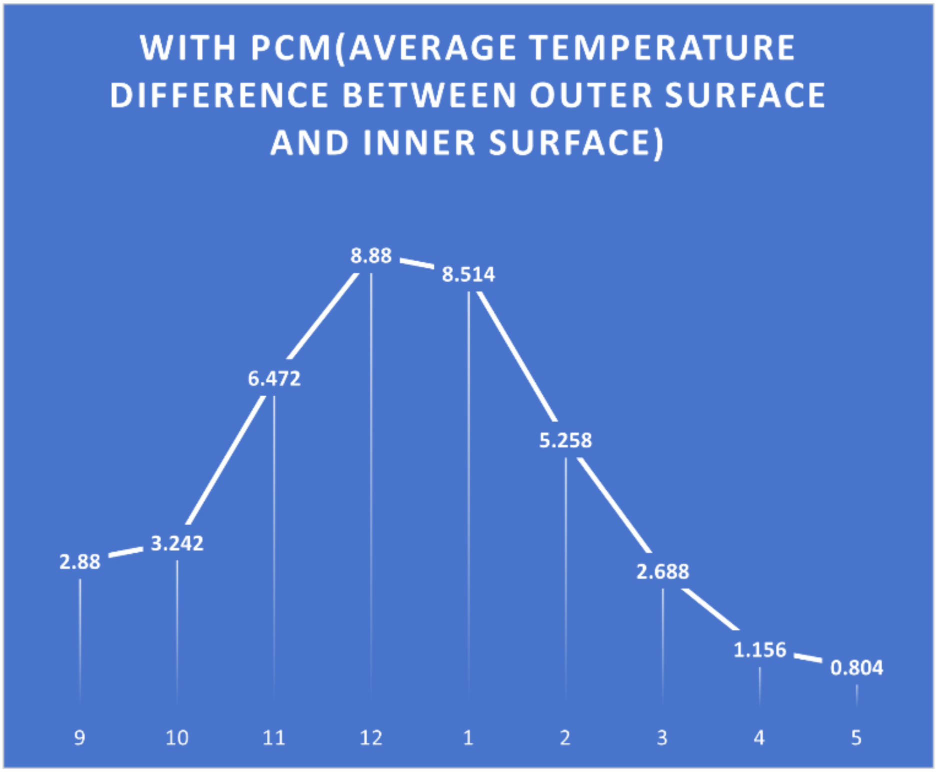


Figure 10:Average Temperature Difference(With PCM)

Measurements for a test incorporating a paraffin PCM showed the PCM increased the effective temperature difference across the outer roof surface and the inner surface by roughly two PCM change over temperatures. Specifically at noon the PCM enabled an increase in the change over temperature of roughly 4.7°C from 4.17°C for the roof without PCM to 8.88°C for the roof with PCM. This enhanced temperature difference occurs primarily during the highest heating hours of the day: 11 AM to 2 PM.

4.3 Temperature Variation of non-PCM Roof Model for Controlled environment

The controlled-environment experiments were designed to remove the inherent variability of outdoor weather and subject the prototype to a repeatable, quantified thermal load. Without any PCM present, the metal roof conducted the supplied heat almost without resistance, resulting in steep and uniform temperature gradients across all three measurement locations.

4.3.1 Temperature Variation for Type-1 setup of non-PCM Roof Model

Under the Type 1 arrangement, two 400 W heating tubes positioned along longer sides of the prototype delivered a combined input of 800 W, equivalent to 5.76 MJ over the two-hour test window with measurements taken at an interval time of 15 minutees. The consistency of results across the three test days confirms the repeatability of the controlled setup and provides a reliable baseline for comparison with the PCM-equipped configuration. The recorded data are presented below; X-axis shows time per 15-minutes interal of time and Y-axis denotes temperature in degree Celsius.

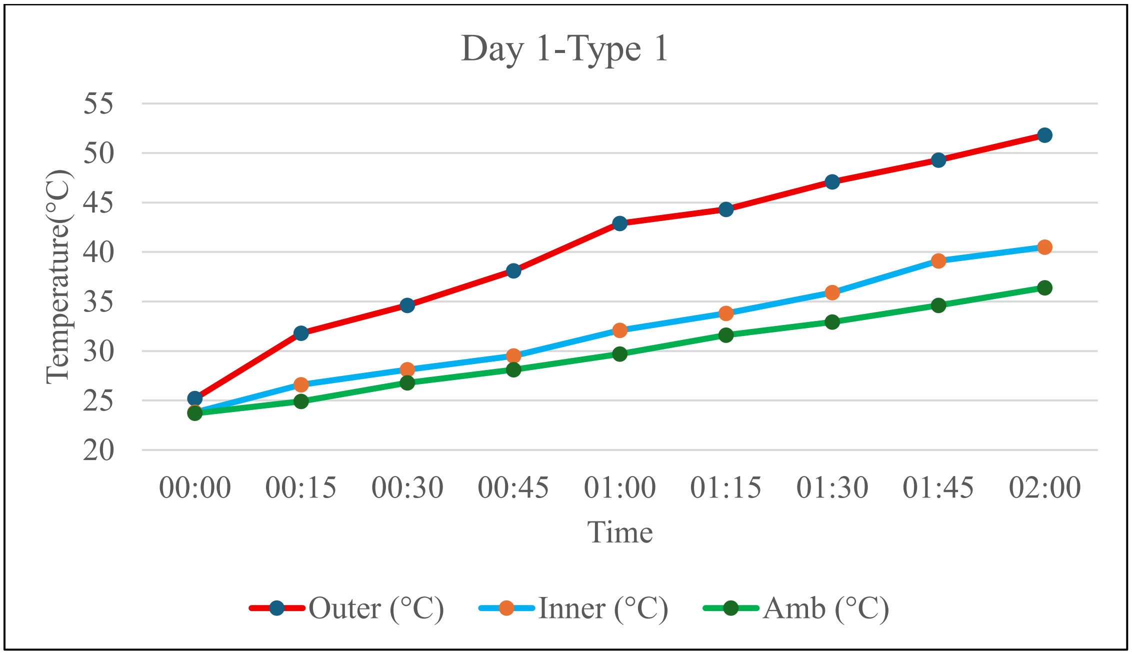


Figure 11: Type 1, Day 1 temperature profile - no PCM, controlled environment

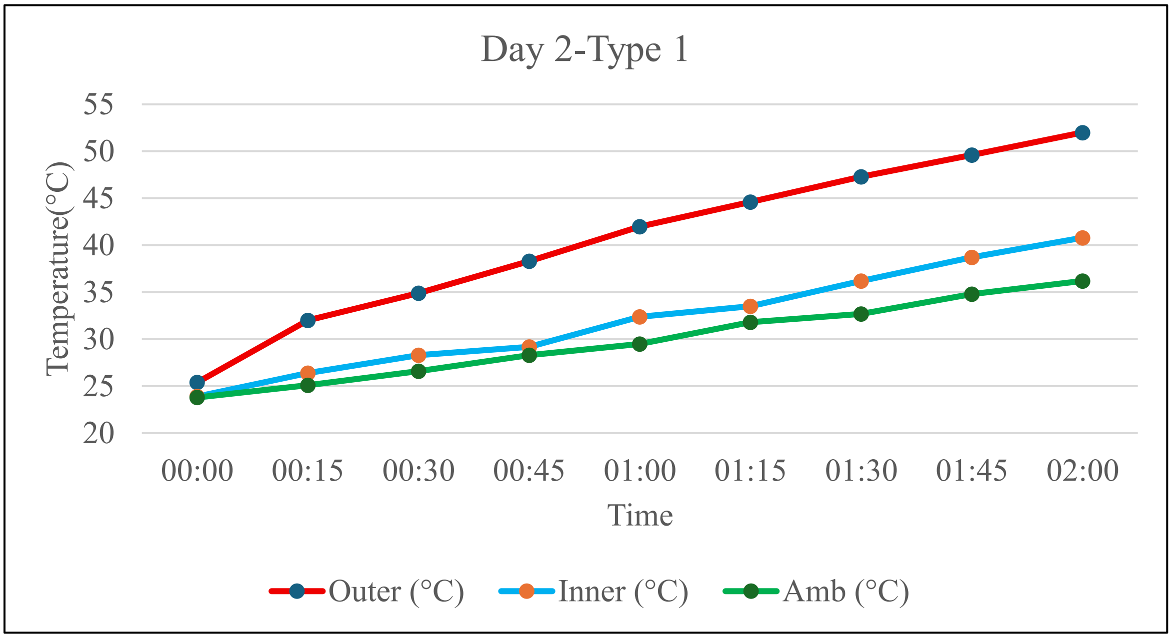


Figure 12:Type 1, Day 2 temperature profile - no PCM, controlled environment

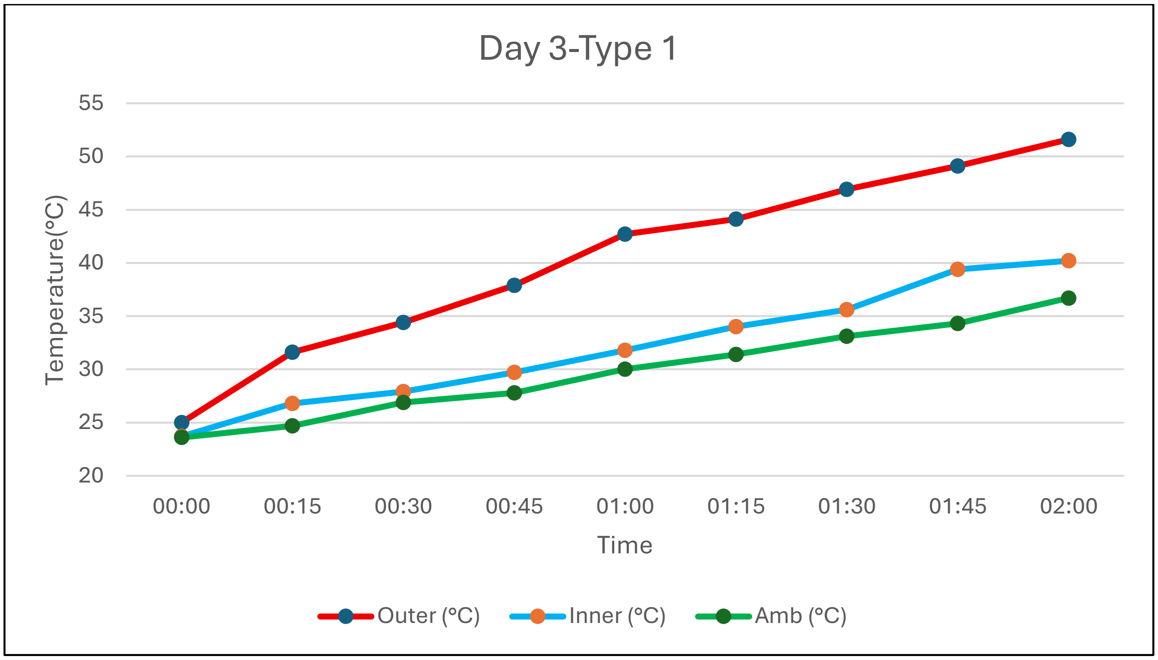


Figure 13:Type 1, Day 3 temperature profile - no PCM, controlled environment

4.3.2 Temperature Variation for Type-2 setup of non-PCM Roof Model

The Type 2 arrangement doubled the heat input to 1600 W by placing four heating tubes symmetrically on both sides of the prototype, delivering 11.52 MJ over two hours. This configuration was intended to simulate more extreme conditions.

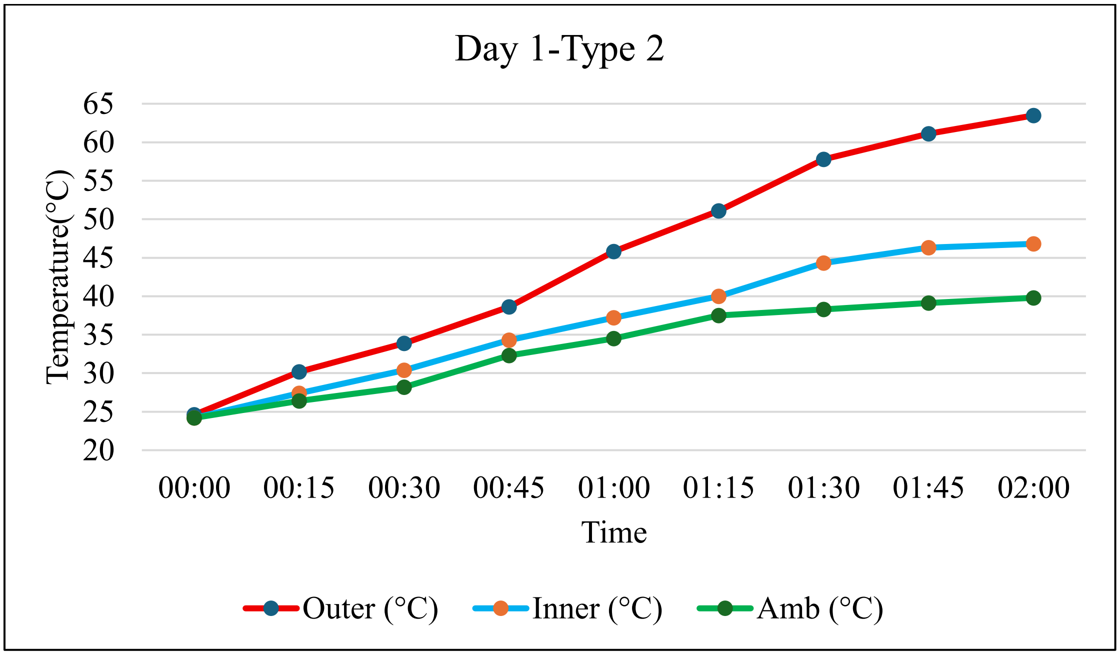


Figure 14:Type 2, Day 1 temperature profile - no PCM, controlled environment

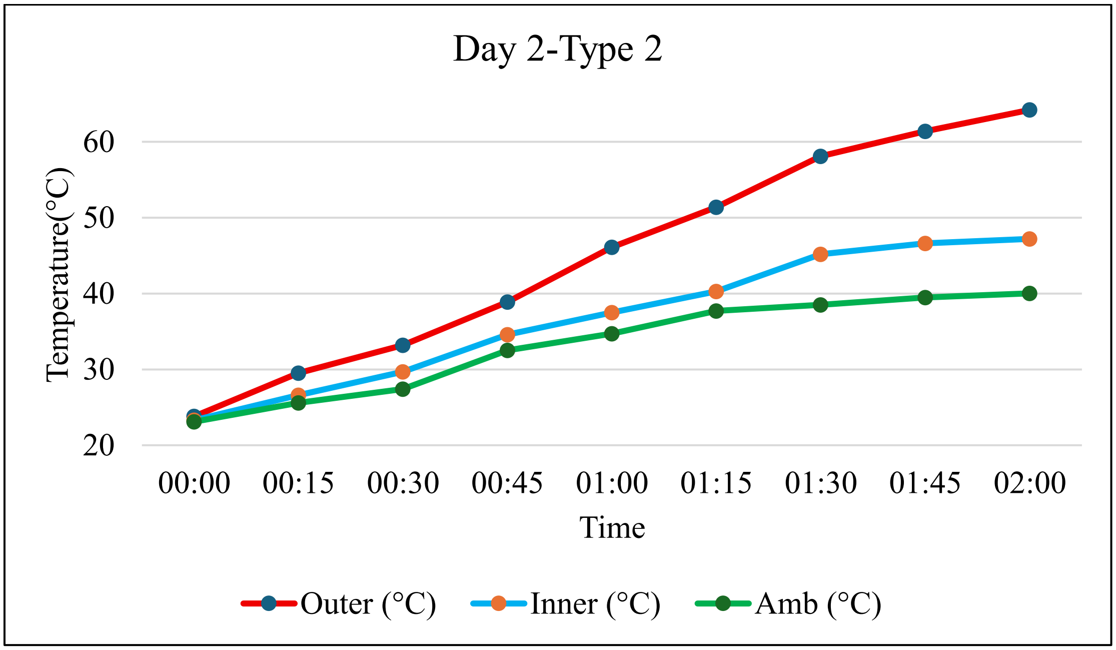


Figure 15:Type 2, Day 2 temperature profile - no PCM, controlled environment

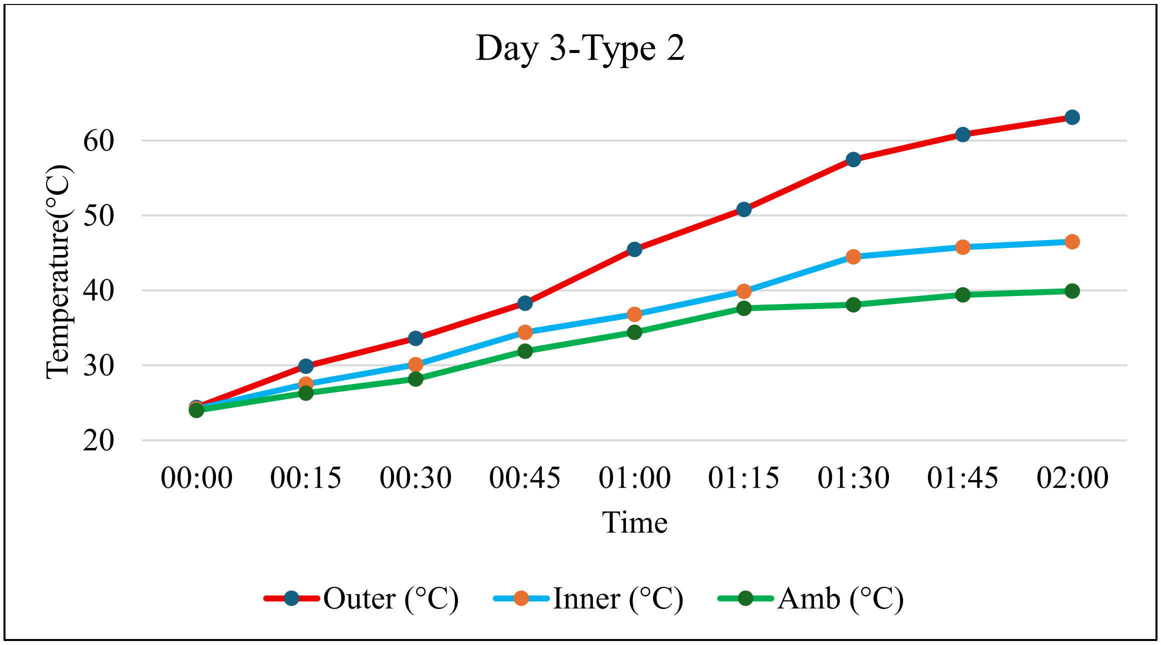


Figure 16:Type 2, Day 3 temperature profile - no PCM, controlled environment

Under the elevated 1600 W load, the outer surface exceeded 60°C on all three test days, reaching as high as 64.2°C on Day 2. The inner ceiling surface climbed to approximately 47°C, and the enclosed air settled near 40°C. These values exceed any reasonable comfort threshold by a wide margin and underscore the inherent thermal vulnerability of lightweight metal roofing systems when subjected to intense radiative input without any form of passive thermal regulation.

4.4 Temperature Variation of PCM Roof Model for Controlled Environment

With PCM present, the metal roof did not directly supplied heat and provided resistance to the heat transfer process, resulting in higher difference in temperature between outer and inner measurements.

4.4.1 Temperature Variation for Type-1 setup of PCM Roof Model

Under Type 1 heating configuration of the experiment, two 400 W heating tubes were positioned along one on each side of the longer side of the prototype delivering a combined input of 800 W, equivalent to 5.76 MJ as shown in the equations above, over the period of two hours. The consistency of results across the three test days confirms the repeatability of the controlled setup and provides a reliable baseline for comparison with the PCM equipped configuration. The recorded data are presented below; X-axis shows time per 15-minutes interval of time and Y-axis denotes temperature in degree Celsius obtained from type-1 experiment.

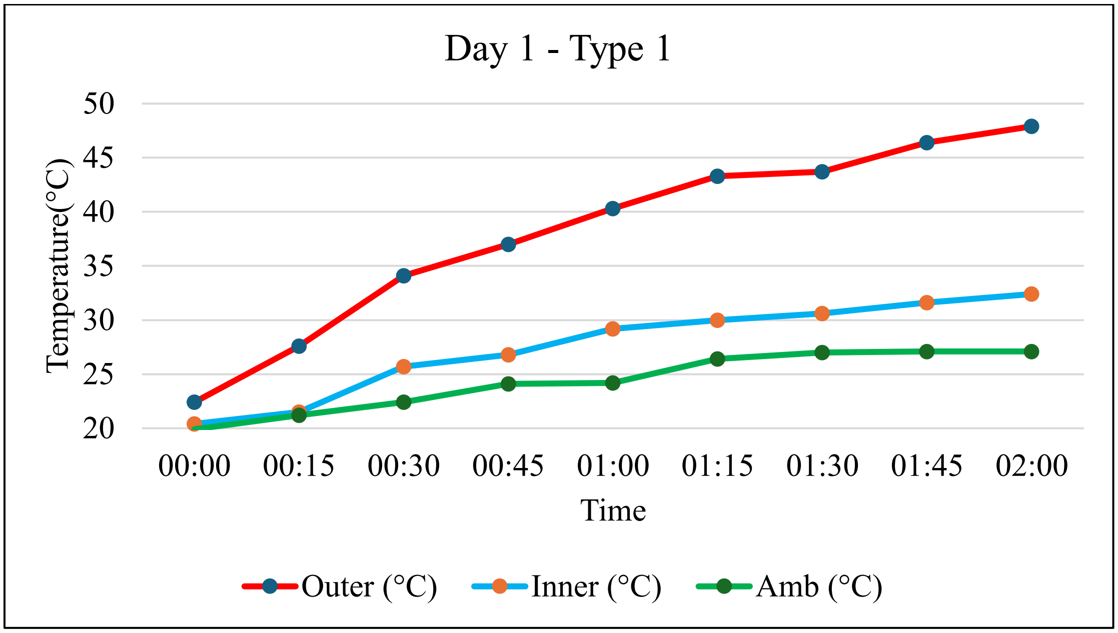


Figure 17:Type 1, Day 1 temperature profile - PCM, controlled environment

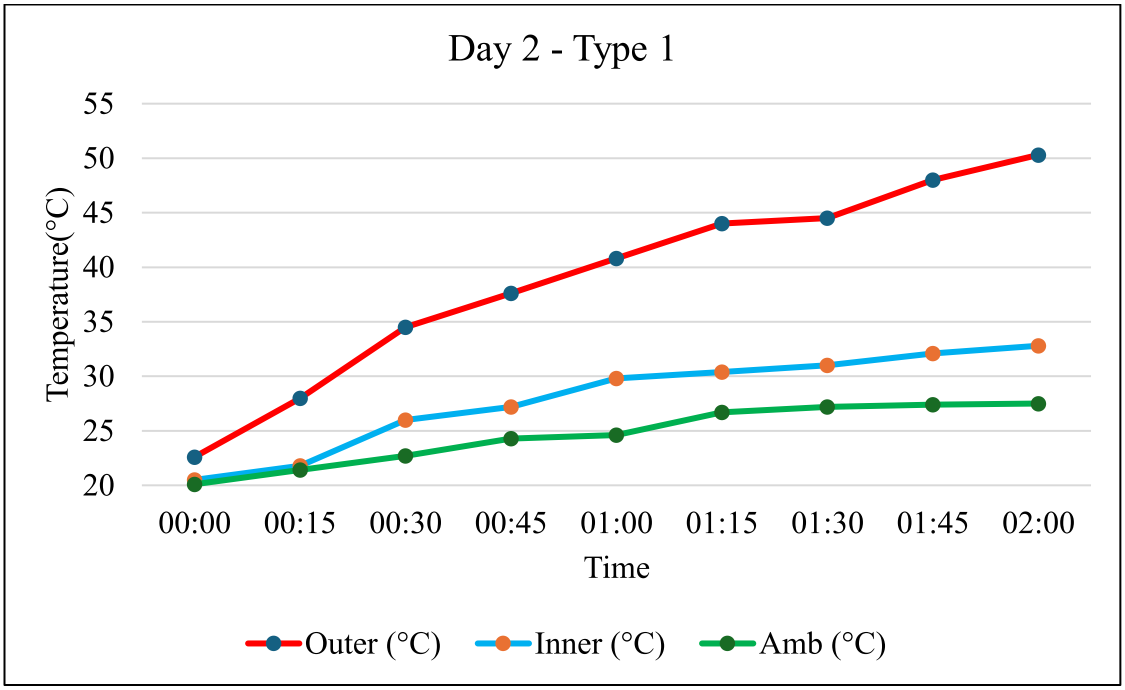


Figure 18:Type 1, Day 2 temperature profile - PCM, controlled environment

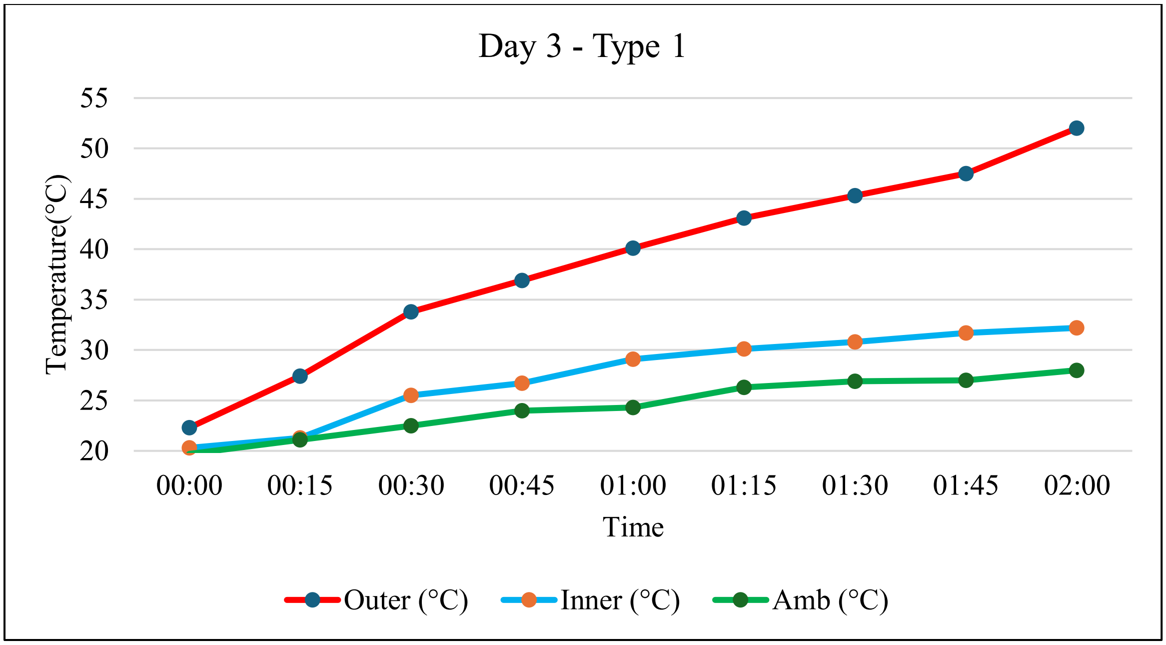


Figure 19:Type 1, Day 3 temperature profile - PCM, controlled environment

The inner surface temperature reached a maximum of approximately 32°C across all three test days, representing a reduction of roughly 8°C in comparison to the 40°C observed under identical heating conditions in the absence of PCM. This is a substantial difference in temperature that reflects the latent heat absorption capacity of the paraffin layer during its melting transition. The inner ambient air temperature remained even more restrained, peaking near 27-28°C as opposed to the 36°C recorded in the non-PCM configuration.

A particularly note-taking feature of these results is the relative flatness of the inner surface and ambient temperature curves in comparison to the steeply increasing temperature profile of the outer surface. The temperature differential between the outer and inner surfaces widened progressively over the two-hour window, eventually reaching 15-20°C, whereas the corresponding gap in the non-PCM configuration remained tighter at approximately 11-12°C. This divergence is a direct consequence of the energy being intercepted and stored within the phase change material rather than being conducted through the roof assembly.

It is also observed that the inner ambient temperature showed minimal variation during the final thirty to forty-five minutes of each test, even as the outer surface continued to climb. This plateau behaviour is characteristic of latent heat absorption: once the paraffin enters its active melting range, it can sequester considerable thermal energy without permitting a proportional temperature increase on the downstream side. In practical terms, this translates to an extended window during which indoor conditions remain within a tolerable range before the space begins to overheat.

4.4.2 Temperature Variation for Type-2 setup of PCM Roof Model

Under Type 2 heating configuration of the experiment, four 400 W heating tubes were positioned along two on each side of the longer side of the prototype delivering a combined input of 1600 W, equivalent to 11.52 MJ as shown in the equations above, over the period of two hours. The type-2 heating configuration was designed to stress the PCM layer by supplying the heat way beyond what the PCM would encounter on normal days or conditions and would only encounter on some parts of extremely hot temperature regions of Terai. The recorded data are presented below; X-axis shows time per 15-minutes interal of time and Y-axis denotes temperature in degree Celsius obtained from type-2 experiment.

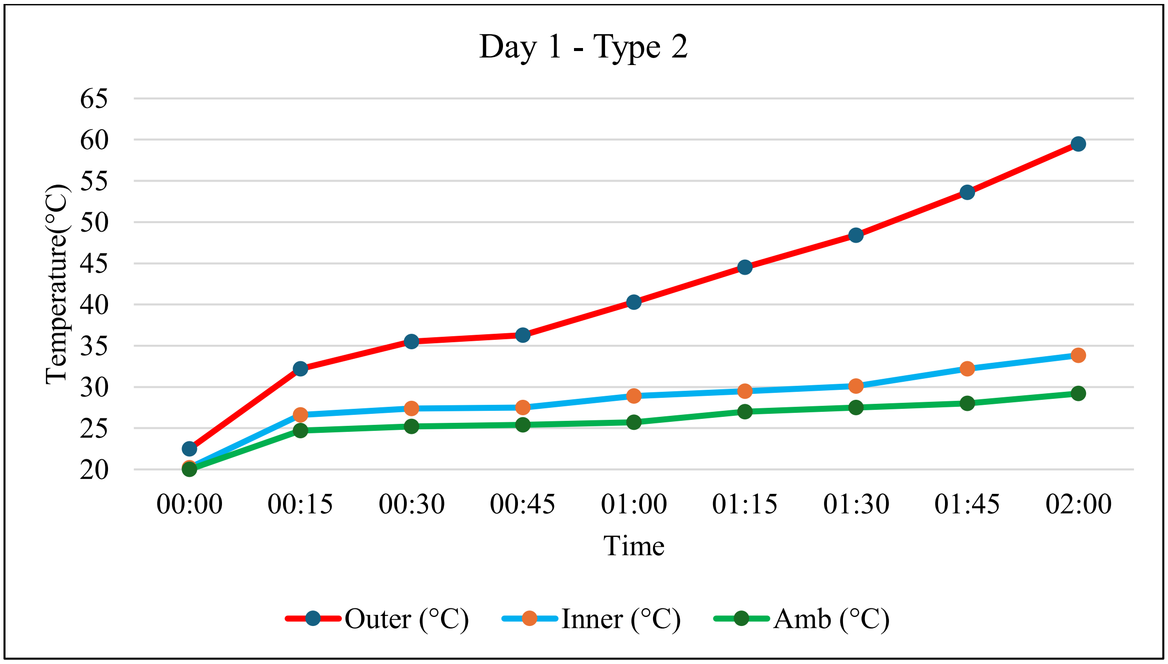


Figure 20:Type 2, Day 2 temperature profile - PCM, controlled environment

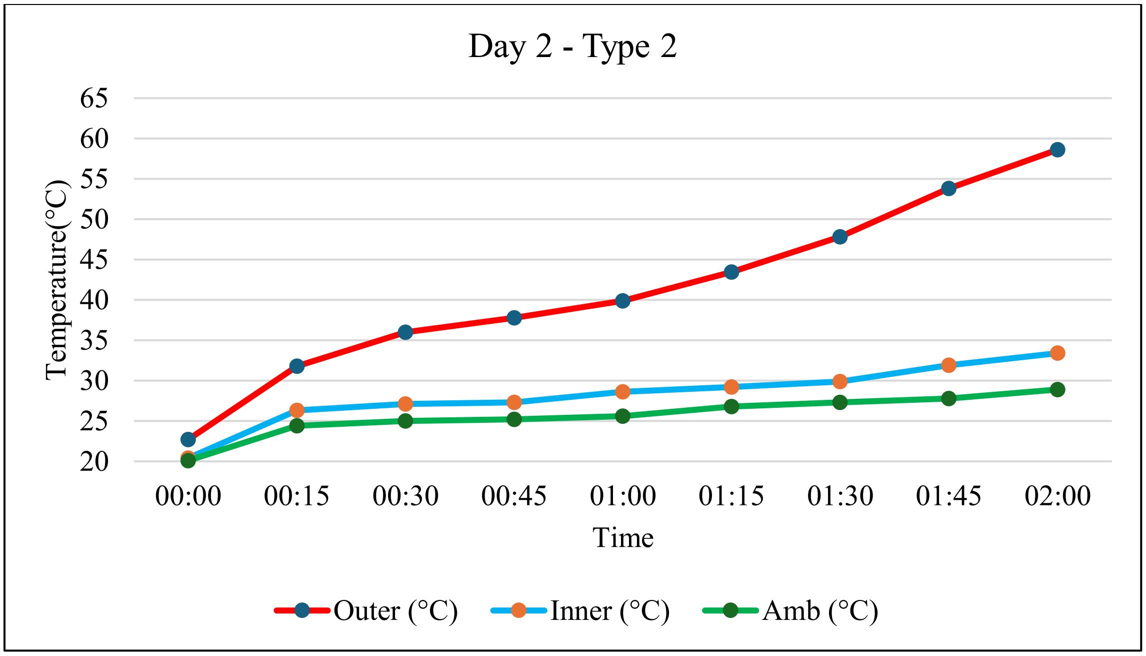


Figure 21:Type 2, Day 2 temperature profile - PCM, controlled environment

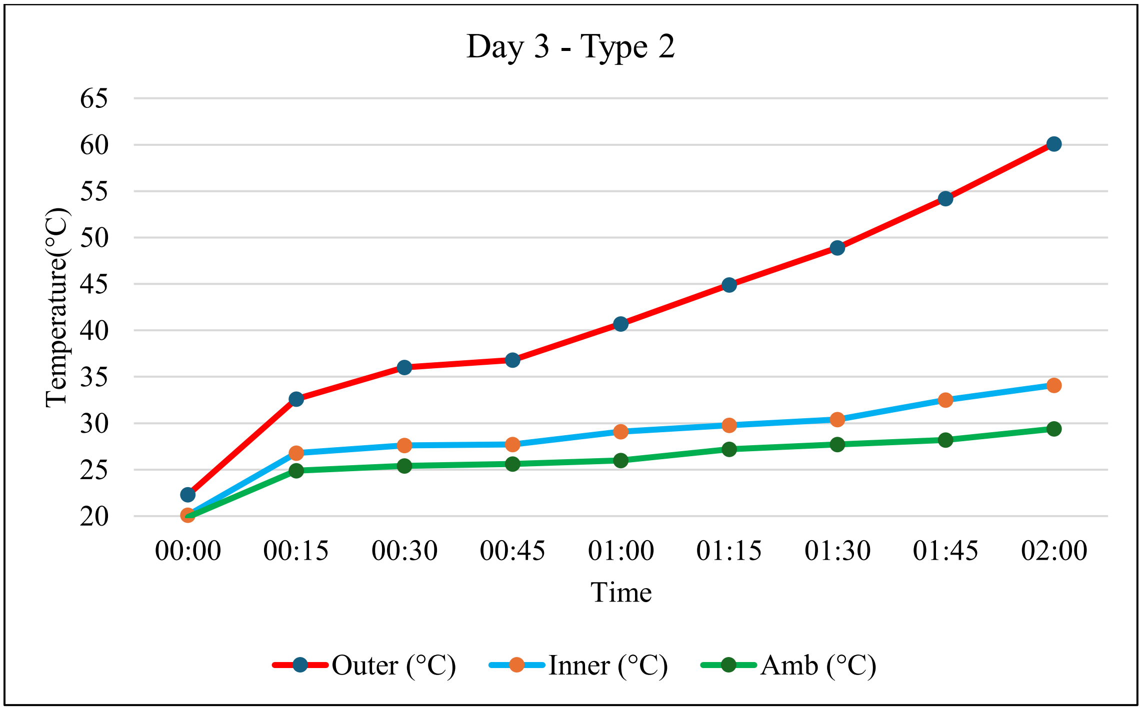


Figure 22:Type 2, Day 3 temperature profile - PCM, controlled environment

Even though the amount of heat being applied was twice as much, the PCM layer still noticeably softened the temperature swings. On each of the three days of the experimental testing conducted, the temperature on the inside of the ceiling only reached about 33°C-34°C. This is around 13°C cooler than the 47°C recorded when the tests were repeated, but without the PCM. The interior air temperatures stayed under 30°C, which is a big difference from approximately 40°C seen without the paraffin wax.

A clear pattern was seen in Type-2 experimental testing, as time went by, the gap between the outer surface temperature and two inner temperatures (Inner ceiling and Inner Ambient) widened. For initial 15-30 minutes of time, all three temperatures rose gradually, with each measurement. But from around thirty minutes in (when the wax started this solid-to-liquid change), temperatures on the inside surface and in the room began to level off, but the temperature of the outside surface kept going up. After two hours the difference between the outside and inside surface temperatures had grown to about 26°C. This was about 17°C in the test without the PCM. While this difference in numbers isn't enormous, it shows a completely different way heat was moving: the PCM layer was busily holding onto energy during its change of state, rather than letting the heat travel directly through it. The controlled environment results strengthen the conclusions drawn from the outdoor testing phase.

4.5 Analysis of Temperature Variation under Outdoor Conditions

The results obtained from the experimental testings conducted at the outdoor conditions indicate that differences exist in the thermal behavior of the prototype structure with and without the inclusion of paraffin as a PCM. This is because the temperature profiles measured on the upper surface of the ceiling, the lower inner surface, and the inner ambient air indicate that the inclusion of the PCM affected the heat transfer characteristics of the roof model and shows paraffin acted as buffer between outside environment and inner compartment.

For the roof without the PCM, the outer surface temperature increased rapidly as the solar radiation increased during the day. The maximum outer surface temperature recorded over the five days of the experiment varied between 38°C and 39°C, while the inner surface temperatures recorded values between 33°C and 35°C during the peak hours when the sun's radiation was intense. The low difference between the outer and inner surface temperatures shows that the metal roofing system transferred heat into the interior space rapidly due to its low thermal resistance and low thermal mass. As such, the inner ambient temperature increased rapidly during the midday hours, with values at 31-33°C recorded, showing the rapid transmission of heat through the roof structure.

In contrast, the roof model with paraffin PCM showed a different response in terms of temperature readings. Although the temperature readings on the external surface showed similar values as in the case of the non-PCM roof model, the temperature readings on the inner surface showed a significant reduction during the peak heating period. In general, over a period of five days during outdoor exposure, the maximum temperature readings on the inner surface in the case of the roof model with paraffin PCM were recorded in the range of 28°C-31°C, which is about 3-6°C lower than the temperature readings recorded in the case of the non-PCM roof model(Boobalakrishnan et al., 2021; Akeiber et al., 2016). This shows that a certain amount of thermal energy was absorbed by the paraffin PCM during this period.

During the experiment process, the inner ambient air temperature was observed to reduce in the PCM configuration as well. While the non-PCM system recorded peak inner ambient temperatures of 31-33°C, the temperatures in the PCM system were maintained at 27-30°C under similar periods of time. This is evidence of the buffering capacity of paraffin wax as it melts and releases heat gradually during the cooling period, thereby reducing the time for the heat to pass through the roof structure and the temperature fluctuation inside the prototype model.

Another observation that was based on the outdoor experiment, was related to the time lag effect, which was introduced by the PCM layer. In other words, the increase in temperature at the inner surface, as well as at the inner ambient air, was more gradual in the case of the PCM setup compared to the non-PCM setup. This effect demonstrates the ability of the PCM to store thermal energy during the day, thus slowing down the rate of heat transfer into the space (Xamán et al., 2020). This effect is particularly important in hot climate zones, as the peak temperature level can be delayed to a period of the day when ambient conditions are more favorable.

The outdoor experiment showed the highest outer-surface temperature at 39 °C which falls below the lower limit of paraffin's melting range which extends from 52 to 58 °C. The outdoor setup shows its buffering effect because the system utilizes the solid paraffin's sensible heat capacity together with the expanded thermal mass of the cavity instead of relying on latent-heat absorption. The controlled-environment system displays latent-heat-driven buffering because its outer surface temperature reaches 58-60 °C which enables paraffin to partially melt at the outer face. The 52-58 °C grade was selected to ensure structural integrity (no leakage) under normal operating conditions; future iterations of the study could compare a lower-melting-point paraffin (30-35 °C) more matched to the diurnal range of Kathmandu in order to access the latent-heat regime under outdoor exposure.

4.6 Analysis of Temperature Variation under Controlled Conditions

In the experiment conducted, tests using controlled temperatures have shown that the outdoor test phase’s observed thermal buffering effect is replicable using paraffin PCM in a controlled environment, utilizing both a Type 1 and Type 2 heating approach. The heating tubes delivered constant thermal loading, and over the two-hour test period the temperature differences recorded between PCM and non-PCM specimens have been primarily due to the thermal buffering effect of the PCM.

For the Type 1 setup, with combined input of 800 W, both sides of the larger side were at outer surface temperature of 47°C to 52°C during all test days. However, the inner surface temperature reached a maximum of about 32°C, which was nearly 8 °C less than the maximum inner surface temperature of 40 °C recorded for non-PCM roof model under same input (Mano & Thongtha, 2021). Inner ambient air temperature varied between 27 °C to 28 °C compared with 36 °C in non-PCM cases. These results show that considerable amount of heat has been absorbed by the solid paraffin within the PCM layer as it went through melting.

The operating conditions for the Type 2 tests were elevated to stress test the PCM layer as though operating above residential heating levels. Under these conditions the surface temperature of the external PCM layer surface reached and, in some cases, exceeded 60°C. However, the inner surface temperature of the PCM roof model achieved the highest temperature of approximately 33-34°C, over the three days of testing. This represents a reduction of approximately 13°C compared with the equivalent non-PCM test temperature of 47°C based on supplied power of 1600 W from both sides. The inner ambient air temperature was found to be less than 30°C across the majority of the base area. In contrast the inner ambient temperature for the non-PCM test achieved temperatures of up to 40°C (Mano & Thongtha, 2021).

Another observation made during the controlled tests was the increasing difference between the outer surface temperature and the two internal measurement points as the test progressed. In the Type 1 test the outer-inner surface difference increased to approximately 15-20 °C by the end of the two-hour test period. The corresponding differences for the Type 2 test were even greater. It increased upto 26°C. This is in contrast to the corresponding non-PCM tests where the temperature differences between outer and inner surfaces increased to approximately 11-12 °C and 23 °C, respectively. The observed trend of the temperature differences is consistent with the behavior of a PCM layer as it reaches the end of its active melting plateau temperature range and the thermal energy is stored as latent heat within the PCM rather than being absorbed by subsequent layers of the roof structure.

It can also be noted that both the inner surface and inner ambient temperature traces exhibit a noticeable levelling-off towards the end of the test. For the Type 1 tests the levelling-off occurred for about thirty to forty-five minutes towards the end of the test, for the Type 2 tests it occurred for about thirty minutes before the end of the test. This form of levelling-off is due to latent heat absorption by the paraffin, taking up large quantities of thermal energy without producing an appropriate rise in temperature on the downstream face of the prototype. The temperature within the prototype boundary thus remains within acceptable limits for a longer period before the inner ambient temperature begins to rise sharply.

This is supplemented by outdoor test results presented in Section 4.5. The controlled environment test results support the conclusion that paraffin PCM behaves as an effective thermal buffer for corrugated metal roof systems. While it does not eliminate all heat transfer, the test results show that there is a reduction in inner surface temperature of the roof and the inner ambient air temperature. The rate of heat build up is slowed down. These results are relevant particularly for warm-weather locations such as the Terai belt in Nepal where most residential buildings are metal roofed and frequently experience high indoor temperatures during the warm hours of the day. Active cooling to mitigate these high indoor temperatures is not economically viable in most residential settings.

4.7 Statistical Analysis of Inner-Surface Temperature

This section consolidates the inner-surface temperature data-one of the primary quantities of interest in this study-from all three experimental conditions into a single comparative form. For the overall experiment process, for every time point, the mean temperature for the Non-PCM and PCM configurations is reported alongside the resulting reduction (ΔT), the percentage reduction, and the corresponding measurement error. Presenting the data this way makes the magnitude of the cooling and buffering effect attributable to the paraffin PCM directly comparable to the precision with which it has been measured. The averaging scheme and the calculation of the error percentage column are described in Section 3.8.

4.7.1 Outdoor Exposure

Hourly readings between 09:00 and 17:00 over five clear-sky days for each configuration.

Time	Non-PCM $\bar{T}$ (°C)	PCM $\bar{T}$ (°C)	Reduction ΔT (°C)	% Reduction	Error %
9:00	24.31	22.44	1.87	7.7 %	2.92 %
10:00	29.34	26.62	2.72	9.3 %	4.08 %
11:00	32.84	28.65	4.19	12.8 %	2.44 %
12:00	33.40	29.32	4.08	12.2 %	3.54 %
13:00	33.87	29.05	4.82	14.2 %	3.74 %
14:00	32.63	28.07	4.56	14.0 %	3.57 %
15:00	29.36	25.43	3.93	13.4 %	3.21 %
16:00	26.52	23.53	2.99	11.3 %	4.45 %
17:00	22.25	21.50	0.75	3.4 %	6.25 %

Table 3:Average-Inner surface temperature, outdoor exposure across 5 days.

4.7.2 Controlled Heating - Type 1, 800 W

Two 400 W incandescent tubes (combined 800 W) directed onto the outer face of the test enclosure for two hours, recorded every 15 minutes.

Time	Non-PCM $\bar{T}$ (°C)	PCM $\bar{T}$ (°C)	Reduction ΔT (°C)	% Reduction	Error %
0:00	23.80	20.40	3.40	14.3 %	2.69 %
0:15	26.60	21.53	5.07	19.0 %	2.67 %
0:30	28.10	25.73	2.37	8.4 %	2.37 %
0:45	29.47	26.90	2.57	8.7 %	2.31 %
1:00	32.10	29.37	2.73	8.5 %	2.27 %
1:15	33.77	30.17	3.60	10.7 %	2.01 %
1:30	35.90	30.80	5.10	14.2 %	1.94 %
1:45	39.07	31.80	7.27	18.6 %	1.93 %
2:00	40.50	32.47	8.03	19.8 %	1.87 %

Table 4:Average-Inner surface temperature, Controlled Type 1 across 3 days.

4.7.3 Controlled Heating - Type 2, 1600 W

Four 400 W incandescent tubes (combined 1600 W), directed onto the outer face of the test enclosure for two hours, recorded every 15 minutes.

Time	Non-PCM $\bar{T}$ (°C)	PCM $\bar{T}$ (°C)	Reduction ΔT (°C)	% Reduction	Error %
0:00	23.90	20.23	3.67	15.3 %	3.22 %
0:15	27.17	26.57	0.60	2.2 %	2.71 %
0:30	30.07	27.37	2.70	9.0 %	2.37 %
0:45	34.43	27.50	6.93	20.1 %	2.00 %
1:00	37.17	28.87	8.30	22.3 %	2.08 %
1:15	40.07	29.50	10.57	26.4 %	1.92 %
1:30	44.67	30.13	14.53	32.5 %	1.96 %
1:45	46.23	32.20	14.03	30.4 %	1.84 %
2:00	46.83	33.78	13.05	27.9 %	1.81 %

Table 5:Average-Inner surface temperature, Controlled Type 2 across 3 days.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study investigated the thermal performance of paraffin wax used as a phase change material (PCM) in a prototype corrugated metal roof model. The objective was to assess the ability of paraffin to reduce the rate of heat transfer through the roofing system, to regulate the temperature fluctuations within the enclosed space, under both outdoor environmental conditions and simulated indoor heating conditions. Results indicate that the paraffin based PCM can act as a passive thermal regulator acting as buffer during the daytime peak hours for lightweight metal roofs.

Experimental outdoor testing results showed that the non-PCM roof model provided very little resistance to solar heat and as a result, the inner surface and inner ambient temperature increased rapidly during the day with a strong correlation between the temperature of the outer surface and the temperature increases of the inner surface and inner ambient. When compared to the non-PCM test, the inner surface of the PCM roof model demonstrated a reduction of approximately 3-6°C.This corresponds to a reduction of approximately 12-15 % relative to the peak inner surface temperature of the non-PCM roof model under the same outdoor conditions. In contrast, for the roof model incorporating paraffin PCM into the roof structure, the temperature of the outer surface of the model increased and behaved similarly to the non-PCM roof. The inner surface and inner ambient, however, experienced reduced temperatures. In addition, a time-lag effect existed for the PCM roof. The inner surface temperature and inner ambient temperature increased more gradually than for the non-PCM test. As a result, the time of the peak indoor temperature was shifted to later in the day. These conditions provided ideal passive cooling through nighttime radiation when outside air temperature was decreasing.

The controlled environment testing utilized for the assessment of the PCM's buffering behaviour differed from the outdoor testing in that the heat input was supplied by electric heating tubes, rather than by variable solar and ambient parameters. The results obtained from the Type 1 testing, which involved a combined input of 800 W to one on each side of the longer length prototype, showed the maximum surface temperature of the PCM roof model to vary between 47°C and 52°C, with the corresponding internal surface temperature being approximately 32°C. This represents a reduction of nearly 8°C compared with the internal surface temperature of the non-PCM model under the same test conditions, in addition to a reduced internal ambient temperature of 27-28°C as opposed to 36°C for the non-PCM model. The results obtained from the more onerous Type 2 test configuration, which involved a constant heating input of 1600 W supplied symmetrically to both sides of the prototype, indicated the outer surface temperature to approach or even exceed 60°C on occasion. Importantly, however, the maximum internal surface temperature was reduced by approximately 13°C compared with the corresponding non-PCM test, peaking at 33-34°C. The internal ambient temperature was also found to be reduced from approximately 40°C for the non-PCM model to below 30°C for the PCM model. Overall, the PCM roof model achieved a reduction in internal ambient temperature of approximately 22–25% under the Type 1 configuration and approximately 25-27% under the Type 2 configuration. The ratio of inner surface temperature to outer surface temperature was approximately 0.64 for the PCM roof compared with 0.80 for the non-PCM model under Type 1 conditions, indicating a 20% improvement in thermal attenuation across the roof assembly.

For the tests conducted, several additional observations were made from the data. Specifically, the temperature differences between the outer surface and the two inner measurement points both increased as the tests progressed. For the Type 1 PCM roof tests, the outer-inner surface temperature difference was seen to increase to approximately 15-20°C by the end of the two hour test period. For the Type 2 tests the outer-inner surface temperature difference increased to nearly 26°C. In contrast, for the comparable non-PCM test configurations the outer-inner surface temperature differences were approximately 11-12°C and 17°C respectively and 23°C for outer-inner ambient. In addition, the inner surface and inner ambient temperature both levelled off towards the end of each test. The levelling-off period was approximately thirty to forty-five minutes towards the end of each Type 1 test and approximately thirty minutes towards the end of each Type 2 test. This behaviour is consistent with the latent heat absorption of the PCM within its melting temperature range, storing large amounts of thermal energy without any corresponding increase in surface temperature on the downstream surface of the roof.

This paper presents an experimental study to evaluate a passive thermal storage system based on encapsulated phase change material (PCM) incorporated within corrugated metal roofing. Outdoor and controlled environment tests demonstrate that paraffin wax is a suitable passive thermal storage medium. While PCM does not eliminate heat transfer through roofing, it reduces the inner surface and inner ambient peak temperatures. PCM also increases the effective thermal resistance of roofing assembly during its active melting window and delays occurrence of peak indoor temperature. Such a system is relevant for warm-weather locations like the Terai region of Nepal where majority of residential buildings have lightweight metal roofing systems. The study results show that paraffin PCM is a cost-effective, locally available passive system for improving indoor thermal comfort. Results from the study provide a basis for future research and development of PCM-based roofing systems in similar climatic regions around the world.

5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed for further research:

- The thermal conductivity of paraffin is relatively low. It can be improved by adding conductive fillers such as expanded graphite, aluminum fins, copper fins or metallic foams. This would allow heat to be absorbed and released more uniformly.
- To evaluate the durability and thermal reliability of paraffin PCM under repeated heating and cooling cycles.
- The effect of varying the thickness and quantity of paraffin in the roof structure should be studied to identify the optimum of paraffin to air ratio to be used. This would help balance thermal performance against added weight and cost.
- A life cycle and economic assessment should be carried out. This would quantify the payback period, energy and environmental benefits of PCM roofs in the Nepalese context.

REFERENCES

Cabeza, L. F., Barreneche, C., Miró, C., Roca, J., & Fernández, I. (2011). Phase change materials (PCM) for improving energy efficiency in buildings. *Renewable and Sustainable Energy Reviews, 15*(3), 1675-1695.

Kuznik, F., David, D., Johannes, K., & Roux, J. J. (2011). A review on phase change materials integrated in building walls. *Renewable and Sustainable Energy Reviews, 15*(1), 379-391.

Mano, C., & Thongtha, A. (2021). Enhanced thermal performance of roofing materials by integrating phase change materials to reduce energy consumption in buildings. Journal of Renewable Materials, 9(3), 495-506.

Sharma, A., Tyagi, V. V., Chen, C. R., & Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews, 13*(2), 318-345.

Zalba, B., Marín, J. M., Cabeza, L. F., & Mehling, H. (2003). Review on thermal energy storage with phase change materials, heat transfer analysis and applications. *Applied Thermal Engineering, 23*(3), 251-283.

Tyagi, V. V., & Buddhi, D. (2007). PCM thermal storage in buildings: A state of art. *Renewable and Sustainable Energy Reviews, 11*(6), 1146-1166.

Pomianowski, M., Heiselberg, P., & Zhang, Y. (2013). Review of thermal energy storage technologies based on PCM application in buildings. *Energy and Buildings, 67*, 56-69.

Castell, A., Martorell, I., Medrano, M., Pérez, G., & Cabeza, L. F. (2010). Experimental study of using PCM in brick constructive solutions for passive cooling. *Energy and Buildings, 42*(4), 534-540.

Kenisarin, M. M., & Mahkamov, K. M. (2007). Solar energy storage using phase change materials. *Renewable and Sustainable Energy Reviews, 11*(9), 1913-1965.

Kharbouch, Y., Ouhsaine, L., Mimet, A., & El Ganaoui, M. (2018). Thermal performance investigation of a PCM-enhanced building roof. *Building Simulation, 11*(6), 1083-1093.

Farid, M. M., Khudhair, A. M., Razack, S. A. K., & Al-Hallaj, S. (2004). A review on phase change energy storage: Materials and applications. *Energy Conversion and Management, 45*(9-10), 1597-1615.

Pasupathy, A., Velraj, R., & Seeniraj, R. V. (2008). Phase change material-based building architecture for thermal management in residential and commercial establishments. *Renewable and Sustainable Energy Reviews, 12*(1), 39-64.

Simon, F., Ruiz-Valero, L., Girard, A., et al. (2024). Experimental and numerical analysis of a PCM-integrated roof for higher thermal performance of buildings. *Journal of Thermal Science, 33*, 522-536.

Yu, J., Leng, K., Wang, F., Ye, H., & Luo, Y. (2020). Simulation study on dynamic thermal performance of a new ventilated roof with form-stable PCM in southern China. *Sustainability, 12*(22), 9315.

Akeiber, H. J., Wahid, M. A., Hussen, H. M., & Mohammad, A. T. (2016). A newly composed paraffin encapsulated prototype roof structure for efficient thermal management in hot climate. *Energy, 104*, 99-106.

Xamán, J., Rodriguez-Ake, A., Zavala-Guillén, I., Hernández-Pérez, I., Arce, J., & Sauceda, D. (2020). Thermal performance analysis of a roof with a PCM-layer under Mexican weather conditions. *Renewable Energy, 149*, 773-785.

Boobalakrishnan, P., Kumar, P. M., Balaji, G., Jenaris, D. S., Kaarthik, S., Jaya Prakash Babu, M., & Karthhik, K. (2021). Thermal management of metal roof building using phase change material (PCM). Materials Today: Proceedings, 47, 5052-5058.

APPENDIX-I

Day 1

Time	Outer (°C)	Inner (°C)	Amb (°C)
9:00	26.34	24.29	24.01
10:00	31.32	29.52	28.32
11:00	36.25	33.25	28.32
12:00	35.44	31.06	29.31
1:00	37.06	32.87	30.31
2:00	38.26	32.94	31.06
3:00	33.63	29.56	28
4:00	29.81	26.87	25.75
5:00	22.7	21.23	20.82

Day 2

Time	Outer (°C)	Inner (°C)	Amb (°C)
9:00	25.97	23.8	23.42
10:00	30.85	28.9	27.6
11:00	35.7	32.8	30.95
12:00	38.9	34.12	32.14
1:00	37.6	33.4	31.5
2:00	36.6	32.92	30.81
3:00	32.71	29.18	28.14
4:00	28.72	26.84	25.62
5:00	24.4	22.8	21.9

Day 3

Time	Outer (°C)	Inner (°C)	Amb (°C)
9:00	27.06	25.1	24.5
10:00	32.1	30.42	29.15
11:00	35.9	33.15	31.8
12:00	38.45	34.2	32.1
1:00	37.2	33.1	31.4
2:00	35.05	31.85	30.05
3:00	31.9	29.4	28.3
4:00	28.4	26.75	25.9
5:00	24.12	22.6	22.02

Day 4

Time	Outer (°C)	Inner (°C)	Amb (°C)
9:00	26.45	24.5	24.02
10:00	31.8	29.75	27.6
11:00	35.2	32.9	30.2
12:00	37.9	34.1	32.05
1:00	39.15	35.11	33.12
2:00	37.4	33.23	31.75
3:00	31.67	29.72	29.02
4:00	28.24	26.02	25.44
5:00	22.55	21.4	21.22

Day 5

Time	Outer (°C)	Inner (°C)	Amb (°C)
9:00	25.1	23.85	22.22
10:00	30.45	28.12	27.5
11:00	34.8	32.1	30.45
12:00	37.15	33.5	31.8
1:00	38.9	34.85	32.6
2:00	36.56	32.2	31.1
3:00	32.8	28.95	26.4
4:00	28.15	26.1	25.84
5:00	24.15	23.21	22.4

Table 6:5 Day outdoor temperature readings (Without PCM)

Day 1

Time	Outer (°C)	Inner (°C)	Amb (°C)
9:00	25.6	22.5	21.3
10:00	31	28.59	26.98
11:00	35.1	29.62	28.3
12:00	36.82	30.42	30.1
1:00	37.5	31.2	29.7
2:00	32.3	29.7	27.8
3:00	25.32	24.34	23.01
4:00	22.8	21.5	21.2
5:00	21.7	20.2	20

Day 2

Time	Outer (°C)	Inner (°C)	Amb (°C)
9:00	26.1	22.8	21.1
10:00	31.02	27.2	25.8
11:00	36	28.7	27.3
12:00	39.3	28.6	27.3
1:00	37.4	28.9	27.8
2:00	33.6	28.7	27.5
3:00	29	26.52	25.21
4:00	25.3	25	23.5
5:00	22.7	23.5	22.1

Day 3

Time	Outer (°C)	Inner (°C)	Amb (°C)
9:00	25.1	22.4	20.9
10:00	29.4	26	24.42
11:00	35.12	28.62	26.94
12:00	39.74	29.64	26.72
1:00	36.91	28.57	27.1
2:00	32.2	26.54	24.84
3:00	27.22	25	23.6
4:00	23.8	23.5	22
5:00	21.02	19.98	19.9

Day 4

Time	Outer (°C)	Inner (°C)	Amb (°C)
9:00	24.2	22.1	21.45
10:00	28.4	25.32	24.01
11:00	34.8	28.02	27.05
12:00	37.24	29.44	27.35
1:00	36.41	28.18	27
2:00	31.63	26.8	25.78
3:00	26.45	24.79	23.68
4:00	24.02	22.64	21.94
5:00	22	20.32	19.6

Day 5

Time	Outer (°C)	Inner (°C)	Amb (°C)
9:00	25.6	22.4	20.8
10:00	29.5	26	24.8
11:00	34.6	28.3	26.9
12:00	37.9	28.5	27.4
1:00	39.6	28.4	27.5
2:00	36.9	28.6	25.9
3:00	32.6	26.5	25
4:00	27.5	25	23.8
5:00	24.1	23.5	23.2

Table 7:5 Day outdoor temperature reading (With PCM)

Day 1

Time	Outer (°C)	Inner (°C)	Amb (°C)
00:00	25.2	23.8	23.7
00:15	31.8	26.6	24.9
00:30	34.6	28.1	26.8
00:45	38.1	29.5	28.1
01:00	42.9	32.1	29.7
01:15	44.3	33.8	31.6
01:30	47.1	35.9	32.92
01:45	49.3	39.1	34.6
02:00	51.8	40.5	36.4

Day 2

Time	Outer (°C)	Inner (°C)	Amb (°C)
00:00	25.4	23.9	23.8
00:15	32	26.4	25.1
00:30	34.9	28.3	26.6
00:45	38.3	29.2	28.3
01:00	42	32.4	29.5
01:15	44.6	33.5	31.8
01:30	47.3	36.2	32.7
01:45	49.6	38.7	34.8
02:00	52	40.8	36.2

Day 3

Time	Outer (°C)	Inner (°C)	Amb (°C)
00:00	25	23.7	23.6
00:15	31.6	26.8	24.7
00:30	34.4	27.9	26.9
00:45	37.9	29.7	27.8
01:00	42.7	31.8	30
01:15	44.1	34	31.4
01:30	46.9	35.6	33.1
01:45	49.1	39.4	34.3
02:00	51.6	40.2	36.7

Table 8:Type 1 - Non-PCM (Controlled Environment)

Day 1

Time	Outer (°C)	Inner (°C)	Amb (°C)
00:00	24.6	24.2	24.2
00:15	30.2	27.4	26.4
00:30	33.9	30.4	28.2
00:45	38.6	34.3	32.3
01:00	45.8	37.2	34.5
01:15	51.1	40	37.5
01:30	57.8	44.3	38.3
01:45	61.1	46.3	39.1
02:00	63.48	46.8	39.8

Day 2

Time	Outer (°C)	Inner (°C)	Amb (°C)
00:00	23.8	23.3	23.1
00:15	29.5	26.6	25.6
00:30	33.2	29.7	27.4
00:45	38.9	34.6	32.5
01:00	46.1	37.5	34.7
01:15	51.4	40.3	37.7
01:30	58.1	45.2	38.5
01:45	61.4	46.6	39.5
02:00	64.2	47.2	40.02

Day 3

Time	Outer (°C)	Inner (°C)	Amb (°C)
00:00	24.4	24.2	24
00:15	29.9	27.5	26.3
00:30	33.6	30.1	28.2
00:45	38.3	34.4	31.9
01:00	45.5	36.8	34.4
01:15	50.8	39.9	37.6
01:30	57.5	44.5	38.1
01:45	60.8	45.8	39.4
02:00	63.1	46.5	39.92

Table 9:Type 2 - Non-PCM (Controlled Environment)

Day 1

Time	Outer (°C)	Inner (°C)	Amb (°C)
0:00	22.4	20.4	19.9
0:15	27.6	21.5	21.2
0:30	34.1	25.7	22.4
0:45	37	26.8	24.1
1:00	40.3	29.2	24.2
1:15	43.3	30	26.4
1:30	43.7	30.6	27
1:45	46.4	31.6	27.1
2:00	47.9	32.4	27.1

Day 2

Time	Outer (°C)	Inner (°C)	Amb (°C)
0:00	22.6	20.5	20.1
0:15	28	21.8	21.4
0:30	34.5	26	22.7
0:45	37.6	27.2	24.3
1:00	40.8	29.8	24.6
1:15	44	30.4	26.7
1:30	44.5	31	27.2
1:45	48	32.1	27.4
2:00	50.3	32.8	27.5

Day 3

Time	Outer (°C)	Inner (°C)	Amb (°C)
0:00	22.3	20.3	19.7
0:15	27.4	21.3	21.1
0:30	33.8	25.5	22.5
0:45	36.9	26.7	24
1:00	40.1	29.1	24.3
1:15	43.1	30.1	26.3
1:30	45.3	30.8	26.9
1:45	47.5	31.7	27
2:00	52	32.2	28

Table 10:Type 1 - PCM (Controlled Environment)

Day 1

Time	Outer (°C)	Inner (°C)	Amb (°C)
0:00	22.5	20.2	20
0:15	32.2	26.6	24.7
0:30	35.5	27.4	25.2
0:45	36.3	27.5	25.4
1:00	40.3	28.9	25.7
1:15	44.5	29.5	27
1:30	48.4	30.1	27.5
1:45	53.6	32.2	28
2:00	59.47	33.84	29.2

Day 2

Time	Outer (°C)	Inner (°C)	Amb (°C)
0:00	22.7	20.4	20.1
0:15	31.8	26.3	24.4
0:30	36	27.1	25
0:45	37.8	27.3	25.2
1:00	39.9	28.6	25.6
1:15	43.45	29.2	26.8
1:30	47.8	29.9	27.3
1:45	53.8	31.9	27.8
2:00	58.6	33.4	28.9

Day 3

Time	Outer (°C)	Inner (°C)	Amb (°C)
0:00	22.3	20.1	19.9
0:15	32.6	26.8	24.9
0:30	36	27.6	25.4
0:45	36.8	27.7	25.6
1:00	40.7	29.1	26.0
1:15	44.9	29.8	27.2
1:30	48.9	30.4	27.7
1:45	54.2	32.5	28.2
2:00	60.1	34.1	29.4

Table 11:Type 2 - PCM (Controlled Environment)

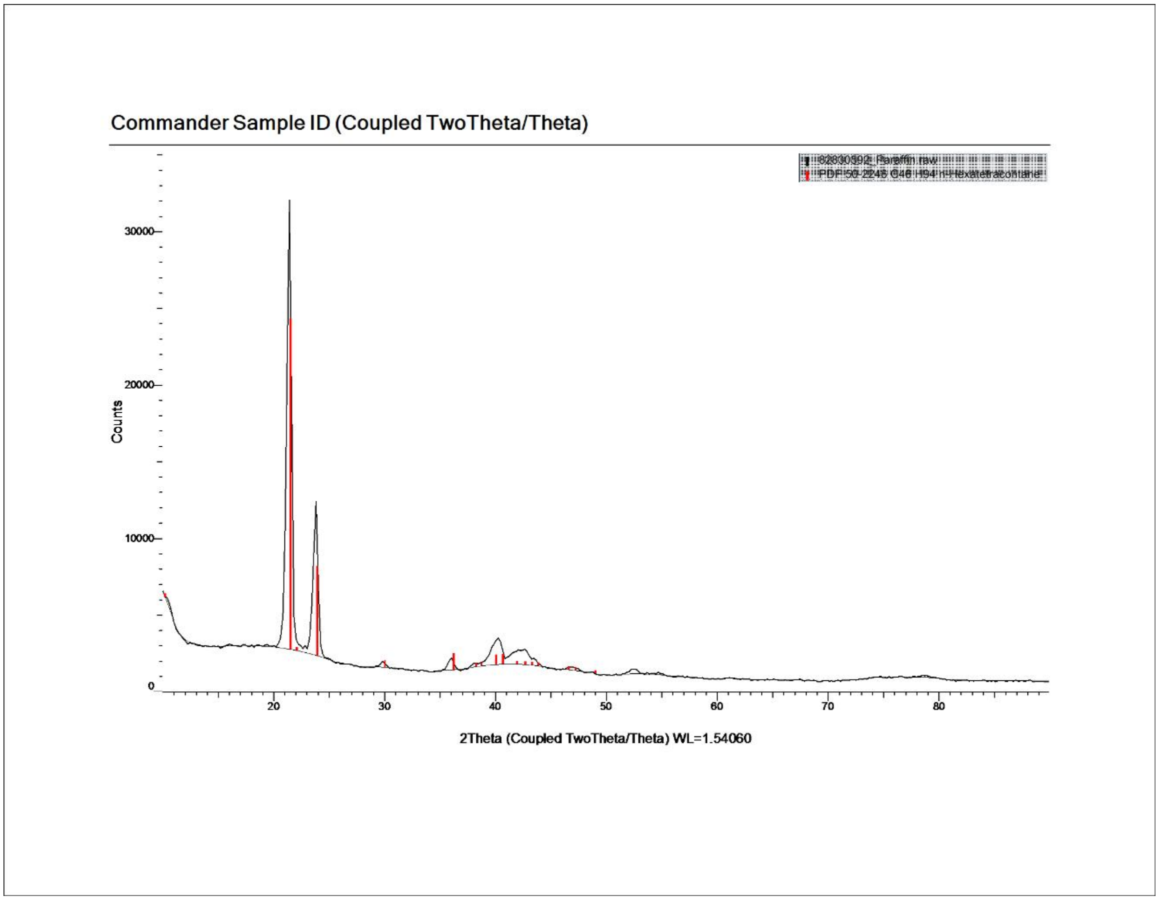


Figure 23:XRD Report(NAST)

APPENDIX-II

Figure 24:Prototype Structure

Figure 25:Prototype Initial Phase(1)

Figure 26:Prototype Initial Phase(2)

Figure 27:DS18B20 temperature sensor

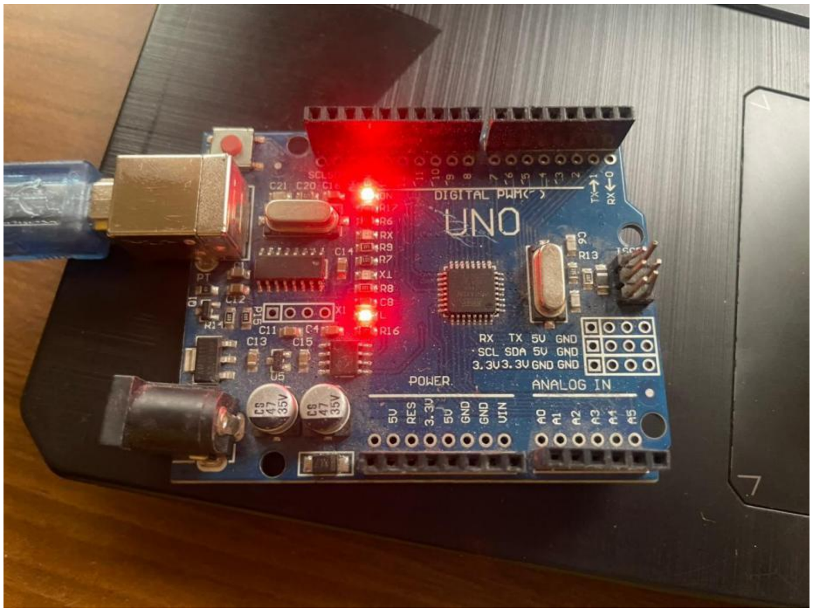


Figure 28:Arduino

Figure 29:Poured Paraffin in Cavity(1)

Figure 30:Poured Paraffin in Cavity(2)

Figure 31:Protoype with inner cavity

Figure 32:Prototype Side view

त्रिभुवन विश्वविद्यालय
TRIBHUVAN UNIVERSITY
इन्जिनियरिङ्ग अध्ययन संस्थान
INSTITUTE OF ENGINEERING
पुल्चोक क्याम्पस
PULCHOWK CAMPUS

Accredited by University Grants
Commission (UGC) Nepal 2020

☎ 5-521260
5-521611
5-522104
5-522809

पुल्चोक, ललितपुर ।
Pulchowk, Lalitpur

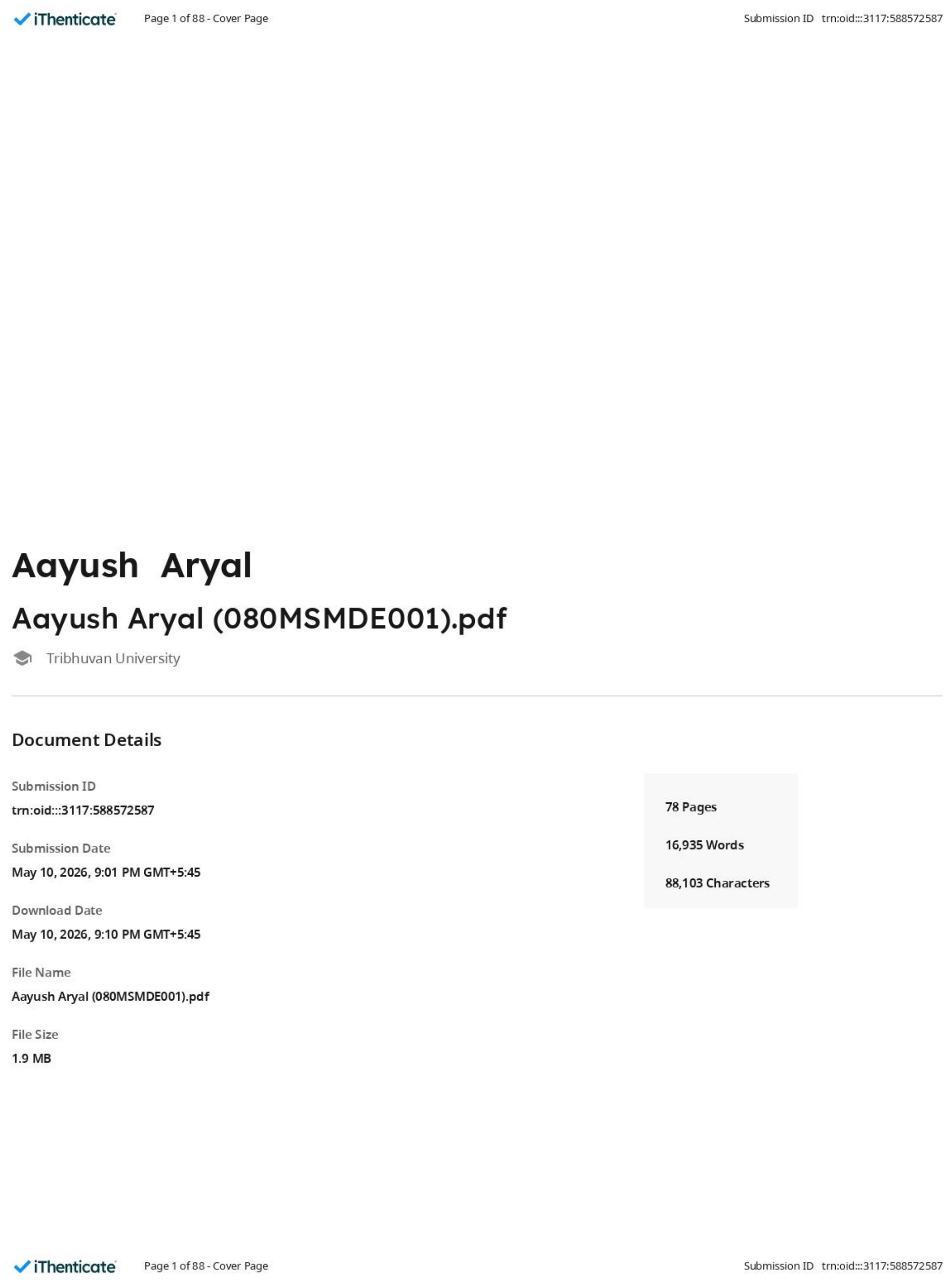
Date: May 9, 2026

To Whom It May Concern:

This is to certify that the paper titled "*Thermal Performance Analysis of Paraffin as Phase Change Material*" (Submission ID #1143), with **Aayush Aryal** as the first author, was accepted through the peer-review process and has been presented at the 18th IOE Graduate Conference, organized at Pulchowk Campus, Lalitpur, Nepal, from May 7 to 9, 2026.

Please note that inclusion of the accepted manuscript in the conference proceedings is contingent upon timely compliance with any further editorial requirements during the publication process.

Prof. Sangeeta Singh
Convener
18th IOE Graduate Conference



Aayush Aryal

Aayush Aryal (080MSMDE001).pdf

Tribhuvan University

Document Details

Submission ID trn:oid:::3117:588572587	78 Pages
Submission Date May 10, 2026, 9:01 PM GMT+5:45	16,935 Words
Download Date May 10, 2026, 9:10 PM GMT+5:45	88,103 Characters
File Name Aayush Aryal (080MSMDE001).pdf	
File Size 1.9 MB	

✓iThenticate Page 2 of 88 - Integrity Overview

Submission ID trn:oid:::3117:588572587

11% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Bibliography
- Quoted Text
- Cited Text
- Small Matches (less than 8 words)

Custom Section Exclusions

{titlesCount} Section Titles, {keywordsCount} Keywords

Section title	No. of Section Starters	Section Starters
"Acknowledgements"	4	Acknowledgements Acknowledgement Acknowledgment Acknowledgments

Match Groups

- **166 Not Cited or Quoted 11%**
  Matches with neither in-text citation nor quotation marks
- **0 Missing Quotations 0%**
  Matches that are still very similar to source material
- **0 Missing Citation 0%**
  Matches that have quotation marks, but no in-text citation
- **0 Cited and Quoted 0%**
  Matches with in-text citation present, but no quotation marks

Top Sources

9%	Internet sources
8%	Publications
0%	Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

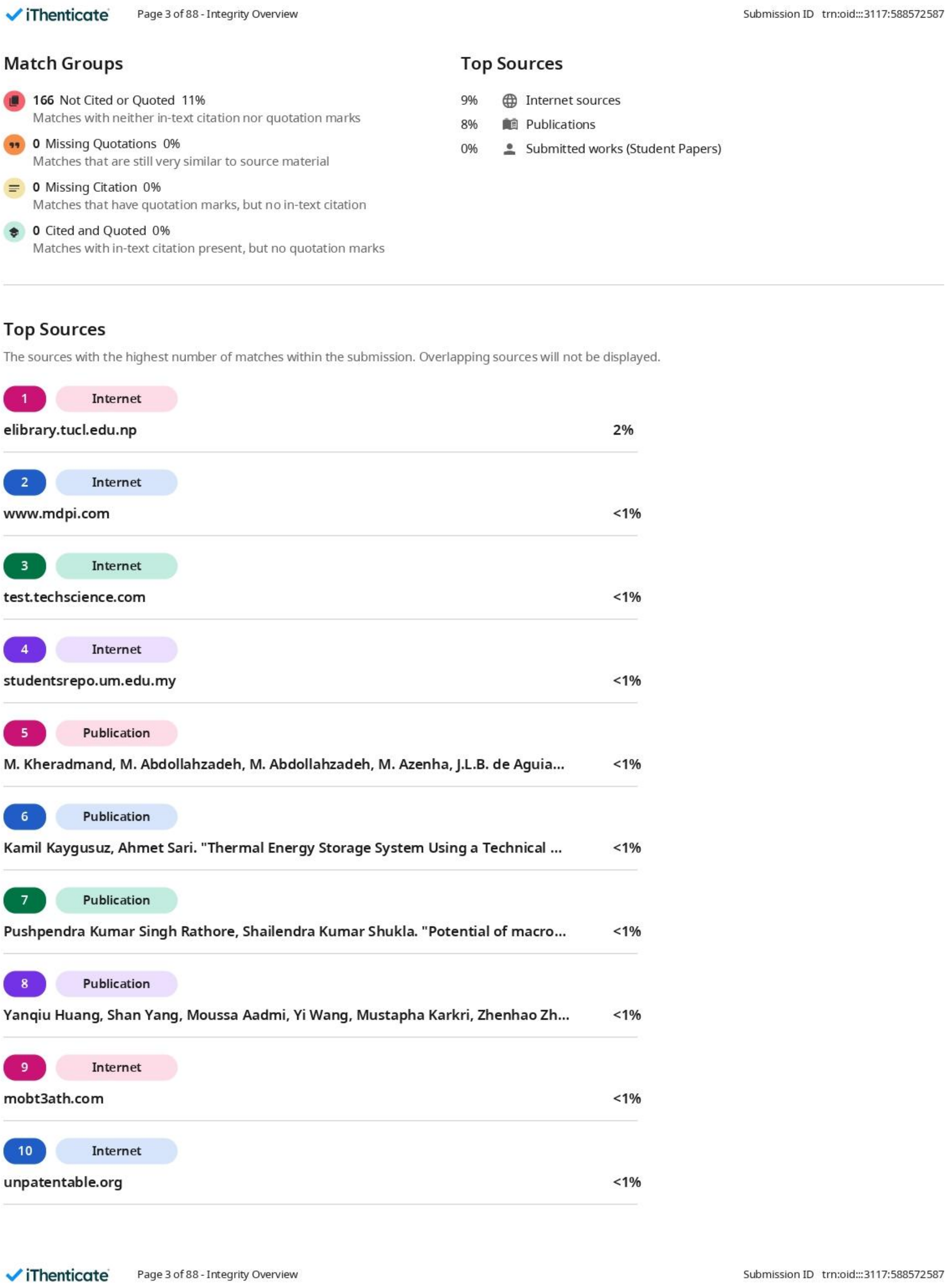
No suspicious text manipulations found.

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

✓iThenticate Page 2 of 88 - Integrity Overview Submission ID trn:oid:::3117:588572587

70



Match Groups

- **166** Not Cited or Quoted 11%
  Matches with neither in-text citation nor quotation marks
- **0** Missing Quotations 0%
  Matches that are still very similar to source material
- **0** Missing Citation 0%
  Matches that have quotation marks, but no in-text citation
- **0** Cited and Quoted 0%
  Matches with in-text citation present, but no quotation marks

Top Sources

9%	Internet sources
8%	Publications
0%	Submitted works (Student Papers)

Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

1	Internet	**elibrary.tucl.edu.np**	**2%**
2	Internet	**www.mdpi.com**	**<1%**
3	Internet	**test.techscience.com**	**<1%**
4	Internet	**studentsrepo.um.edu.my**	**<1%**
5	Publication	**M. Kheradmand, M. Abdollahzadeh, M. Abdollahzadeh, M. Azenha, J.L.B. de Aguia...**	**<1%**
6	Publication	**Kamil Kaygusuz, Ahmet Sari. "Thermal Energy Storage System Using a Technical ...**	**<1%**
7	Publication	**Pushpendra Kumar Singh Rathore, Shailendra Kumar Shukla. "Potential of macro...**	**<1%**
8	Publication	**Yanqiu Huang, Shan Yang, Moussa Aadmi, Yi Wang, Mustapha Karkri, Zhenhao Zh...**	**<1%**
9	Internet	**mobt3ath.com**	**<1%**
10	Internet	**unpatentable.org**	**<1%**