REPUBLIC OF TÜRKİYE

YILDIZ TECHNICAL UNIVERSITY

GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

DEVELOPMENT OF A PHASE-CHANGING MATERIAL ADDITIVE RADIANT HEATING-COOLING PANEL FOR ENERGY EFFICIENCY IN BUILDINGS

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MASTER OF SCIENCE THESIS

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Energy Program

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A thesis submitted by Muhammed Salih in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE is approved by the committee on 01.05.2023 in Department of Mechanical Engineering, Energy Program.

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Muhammed SALIH

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Dedicated to my father.

and my best Daughter

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LIST OF SYMBOLS

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning engineers
C	Specific heat capacity (J/(kg K))
CFD	Computational fluid dynamics
EER	Energy efficiency ratio
h	Convective heat transfer coefficient (W/(m^2 K))
HVAC	Heating, ventilation, and air conditioning
k	Thermal conductivity (W/(m K))
Lc	Latent heat of crystallization (J/kg)
Lf	Latent heat of fusion (J/kg)
LHS	Latin hypercube sampling
PCM	Phase-changing material
PCMs	Phase-changing materials
Q	Heat transfer (W)
$\dot{Q}$	Heat transfer rate (W)
RTD	Resistance temperature detector
R-value	Thermal resistance (m^2 K/W)
SHGC	Solar heat gain coefficient
T	Temperature (°C)
Tc	Crystallization temperature (°C)
Tm	Melting temperature (°C)
ΔH	Enthalpy change (J/kg)
ΔHc	Crystallization enthalpy (J/kg)
ΔHm	Melting enthalpy (J/kg)
ΔT	Temperature difference (°C)
ρ	Density (kg/m^3)

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ABSTRACT

Development of a Phase-Changing Material Additive Radiant Heating-Cooling Panel for Energy Efficiency in Buildings

Muhammed SALİH

Department of Mechanical Engineering

Energy Program

Master of Science Thesis

Supervisor: Prof. Dr. Hakan DEMİR

Co- supervisor: Assoc. Prof. Dr. Aliihsan KOCA

This thesis presents the experimental investigation of Phase Change Material (PCM) effects on thermal performance through three different methods. The first method focuses on the surface temperature and cooling time of radiant system panels with varying mass mixing ratios of PCM. The experiments involved three types of panels: a reference panel without PCM (Panel-0), a panel with 6% PCM content (Panel-1), and a panel with 10% PCM content (Panel-2). Measurements were taken at different outdoor air temperatures (0°C, 3°C, and 8°C) after reaching a steady state. The results showed that PCM significantly delayed the cooling of the panel surface, maintaining thermal comfort for an extended period. The second method investigated the effect of PCM on comfort by simulating temperature variations in an outdoor environment using a water heater connected to a PLC system. The experiment replicated daytime temperature increase (0°C to 8°C) and nighttime temperature decrease (8°C to 0°C) to mimic daily diurnal cycles. PCM contributed to energy efficiency by providing energy to the environment without increased energy supply. Thermal comfort conditions were achieved with a constant thermal distribution on the panel surface. The experiments demonstrated that PCM mitigated temperature peaks, resulting in a constant surface temperature and compliance with the Ashrae 55 standard. To validate the experimental results, CFD analysis was performed for the second and third methods. The findings confirmed the observed effects of PCM on thermal performance and comfort. Additionally, the thermal performance of PCM-enhanced wall panels was investigated, showing a remarkable 17% improvement. This research contributes to the knowledge of PCM application in enhancing thermal performance and improving comfort in building environments. The findings have practical implications for sustainable building design and energy-efficient systems.

Keywords: Phase Change Material, Thermal Performance, Comfort, Energy Efficiency, Computational Fluid Dynamics.

ÖZET

Binalarda Enerji Verimliliğine Yönelik, Faz Değiştiren Malzeme Katkılı Radyant Isıtma Soğutma Paneli Geliştirilmesi

Muhammed Salih

Makine Mühendisliği Anabilim Dalı

Yüksek Lisan Tezi

Danışman: Prof. Dr. Hakan DEMİR

Eş-Danışman: Doç. Dr. Aliihsan KOCA

Bu tez, Faz Değiştirici Malzeme'nin (FDM) ısıl performans üzerindeki etkisini üç farklı yöntem kullanarak deneysel olarak incelemeyi amaçlamaktadır. İlk yöntem, farklı kütlesel karışım oranlarına sahip FDM'nin radyant sistem panel yüzey sıcaklığı ve soğuma süresi üzerindeki etkisini araştırmaktadır. Deneyler, FDM içermeyen referans panel (Panel-0), %6 FDM içeren panel (Panel-1) ve %10 FDM içeren panel (Panel-2) kullanılarak gerçekleştirilmiştir. Sistem istikrar kazandıktan sonra farklı dış hava sıcaklıklarında (0°C, 3°C ve 8°C) ölçümler alınmıştır. Elde edilen sonuçlar, FDM'nin panel yüzeyinin soğumasını önemli ölçüde geciktirdiğini ve termal konforun daha uzun süre sağlandığını göstermektedir. İkinci yöntem, FDM'nin konfor üzerindeki etkisini araştırmak için dış ortam şartlarını simüle etmek amacıyla su ısıtıcısı ve PLC sistemine bağlanarak deneyler yapılmasını içermektedir. Deneyler, gündüz dönemindeki sıcaklık artışını (0°C ila 8°C) ve gece dönemindeki sıcaklık azalışını (8°C ila 0°C) taklit etmektedir. FDM, enerji verimliliğini artırarak çevreye enerji sağlamada ek enerji tüketimi gereksinimini ortadan kaldırmıştır. Sabit bir termal dağılım ile termal konfor koşulları elde edilmiştir. Deneyler, FDM'nin sıcaklık piklerini azaltarak sabit bir yüzey sıcaklığı elde edilmesini sağladığını ve Ashrae 55 standardına uyumlu olduğunu göstermektedir. Deneysel sonuçların doğrulanması amacıyla ikinci ve üçüncü yöntemler için CFD analizi yapılmıştır. Elde edilen bulgular, FDM'nin ısıl performans ve konfor üzerindeki etkilerini teyit etmektedir. Ayrıca, deneysel olarak geliştirilen FDM katkılı duvar panellerinin ısıl performansı incelenerek %17 oranında iyileşme gözlendiği tespit edilmiştir. Bu araştırma, FDM'nin ısıl performansı artırmada ve bina ortamlarında konforu iyileştirmede uygulanmasına ilişkin bilgi birikimine katkı sağlamaktadır. Bulgular, sürdürülebilir bina tasarımı ve enerji verimli sistemler açısından pratik sonuçlar sunmaktadır.

Anahtar Kelimeler: Faz Değiştirici Malzeme, Isıl Performans, Konfor, Enerji Verimliliği, Hesaplamalı Akışkanlar Dinamiği.

1

INTRODUCTION

Building energy use plays a significant role in greenhouse gas emissions and climate change. A sizable fraction of this energy use is caused by heating and cooling systems, particularly in areas with harsh weather. Traditional HVAC systems have been demonstrated to be less energy-efficient and more expensive than radiant heating and cooling systems. However, the materials employed in their construction have a limit on their efficacy.

By storing and releasing thermal energy, phase-changing materials (PCMs) have the potential to increase the effectiveness of radiant heating and cooling systems. There is less of a requirement for mechanical heating and cooling systems since these materials can collect heat during the day when temperatures are high and release it at night when temperatures are low. In order to enhance the energy efficiency of building envelopes, this project intends to create a PCM additive radiant heating-cooling panel.

To assess the thermal performance of the PCM additive radiant heating-cooling panel, the study will use a mixed-methods strategy that incorporates lab tests and computer simulations. The research will help create a more sustainable and energy-efficient building technology that can lessen buildings' carbon footprints and lessen the effects of climate change.

Overall, this research will deepen our understanding of how PCM-based radiant heating-cooling systems can improve buildings' energy efficiency and lay the groundwork for future research and development in this area.

1.1 Review of Thermal Energy Storage for Sustainable Heating

Atomic or molecular vibrations produce heat energy, which is the sum of the kinetic and potential energies of the atoms or molecules that make up a material. By altering the substance's internal energy, heat energy can be stored as perceptible heat, latent heat, reaction heat, or a mix of these. Sensible heat storage makes use of the heat produced when the temperature of the storage medium changes. Materials that experience a phase shift are used for latent heat storage. At a sufficient temperature range, the latent heat produced by the phase shift of the storage medium is calculated. For this, materials that melt, evaporate, or transform into other phases at particular temperatures are employed.

The bond energy of a molecule may be used to store heat energy in the thermochemical storage technique, and the same energy-reversible chemical processes can be used to release it.

Water storage tanks, underground and fill-bed storage systems, solar heating/cooling equipment, solar collector water heating systems, heat pump systems, and latent heat storage systems linked to phase-changing materials in thermochemical storage are just a few of the systems that are currently available that use heat energy storage techniques.

The majority of the research in the subject of latent thermal energy storage methods is academic in nature and is currently under progress. The following list includes a few impMiddlent studies.

CFD simulations were used in this work to examine the potential of a thermal storage system (TDS) made up of radiant cooling panels and an active phase-changing material (PCM) for space cooling. Installing PCM cooling pipes between the concrete ceiling slab and the ceiling covering layer allowed for the creation of the TES system. This study showed a 6.8°C drop in the daily average room temperature and highlighted key variables for an active TDS's optimal performance. A nice example of this kind of research may be found in the publication "Perf. Evaluation of an Active PCM TES System for Space Cooling in Residential Buildings" by Sandris RUCEVSKIS, Pavel AKISHIN, and Aleksandrs KORJAKINS (2019).

In a different investigation, L. Klime, P. Charvát, and M. Ostr (2019) compared the TRNSYS software and COMSOL's 1B and 3B modeling of microencapsulated PCM-active wall panels. The PCM models' salient features and crucial variables were noted. For best thermal performance in both models, variables including surface temperatures and system fluxes were tuned, and a sensitivity analysis was carried out. The closeness of the findings was noted, and it was stressed that 1B simulations were successful in terms of computing burden.

Thermal comfort tests of radiant heating and cooling panels from the floor, wall, and ceiling were carried out using CFD analyses in accordance with ISO 7730 and

ASHRAE 55 standards. Measurements were made when needed, and PMV values were computed. It was concluded as a consequence that these systems are generally more comfMiddleble and cost-effective than traditional systems (Aliihsan Koca, Zafer Gemici et al., 2014). There have been discussions on the effectiveness and potential of radiant panel/wall systems using PCMs.

1.2 Building Energy Consumption

Building thermal comfort requirements have been growing in recent years, which has resulted in a significant growth in worldwide energy usage. For instance, between 20 and 40 percent of the energy consumed in developed nations is used for residential and commercial building heating and cooling (Pout, 2008). Between 30 and 50 percent of a building's energy losses can be attributed to windows (U.S. Energy Information Administration, 2014). In contrast to most developed nations, 63% of the natural gas used in US residences went toward heating buildings; the remaining 37% was used for cooking, heating water, and other purposes (U.S. Energy Information Administration, 2014). Heating, ventilation, and air conditioning (HVAC) systems account for two-thirds of the energy consumed by the building sector in the European Union, which accounts for 40% of the world's energy consumption. Consequently, it is crucial to lower the energy requirements of buildings (Cabeza, 2012). By using renewable energy sources, passive building design, increasing the thermal insulation of the building envelope, and storing energy for later use, it is possible to lower the energy demand in buildings and help save fossil resources.

One of the most popular energy sources for space heating, cooling, or solar hot water in buildings between 2010 and 2020 is solar energy, and generation from renewables is growing at a rate of 5.2% per year, as opposed to 3.9% per year between 2000 and 2010. Between 2010 and 2035, it is predicted that the amount of power generated worldwide from renewable sources would increase by 2.7 times (International Energy Agency ,2012). Solar energy is used in solar heating systems to either heat the interior area or store the energy for later use. A heat transfer fluid (HTF), which can be either liquid or air, transfers the heat. Using liquid systems is more frequent when

Storage is provided, and they work well with absorption heat pumps, radiator heating systems, and even boilers with hot water radiators. Innovative solar space cooling technology transforms solar heat into cooling that may be used for things like air conditioning in buildings. Through the use of "sorption" cooling, solar collector-generated heat is transformed into cold.

A HTF (chilled water or dry cool air) is used to deliver the generated cold to the application. Solar hot water is an easy and reasonably priced approach to lower energy usage in home and commercial structures. Solar collectors and an automated control unit form the basis of the solar hot water system.

The devices can cut the requirement for electricity by 25–50% by using solar energy. An auxiliary system delivers the extra heat in the event that the solar system is unable to adequately heat the room.

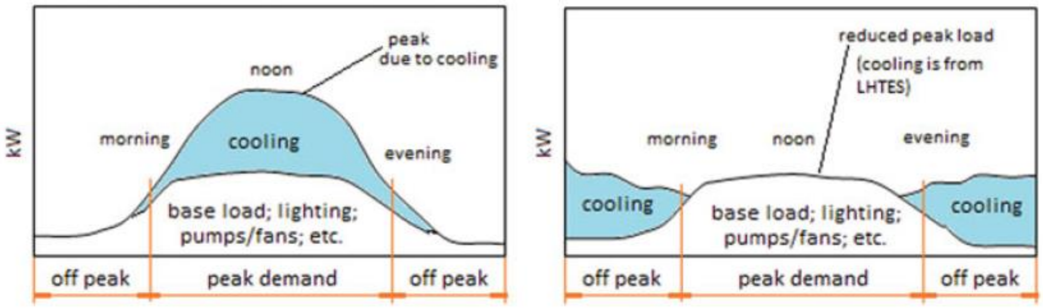


Figure 1.1 Electrical profile: TES electrical profile against traditional construction with chillers

Along with various shading techniques, solar attic cooling, and façade cooling, buildings can also use less energy. The entire home becomes warmer as a result of hot attics.

Attic air may get hotter than 70 °C. Attics become entrapped with extremely hot air that builds up, which causes heat to build up inside the structure.

Building energy consumption might be significantly decreased by new technologies that enhance building envelope performance. The actual savings from these technologies will largely rely on how well they work under various operating and climatic situations. Performance thresholds are established to also outperform current window technology. The effectiveness of blocking solar heat determines the overall savings on heating and cooling (Milliron, 2013).

One of the main technological issues of the ensuing decades is energy and its storage. Reactive building components like thermal energy storage (TES) systems can help lower the demand for power during peak hours. Thermal latent energy Storage (LHTES) has a high energy storage density per unit of mass at constant or almost constant temperature, making it an appealing method for energy accumulation.

As a result, LHTES uses less phase change material (PCM) to store the same amount of energy. A straightforward endothermic and exothermic process serves as the basis of PCM.

According to Fig. 1.1, the bulk of the electrical load for the building may be moved from expensive "on-peak" hours to inexpensive "off-peak" hours.

In order to charge the TES/LHTS system, low-cost ("off-peak") electricity from the power grid is taken throughout the night and used for cooling during the following day ("on-peak" hours). Another method for providing warmth in the winter is to collect solar heat during the day and use it at night.

Conventional systems need the chiller to be activated only when the building's inhabitants seek cool air, as shown in Fig. 1.1. As much as half of the energy utilized in a business building is used for cooling and heating, but with a thermal energy storage system, the chiller may be used when there is no need for cooling. Up to 30–40% of this energy consumption may frequently be avoided by adopting well designed TES systems (Duraković and Ali, 2019).

1.3 Storing Thermal Energy

Sensible heat, latent heat, or chemical energy are all possible forms of thermal storage.

The thermal energy storage forms are shown with examples in Figure 1-2.

In this thesis we will focus is on the latent heat thermal energy storage in materials that undergo phase changes from solid to liquid. These substances fall within the categories of organic and inorganic materials, which are covered in further depth in Chapter 2. For a passive dwelling, Figure 1-3 compares the volumes of heat storage systems based on sensible heat, latent heat, and thermochemical heat storage.

Figure 1-3 demonstrates that thermochemical systems, which are appropriate for seasonal storage applications, have the largest heat storage density but at much higher temperatures. The estimate is based on a passive house's 6480 MJ energy demand (Luo, 2013).

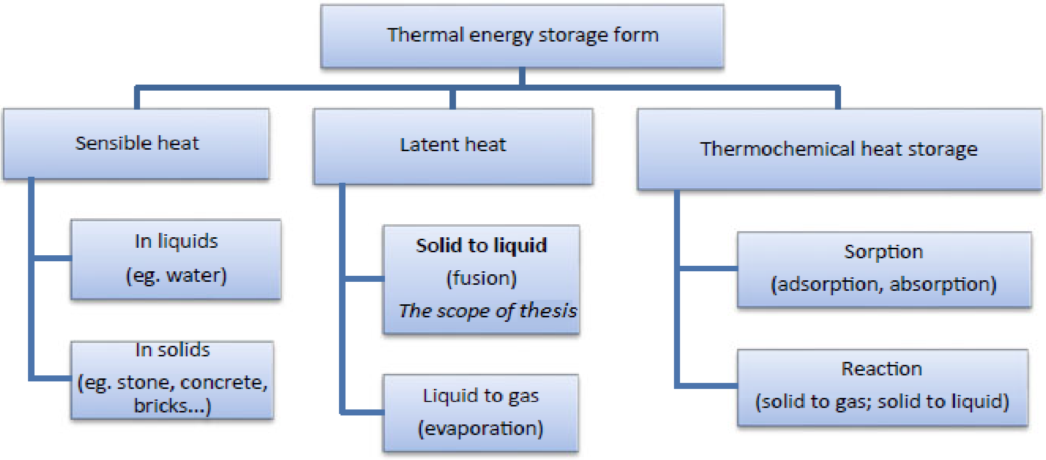


Figure 1.2 The storage of heat

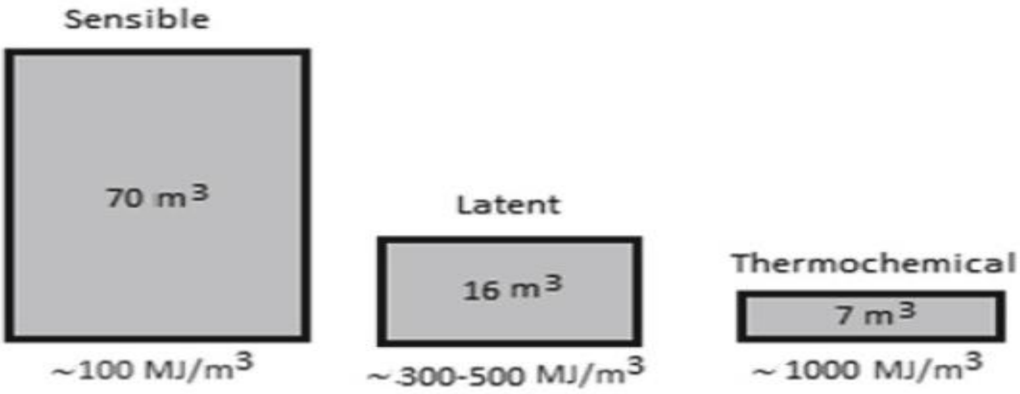


Figure 1.3. Volume required to meet a passive house's whole yearly storage requirements

1.4 Sensible Heat Storage (SHS)

Adding energy to a substance to raise its temperature without altering its phase is the sensible heat storage (SHS) approach (S. Scalat,1996). The following factors affect how much heat is stored:

- Changing temperatures
- Heat capacity of the material
- Storage capacity

1.5 Latent Heat Storage (LHS)

The concept of latent heat storage (LHS) is based on the heat that is emitted or absorbed as a storage medium changes from solid to liquid, liquid to gas, or vice versa. In comparison to delicate heat storage substances like paraffin wax, salt hydrates, and molten salts, it offers a definite advantage. LHS provides a greater energy storage density with almost no temperature fluctuation as compared to SHS. The modest density change, thermal conductivity, undercooling of phase change materials, stability of characteristics under lengthy cycles, and sometimes phase separation present difficulties in practice. Phase change materials may be referred to as latent heat storage materials for PCM since they are often employed in latent heat energy storage systems. The phase shift of the material from liquid to solid or solid to liquid happens during loading or unloading (melting or solidification) of the PCM (Telkes, 1975).

1.6 Thermochemical

In a thermochemical energy storage system, energy is stored after the breaking or dissociation of chemical bonds that release energy at the molecular level, and is then recovered in a reverse chemical process that may be reversible. The system is more compact with this way, which is a benefit. In comparison to SHS and LHS, thermochemical energy storage devices have greater energy densities (Mehling, 2007).The most crucial material characteristic when PCMs are used for TES is the heat storage capacity, which is often expressed as an enthalpy as a function of temperature; PCMs exhibit a significant change in enthalpy across a constrained range of temperatures. Enthalpy quickly shifts at a phase transition temperature in an idealized scenario. The heat that has been stored is therefore known as latent heat, while heat that has been stored with a change in temperature is known as sensible heat (Mehling, 2007).

1.7 Phase Change Theory

Phase Change Materials (PCMs) are substances that can release or absorb sufficient energy during phase transition to provide useful heating or cooling. Phase transition in a material can occur in the forms of solid-solid, solid-liquid, solid-gas, and liquid-gas. When looking at diverse applications that are done utilizing PCMs, it can be noticed that vaporization (liquid-gas or solid-gas) is typically a phase change with high enthalpy. However, the vaporization process is sensitive to boundary restrictions. Vaporization at constant volume results in a large heat and pressure change, making it difficult to use for technical reasons. It has limited usage only for water. On the other hand, during solid-solid phase change, the released phase change enthalpy is often modest (Mehling, 2003).

The working premise of PCMs is straightforward. As the temperature increases, the material undergoes a phase change from solid to liquid. The PCM absorbs heat since the process is endothermic. Similar to this, a substance transitions from a liquid to a solid state when the temperature drops. In this situation, the reaction is exothermic, and the PCM releases heat. The workings of PCMs and their thermal behavior are illustrated in Figures 1-4 and 0-5 (FEUP, 2013).

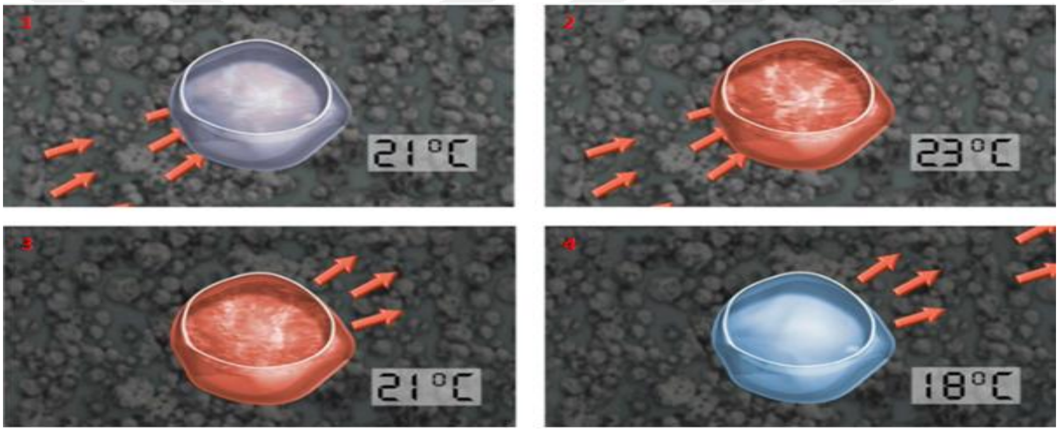


Figure 1.4 PCM theory of phase transition

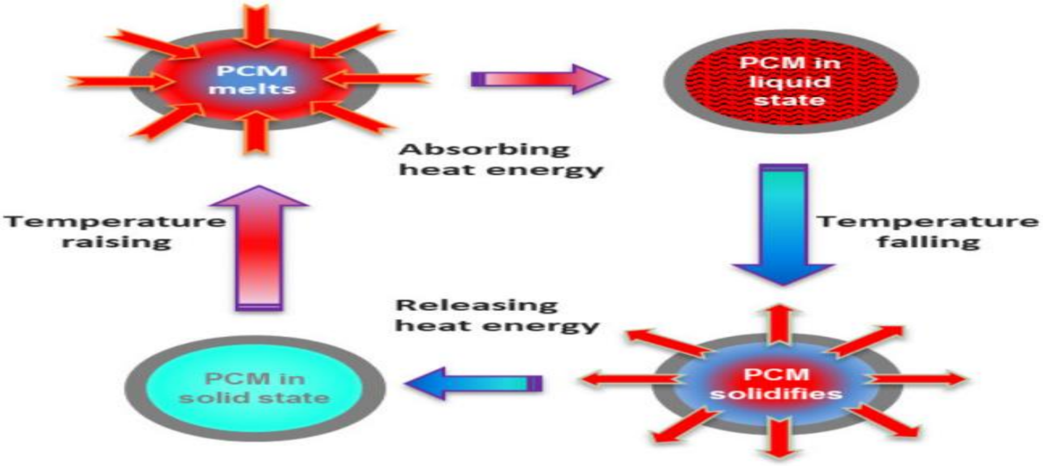


Figure 1.5 PCM Working principle

The material and liquid phase are used to store latent heat energy. It is known as melting or fusion when a solid turns into a liquid, and solidification when a liquid turns into a solid (Fleischer,2015).

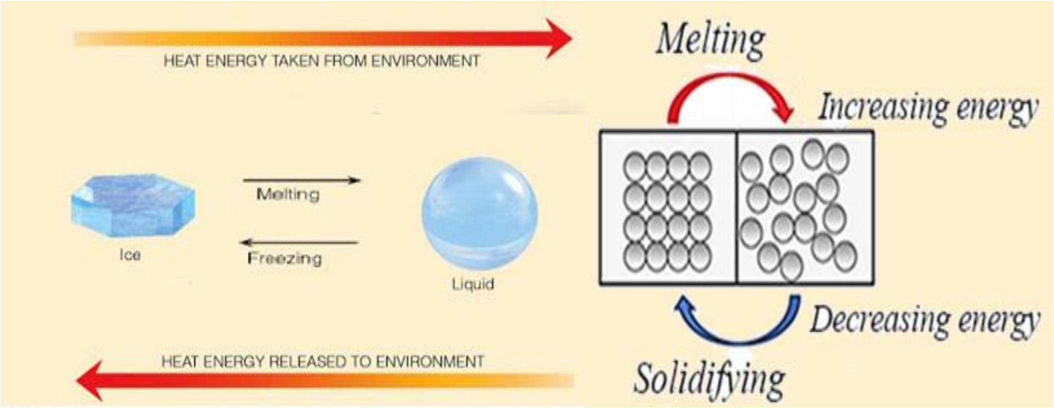


Figure 1.6 Melting-Solidization

The amount of energy stored as sensible heat can be expressed mathematically as follows:

$$\mathrm{Q} = \int_{T_1}^{T_2} mc_p\, dt = mc_p(T_{2\_}T_1) \tag{1.1}$$

The energy storage in PCMs is stored as sensible heat in the solid and liquid phases and as latent heat during phase transition. The amount of stored energy can be expressed mathematically as follows:

$$\mathrm{Q} = \int_{T_1}^{T_{pc}} mc_p\, dT + ma_{pc}\Delta h_{pc+} \int_{T_{pc}}^{T_2} m\, c_p dT \tag{1.2}$$

$$\mathrm{Q} = mc_p(T_{pc-}T_1) + ma_{pc}\Delta h_{pc+}mc_p(T_{pc-}T_1) \tag{1.3}$$

where m is the mass in kilograms, Cp is the specific heat capacity in J/kgK, T1 and T2 are the initial temperatures in the solid state, Ts is the final temperature in the liquid state of the PCM in K, Tpc is the phase transition temperature of the PCM in K, hpc is the enthalpy of the phase change material in J/kg, and a_pc is the melted fraction of a PCM (Benjamin, 2020).

1.8 Classification of PCMs

Organic and inorganic PCMs are the two primary divisions. Not all PCM can be used to construct buildings. Only materials having phase transition temperatures near to that of human comfort can be employed in construction applications. The concentration of the material to be used and which material would perform best in various climates are the primary concerns that need to be addressed in order to make the use of PCMs in construction applications practicable (Zhang, 2017).

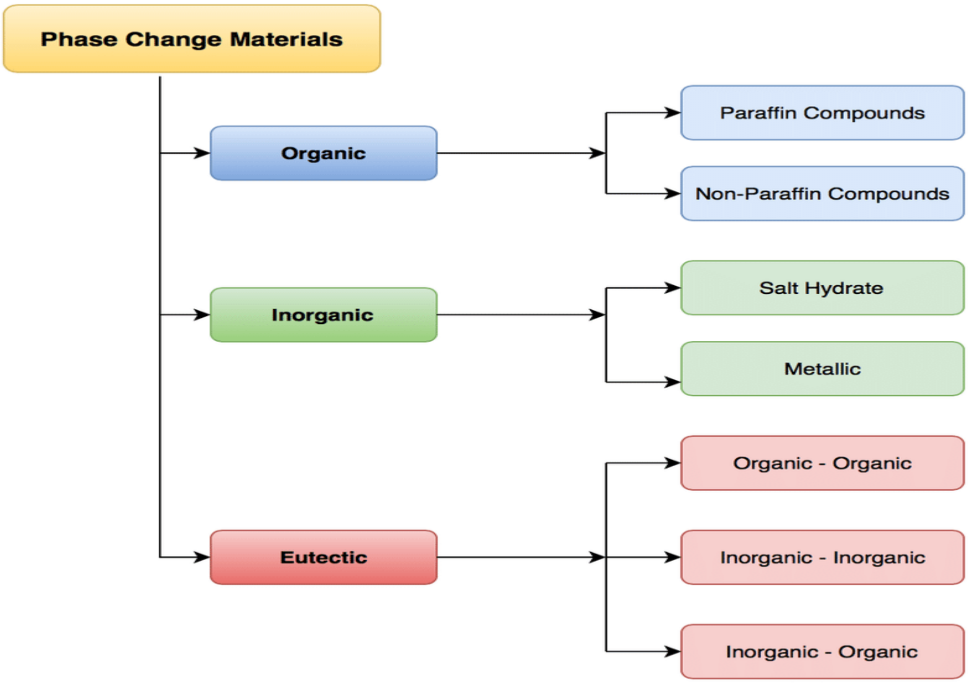


Figure 1.7 Classification of thermal energy storage materials

1.8.1 Organic

Paraffinic and non-paraffinic organic phase transition materials are distinguished. In general, phase separation has little effect on organic PCMs, and they crystallize with little to no supercooling.

A combination of straight chain n-alkanes with the general formula CH3-(CH2)n-CH3 generally makes up paraffin. It has a density of around 800 kg/m3, a poor thermal conductivity of about 0.2 W/mK, a wide temperature range, is incompatible with plastic containers, and is mildly flammable (Rathod, 2016).

Table 1.1 Some commercial organic PCMs

Material	Chemical Formula	Melting Temperature (°C)	Melting Enthalpy (J/g)	Thermal Conductivity (W/(mK))	Density (kg/m3)
n-Hexadecane	$C_{16}H_{34}$	18	211-238	0,2 (solid)	760 (liquid 20 °C)
n-Heptadecane	$C_{17}H_{36}$	19	240	0,2	776 (liquid 20 °C)
Paraffin	$C_{13}C_{24}$	22-24	189	0,21 (liquid)	760 (liquid) 900 (solid)
Paraffin	C_{18}	28	244	0,15	774(liquid) 814 (solid)
n-Octadecane	$C_{18}H_{38}$	28	201-245	0,15 (liquid, 40 °C), 0,36 (solid 25°C)	760 (liquid 70 °C) 814 (liquid 20 °C)
n-Nondecane	$C_{19}H_{40}$	32-33	222	0,18(liquid, 60°C) 0,26 (solid 19°C)	780

Esters, fatty acids, alcohols, and glycols are examples of non-paraffinic organic PCMs that are ideal for storing heat. Fatty acids have certain advantages over inorganic PCMs, including compatibility with melting, high chemical stability, non-toxicity, and an appropriate melting temperature range for construction applications. Fatty acid ester PCMs may go through thousands of phase change cycles without the risk of oxidation, and they are stable for years. Similar to paraffin-based PCMs, these bio-based PCMs have a great capacity for latent heat absorption, storage, and release with little to no supercooling. Fatty acid esters can also be microencapsulated with comparable ease. But because of their acidic structures, they frequently react with their surroundings.

Overall, organic PCMs have numerous qualities that make them appropriate for use in construction, but many of these organic PCMs are also thought to be combustible, which has a big impact on their safety when used in construction (Rathod, 2016).

1.8.1 Inorganic

Metals and hydrated salts make up the relevant inorganic phase transition materials. Salt hydrates have a large amount of storage space and can work in phase transition at room temperature, making them ideal for construction applications. They are desired because of their accessibility, affordability, and inflammability. About 1700 kg/m3 is the density of salt hydrates, which is twice that of paraffin. With a maximum of roughly 200 J/g latent heat, their heat storage capacity per unit volume is about 350 MJ/m3, which is significantly more than that of organic goods. They have good thermal conductivity (approximately 0.5 W/(mK)), and by adding gelling or thickening agents, liquid phase separation and segregation may be avoided. Another issue related to salt hydrates is subcooling (Sharma, 2015). Table 1.2 displays product specs from several manufacturers.

Table 1.2 Commercially produced PCMs that can be used for thermal storage

Product	Type	Melting Temperature (℃)	Enthalpy of Melting (kj/kg)	Thermal Conductivity (W/(m.K))	Source
RT 20	Paraffin	22	172	0,88	Rubitherm GmbH
CLİMSEL C23	Salt hydrates	23	148	-	Climator
E 23	Salt hydrates	23	155	0,43	EPS Ltd.
CLİMSEL C24	Salt hydrates	24	108	1,48	Climator
TH 24	Salt hydrates	24	45,5	0,8	TEAP
RT 26	Paraffin	25	131	0,88	Rubitherm GmbH
RT 25	Paraffin	26	232	-	Rubitherm GmbH
STL 27	Salt hydrates	27	213	1,09	Mitsubishi Chemical
S 27	Salt hydrates	27	207	-	Cristopia
AC 27	Salt hydrates	27	207	1,47	Cristopia

Table 1.3 below (Pasupathy et al., 2008) lists the benefits and drawbacks of employing organic and inorganic PCMs in the creation of structural components.

Table 1.3 Comparison of organic and inorganic PCMs

Organic		Inorganic
Advantages	1. Accessibility across a broad temperature spectrum. 2. There is not any supercooling. 3. Constantly transforming into the same character 4. Self-nucleation. 5. Compatibility with customary construction supplies. 6. Lack of stratification. 7. Very hot fusion. The color chemical black. 9. It is secure and unresponsive. 10. Usable again	1. A high latent heat storage capability in volume. 2. Low price and simple accessibility. 3. exact melting point. 4. Excellent heat conductivity. 5. High fusion heat 6. Low volume variation. 7. Non-flammability.
Disadvantages	1. Due to the limited thermal conductivity of solids, the freezing cycle calls for rapid heat transmission. 2. A low latent heat storage capability in volume. 3. Flammability (Easily decreased with the use of an appropriate container). 4. Due to the high expense of refining, only paraffin mixes are available.	1. A significant volume fluctuation. 2. supercooling during the transition of solid to liquid. 3. Auxiliary substance necessary for nucleation in repeated cycles.

Table 1.4 Compares the characteristics of organic and inorganic phase transition materials

Feature/characteristic	Paraffin wax	Non-paraffin	Salt Hydrates
Heat of fusion	High	High	High
Thermal conductivity	So Low	Low	High
Melting temperature (℃)	-20 to 100+	5 to 120+	0 to 100+
Latent heat (kj/kg)	200 to 280	90 to 250	60 to 300
Corrosive	Not	lightweight	YES
thermal cycling	stable	High temperature can cause decomposition	unstable in repeated cycles
Weight	Middle	Middle	Heavy
Economics	$$	$$$ to $$$$	$

2
LITERATURE REVIEW

2.1 Integration of PCMs with Building Materials

Complex systems like building structures are susceptible to both internal and external effects (see Figure 2.1). Weather conditions outside are the result of outside influences. Solar radiation and internal loads are the major sources of internal factors.

With regard to energy needs in particular, energy-efficient buildings, also known as zero-energy buildings, have recently been built to meet specific standards. These structures have a highly efficient building envelope that may offer comfort for building occupants with the least amount of energy consumption. The ability of the building envelope to store thermal energy is crucial from this perspective (Dincer and Rosen, 2002).

Convective heat transfer between the air and the surface and radiant heat transfer between surfaces are two heat transfer mechanisms that take place at the wall surface inside a room.

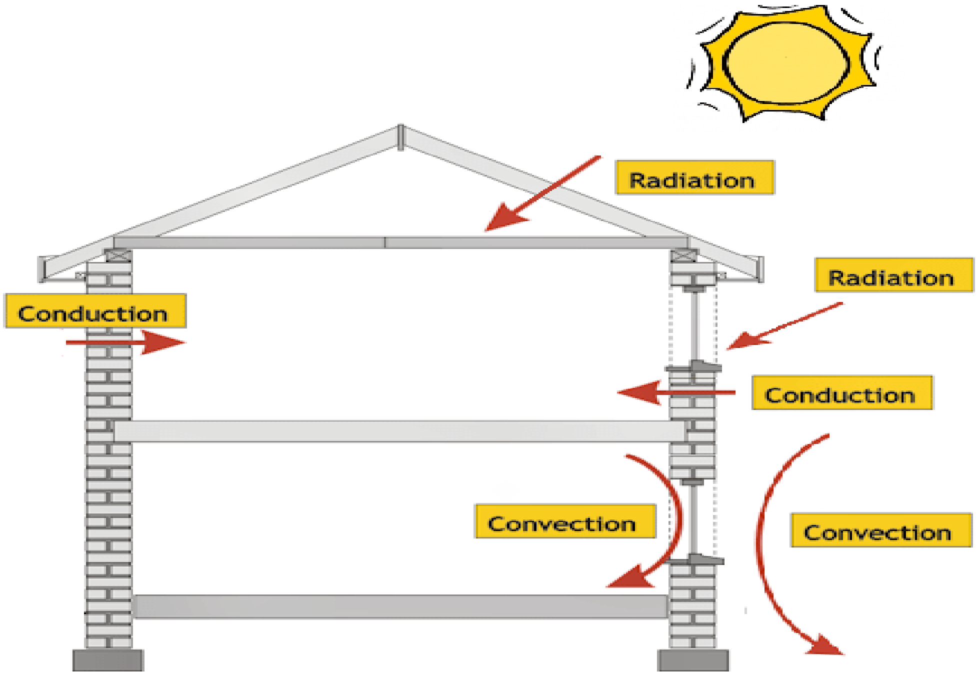


Figure 2.1 An illustration of the building's heat transfer systems

A high-energy-efficient building envelope should generally have the following characteristics:

- Low heat energy loss with thermal insulation,
- Effective use of renewable energy,
- Limitation of overheating or peak energy demand with the use of building walls integrated with PCM.

There are various studies in the literature on the integration of PCMs. Hawes et al. (1991) identified direct fusion, impregnation, immersion, and encapsulation as promising methods for PCM integration. Zhou et al. (2012) stated that the melting and freezing temperatures of PCMs change slightly when incorporated into building materials. Additionally, PCMs can be integrated with other building components by using a single laminated sheet (Darkwa, 2004).

2.2 Direct Incorporation and Impregnation

The easiest and most cost-effective approach for manufacturing PCM is to add it directly to construction materials like plaster, concrete, or mortar in liquid or powder form. Although this approach doesn't need any additional equipment, leakage and incompatibility with construction materials are common issues (Zhou, 2012). One example is the production of laboratory-scale energy storage gypsum board panels using butyl stearate (BS) at a concentration of 21-22% during the mixing stage (Feldman, 1991).

When a porous material, such as a brick or wick, comes into contact with a liquid, it will start to absorb the liquid at a decreasing rate over time. Assuming evaporation, liquid penetration will reach a limit dependent on temperature, relative humidity, and permeability parameters (Zhang, 2007). In this method, the porous building material (such as gypsum board, brick, or concrete block) is dipped into the hot, melted PCM that is absorbed into the pores The process of impregnation is finished as a result. PCM is left trapped in the building material's pores when the porous material is taken out of the liquid and allowed to cool (Kaasinen, 1992). By researching the mechanics of this method's absorption, Hawes and Feldman (1992) were able to more successfully achieve the appropriate level of PCM diffusion. Schossig et al. (2005) noted that leaking could be a persistent issue with this approach, though.

2.3 Encapsulation

To avoid negative effects such as corrosion on building materials, phase change materials can be encapsulated before being integrated into the structures. Encapsulation can be applied in two ways: macro-encapsulation and micro-encapsulation (Mehling, 2007).

Macro-encapsulation refers to the technology where the PCMs are encapsulated in a closed enclosure such as tubes, spheres, or panels. It is more advantageous in the long term compared to non-encapsulated PCMs. RUBITHERM produces a type of macro-encapsulated PCM panels called CSM (compact storage modules) that are shown in Figure 2.2, which have a corrosion-resistant aluminum coating (Castell, 2010).

Figure 2.2 CSM panel with Rubitherm PCM

When macro-encapsulated PCMs are used, the function of the building structure is less affected due to the prevention of leakage problems. However, they have disadvantages such as weak thermal conductivity, tendency to solidify at the edges, and complex integration into building materials (Kaasinen,1992).

Zhang et al. (2005) developed and tested a phase change material wallboard with high crystalline paraffin macro-encapsulated as the phase change material. As a result of the analysis, it was noted that the use of macro-encapsulated PCM structures resulted in approximately a 38% reduction in heat peaks. However, the use of macro-encapsulation requires relatively more work to be integrated into the building structure, making it an expensive method (Kaasinen, 1992).

Micro-encapsulation is another technology used for thermal energy storage in buildings. Micro-encapsulation is a technology where PCM particles are enclosed in a thin, closed, and high molecular weight polymeric film that preserves the shape of the PCM particles and prevents them from leaking during the phase change process (see Figure 2.3.).

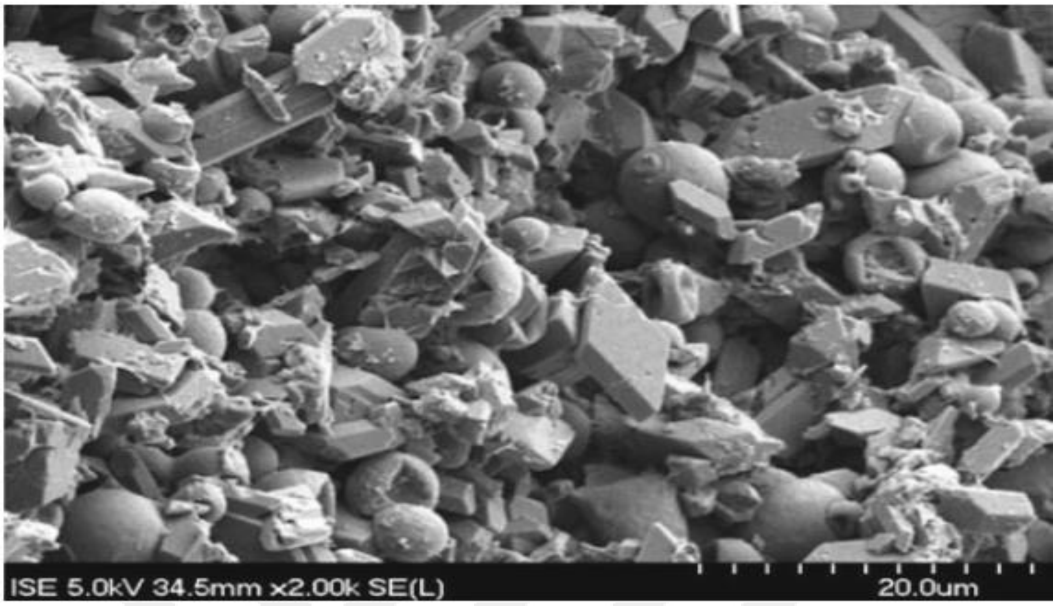


Figure 2.3 Image of microencapsulated PCMs in gypsum plaster (microcapsules of PCMs with an average diameter of 8 μm among gypsum crystals)

Microencapsulated PCMs are considered to be more easily and economically integrated with building materials (Kaasinen, 1992). In a study conducted by Hawlader et al. (2003), it was found that microencapsulated paraffin maintained its geometric profile and heat capacity even after 1000 cycles, as a result of thermal analyses performed. It was also measured to have a thermal energy storage capacity of approximately 145-240 kJ/kg.

An important issue to be aware of is that the microencapsulated PCMs included in building structures may affect the mechanical strength of the structure (Khudhair, 2004). In a study conducted by Cabeza et al. (2007), two concrete structures of the same size and shape were designed, one using microencapsulated PCMs (Mopcon concrete) and one without. It was found that the Mopcon concrete achieved a compressive strength of over 25 MPa and a tensile strength of over 6 MPa, meeting the general structural requirements.

The figure below shows an example produced by a company called National Gypsum, called the Thermal-CORE Panel. The melting point and latent heat capacity of the PCM used in the product are stated as 23°C and 22 BTU/ft2, respectively.

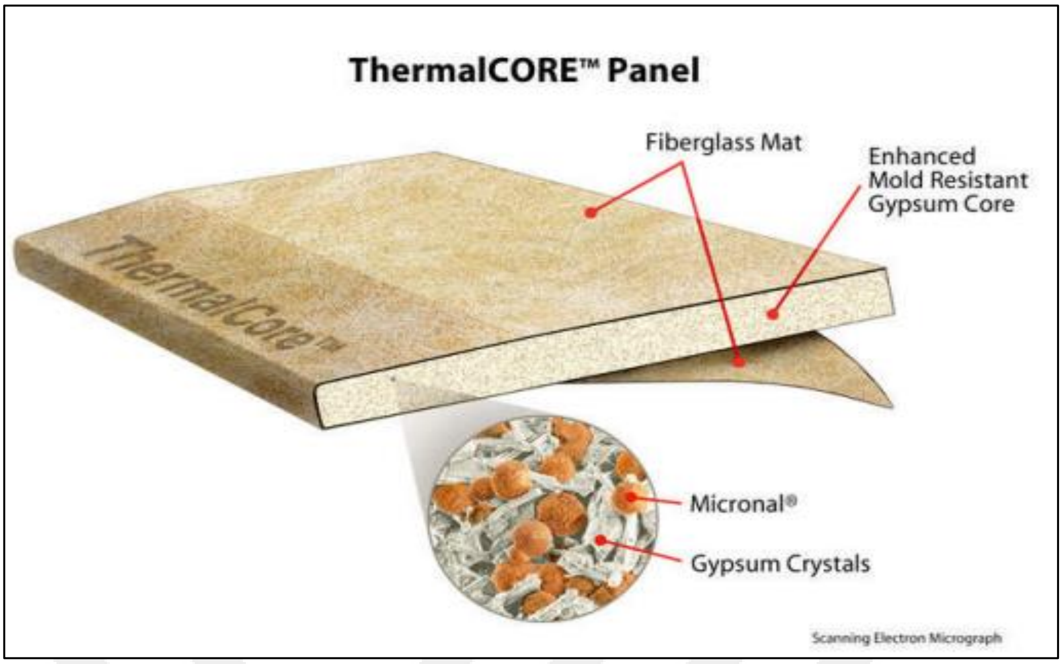


Figure 2.4 ThermalCORE phase change drywall

2.4 Existing Applications and Thermal Performance

it is known, many factors affect the indoor temperature of a building. These include climate conditions (external temperature, wind speed, solar radiation), building structure, and the thermophysical properties of building materials (wall thickness, ratio of windows to wall area, thermal conductivity, and specific heat of wall materials), indoor heat sources, hourly air exchange rate, and auxiliary heating/cooling systems (Zhang, 2007).

Certain building materials can be referred to as ideal building materials if they have specific thermal conductivity (λ, W/mK) and specific volumetric heat (the product of density and specific heat, C = ρ.cp, kJ/m3 K) values that can provide the conditions Ikış = Iyaz ≈ 0. Here, Ikış can be defined as the integrated discomfort level for the indoor temperature during winter, and Iyaz can be defined as the integrated discomfort level for the indoor temperature during summer. This means that the indoor temperature will be within the comfort range throughout the year without any auxiliary heating or cooling. However, it is quite difficult to find or create such a material in reality.

Phase-change materials (PCMs) change from a solid state to a liquid state when heated, absorbing energy in an endothermic process. When the ambient temperature drops again, PCM materials that have transitioned back to the solid phase release the previously absorbed heat in an exothermic process. This balancing of the building's indoor temperature reduces heating and cooling loads. This is achieved not by affecting the thermal resistance of the building envelope, but by affecting the surface temperatures. Various paraffins are typical examples of PCM materials, but the low thermal conductivity and large volume change during phase transition limit the use of these materials in building applications.

There are two main purposes for using PCMs in building structures. These are to utilize the energy emitted by the sun during the day and to use the existing cold for cooling at night, in addition to increasing the efficiency of secondary sources such as heating and cooling equipment. Essentially, there are three different ways to heat or cool a building using PCM:

- PCM in building walls
- PCM in other building components
- PCM in hot and cold storage components

The first two options are passive systems where the stored latent heat energy is automatically released when the indoor or outdoor temperature rises above or falls below the melting point of the PCM. In the third option, an active system is used where the stored heat or cold is located in a separate location from the building through insulation, and heating or cooling is performed only on demand (Haghighat, 2015).

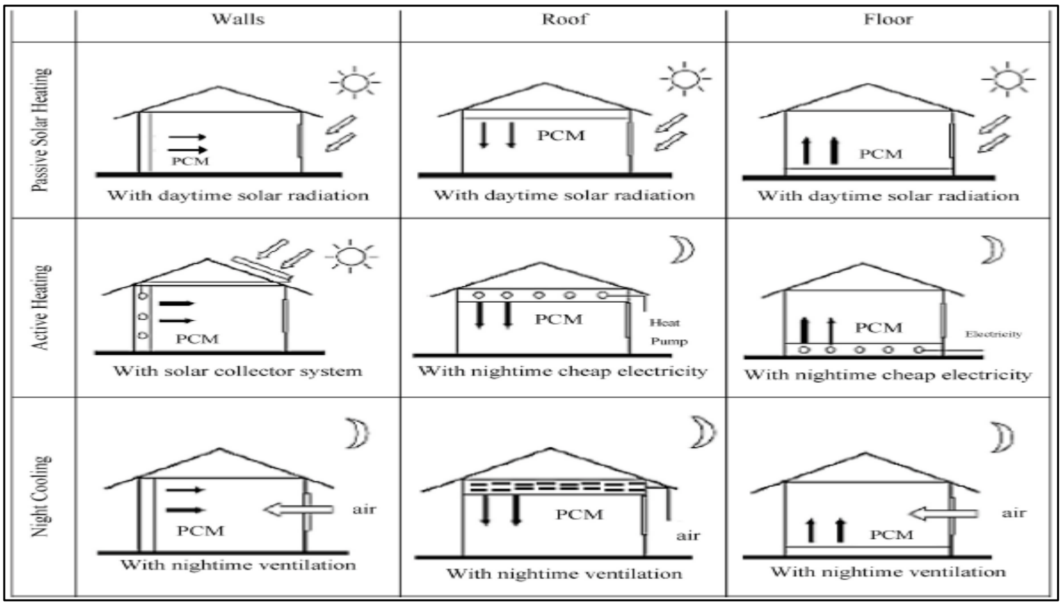


Figure 2.5 Various PCM integrated building surface forms and effects

Passive system applications of PCM in buildings can be divided into two main categories: "integrated" and "component", as evaluated. The fundamental difference between them is that the component can be produced before the building is constructed and has a specific design. For example, integrated PCM shutters are considered a component (Biswas, 2014).

PCMs included in building structures (walls, roofs or ceilings, and floors) used for heating with passive solar energy during the winter can increase the thermal capacity of lightweight building structures, thereby reducing peak heat loads and decreasing room temperature fluctuations. Various PCM applications for passive solar heating, active heating, and nighttime cooling in buildings are shown in Figure 2.5 (Zhang, 2006).

As a result, progress has been made in increasing thermal performance with PCM applications in buildings, such as PCM walls, PCM ceilings, electrically heated PCM floors, and night ventilation.

When selecting PCMs, suitable values should be sought for latent heat, thermal conductivity, and the phase change temperature should be close to the average room temperature. Characteristics such as combustion properties and long-term stability should also be considered for organic and inorganic PCMs.

PCMs can be directly incorporated into buildings, immersed, encapsulated, or integrated as a single laminated panel. Therefore, each application can be evaluated based on its own advantages and disadvantages. The Shape-stabilized Phase Change Materials method is noteworthy as a promising encapsulation method due to its effectiveness in reducing leakage risks and relatively low cost.

Thermal performance analyses in the literature indicate that applications of PCM in walls, floors, ceilings, etc. can be beneficial in shifting heating and cooling loads from periods of intensive electricity use to non-intensive periods, and in effectively storing solar radiation for use in non-sunny hours.

2.5 Passive Applications in Building Structures

As illustrated in Figure 2.6, PCM may be used passively in building constructions for a variety of building envelope elements, including the roof, ceiling, walls, windows, floors, and solar chimney. PCM specifically lessens heat flow between buildings and the outside environment at periods of peak energy demand by increasing the thermal mass of the major building envelope components. As a result, it helps to lower a building's high heating or cooling requirements at peak hours (Song, 2018). As a consequence, it works well to keep rooms at a temperature that falls within the range of thermal comfort for building inhabitants.

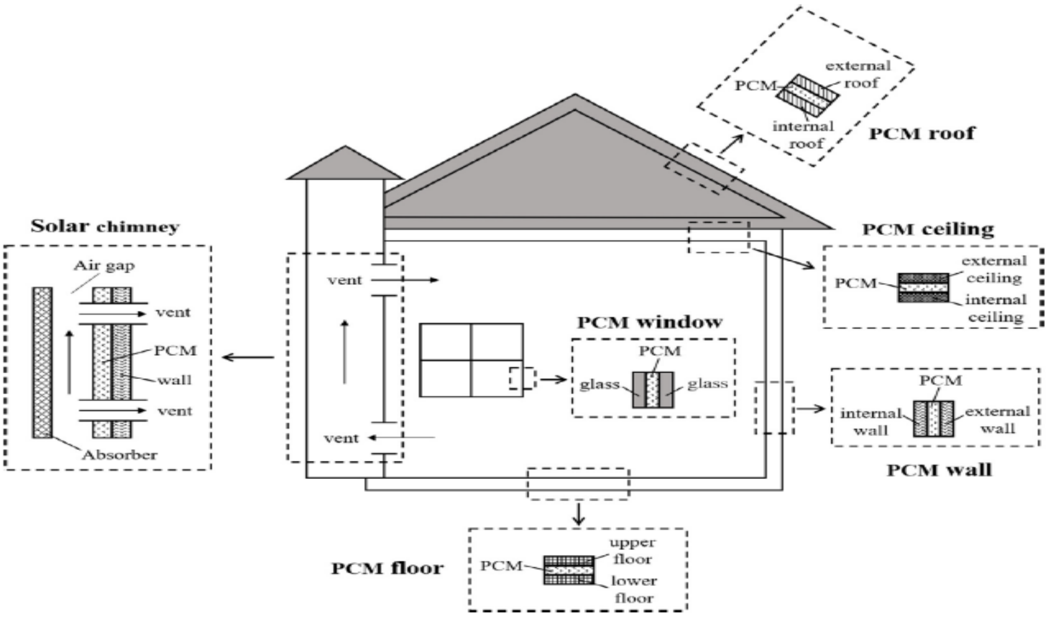


Figure 2.6 Passive applications of phase change materials in buildings

Table 2.1 A summary evaluation of the basic benefits and drawbacks for PCM-based ceiling, floor, and walls.

Building component	**Wall**
Advantages	Increase in thermal inertia of lightweight structures; Improving thermal comfort; Reducing building energy demand for heating and cooling
Trends	PCM integration with brick, concrete, drywall, mortar
Disadvantages	The absence of solidification; the inability to fully benefit from latent heat; low latent heat.
Opportunities	For storing excess heat for later use, reducing the building's energy demand, and decreasing fluctuations in wall temperature.
Building component	Ceiling and Floor
Benefits	Low fluctuations in indoor temperatures; Ensuring thermal comfort in indoor spaces.
Trends	Identification of suitable PCMs in different seasons and climate regions
Issues	Not working at the same efficiency in every season; Especially in summer and winter, there are significant differences in performance.
Opportunities	High energy storage densities; Prevention of peak electricity demand in case of using an active heating/cooling system.

Utilizing PCM in building heating applications, specifically on walls, ceilings, and roofs, has demonstrated notable benefits according to numerous studies. These advantages encompass a reduction in heating demand, improvement in thermal comfort, and optimization of solar energy utilization. The results of extensive research conducted in different climate zones reveal insights in table 2.2 below.

Table 2.2 Results of extensive research in different climate zones

References	Topic Investigated	Key Findings
Kheradmand vd., 2016	Thermal behavior analysis of PCM-enhanced gypsum board: PCM-enhanced gypsum board	efficiently diminish a building's heating requirements when contrasted with conventional gypsum wall cladding.
Meng, Yu and Zhou, 2017	Thermal efficiency evaluation of a composite PCM room versus a standard room.	Throughout the heating season, the PCM room maintained an indoor air temperature 6.92 K to 9.47 K higher than the regular room during nighttime.
Mi et al. 2016	Evaluation of PCM wall cladding's energy and financial performance in offices throughout five climate zones	PCM can significantly boost the wall's ability to store heat.
Wang et al., 2016	Evaluation of PCM wall panel application through experimentation	The room with PCM wall panels had a 10% to 30% reduced winter heating demand than the one with standard wall panels.
Jamil et al., 2016	Study on the use of PCM in a house in Australia	A building's ceiling PCM installation can significantly shorten the hours of thermal discomfort.

Table 2.2 (continued) Results of extensive research in different climate zones

Marin et al., 2016	An estimate of PCM wall cladding's global energy savings in typical cities with varying climates	In dry and hot temperate climatic locations, applying gypsum boards reinforced with PCM can increase buildings' energy performance.
Akeiber et al., 2017	Energy performance of buildings with and without PCM is experimentally compared.	Comparing buildings with and without PCM, those with PCM can achieve significant energy savings and good indoor thermal comfort.
Fateh et al., 2017	Computational and empirical evaluation of PCM wall panelling in construction	Buildings with the highest heating loads have seen a 15% reduction when PCM is utilised.
Guarino et al., 2017	Analysing the performance of a space with PCM wall panels that faces a window	CM wall cladding can lower the annual heating demand by more than 17% and greatly increase the efficiency of solar energy in buildings.
Kusama and Ishidoya, 2017	Examining the PCM wall and ceiling experimentally	Comparing PCM gypsum wall panels to standard gypsum wall panels, buildings can achieve superior thermal comfort benefits, make better use of solar energy, and perhaps save more energysavings compared to traditional gypsum wall panels.

Table 2.2 (continued) Results of extensive research in different climate zones

Berthou et al., 2015	A novel semi-transparent solar wall covering that blends PCM bricks and silica aerogels	This kind of wall panel may efficiently boost heat gain and reduce heat loss.
Plytaria et al., 2018	Investigation of a building's PCM wall using simulation	The heating load of the building has dropped by about 1.54% when PCM is used in the northern and southern walls.

Table 2.3 below summarizes key findings on the use of PCM-containing walls, ceilings and roofs.

Table 2.3 Key findings on the use of PCM-containing walls, ceilings and roofs

References	**Review**	**Key Findings**
Thiele, Sant and Pilon, 2015	The thermal behaviour of microencapsulated PCM wall coating applied to building envelopes is analysed numerically.	Thermal energy flow can be decreased by activating PCM's melting temperature in proximity to the desired internal temperature.
Soares et al., 2016	The thermal performance of PCM wall coating for building applications is experimentally studied, taking into account both extreme cooling phenomena and natural convection.	Fins might enhance the discharge procedure by conduction.
Biswas and Abhari, 2014	An experimental and numerical investigation of a particular kind of inexpensive PCM wall covering.	It was more cost-effective to use PCM on the inside of the wall rather than the entire surface.

Table 2.3 (continued) Key findings on the use of PCM-containing walls, ceilings and roofs

Kant, Shukla and Sharma, 2017	Numerical analysis of building beam thermal performance using different types of Phase change mat.	During the heating season, less energy was needed to heat buildings because capric acid was more efficient in reducing heat flow than paraffin.
Lachheb et al., 2017	The wall thickness and PCM mass fraction in composite plaster are analysed numerically.	Building thermal comfort can be enhanced by thicker walls, and heat flow can be decreased by raising the PCM mass percentage in plaster.
Saffari, 2016	An analysis using numbers to examine how the attire of building inhabitants affects the energy consumption of PCM wall panels for building envelopes.	Encouraging passengers to wear slightly warmer clothing can contribute to the system's energy saving potential.
Barzin, 2016	An experimental investigation combining weather forecasting and price-based control techniques with PCM is conducted on a passive building heating system.	The utilisation of price-based control mechanisms can result in a potential 14% energy savings. Furthermore, an energy savings rate of up to 31% can be attained when taking weather predictions into account.

The following table presents appropriate variables and techniques for enhancing the system's performance, derived from parametric studies of PCM-containing walls, ceilings, and roofs. The results of the previously described studies in these applications also show how important optimisation is to raising system performance. For performance optimisation, there is mutual support among the application techniques, optimisation goals, decision variables, and outcomes. Table 2.4 below provides a summary of the data collected on the performance optimization of PCM walls, ceilings and roofs.

Table 2.4 A summary of the data collected on performance optimization of PCM walls, ceilings and roofs is included

References	Decision Variable	Optimization Goals	Analysis Methods	Findings
Saffari et al., 2017	Melting temperature	Using PCM wall panels to optimise a building's energy benefits	Energy+ Gen.Opt	For PCM, the ideal melting temperature is 20°C in order to maximise annual energy savings.
Soares et al., 2014	PCM layer thickness, PCM layer location on the wallboard, PCM thermal characteristics, and solar absorption on the inner surface	maximising the system's capacity for energy conservation	Energy+ Gen.Opt	Cities like Milan, Paris, and Bucharest can save 33% to 38% on their heating season energy bills by using PCM wall covering.
Tokuç, Başaran and Yesügey, 2015	Layer thickness of PCM	Improved energy benefits for PCM-equipped buildings	CFD	A PCM thickness of 2 cm was discovered to be appropriate when applied to a building's roof in Istanbul, Turkey.
Jin, Medina, Zhang, 2016	PCM layer position on the wall panel	maximising the reduction of heat flux	Analytical numerical	The PCM characteristics and the surrounding environment determine the PCM layer's ideal placement.

Ground heating systems' winter performance can be greatly enhanced with PCM-based flooring. Despite the fact that this topic has been the focus of numerous research, considerable savings can be made, especially when it comes to lowering heat losses in real-world applications.

In a research by Plytaria et al. (2018), a system utilising PCM in the floor and a solar-assisted heat pump was investigated in a 100 m2 building. Figure 2.7 displays the schematic representation of the PCM floor that was employed. Plaster, concrete, pipes, PCM, insulation, and concrete make up the floor, in that order. It was determined that using the PCM floor reduced the building's heating load by about 40%. It was reported in a different study by Plytaria et al. (2019) that on some cold days, the indoor temperature could rise by about 0.8–2 K.

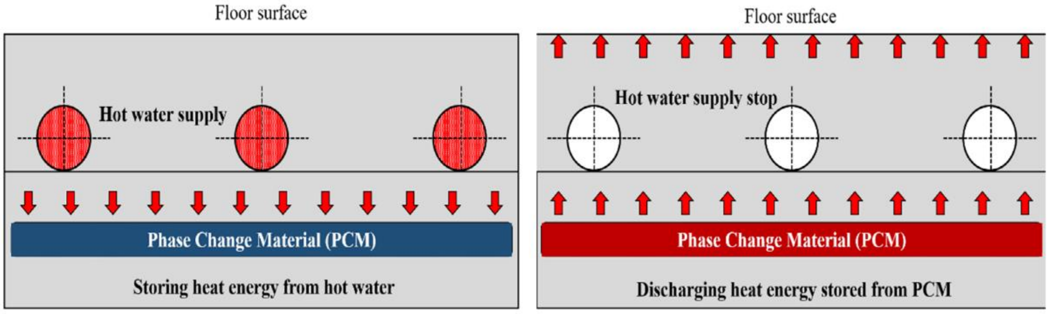


Figure 2.7 Floor with PCM.

According to Devaux et al. (2017)'s study on PCM-enhanced floors and other related topics, the energy and cost savings of the underfloor heating system were 32% and 42%, respectively, when PCM panels with higher melting temperatures were positioned between the floor and the heating system.

In Chiba Prefecture, Japan, Kim et al. (2017) conducted an experimental investigation on a PCM-enhanced floor. A conventional wall panel, four PCM panels on the floor, and one PCM panel on the wall, ceiling, and floor, respectively, were used to construct three distinct test rooms. It was discovered that, in comparison to the typical room, the energy used for heating in the second and third rooms had decreased by 9.2% and 18.4%, respectively.

Although there is not as much research on PCM windows and solar chimneys in literature as there is for PCM-enhanced roofs, ceilings, walls, and floors, the results obtained have not yet reached satisfactory levels.

3

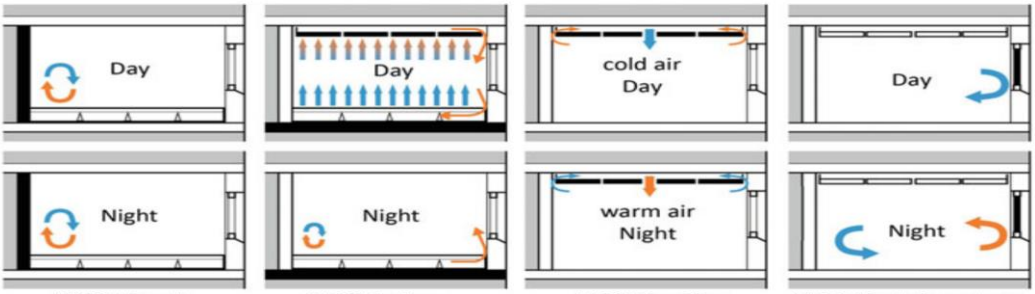
ENCAPSULATION TECHNIQUES AND EXPERIMENTAL SETUP

3.1 A Review of Microencapsulation and Macroencapsulation Techniques

According to Soares (2013), PCMs that are microencapsulated are those that are incorporated straight into the walls, ceilings, and floors of the building. Gypsum plasterboards (Banu, 1998), plaster (Liu, 2009), concrete (Cabeza, 2007) and glazing systems (Durakovi´c, 2019) are frequently used construction materials containing microencapsulated PCMs. The fundamental idea behind indoor temperature

Fig. 3-15 displays control utilizing PCM incorporated within the building's structure and glass.

As seen in the picture, more heat from the area is retained in the PCM when the room's temperature is lowered on a hot day. Active or passive ventilation releases heat that has been stored during the night. Microencapsulated PCMs are frequently incorporated into the design of walls, whilst macroencapsulated PCMs can be installed in floors and ceilings. Scholars employ multiple methodologies to investigate the thermo-physical properties of innovative phase transition materials. Regarding container designs and PCM integration in building elements, they used theoretical/analytical, experimental (Durakovic, 2017), and applications in structures and various geometries, respectively.

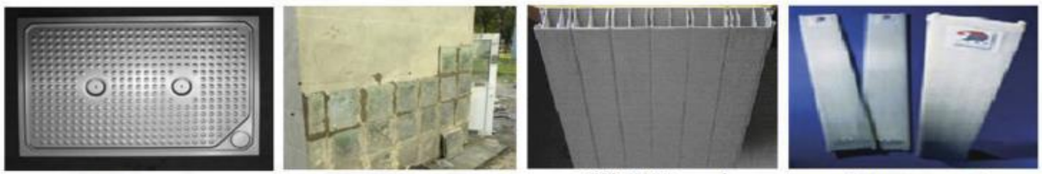


(a) PCM in wall (b) PCM in floor (c) PCM in ceiling (d) PCM in glazing systems

Figure 3.1 PCM in glazing and building construction.

3.2 Macroencapsulation Forms

Different shell shapes have been created with PCM encapsulation in mind. These forms, which are primarily panel (iv), brick (vi-vii), plate (vii-ix), lath (x), blade (xi), bag (xii-xiii), sphere (xiv-xv), and tube (xvi), are summarised in Figure 3-2.


(i) PCM panel (ii) PCM panel (iii) PCM panel (iv) PCM panel


(v) PCM panel (vi) PCM brick (vii) PCM brick (viii) PCM slab


(ix) PCM slab (x) PCM slat (xi) PCM blade (xii) PCM pouch

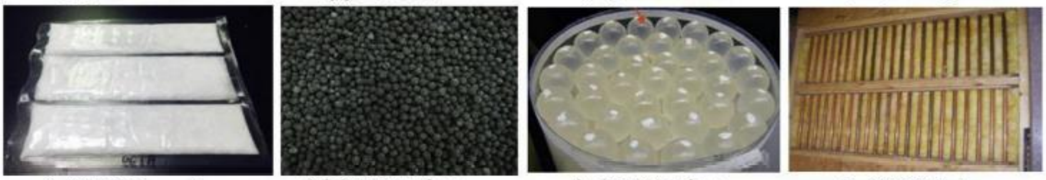

(xiii) PCM pouch (xiv) PCM sphere (xv) PCM sphere (xvi) PCM tube

Figure 3.2 Common forms of macroencapsulation used in building envelopes.

These forms can also be divided into three categories according to geometric forms: spherical, cylindrical, and rectangular. Panels, bricks, slabs, battens, and blades are examples of rectangular shells, however they haven't been clearly defined to separate them yet. Rectangular shells are the most common forms in building envelopes because they can integrate flat surfaces in an appropriate way. Any building shell, such as the walls, floors, roofs, ceilings, and windows, can be integrated with rectangular shells. Furthermore, hollow bricks, window glass, and window blind frames are examples of rectangular structural elements that can be utilised as PCM shells.

Cutting shells can also be thought of as rectangular shells composed of pliable materials, like nylon (xii) and aluminium foil (xii). In order to prevent buildup on one side, PCM is typically separated into multiple parts using heat bonding devices when it is liquid. The primary benefits of this approach are its easy installation and disassembly processes and comparatively cheap production costs. However, because of their low pressure carrying capability, they are readily distorted, which could result in leakage hazards. Cutting shells have been used on roofs, floors, and walls in literature.

Shells that are spherical or cylindrical stand in for spheres and tubes, respectively. Only a small number of research examining their applications and effects in building envelopes were discovered during the literature study. PCM spheres are used on floors in a number of investigations. Regarding PCM tubes, there are systems that are integrated into walls after being fastened to timber frames or placed into horizontal gaps in polystyrene foam. Compared to rectangular shells, these shells are used in building envelopes less frequently. The difficulty of wall attachment, particularly for spherical and cylindrical shells, could be one explanation for this.

3.3 Enhancing Thermal Performance in Macroencapsulation

PCM in window and building designThe positioning of PCM macroencapsulation systems in relation to the exterior and inner surfaces of building envelopes has a significant impact on changes in interior temperature and the reduction of peak heat flow through the building shell. A number of research have examined the impacts of PCM macroencapsulation systems in various settings, with the majority concentrating on walls. The numerous ideal sites discovered via these investigations demonstrate that placement depends on a variety of elements, such as wall orientation, PCM system thicknesses, and PCM thermal characteristics, among others.

It is commonly known that variations in solar light obtained from various angles cause wall orientations, which in turn determine how PCM systems should be positioned. (Lee et al, 2011) looked at the optimal location of cut PCM systems for the south and west walls of standard homes in Lawrence, USA. The results showed that the optimal PCM sites for the south and west walls were 1.27 cm and 2.54 cm from the inner surface, respectively. Mankibi and others (2017). asserted that the inner surface is the best location for PCM systems in all directions. This could be the result of regional design standards that give less weight to a wall's thermal resistance regardless of its orientation.

(Jin et al,2015) used numerical analysis to examine the effects of PCM system thickness and thermal characteristics on the ideal location of cut PCM systems. The results showed that the optimal locations from the inner surface of walls were (1/16), (2/16), (3/16), and (3/16) L (where L is the wall thickness) when the PCM system thicknesses were 1 mm, 2 mm, 5 mm, and 7 mm, respectively. It was found that when the thickness of the PCM system was raised, the PCM material had to move towards the exterior surface of walls in order to absorb more heat. Similar trends were seen in PCM's melting temperature and heat fusion.

A PCM system's ideal placement in walls depends on a number of variables. More components and their combined impacts should be researched because existing studies mostly concentrate on the individual effects of a small number of elements. For instance, decreased loads like those produced internally and externally connected to air are a factor in the ideal placement of PCM in walls. This should be regarded as a crucial element as well. Common research on the ideal placement of PCM systems inside structure envelopes are compiled in the following table 3.1.

Table 3.1 Summary of PCM Application Strategies for Building Envelopes in Different Regions and Climates

Application Site	Applied Area	Considered Factors of Impact	Evaluation Standard	Notes	Citation
Lawrnce, Kansa, America	Wall	Wall placement	Diminished heat flux	The ideal distance from the wall surface for the PCM locations on the south and west walls are, respectively, 2.53 and 1.26 cm.	Zhai et al., 2011
North USA	Wall	Climate, wall construction, and PCM thermal characteristics	Maximum decrease in heat flux	On the innermost surface of the gypsum wallboard lies the ideal PCM layer.	Khedari and Akbar, 2006
Tianjin, China	ceiling and wall	PCM thermal characteristics, climate, and building structure design	Potential for conserving energy	The performance of PCM panels installed on the inside of the walls and roof is superior than that of the panels positioned on the exterior.	Huang, Zhang and Wang, 2012

Table 3.1 (continued) Summary of PCM Application Strategies for Building Envelopes in Different Regions and Climates

North USA	Wall	PCM heat characteristics	reduction in peak heat flow	The ideal distance between the PCM and the wall's inner surface is one-fifth of the cavity depth.	Kim and Yeo, 2003
Lawrnce, Kansa, America	Wall	Environmental factors and PCM thermal characteristics	Decrease in thermal mass and maximum heat flux	As the melting temperature and enthalpy rise, the ideal PCM thickness moves closer to the wall's outer surface; conversely, as the wall temperature rises, it moves closer to the inner surface. The best position is 3/16 L away from the wall surface with a large peak decrease for the majority of climate zones.	Feng et al., 2016
Minneapolis, Louisville, Miamii, America	Wall	Weather	An improvement in heat resistance	PCM functions better when positioned in the centre of composite wall panels than when it is placed outside or inside.	Sharma et al., 2009
Minneapolis, Louisville, and Miami, USA	Wall-	Thermal characteristics of PCM and wall architecture	decrease in heat flow and temperature of the wall surface	When the PCM layer is positioned near the heat source, it lowers the outer surface temperature by 2°C; however, this impact is not felt when the PCM layer is positioned on the wall's outside.	Adebayo, Fagbenle and Adegun, 2019

3.4 Prototype Panel Design, Production and Test Method

Within the scope of this study, different panel geometries suitable for the tube form of macroencapsulated PCM were created for the design and production of panels integrated with macroencapsulated PCM. Subsequently, panel production was carried out. The way wall panels with various features and models function thermally, the examination of surface temperature distribution, and the investigation of panel cooling time were conducted to compare and optimize the wall panels. Panels were produced using different PCM shells. Specific experimental parameters were established for panel design and production. The panel design consists of five different stages, namely:

- Gypsum design,
- Aluminum design,
- Piping design,
- Macroencapsulated PCM tube design, and
- EPS (Expanded Polystyrene) design.

3.5 Panel Design

In these studies, the effect of Experimental research was done on the effect of (PCM) with various mass mixing ratios on the radiant system's surface temperature.. Three different types of panels were used in the experiments: the PCM-free panel (reference panel), the panel with 6% PCM content (Panel-1), and the panel with 10% PCM content (Panel-2).

For the comparison between the PCM panel and the non-PCM panel, the "Reference Panel" design and production were carried out. The production of the reference panel involved gypsum board design, foil design, piping design, and EPS design.

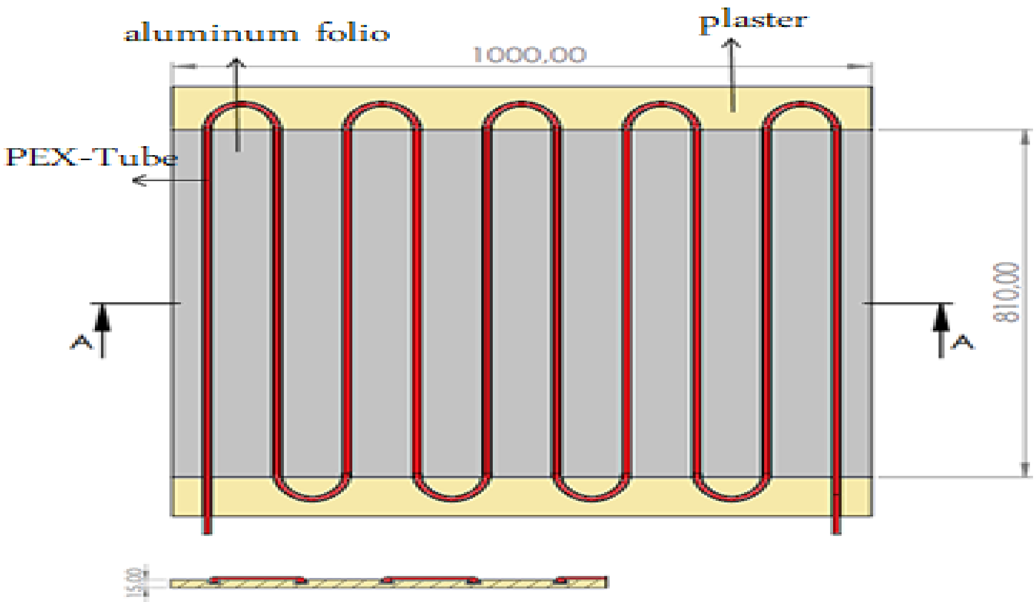


Figure 3.3 the reference panel's picture

The cutting process of the shell material has been carried out according to the predetermined dimensions in the panel designs. One end of the shell material has been sealed with the help of heat-resistant silicone capable of withstanding 300°C. The internal volume of the shell material has been calculated to determine the maximum amount of material that can be filled inside. The density of PCM at the appropriate temperature has been taken into account to determine the required quantity of PCM for the analysis. The determined amount of PCM has been filled into the shell material within a hot water bath. After the filling process, the open end of the shell material has been sealed with heat-resistant silicone capable of withstanding 300°C. The macroencapsulation process has been successfully completed.

The tube filling process for macroencapsulation is shown in Figure 3-4. After sealing the macrocapsule tube, it has been left to dry overnight.

Figure 3.4 Macrocapsule tube filling and tube sealing process.

Panel production for the experimental setup, gypsum boards were cut in dimensions of 1x1 m. Drawing processes were performed on the cut gypsum boards as specified in the designs for heat exchanger pipes and macroencapsulated tubes. To facilitate the drawing process, a plate was designed to determine the locations of the channels. After the drawing process, the channels were opened, and piping was applied to the panels. To ensure the stability of the pipes and the proper completion of the panel production process, a hot silicone adhesive was used for bonding.

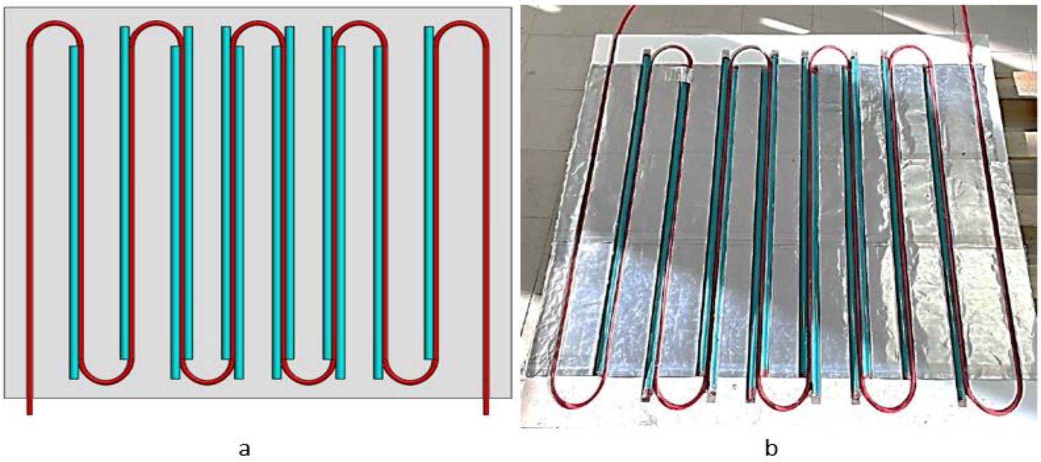


Figure 3.5 Pictures of panel 1 a) Solidworks b) Experimental

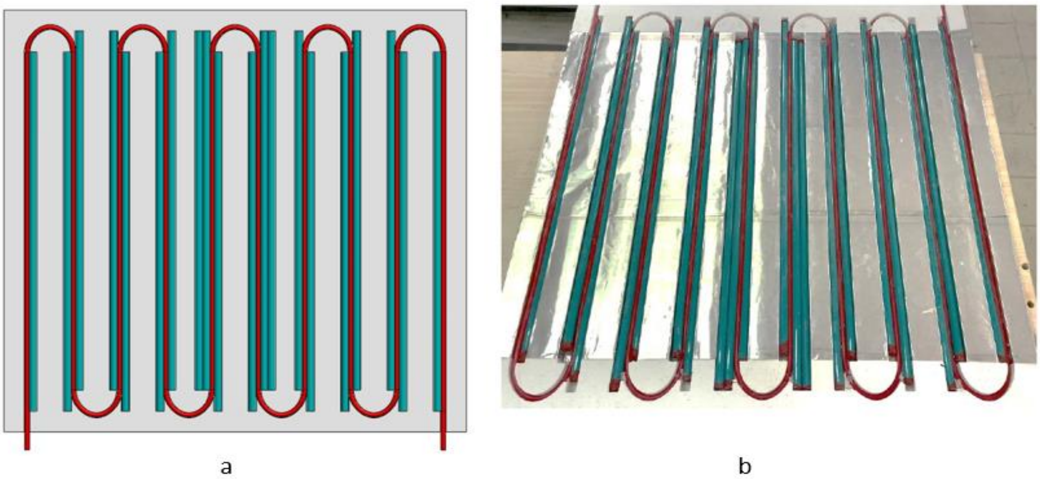


Figure 3.6 Pictures of panel 2 a) Solidworks b) Experimental

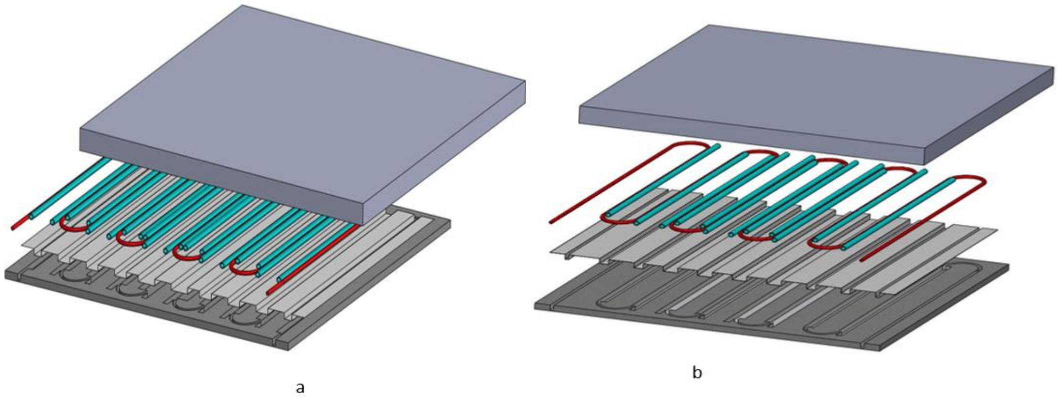


Figure 3.7 Assembly pictures a) Panel 1 b) Panel 2

3.6 Test method and standards used

This study was conducted by conducting a literature review, referencing relevant sources, and following international standards. The study involved a three-stage point test.

The first stage aimed to test the surface temperature cooling time of the panel. This test was performed to experimentally investigate the effect of (PCM) additives with various mass-mixing ratios on the surface temperature of the radiant system. PCM additives were applied at rates of 0%, 6%, and 10%. To better examine heat loss and phase change, appropriate sensor distribution was implemented. The test was conducted by repeating the experiments of the 0% PCM panel (reference panel), 6% PCM panel, and 10% PCM panel for three different external air temperatures (0°C, 3°C, 8°C). The effect of PCM additives with different mass mixing ratios on the surface temperature of the radiant system was tested using the thermal performance test setup.

In the second stage, an investigation was conducted on the comfort impact of PCM in accordance with the Ashrae 55 (Thermal Environmental Conditions for Human Occupancy) standard. Referring to the Limits on Temperature Drifts and Ramps table in the standard, an experiment was conducted where the sample's external environment, simulating the external air temperature, was exposed to a temperature change by connecting it to a water heater PLC. The experiment was performed in an environment where the external air temperature ranged from 0°C to 8°C to simulate daytime temperature increase and then from 8°C to 0°C to simulate nighttime temperature decrease. The experimental setup was updated to simulate daily life under both daytime and nighttime conditions. A limited amount of energy was provided to the PCM during the experiment, allowing it to solidify and release energy to the environment as the external temperature decreased.

The third stage aimed to validate the thermal performance capability of the panel and the comfort impact of PCM using CFD analysis.

3.7 Surface cooling time and Thermal Performance Test (Preparation and standardization of Thermal Performance Test Apparatus according to EN 14037 and EN14240)standard)

EN 14037 and EN 14240 are European standards that determine the performance testing and ratings for heating and cooling systems in buildings. These standards are used to evaluate the energy efficiency, performance, and environmental impact of heating and cooling systems.

EN 14037 specifies the performance testing for radiant heating and cooling systems. This standard is used to determine the heat transfer capacity, efficiency, and heating/cooling distribution of radiant heating and cooling systems. It also provides information about the lifespan, maintenance, and servicing of radiant heating and cooling systems.

EN 14240 specifies the performance testing for water heating systems. This standard is used to evaluate the energy efficiency, capacity, reliability, and environmental impact of water heating systems. It also provides information about the lifespan, maintenance, and servicing of water heating systems.

To enhance the accuracy of this study, calibrated measuring instruments were used. The machinery and equipment used within the scope of this study are listed below (Table 3.2):

Table 3.2 Equipment used in the test system

Equipment	Description
Labo C201-H13 water bath	It circulates the fluid to the cooling plates and the hybrid wall panel.
Agilent 34970 A	Multiple measurement units for measurements.
Agilent 34901 A	Multiple measurement units for measurements.
RTD Reference sensor	Reference temperature sensor calibrated by a calibration laboratory.
RTD Reference water temperature sensor	Water temperature sensor calibrated by UML Calibration Laboratory.
6 pcs PT 100 for water temperature	Platinum resistance thermometers used to measure water temperature.
30 T-type thermocouples for surface temperature	Thermocouples used to measure the surface temperature on the hybrid wall panel and cooling plates.
2 Aluminum plate	It was used in the experimental setup to simulate the outdoor and indoor environment.
Air purifier	Automatic air purifier used to remove air from the installation.

Figure 3.8 Water bath used.

Figure 3.9 Datalogger used (a) Front view, (b) Rear view.

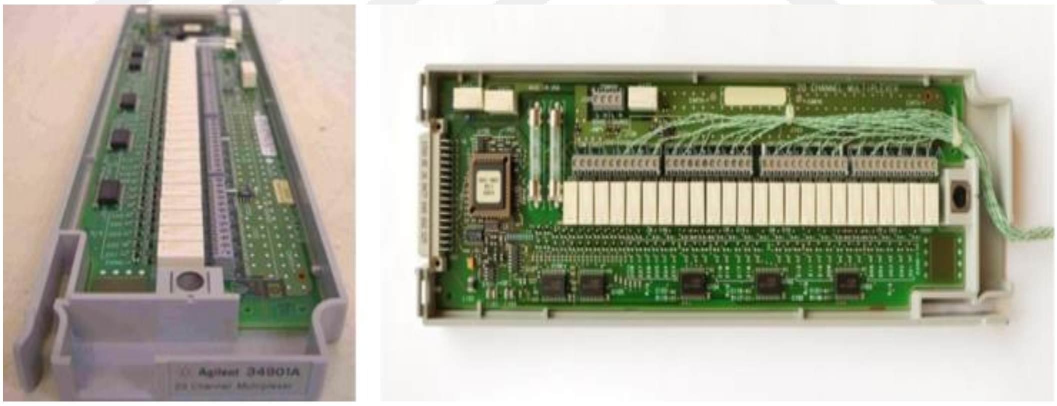


Figure 3.10 View of the module used


(a) (b) (c)

Figure 3.11 Sensors used for temperature measurement (a) RTD sensor, (b) PT100 for water temperature, (c) T-type thermocouple for surface temperature.

As part of the experimental study, the experiments of hybrid wall panels with different pipe spacing will be conducted. After the calibration of the thermal couples is completed, the preparation phase of the experimental setup has been initiated.

Firstly, the prepared cooling plate is placed on the platform where the experimental setup will be positioned. Five thermal couples are placed on the surface of the first cooling plate, which will simulate the outdoor conditions. Assuming that the bottom left corner of the cooling plate is considered as the (0,0) point in the xy axis, the thermal couples are positioned at the points (25, 75), (75, 75), (25, 25), (75, 25), and (50, 50).

Figure 3.12 Cooling plate and thermocouples placed on it

A hybrid wall specimen was placed on the cooling plate for testing. In order to determine the surface temperature distribution on the hybrid wall specimen, 18 thermal couples were placed in two axes. The thermal couples were evenly distributed between the points (35, 75) to (55, 75) and (35, 25) to (55, 25) in the coordinate system, with a total of 9 couples in each axis. Figure 3-12 and 3-13 illustrate the arrangement of the specimen in the testing setup and the location of the thermal couples.

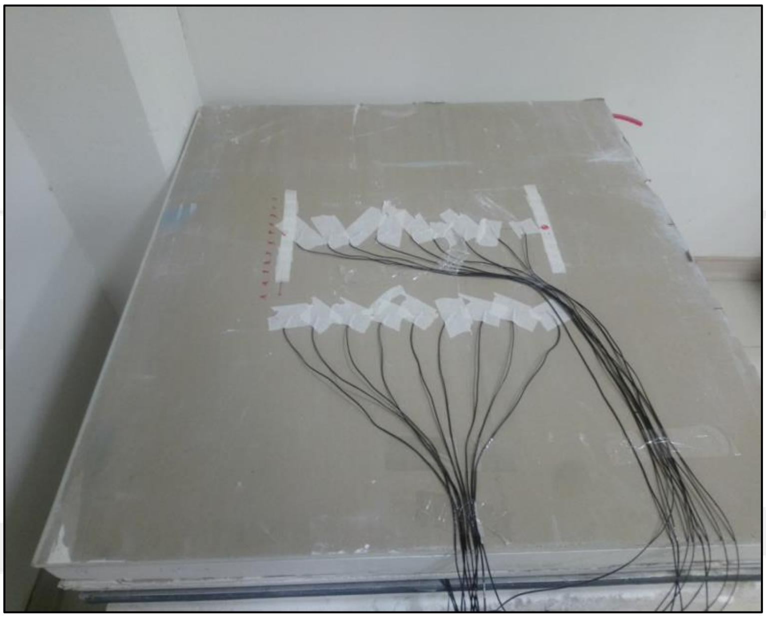


Figure 3.13 Thermocouples placed on the hybrid wall specimen.

A heat transfer plate has been placed on the hybrid wall to model the convection and radiation within the room for wall-to-wall heating and cooling. For this purpose, two gypsum boards with a thickness of 15 mm each were used. Figures 3-14 and 3-15 illustrate the heat transfer plates.

Figure 3.14 Heat transfer layer placed on the hybrid wall specimen.

Figure 3.15 Cross-sectional view of the heat transfer layer placed on the hybrid wall sample.

A heat transfer plate is placed to model the convection and radiation in the room. A cooling plate is placed on top of the heat transfer plate to simulate the indoor conditions. Thermal couples are inserted between the cooling plate and the heat transfer plate, similar to the arrangement in the first cooling plate. Figure 3-16 illustrates the placement of thermal couples on the heat transfer plate and the arrangement of the second cooling plate in the experimental setup.

Figure 3.16 Thermocouples placed on the heat transfer plate.

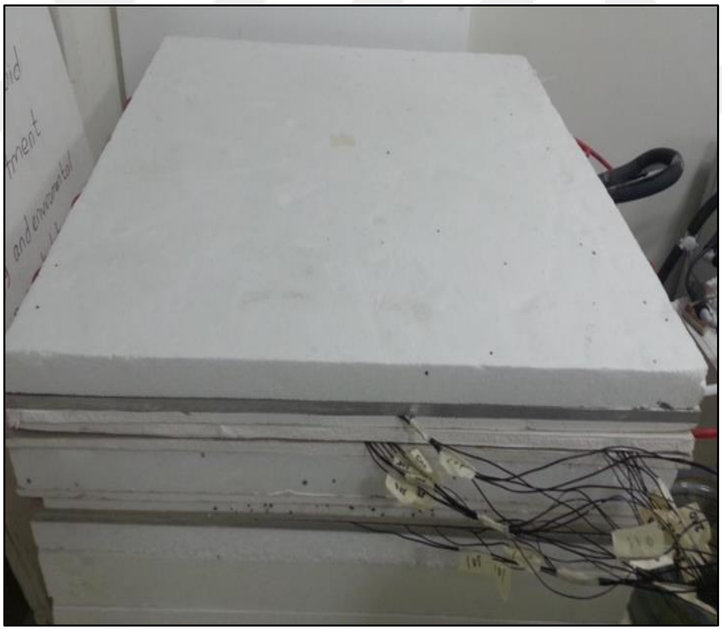


Figure 3.17 Cooling plate placed in the experimental setup.

Finally, temperature measurements were taken at two points on the insulation layer on the cooling plate to measure the ambient temperature (Figure 3-18).

Figure 3.18 Thermocouples placed to measure the air temperature in the experimental setup.

The plate located on the front surface of the wall among the cooling plates shown in Figure 3-18 simulates the indoor conditions, while the other plate simulates the external weather conditions. Therefore, the heating and cooling plate located on the inside is conditioned to 20°C, while the cooling plate on the outside is conditioned to 0°C to simulate the external climate. Measurements are initiated once the system reaches a steady state. After the start of measurements, data should be collected for at least 30 minutes.

The amount of heat obtained from the fluid is calculated using the Q equation. Here, $\dot{Q}$ represents the heat transfer rate obtained from the test sample, and $\dot{m}$ represents the measured water flow rate. The same process is performed for the cooling plates. Thus, the heat transfer from the panel to both the external and internal environments is determined. Additionally, by obtaining surface temperatures from each layer, the heat transfer resulting from the temperature difference in the circulating water in the energy balance will be verified using heat conduction equations.

$$\dot{Q} = \dot{m} Cp \Delta T = \dot{m} Cp \, (Ti - To) \tag{3.1}$$

$\dot{m}$: Flow rate of water (kg/s)

Cp: Specific heat capacity of water (J/kg·K)

ΔT: Temperature difference between inlet and outlet water (°C)

As specified in the experimental setup, water temperature measurements and flow rate measurements were taken at the inlet and outlet of the cooling plates and the hybrid wall panel.

$$\dot{Q} = \dot{m}Cp\Delta T = hA\partial T/\partial x \tag{3.2}$$

h: Depends on the surface geometry, nature of fluid flow, fluid properties, and mass velocity of the fluid. (W/m^2·°C)

A: Surface area involved in heat transfer (m^2)

In accordance with the experimental setup, water temperature measurements and flow rate measurements were taken at the inlet and outlet of the cooling plates and the hybrid wall panel. Additionally, an automatic air vent valve was installed on the pipeline to remove air from the system. Figures 3-19 and 3-20 illustrate the appearance of the experimental setup.

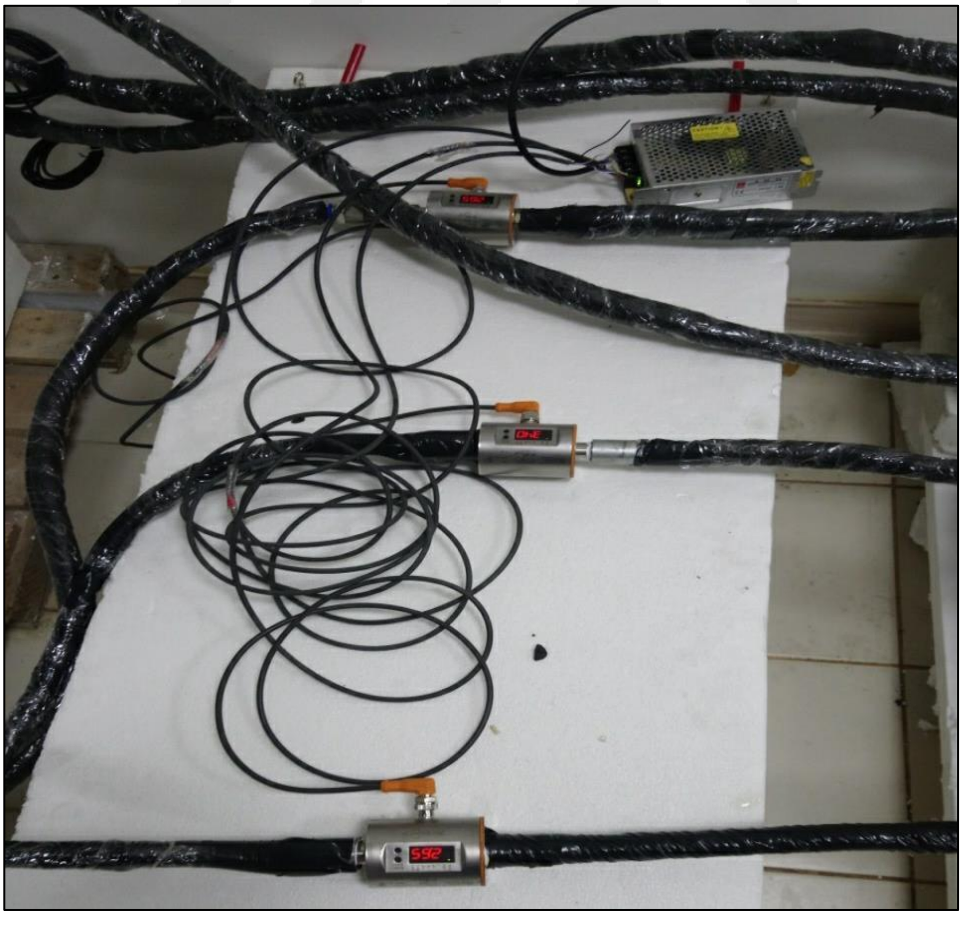
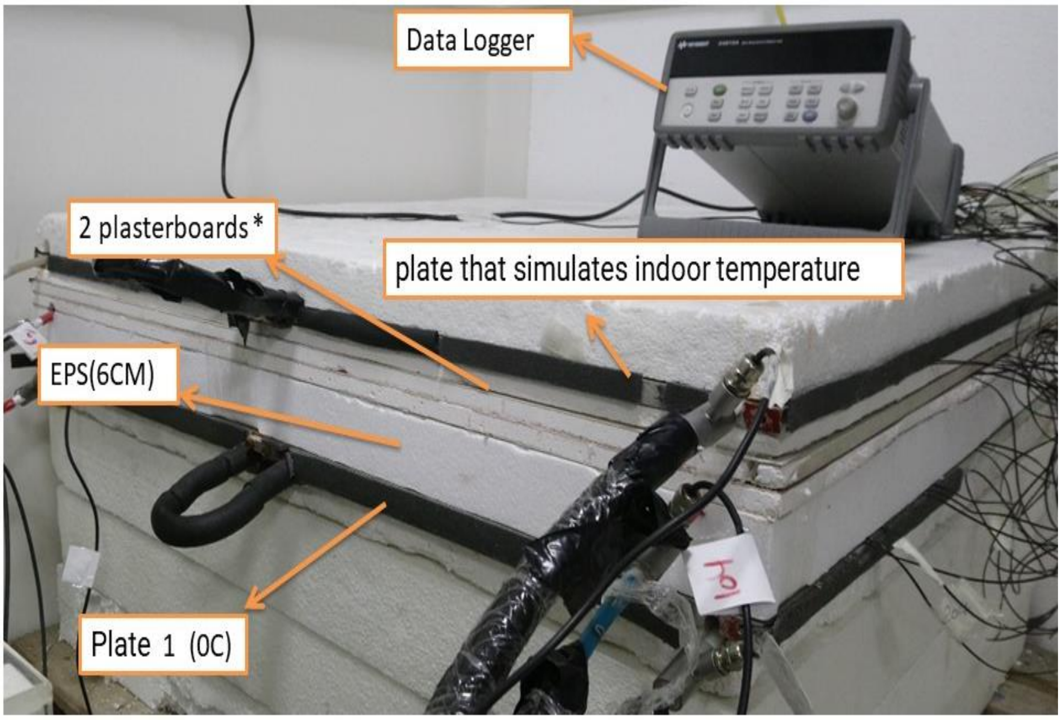


Figure 3.19 Test installation 1

Figure 3.20 Test installation 2



* A heat transfer plate is placed to model the convection and radiation in the room.

Figure 3.21 Test installation 1

The circulation of the fluid to the cooling plates and the hybrid wall panel was achieved using LABO brand C201-H13 model water baths. "Water" was used as the fluid in the hybrid wall panel and the cooling plate, which models the internal environment conditions. In order to ensure a surface temperature of 0°C in the cooling plate that simulates the external environment conditions, it was determined through experiments that an average temperature of -5°C needs to be achieved within the water bath.

3.8 ASHRAE 55 Standard and Preparation of Test Setup

The ASHRAE Standard 55, also referred to as " Temperature-Related Environments for Human Use," is a voluntary standard that offers recommendations for attaining cosy interior temperatures that promote building occupants' health, well-being, and productivity. The standard defines a number of variables, including as air temperature, humidity, air velocity, and radiant temperature, that impact thermal comfort. It also contains recommendations for metabolic rate and garment insulation, both of which might affect how people feel about their thermal comfort.

The Adaptive Comfort Model is the most commonly used method for determining indoor thermal comfort. This model takes into account a person's activity level, clothing, and other factors that can impact thermal comfort, providing a range of acceptable thermal conditions that can vary based on individuals' activity levels and clothing. The PMV/PPD Model is another method used to determine indoor thermal comfort, calculating the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) based on factors such as air temperature, humidity, and others.

ASHRAE Standard 55 also includes specific requirements for thermal comfort in different environments, such as residences, hospitals, and industrial settings. These requirements take into account factors such as age, activity level, and clothing for individuals in these different settings.

The following diagrams illustrate the key concepts of ASHRAE Standard 55: the thermal comfort zone, the PMV/PPD model, and the thermal comfort requirements in different environments. These diagrams can assist building professionals in understanding and implementing the guidelines of the standard (ASHRAE Standard 55, 2017).

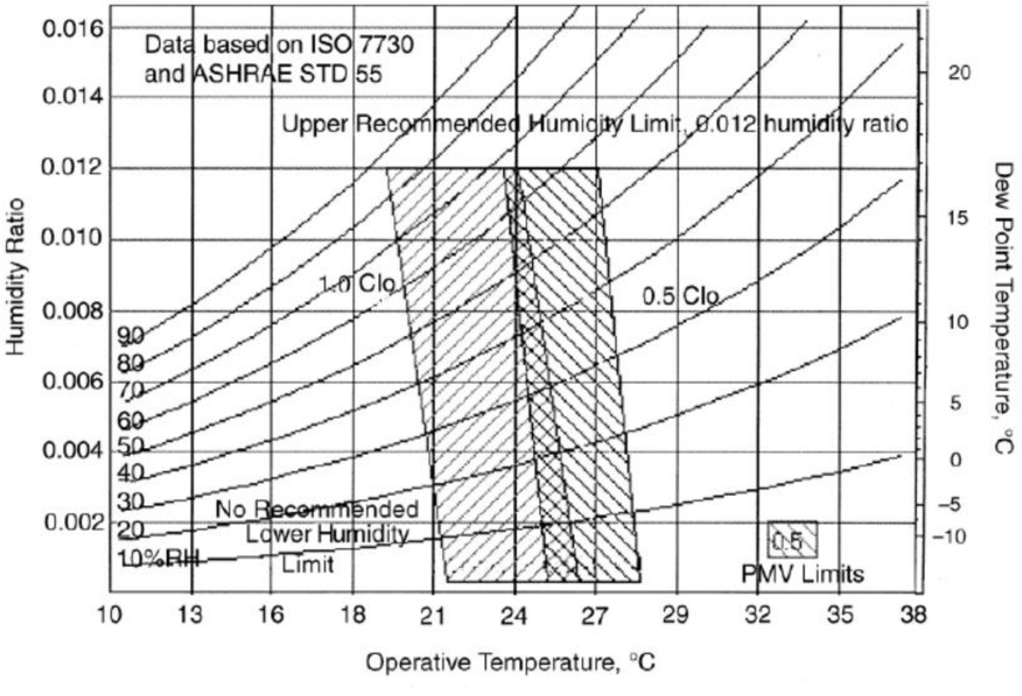


Figure 3.22 Acceptable ranges for operative temperature and humidity

In summary, ASHRAE Standard 55 is a crucial standard that offers recommendations for obtaining a satisfactory level of indoor thermal comfort. The given graphs in this report can help with understanding and putting into practice the standard's standards, which have the added benefit of enhancing the health of building occupants.

An analysis of PCM's effects on comfort was done using ASHRAE Standard 55 (Temperature-Related Environments for Human Use).

The following are the restrictions listed in the standard's "Limits on Temperature Drifts and Ramps" section:

Monotonic, non-cyclic, and cyclic alterations lasting more than 15 minutes are not permitted to persist longer than the permitted time frame.

For instance, according to ASHRAE Standard 55 from 2017, the working temperature should not fluctuate by more than 2.2°C over the course of an hour and by more than 1.1°C over any 0.25-hour window inside that hour.

Table 3.3 Limits to Temperature Change

Period of Time, h	**0,25**	**0,5**	**1.0**	**2.0**	**4.0**
Allowed Maximum Operating Temperature Change, °C	1,10	1,70	2,20	2,80	3,30

The working principle of the equipment used in the test setup and its role in the system are as follows:

Table 3.4 Equipment used in the system and its task.

Device name	**Description**	**Function**
PLC DVP12SA211R	Programmable logic controller	Control and automation of the system
DTC1000V	Temperature controller	Maintains the desired temperature setpoint
DOP-107BV	Human machine interface	Provides a graphical interface for users to interact with the system
G2RV-SR in/out relay	Control relay	Controls the on/off switching of system components

DURUM 2

1. SAAT	8.0	C	🟩	13. SAAT	-2.0	C	🟥
2. SAAT	7.0	C	🟩	14. SAAT	-1.0	C	🟩
3. SAAT	6.0	C	🟩	15. SAAT	0.0	C	🟩
4. SAAT	5.0	C	🟩	16. SAAT	1.0	C	🟥
5. SAAT	4.0	C	🟩	17. SAAT	1.5	C	🟩
6. SAAT	3.0	C	🟩	18. SAAT	2.0	C	🟩
7. SAAT	2.0	C	🟩	19. SAAT	3.0	C	🟥
8. SAAT	1.5	C	🟥	20. SAAT	4.0	C	🟩
9. SAAT	1.0	C	🟥	21. SAAT	5.0	C	🟩
10. SAAT	0.0	C	🟩	22. SAAT	6.0	C	🟥
11. SAAT	-1.0	C	🟩	23. SAAT	7.0	C	🟩
12. SAAT	-2.0	C	🟩	24. SAAT	8.0	C	🟥

Figure 3.23 Control panel providing temperature change every hour

Figure 3.24 System working principle diagram

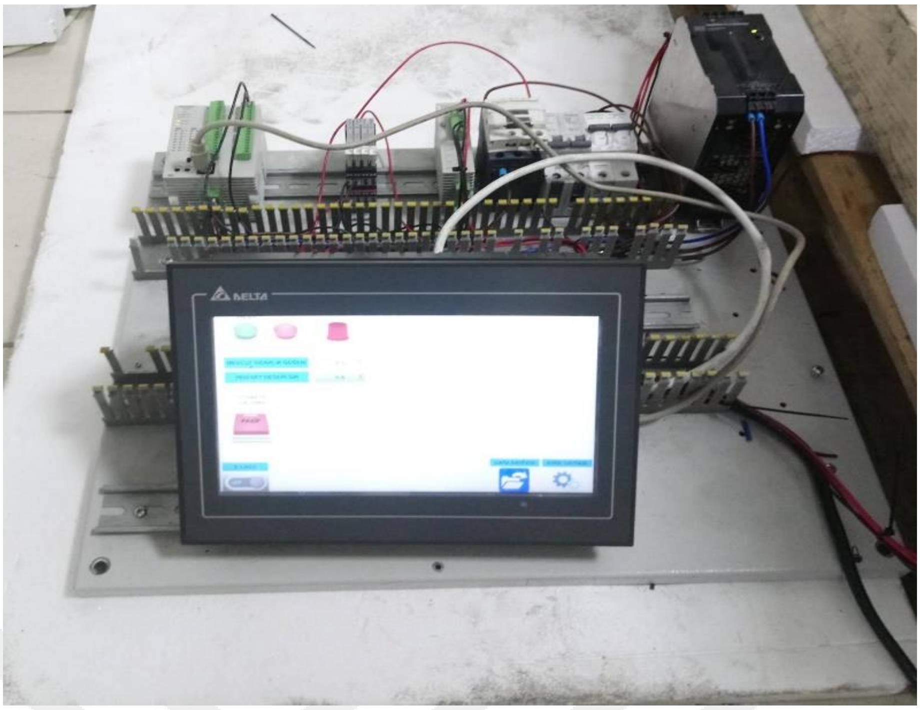


Figure 3.25 System operation image-1

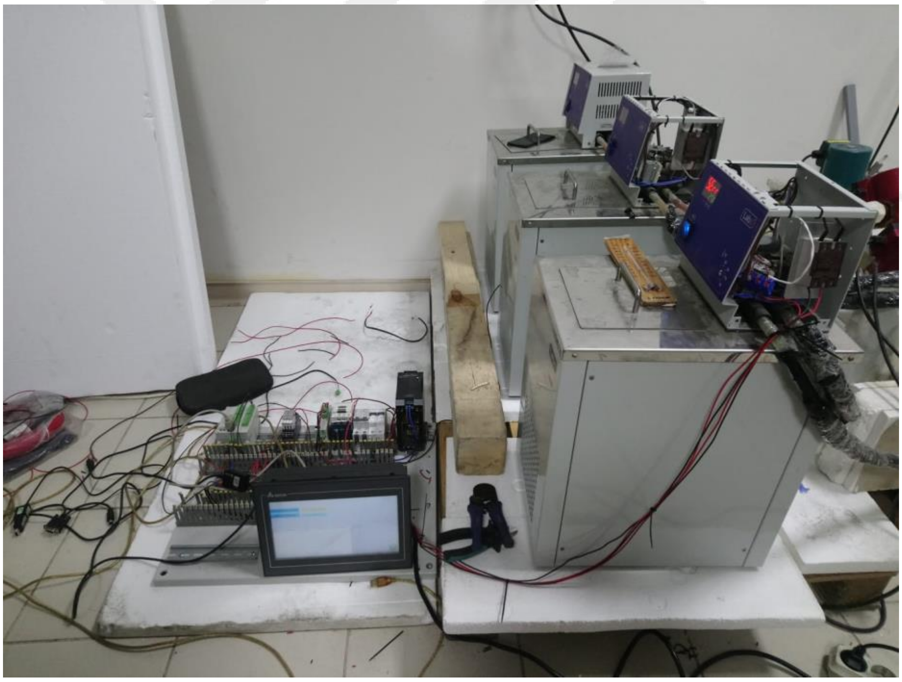
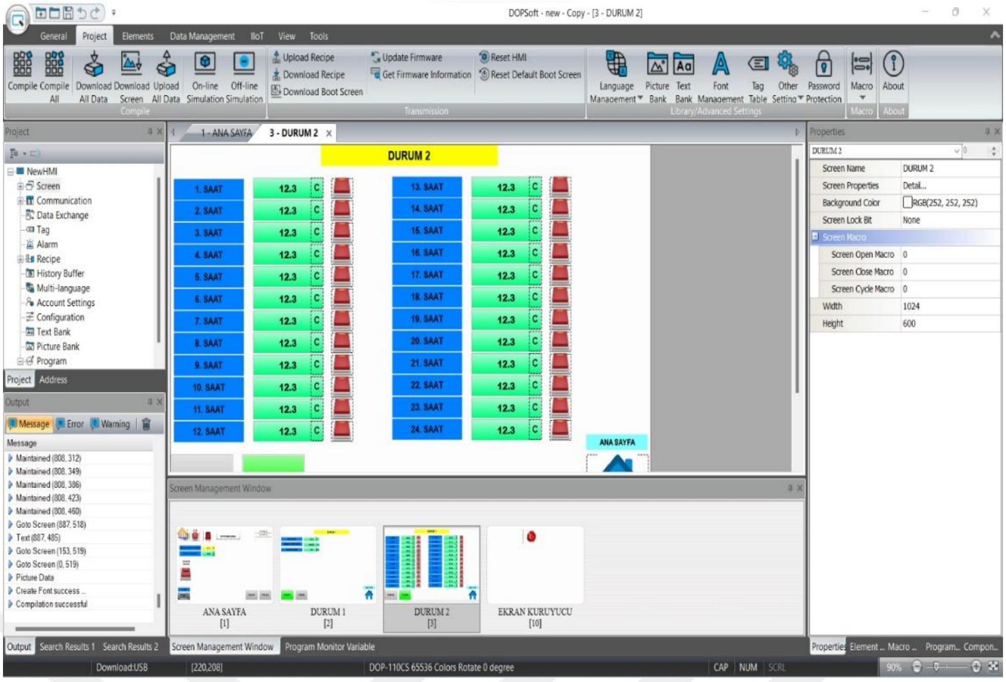


Figure 3.26 System operation image-2



Output

Message | Error | Warning

```
Message
Maintained (808, 312)
Maintained (808, 349)
Maintained (808, 386)
Maintained (808, 423)
Maintained (808, 460)
Goto Screen (887, 518)
Text (887, 485)
Goto Screen (153, 519)
Goto Screen (0, 519)
Picture Data
Create Font success ...
Compilation successful
```

Properties

DURUM 2

Screen Name	DURUM 2
Screen Properties	Detail...
Background Color	RGB(252, 252, 252)
Screen Lock Bit	None
Screen Macro	
Screen Open Macro	0
Screen Close Macro	0
Screen Cycle Macro	0
Width	1024
Height	600

Figure 3.27 HMI general programming view-1

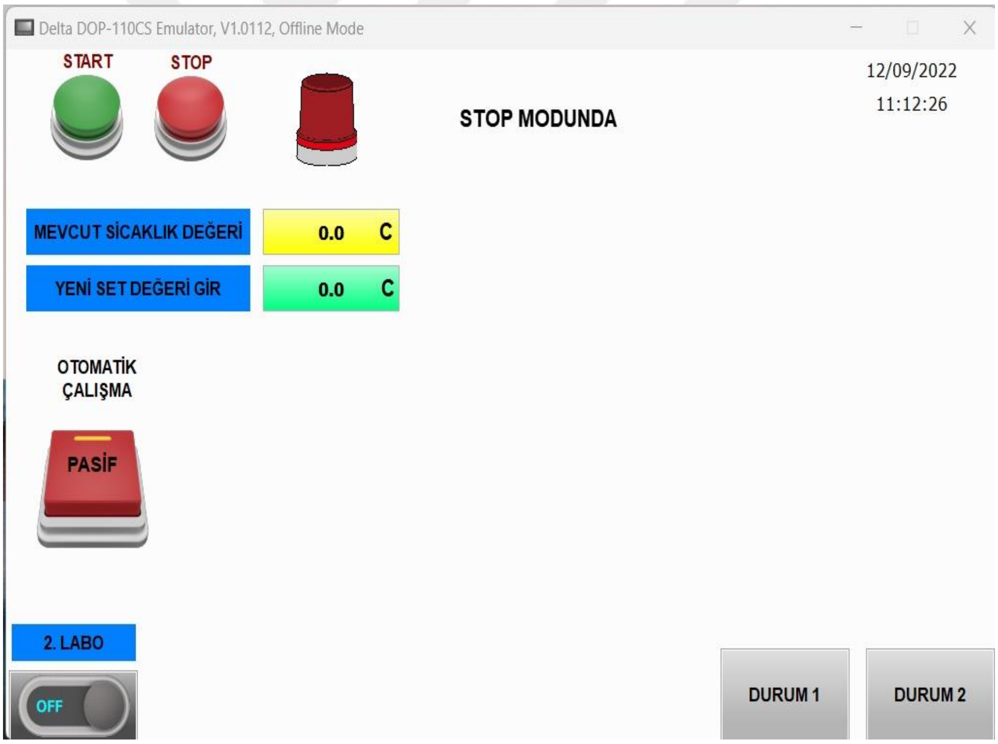
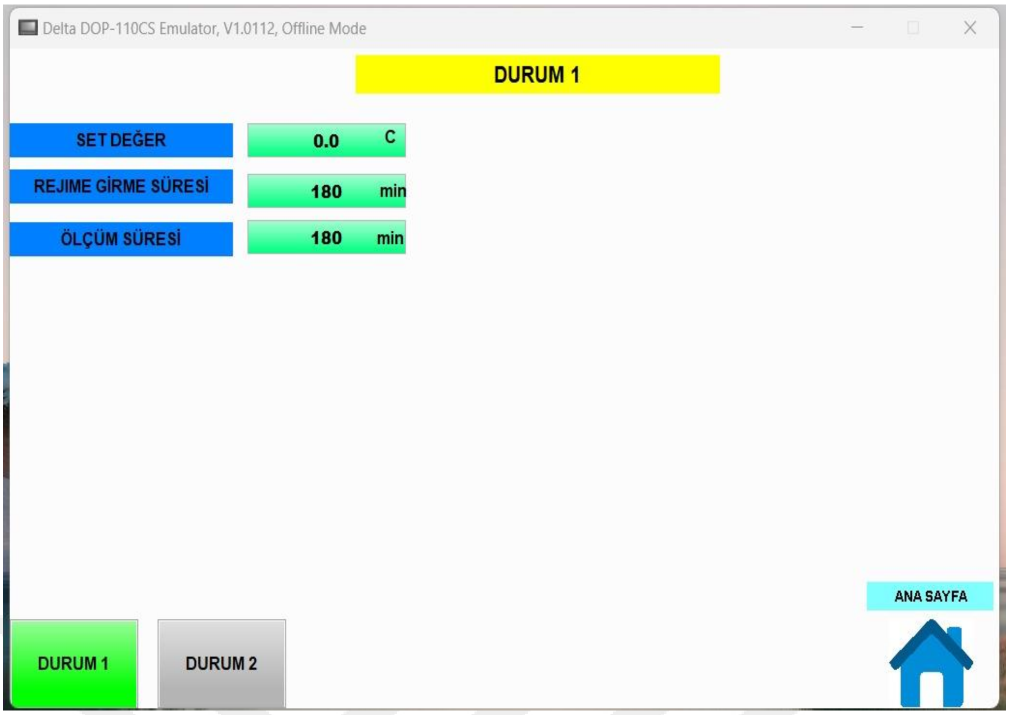


Figure 3.28 HMI general programming view-2



SET DEĞER 0.0 C

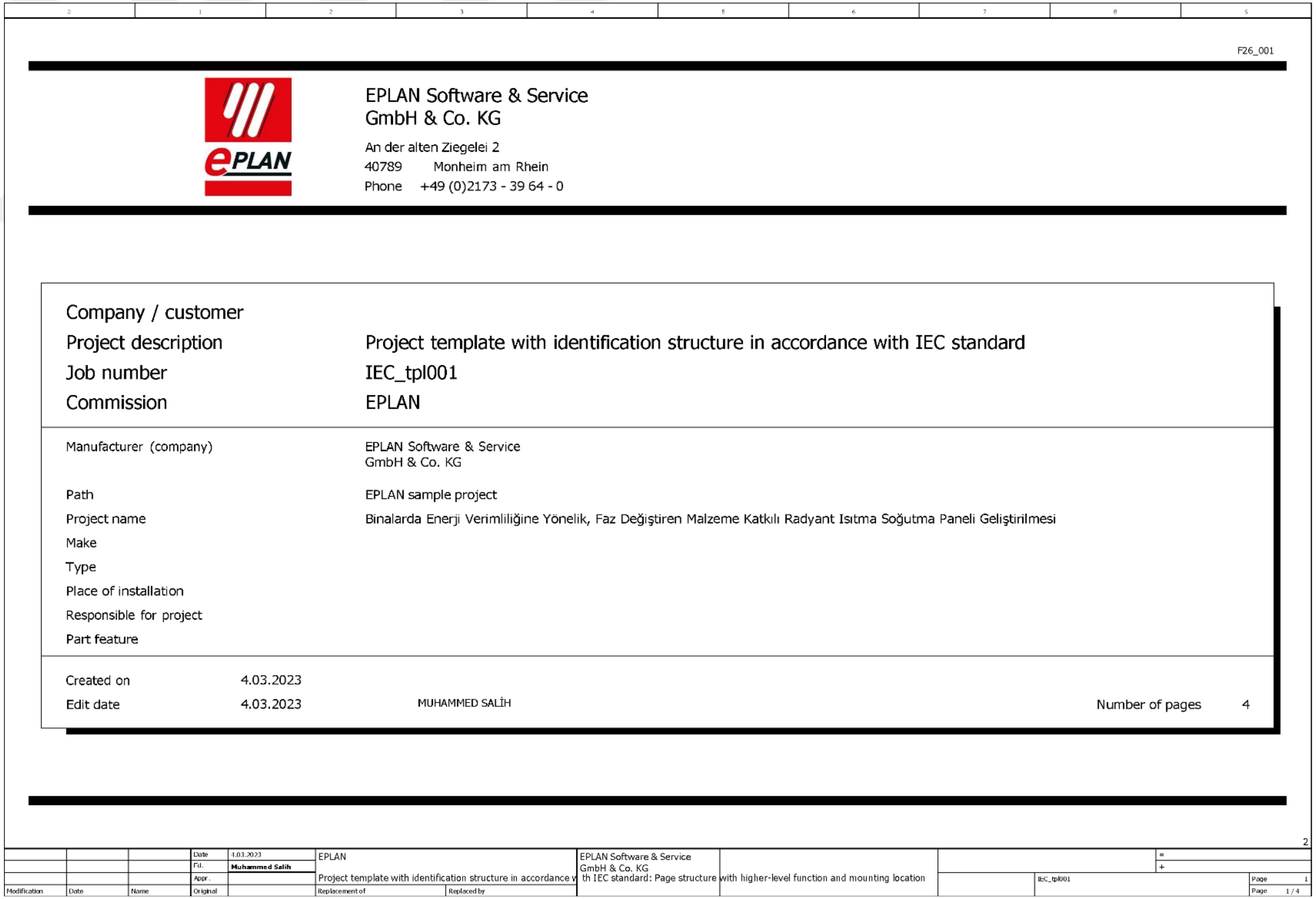
REJIME GİRME SÜRESİ 180 min

ÖLÇÜM SÜRESİ 180 min

Figure 3.29 HMI general programming view-3

1. SAAT	0.0	C	13. SAAT	8.0	C
2. SAAT	0.6	C	14. SAAT	6.6	C
3. SAAT	1.2	C	15. SAAT	6.0	C
4. SAAT	1.8	C	16. SAAT	5.4	C
5. SAAT	2.4	C	17. SAAT	4.8	C
6. SAAT	3.0	C	18. SAAT	4.2	C
7. SAAT	4.2	C	19. SAAT	3.0	C
8. SAAT	4.8	C	20. SAAT	2.4	C
9. SAAT	5.4	C	21. SAAT	1.8	C
10. SAAT	6.0	C	22. SAAT	1.2	C
11. SAAT	6.6	C	23. SAAT	0.6	C
12. SAAT	8.0	C	24. SAAT	0.0	C

Figure 3.30 HMI general programming view-4



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Commission	EPLAN
Manufacturer (company)	EPLAN Software & Service GmbH & Co. KG
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Make	
Type	
Place of installation	
Responsible for project	
Part feature	

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Edit date 4.03.2023 MUHAMMED SALİH

Number of pages 4

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Date 4.03.2023
Ed. Muhammed Salih
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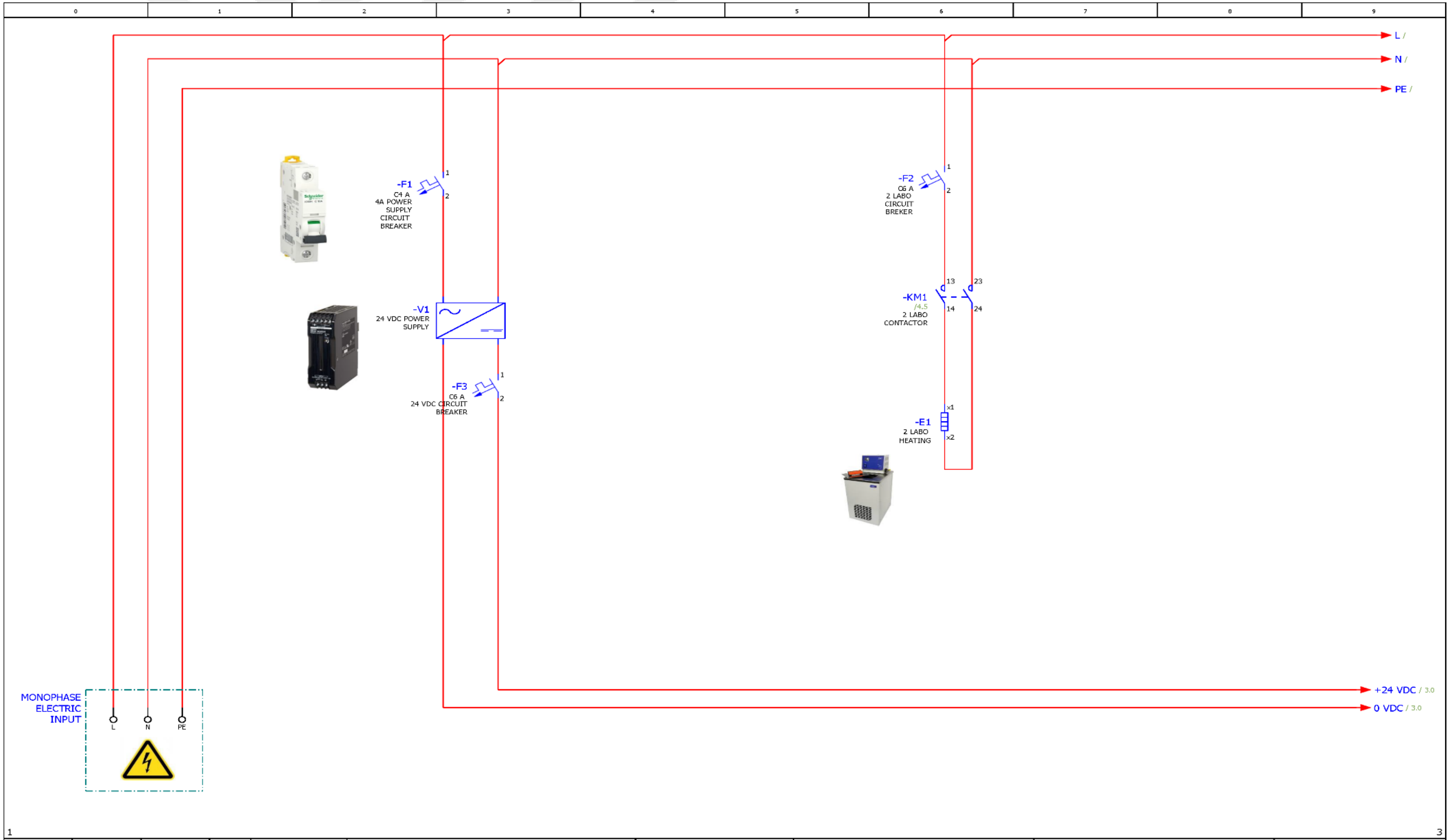

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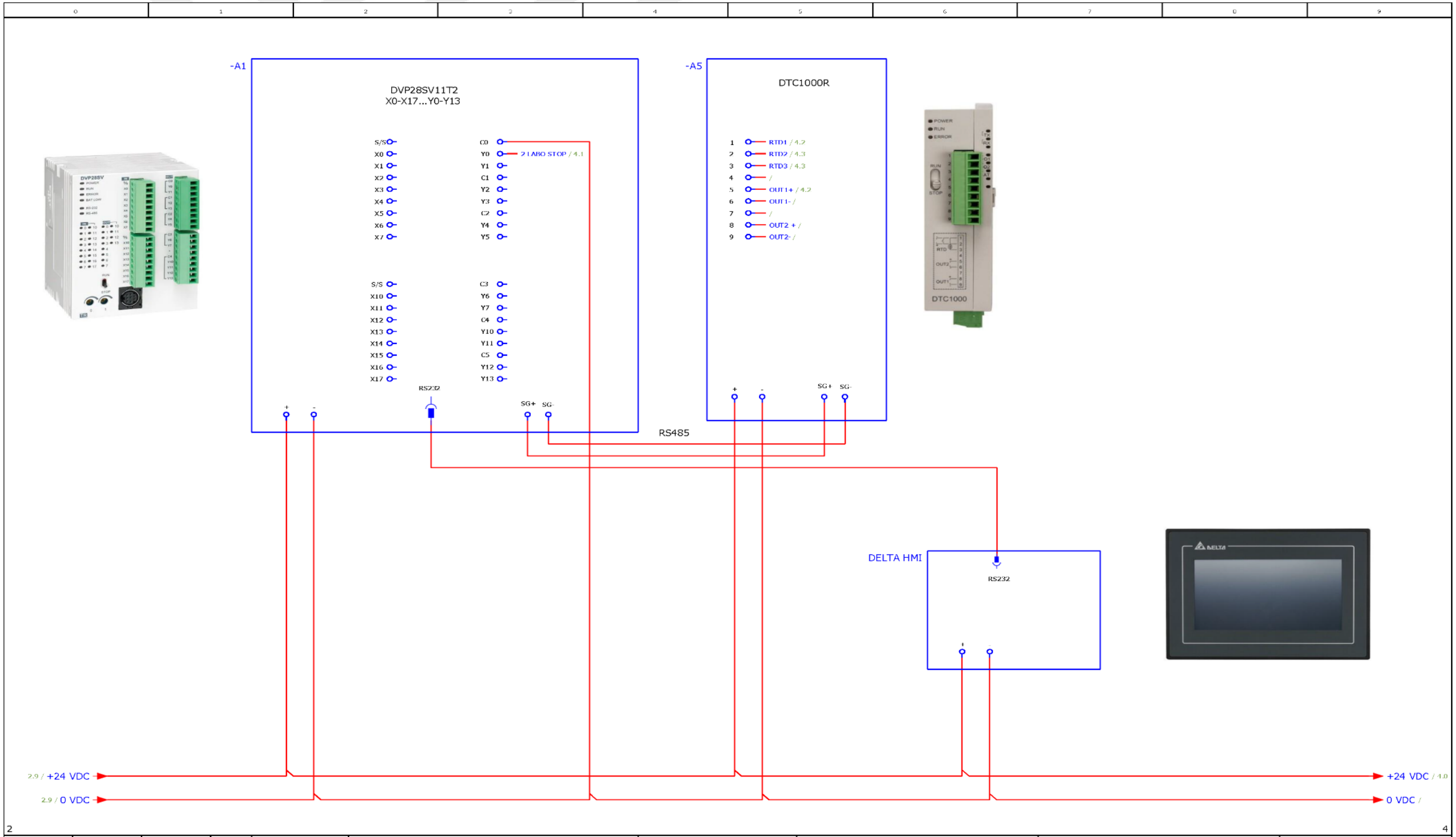

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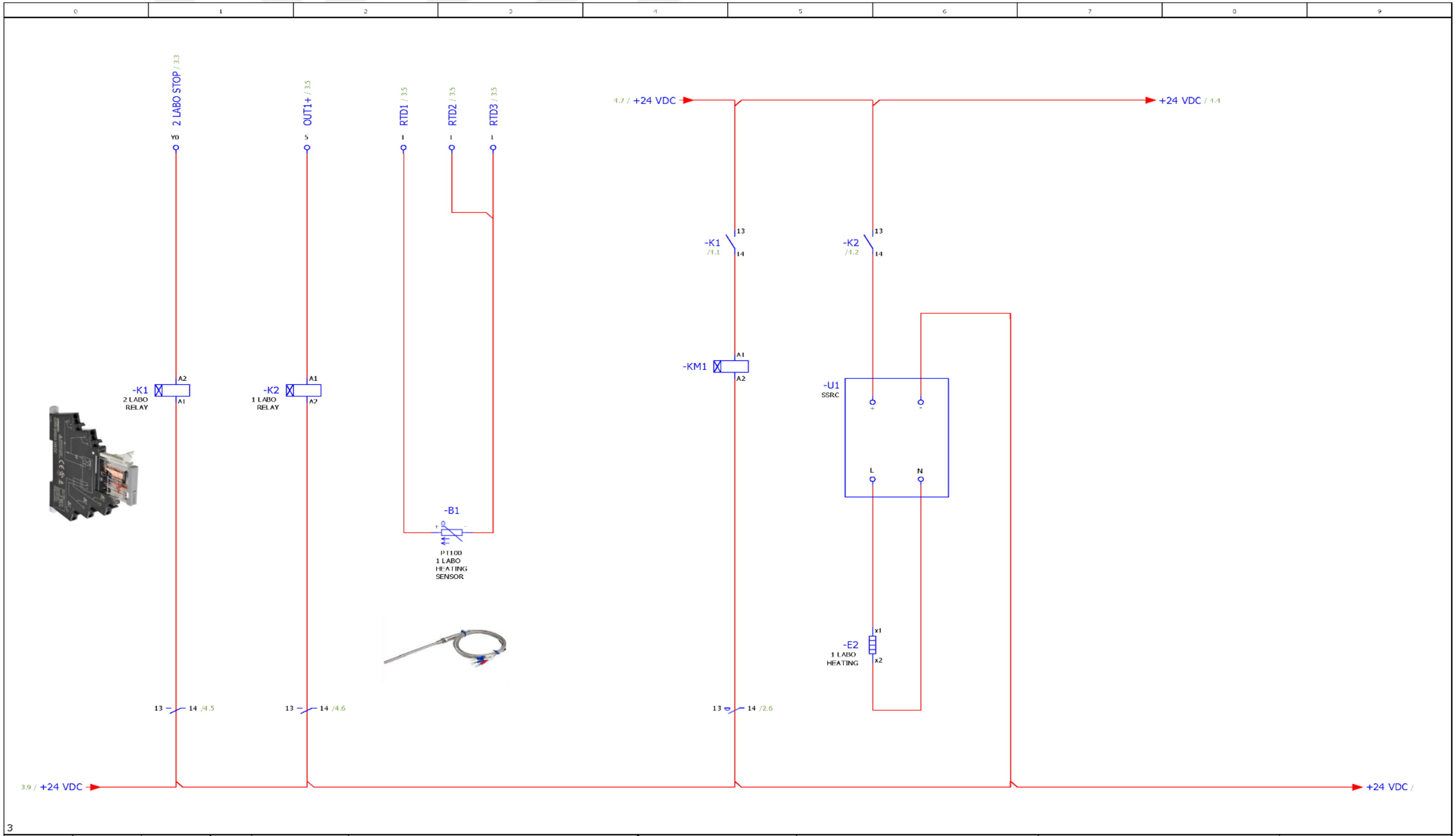
Modification	Date	Name	Original		Replacement of / Replaced by			Page 3 / 4



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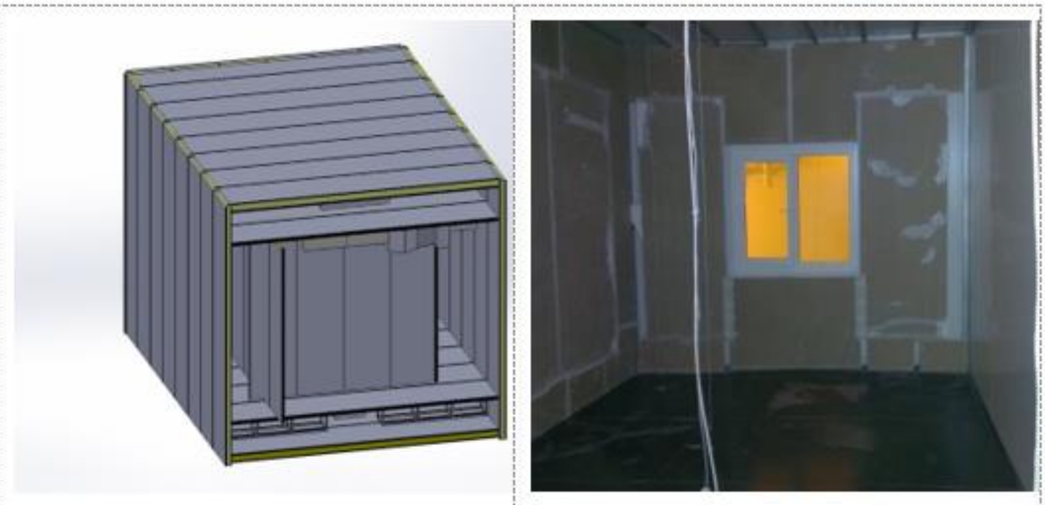
3.9 Test Chamber Construction

The The test chamber consists of two distinct zones: the interior zone and the exterior zone. The interior zone is a suspended volume within the exterior zone, simulating a room within a building, while the exterior zone consists of five separate volumes designed to simulate environmental conditions.



(a) Test room setup in CAD environment

(b) Test chamber setup for experimental study

Figure 3.31 Computer environment of the test room (CAD) (a) and test room for experimental work (b)

The dimensions of the interior and exterior zones' constructions are as follows:

Interior Zone Length: (6 ±0.02) m Width: (4 ±0.02) m Height: (3 ±0.02) m

Exterior Zone Length: (8 ±0.02) m Width: (6.4 ±0.02) m Height: (5.5 ±0.02) m

The test chamber is constructed with adequate sealing to prevent uncontrolled air leakage. The air exchange rate in the chamber under a pressure difference of 50 Pa exceeds 0.8 h-1, and the surface emission value is at least 0.9 to ensure a controlled environment.

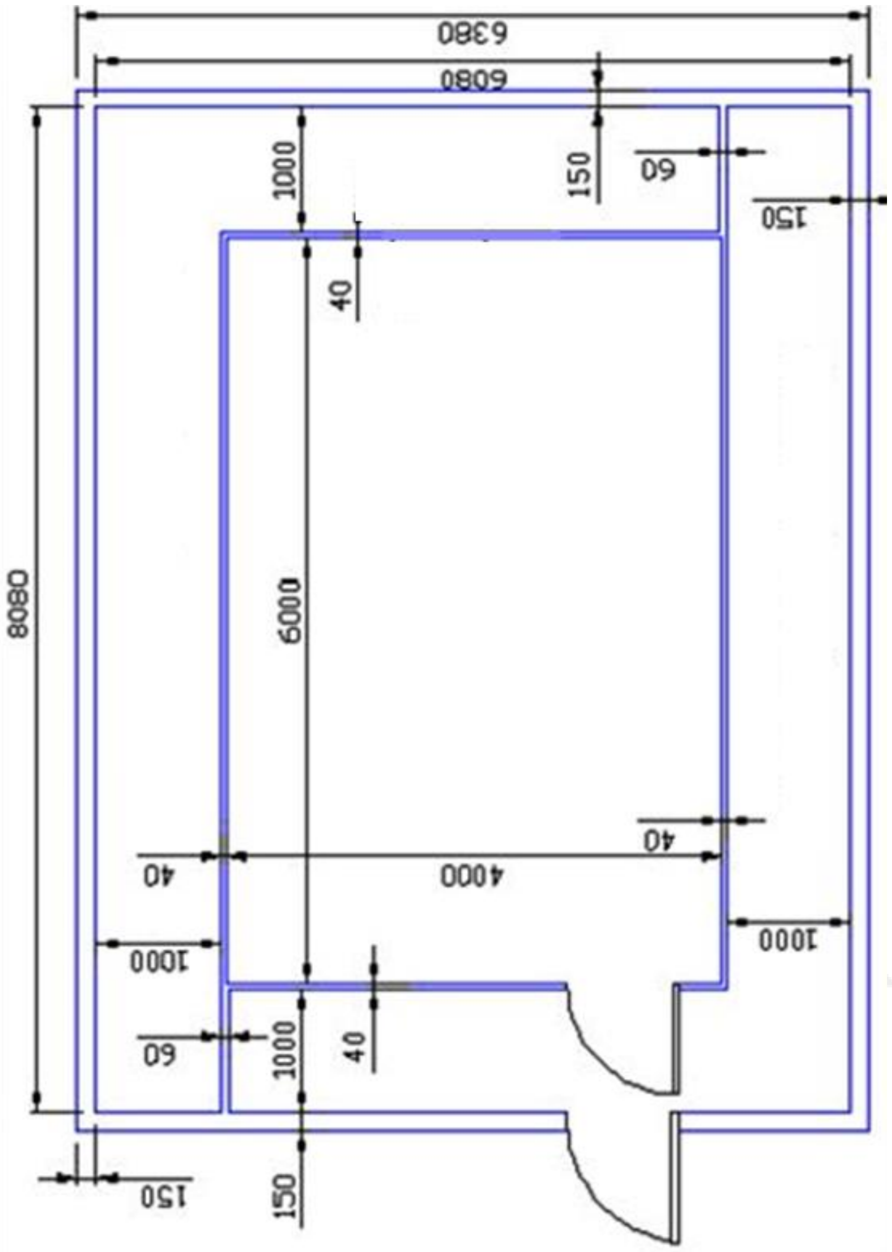


Figure 3.32 Test room general dimensions

Figure 3-32 displays the top view of the test chamber arrangement, illustrating both the interior and exterior zones. The test chamber consists of a total of five distinct zones (volumes).

Some modifications have been made to the test chamber, resulting in the transformation of the test chamber into a structure that includes two separate rooms by dividing the interior zone into two. This modification was carried out with the aim of examining the effects of PCM in a more specific manner. Room 1 is designed to be a room containing PCM, while Room 2 is designed as a room without PCM.

Some modifications have been made to the test chamber, resulting in the transformation of the test chamber into a structure that includes two separate rooms by dividing the interior zone into two. This modification was carried out with the aim of examining the effects of PCM in a more specific manner. Room 1 is designed to be a room containing PCM, while Room 2 is designed as a room without PCM.

Figure 3.33 Room division process

3.10 Test Chamber Setup

An important stage in the design of the test chamber involves the production of new panels and their placement on the chamber walls after the completion of the piping process. Additionally, ensuring an appropriate sensor distribution and placement is of great significance during this stage. The initial step of this process involved the production of new panels measuring 60 cm in width and 240 cm in length. These panels were carefully manufactured, taking into consideration strength and durability requirements, as they would undergo a specific piping process and later be placed on the chamber walls. Once the panel production was completed, they were subjected to the piping process. This process was carried out with the purpose of enabling the integration of the panels into the heating and cooling system at a later stage. The piping process involved the installation of the plumbing system that would facilitate the circulation of hot water within the panels.

Figure 3.34 New panel view

After the piping process was completed, the carefully manufactured panels were placed on the chamber walls. During this stage, the placement of the panels was carried out with great precision to ensure they were positioned correctly and in a uniform manner. The installation of the panels emerged as a critical phase that significantly impacts the thermal performance of the test chamber.

Figure 3.35 Reference Wall layout and installation process

Figure 3.36 PCM wall layout and installation process

During the placement of the panels, careful attention was given to the appropriate sensor distribution and positioning. Sensors were strategically positioned at various points to measure the surface temperatures and other thermal characteristics of the panels. These sensors played a crucial role in ensuring the accuracy and reliability of the data obtained during the experiments.

Figure 3.37 Sensor placement image

Once the panels were in place and the sensors were properly positioned, the wall surfaces were covered with plaster. This step served two purposes: to ensure that the wall surfaces where the panels were installed had a smooth appearance and to enhance the thermal insulation performance.

Figure 3.38 Reference wall plastering process

Figure 3.39 PCM wall plastering process

In conclusion, the production of new panels, the piping process, the installation of panels on the walls, and the proper sensor placement constituted a critical phase for the accurate measurement and analysis of the test chamber's thermal performance. The meticulous execution of these stages contributed significantly to enhancing the accuracy and reliability of the data provided by the test chamber.

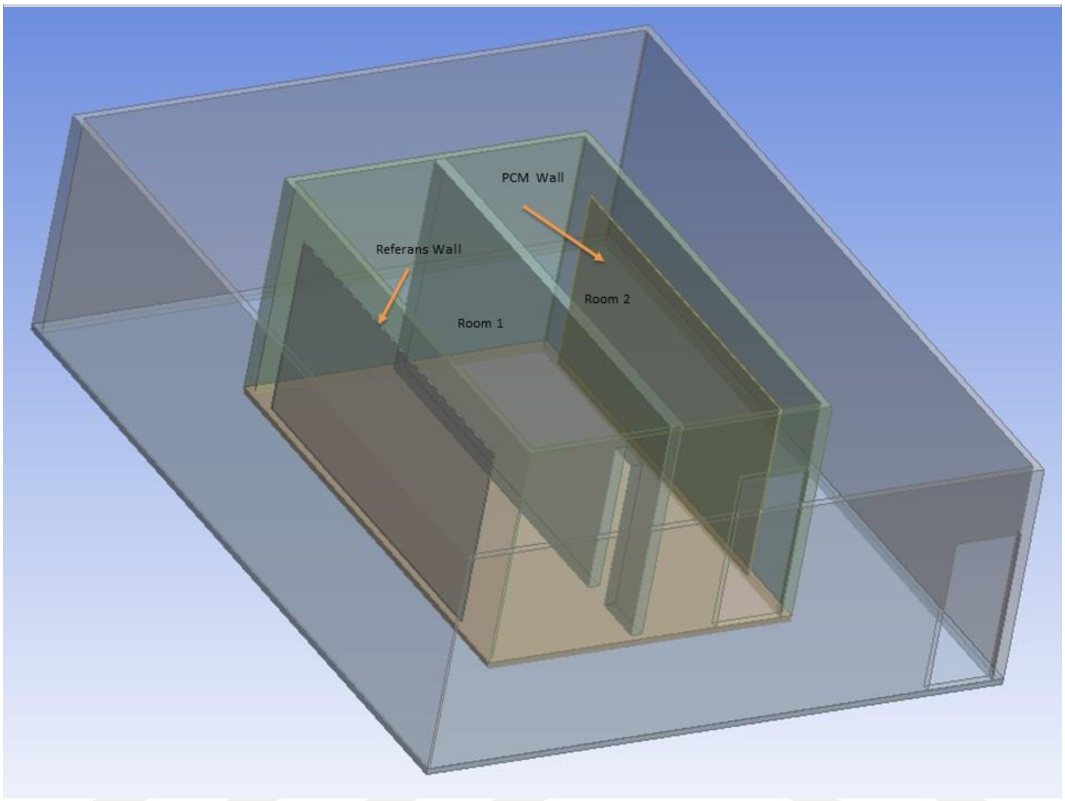


Figure 3.40 CAD Image of Two Rooms

4
CONCLUSION

4.1 Findings

In the experimental studies conducted in this work, the effect of PCM was investigated through three different methods.

The first method (Panel Surface Temperature and Cooling Time) examined the effect of Phase Change Material (PCM) with different mass mixing ratios on the surface temperature of the radiant system. Three types of panels were used in the experiments: a reference panel without PCM (Panel-0), a panel with 6% PCM content (Panel-1), and a panel with 10% PCM content (Panel-2). The experiments were repeated for three different outdoor air temperatures (0°C, 3°C, and 8°C). The panel inlet temperature (60°C) and flow rates (3.5 L/min) were kept constant during the experiments. After the system reached a steady state, initial measurements were taken (1 min), and then the hot water supply was turned off while temperature measurements continued for 150 minutes. The surface temperatures of the panels at the 150th minute were compared. Additionally, the surface temperatures of the hot water pipes and the pipes containing PCM were measured to check if the PCM had reached its melting point. Temperature measurements on aluminum foil surfaces in the panel cross-section were also conducted to observe temperature distribution.

The second method (PCM Effect on Comfort) involved conducting experiments where a water heater was connected to a PLC to simulate the temperature variation in an outdoor environment. The experiment was carried out in an environment where the outdoor temperature ranged from 0°C to 8°C to simulate daytime temperature increase, followed by a range of 8°C to 0°C to simulate nighttime temperature decrease. The experimental setup was designed to simulate daily life conditions during both daytime and nighttime. A limited amount of energy was supplied to the system while the outdoor temperature decreased to allow PCM to solidify and release energy to the environment.

The third method involved validating the results using CFD analysis for the second and third methods.

In this project, a radiant panel is numerically investigated. The 3D model is designed in ANSYS Spaceclaim software. Then, an unstructured meshgrid is generated. It is worth noting that boundary layer is used near the tubes to increase the accuracy of the simulation. The following figures shows the modeled geometry and Mesh.

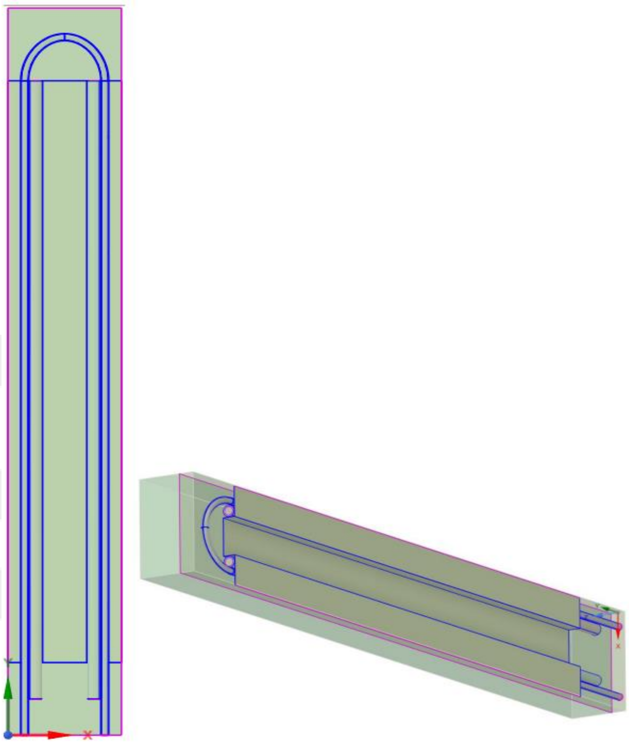


Figure 4.1 The modeled geometry

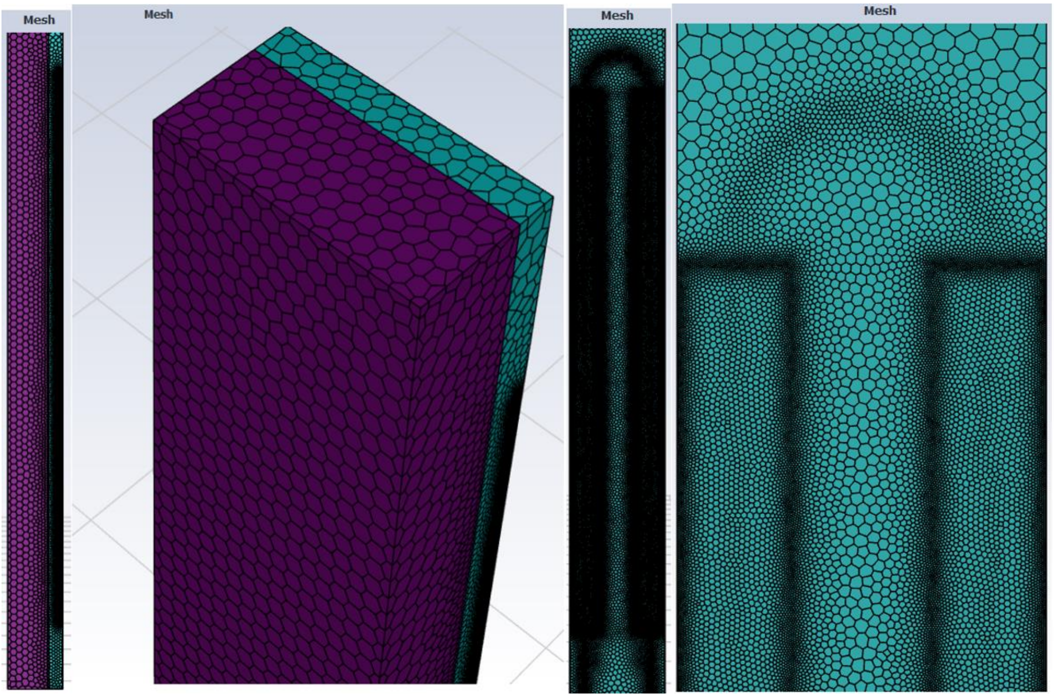


Figure 4.2 Mesh view

4.2 Panel Surface Temperature and Cooling Time Experimental Results

In the case where the ambient temperature is defined as 0°C, after the system reaches steady state (after the hot water supply is turned off), the surface temperature of the reference panel (representing the surface facing the room) drops to 22°C while it drops to 31.1°C in Panel-1 and 33.5°C in Panel-2. These results indicate that the PCM contribution significantly delays the cooling of the surface. Similar conclusions can be drawn from the results at other ambient temperatures. As the ambient temperature increases, the PCM-enhanced panel will maintain thermal comfort for an extended period.

Table 4.1 Panel 1 test results

from 0C to rest						
After SCAN/ min	**Reference Panel surface temperature C^0**	**Panel 1 surface temperature C^0**	**Outside air temperature C^0**	**PCM -pipe C^0**	**Heat exchanger tube surface temperature C^0**	**Aluminum foil C^0**
1	38	38,065	0	48,14	61	43,7
150	22	31,10		35,92	-	30,9

from 3C to rest						
After SCAN/ min	**Reference Panel surface temperature C^0**	**Panel 1 surface temperature C^0**	**Outside air temperature C^0**	**PCM -pipe C^0**	**Heat exchanger tube surface temperature C^0**	**Aluminum foil C^0**
1	38	38,126	3	48,27	60,06	43,38
150	22	32,17		35,95	-	32,1

from 8C to rest						
After SCAN/ min	**Reference Panel surface temperature C^0**	**Panel 1 surface temperature C^0**	**Outside air temperature C^0**	**PCM -pipe C^0**	**Heat exchanger tube surface temperature C^0**	**Aluminum foil C^0**
1	38	38,61	8	48,53	61,5	43,71
150	22	33,24		36,14	-	33,04

Table 4.2 Panel 2 test results

from 0C to rest						
After SCAN/ min	**Reference Panel surface temperature C^0**	**Panel 2 surface temperature C^0**	**Outside air temperature C^0**	**PCM-pipe C^0**	**Heat exchanger tube surface temperature C^0**	**Aluminum foil C^0**
1	38	38,96	0	49,76	60,01	47,29
150	22	33,45		40,74	-	37,015

from 3C to rest						
After SCAN/ min	**Reference Panel surface temperature C^0**	**Panel 2 surface temperature C^0**	**Outside air temperature C^0**	**PCM-pipe C^0**	**Heat exchanger tube surface temperature C^0**	**Aluminum foil C^0**
1	38	38,78	3	49,83	60,10	47,37
150	22	33,018		40,57	-	37,078

from 8C to rest						
After SCAN/ min	**Reference Panel surface temperature C^0**	**Panel 2 surface temperature C^0**	**Outside air temperature C^0**	**PCM-pipe C^0**	**Heat exchanger tube surface temperature C^0**	**Aluminum foil C^0**
1	38	39,21	8	50,1	61,2	47,71
150	22	34,52		41,3	-	37,01

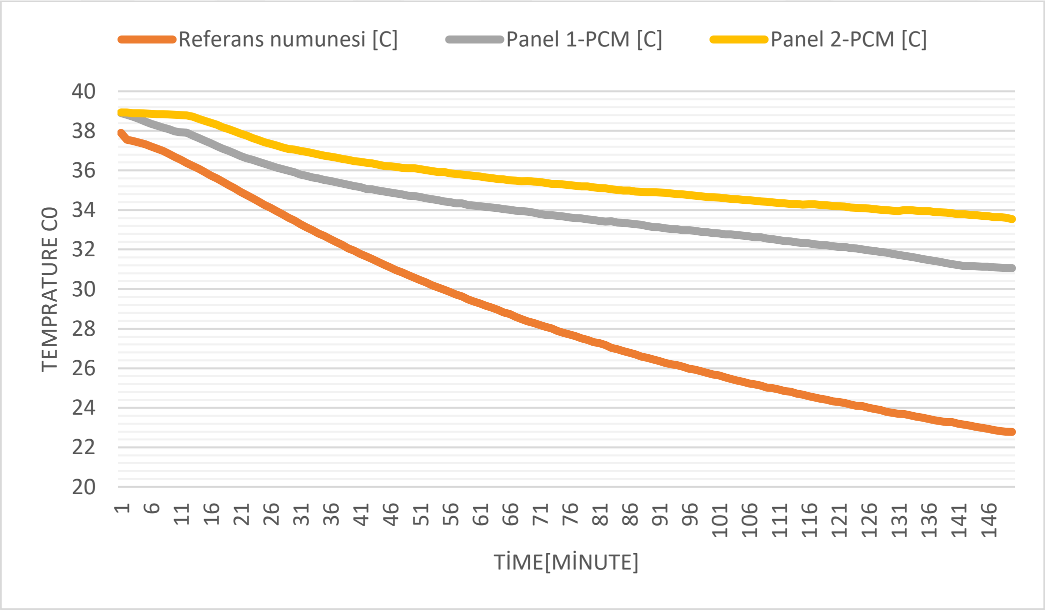


Figure 4.3 Temperature changes according to the cooling time of the panel when the outside air temperature is 0C.

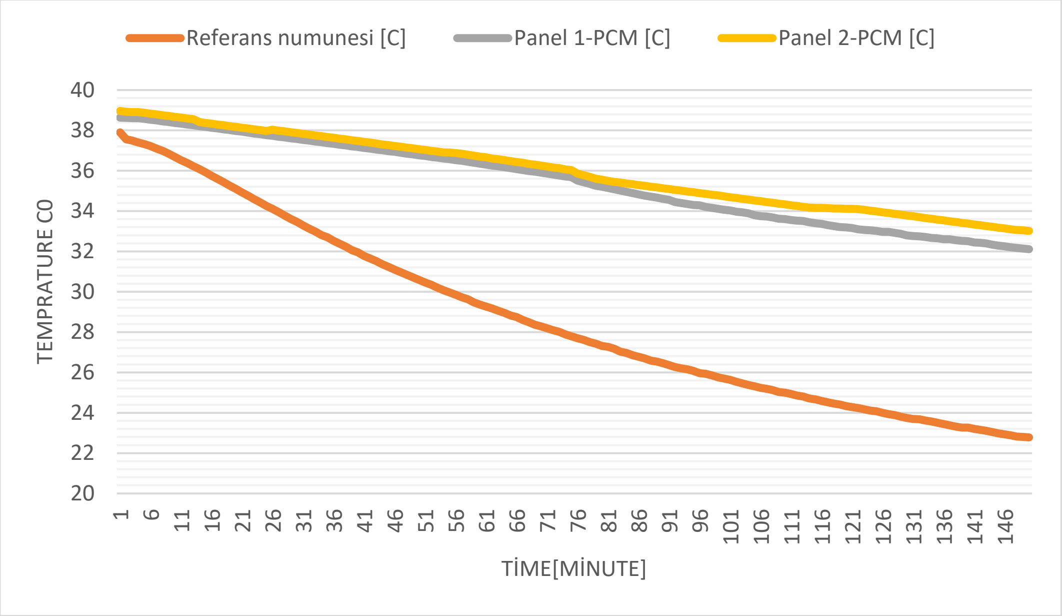


Figure 4.4 Temperature change according to the cooling time of the panel when the outside air temperature is 3C.

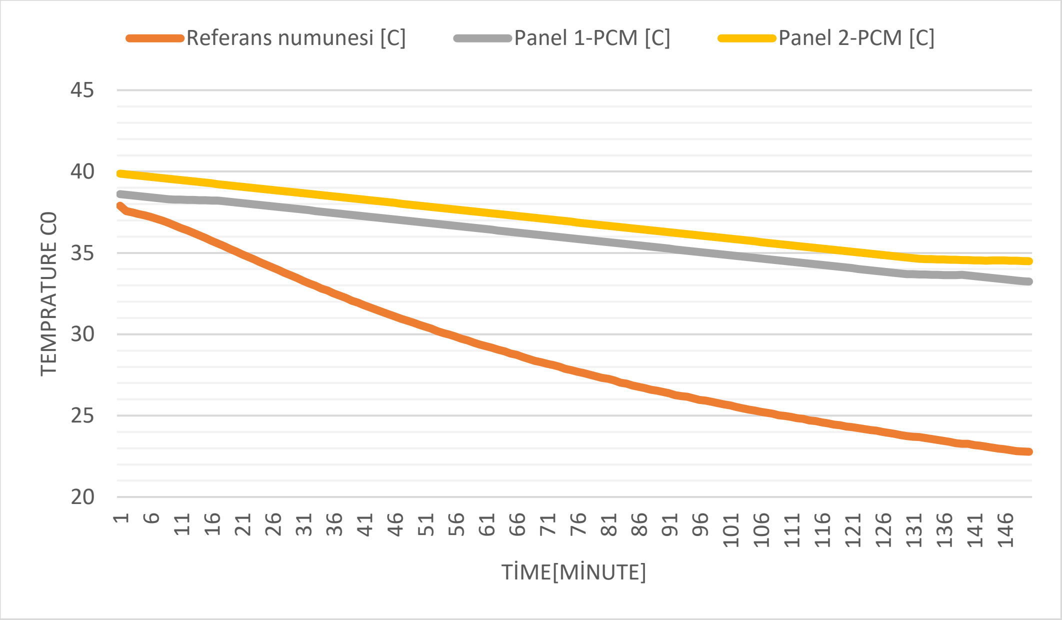


Figure 4.5 Temperature changes according to the cooling time of the panel when the outside air temperature is 8C.

4.3 The Comfort Effect of PCM Experimental Results

The observed results from the tests are as follows:

- When the external temperature is low, energy efficiency has been achieved by providing energy to the environment without the need to increase the amount of energy provided, thanks to PCM, which plays an important role.

- Thermal comfort conditions were achieved due to a constant thermal distribution on the surface of the analyzed model.
- A positive effect of PCM was observed when the external temperature dropped.
- By reducing the variable temperature peaks during heating in conventional systems, thermal comfort was achieved, and a constant surface temperature was obtained, thereby achieving the desired goal.
- The Ashrae 55 standard allows for a 2.2°C operative temperature change over a one-hour period. The temperature change in the PCM panel is approximately 0.5°C, indicating compliance with the standard.
- By overcoming the variable temperature during heating in conventional systems, thermal comfort was achieved, and a constant surface temperature was obtained, thereby achieving the desired goal.

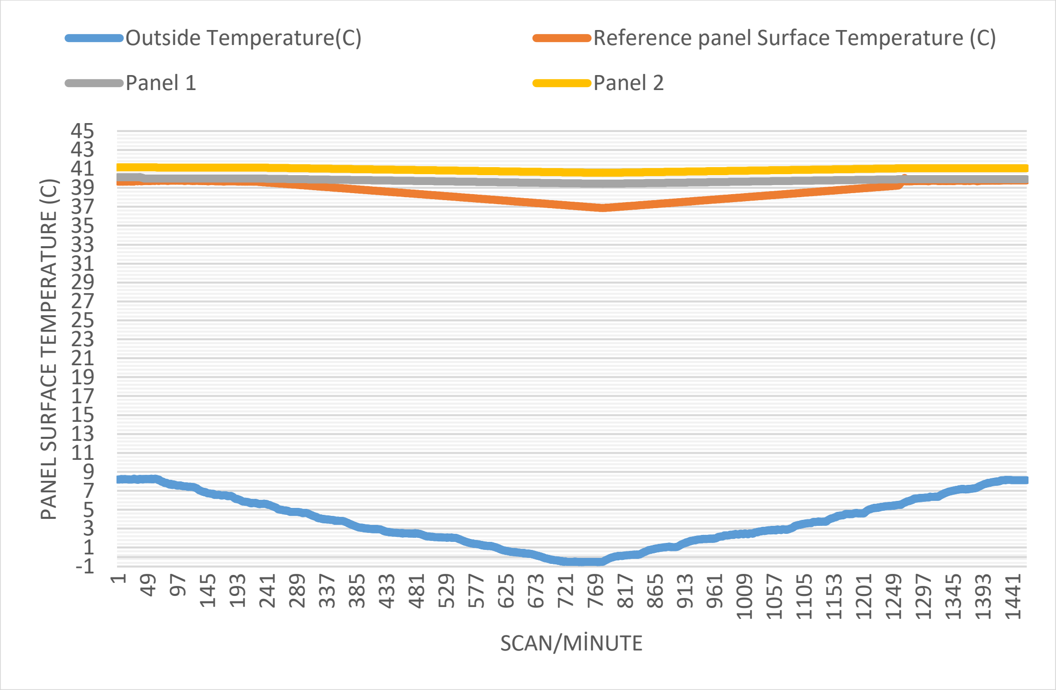


Figure 4.6 Panel surface temperature change depending on outside air temperature

4.4 Thermal Performance Effect

In this study, the thermal performance of wall panels with PCM (Phase Change Material) addition, developed experimentally, was investigated, and it was observed that it increased by 17%.

Table 4.3 Results table for reference panel and PCM additive panel

		Referans	**PCM**
1st Plate surface temperature (°C)	T_0	0,93	1,01
2nd Plate surface temperature (°C)	T_{20}	24,32	24,24
Sample surface temperature (°C)	$T_{S,n0}$	39,03	41,2
The temperature difference of the 1st plate for water (°C)	ΔT_0	1,08	3,69
Temperature difference of the 2nd plate for water (°C)	ΔT_{20}	0,91	0,91
Temperature difference of the sample water (°C)	ΔT_n	1,172	1,28
Tsurface -Treferans (°C)	ΔT_{s_ref}	14,71	15,31
1st Plate Heat Transfer [W/m2]	Q_0	63,78	217,92
2nd Plate Heat Transfer [W/m2]	Q_{20}	77,41	77,41
Heat Transfer from the Sample [W/m2]	Q_{n0}	127,2	149,78

4.5 CFD Analysis Results

The phase transition to metallic (PCM) region is simulated using the solidification and melting module.

The SIMPLE algorithm is used to independently resolve the equations of motion and energy. Further, the second-order upwind approach is used to discretize the pressure, momentum, and energy term. The average temperature and liquid fraction of PCM zones, as well as the reported findings on a panel surface, may be found in the accompanying tables. The final numbers are displayed in the table and figures below.

Hours of the Day	**Avg. Temperature of the panel (C)**	**Energy Obtained (W/m2)**	**PCM Liquid Fraction (%)**
1	41.63	234.77	8
2	41.83	202.55	27.4
3	41.89	195.07	36.4
4	41.94	190.41	39.5
5	41.98	186.59	40.5
6	42.02	181.45	41.2

7	42.06	177.57	41.5
8	42.09	174.34	41.8
9	42.13	174.1	42.2
10	42.17	168.76	42.3
11	42.21	166.49	42.5
12	42.25	163.14	42.7
13	42.29	159.73	43.1
14	42.32	160.96	43.3
15	42.35	162.33	43.4
16	42.38	165.92	43.5
17	42.41	169.5	43.6
18	42.43	176.69	43.9
19	42.44	183.14	43.9
20	42.44	188.37	44.1
21	42.45	206.75	44.1
22	42.46	211.76	44.2
23	42.49	228.2	44.4
24	42.5	229	44.5

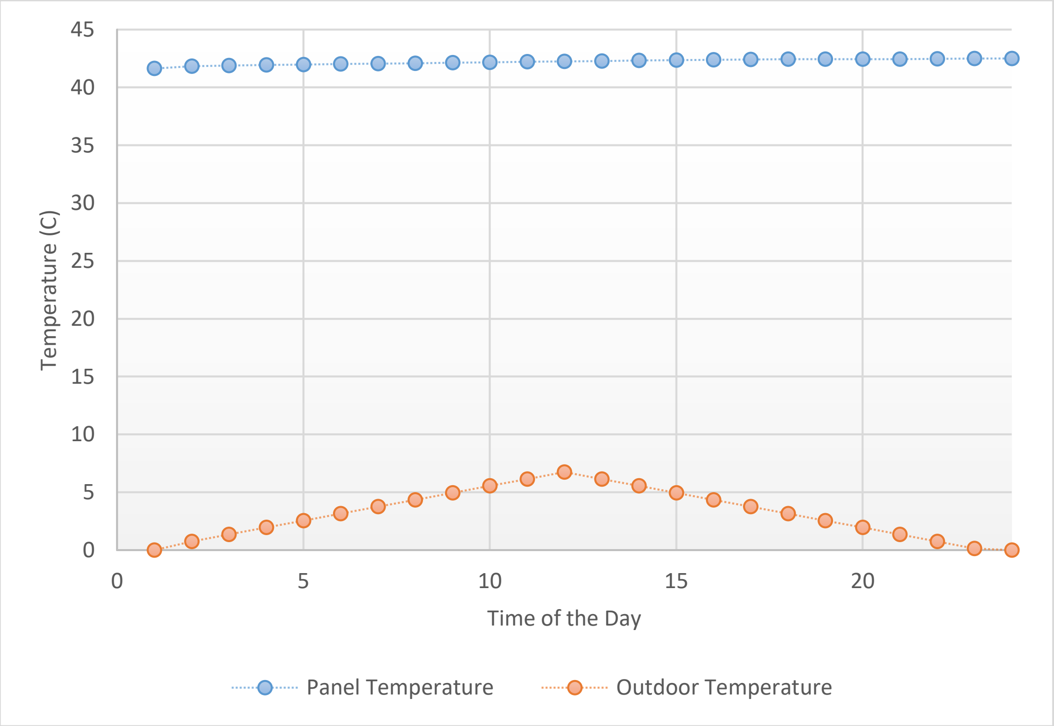


Figure 4.7 Exploring panel surface temperature variation with CFD analysis under different outdoor air temperatures

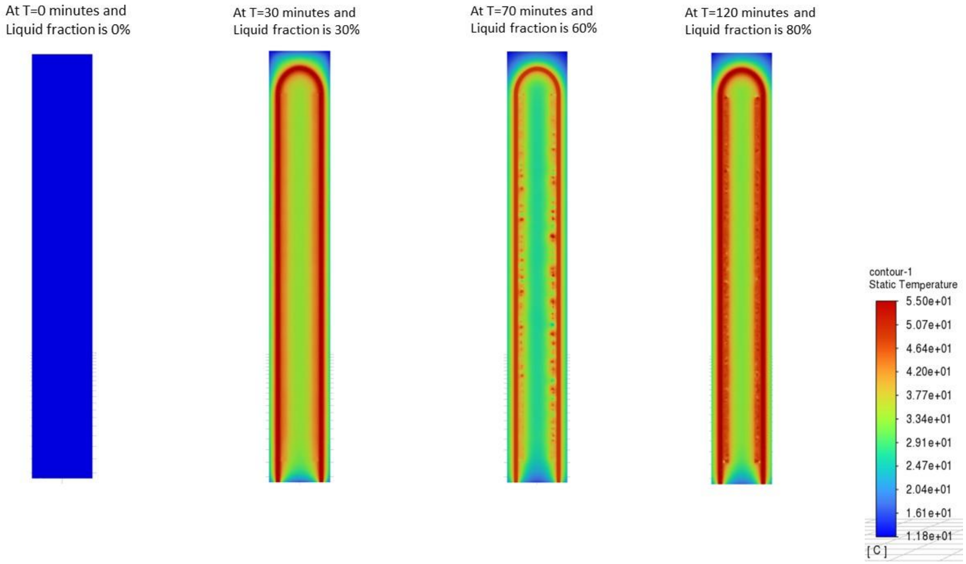


Figure 4.8 Visualization of thermal performance through CFD analysis of the panel

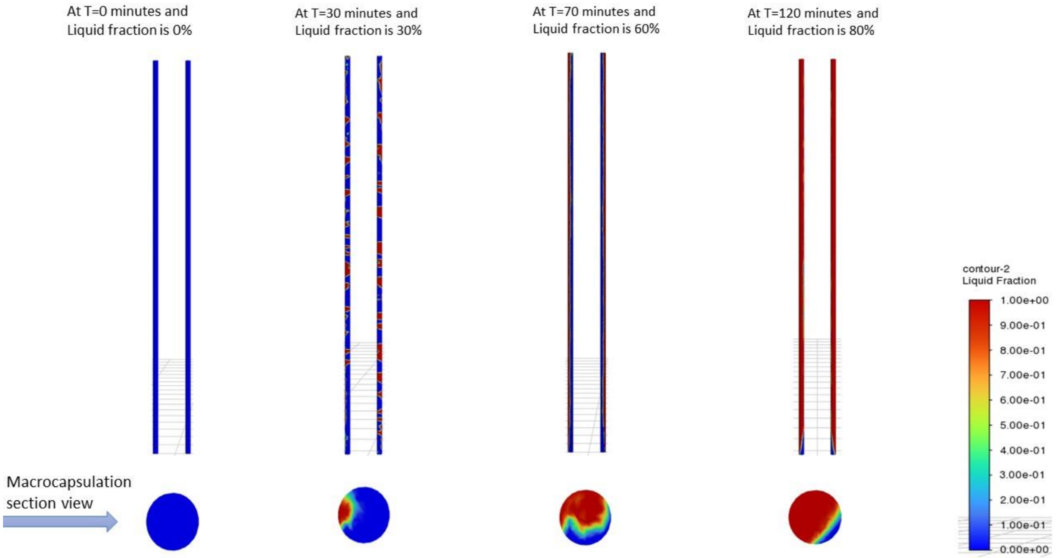


Figure 4.9 PCM melting and solidification through liquid fraction analysis

4.6 Test room results

The recent tests have revealed highly intriguing results, emphasizing significant distinctions in terms of thermal performance between the reference wall and the PCM-enhanced wall. Particularly, the observed temperature changes upon shutting down the heat source delivered remarkable insights.

In the case of the reference wall, when the heat source was turned off, the surface temperature immediately began to decline. In contrast, the surface temperature of the PCM-enhanced wall remained almost stable, with no rapid drop initially. After approximately 100 minutes, the surface temperature of the PCM-enhanced wall started to decrease. At this point, a pronounced difference between the reference wall and the PCM-enhanced wall became evident. The surface temperature of the PCM-enhanced wall remained stable for a longer duration compared to the reference wall.

These results indicate the successful achievement of two primary objectives. The first objective was to extend the duration of thermal comfort. The relative stability of the PCM-enhanced wall's surface temperature, especially in the initial 100 minutes, demonstrated the attainment of this goal. In contrast to the reference wall, the surface temperature of the PCM-enhanced wall did not undergo a decrease, indicating prolonged comfort.

The second objective aimed at prolonging the cooling period. While not experiencing a rapid decline like the reference wall, the PCM-enhanced wall eventually displayed a decrease in surface temperature. However, the initiation of this decline signifies an enhancement in the thermal performance of the PCM-enhanced wall. For example, even after 3 hours, the surface temperature of the reference wall was 29 degrees, while the PCM-enhanced wall's surface temperature remained at 34 degrees. This indicates that the PCM-enhanced wall maintained comfort for a longer duration.

In conclusion, the recent test results confirm the success of the PCM-enhanced wall in achieving the desired objectives. Both the extension of the comfort duration and the delay in the cooling period have been validated through these tests. These outcomes underscore that the PCM-enhanced wall is an effective solution for thermal management.

As a result of experimental studies, thermal camera images were utilized to gain a clearer understanding of phase change and the impact of PCM on thermal performance. These images allowed for the visual monitoring of the thermal behavior and phase change of the PCM-enhanced and reference walls.

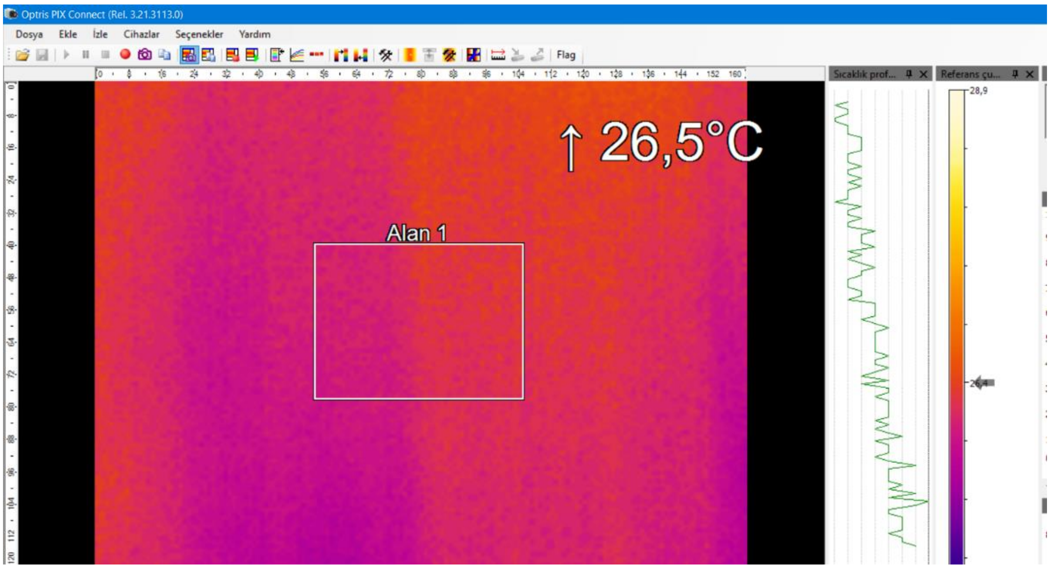


Figure 4.10 Wall view without turning on the heat source

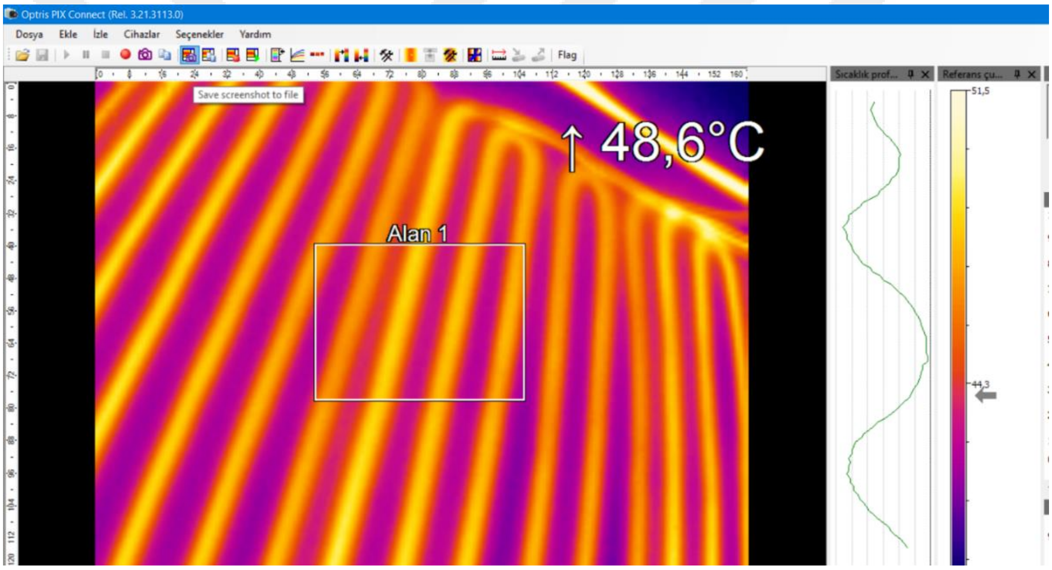


Figure 4.11 Reference wall thermal camera image-1

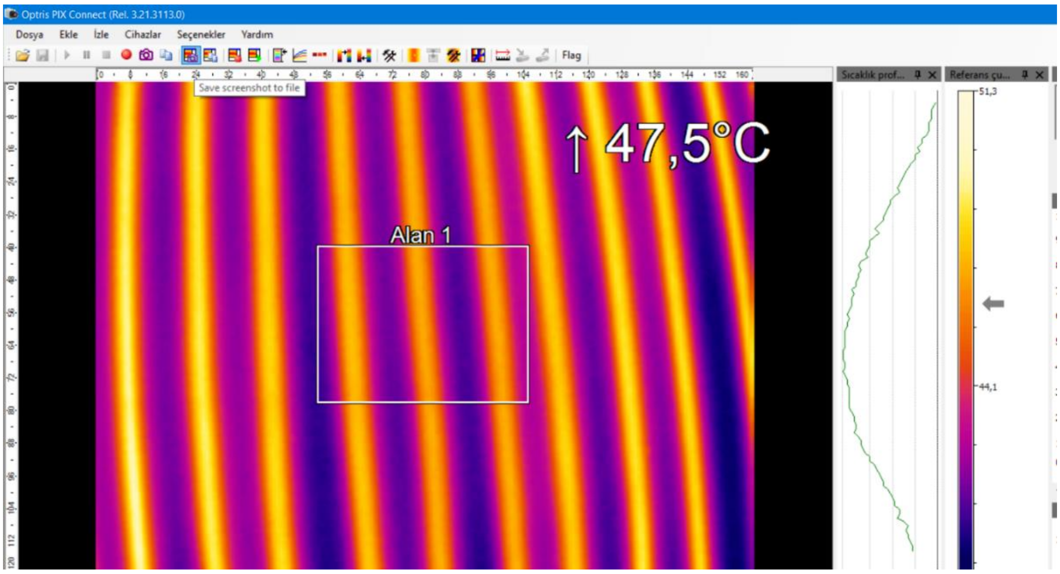


Figure 4.12 Reference wall thermal camera image-2

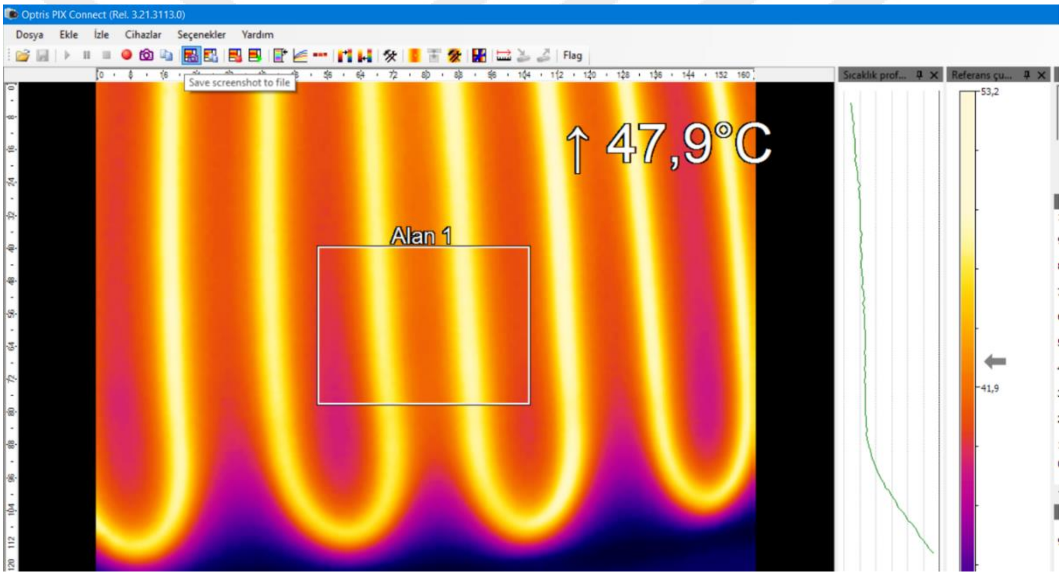


Figure 4.13 Reference wall thermal camera image-3

The obtained thermal camera images vividly illustrated the distinctions in surface temperatures between the PCM-enhanced and reference walls. The temperature distribution on the surface of the PCM-enhanced wall appeared more uniform and stable compared to the reference wall. This observation visually emphasized the thermal energy storage and release capability of PCM.

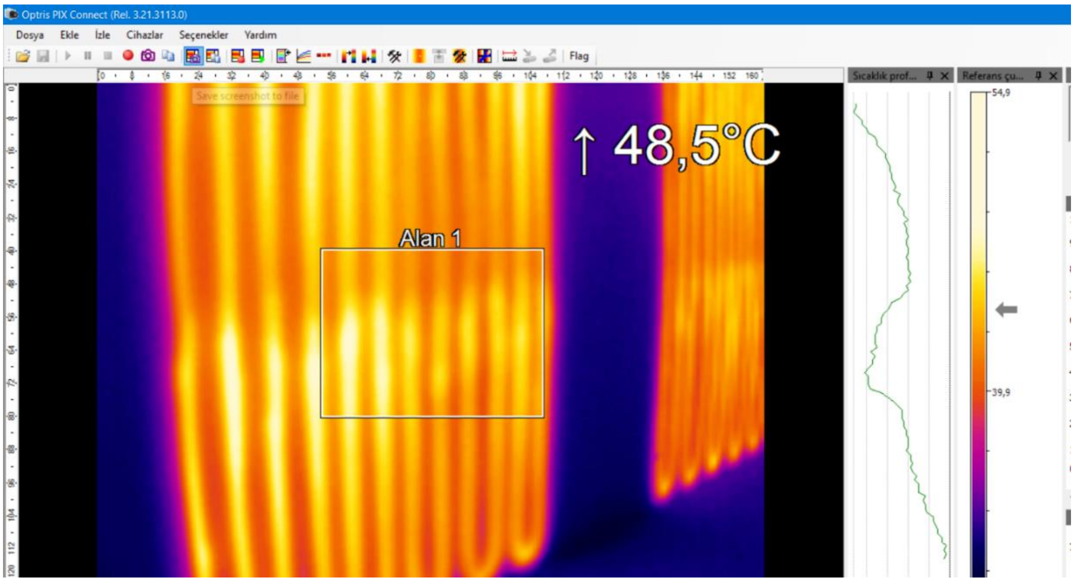


Figure 4.14 PCM wall thermal camera image-1

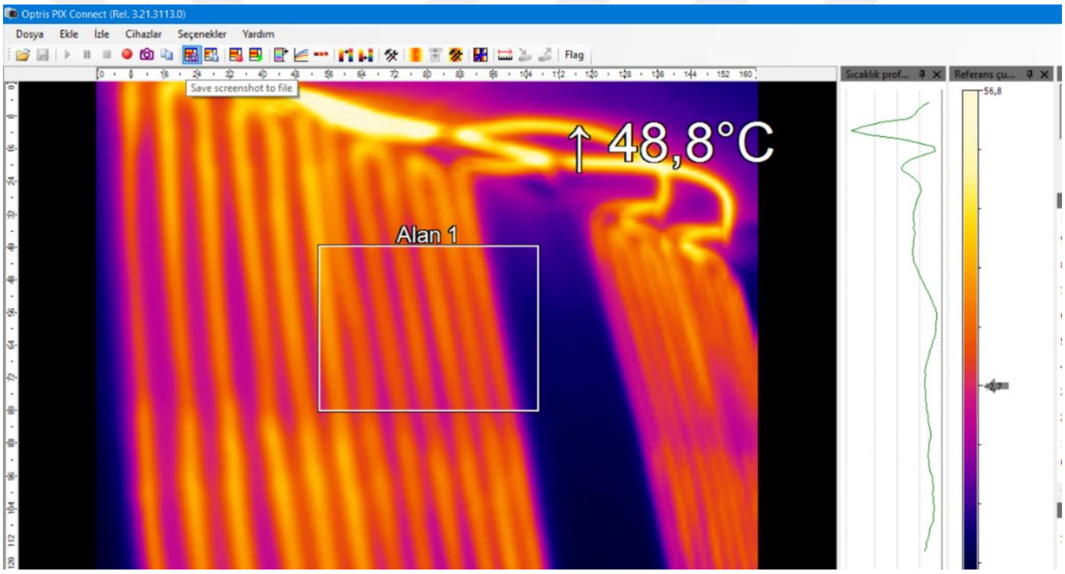


Figure 4.15 PCM wall thermal camera image-2

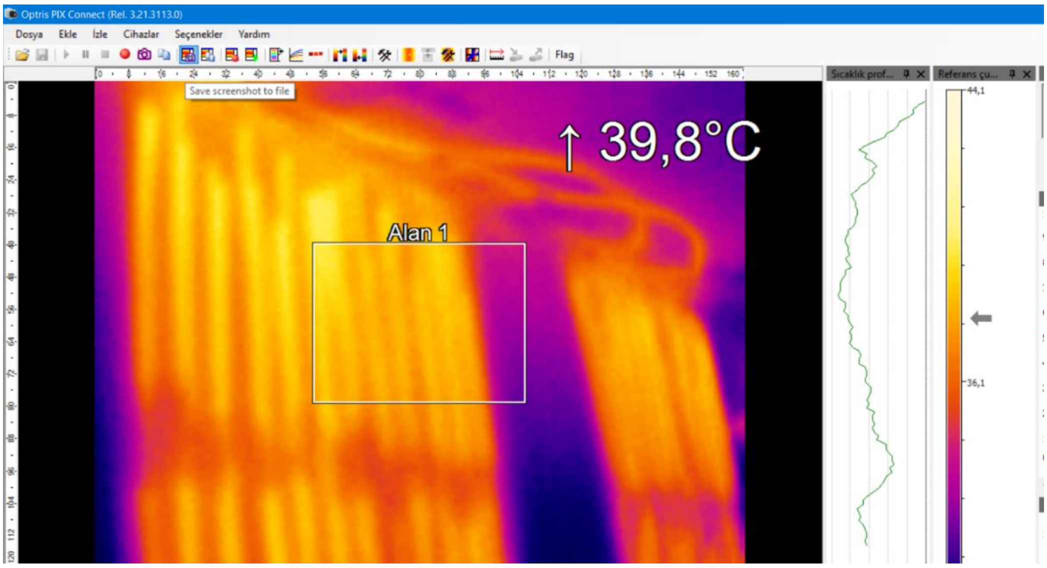


Figure 4.16 PCM wall thermal camera image-3

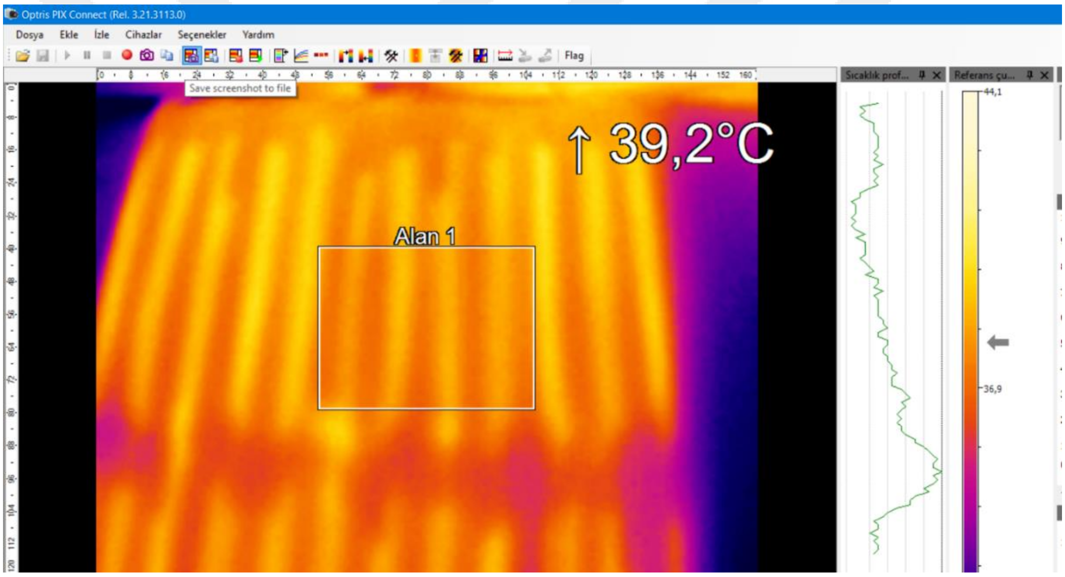


Figure 4.17 PCM wall thermal camera image-4

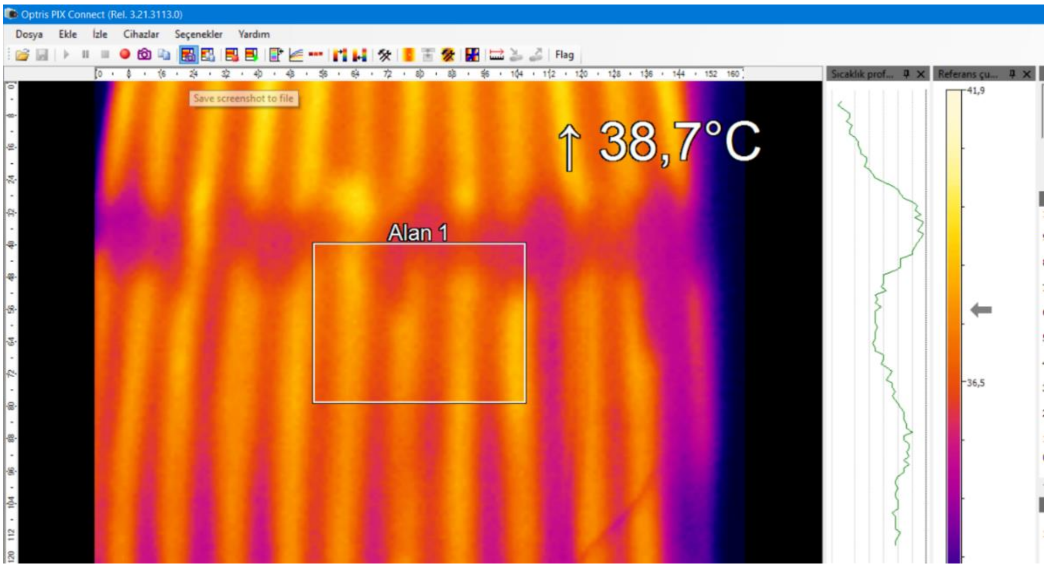


Figure 4.18 PCM wall thermal camera image-5

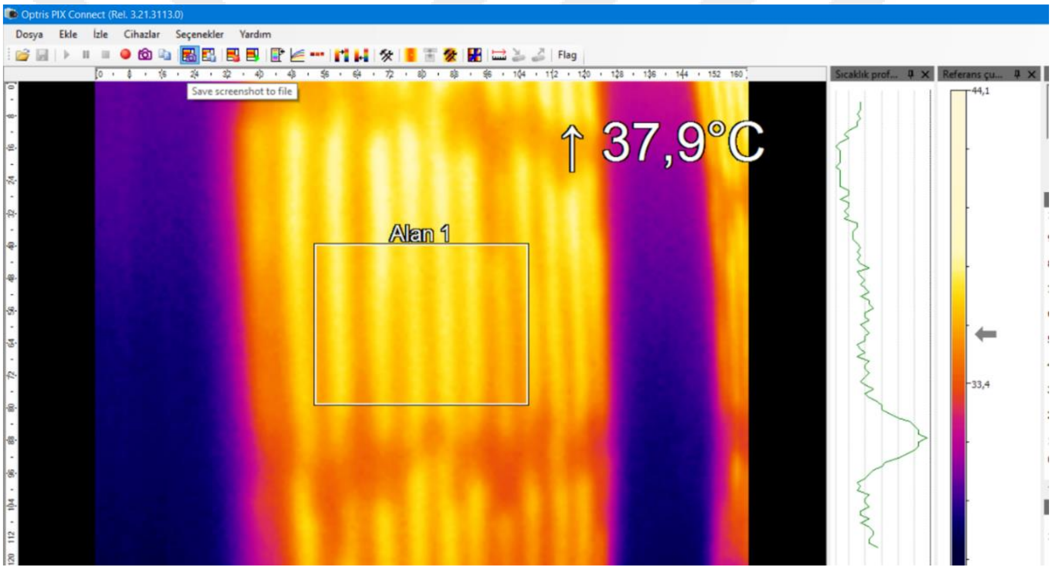


Figure 4.19 PCM wall thermal camera image-6

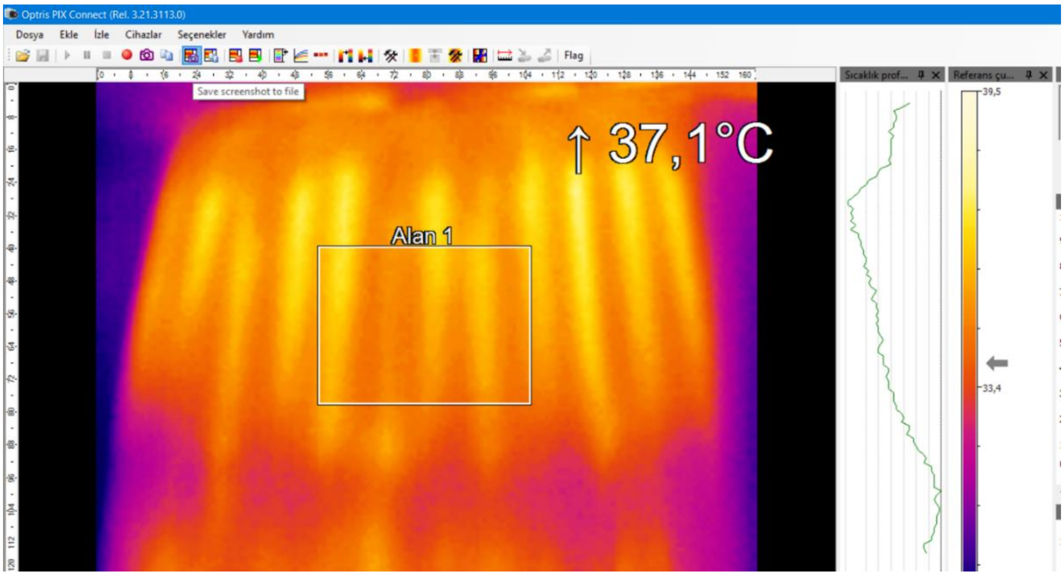


Figure 4.20 PCM wall thermal camera image-7

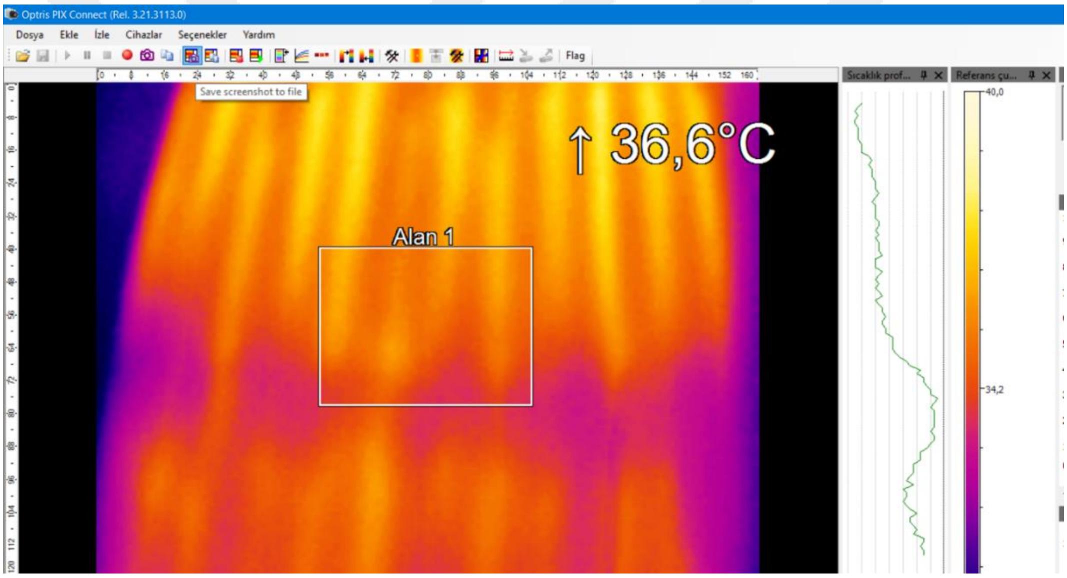


Figure 4.21 PCM wall thermal camera image-8

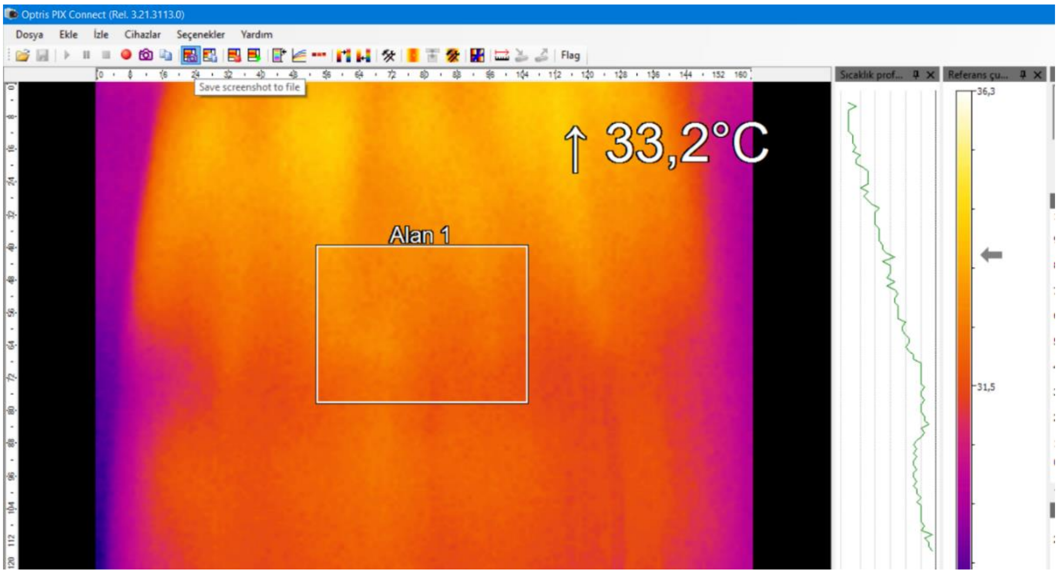


Figure 4.22 PCM wall thermal camera image-9

In conclusion, to further enhance the scope and depth of this research, future investigations could explore the utilization of various PCMs along with different encapsulation methods, such as tube and shell configurations. Exploring a diverse range of PCM options and encapsulation techniques can provide valuable insights into optimizing thermal energy storage systems for enhanced efficiency and applicability. This avenue of research holds the potential to contribute significantly to the field, advancing our understanding and application of sustainable heating and cooling Technologies.

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APPENDIX CHAPTER HEADING

PUBLICATIONS FROM THE THESIS

Conference Papers

1. 9TH INTERNATIONAL "BAŞKENT" CONGRESS ON PHYSICAL, ENGINEERING, AND APPLIED SCIENCES PROCEEDINGS BOOK

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