MARMARA UNIVERSITY

INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES

EXPERIMENTAL ANALYSIS OF REFRIGERATION SYSTEM USING PHASE CHANGE MATERIAL FOR ENERGY EFFICIENCY IMPROVEMENT

DİLARA KURTBOĞAN

MASTER THESIS

Department of Mechanical Engineering

Thesis Supervisor

Asst. Prof. Dr. Barış YILMAZ

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TABLE OF CONTENTS

ÖZET

ENERJI VERİMLİLİĞİNİ GELİŞTİRMEK İÇİN FAZ DEĞİŞTİREN MALZEME KULLANILAN SOĞUTMA SİSTEMİNİN DENEYSEL ANALİZİ

Bu çalışmada bir soğuk oda içersine yerleştirilmiş faz değiştiren malzemelerin (FDM) seçimi yapılıp, FDM eklenmesinin kabin içi hava sıcaklıklarının değişimine, kompressor dur-kalklarına, enerji verimliliğine, güç kesintisi sırasındaki sıcaklık korunumuna olan etkileri incelenmiştir. Deneyler için sentezlenmiş ve kapsüllenmiş FDM'lerin seçimi geniş bir literatür taraması ve titiz laboratuvar testleriyle yapılmıştır. FDM kapsülleri test edilmek üzere içi içe iki odadan oluşturulmuş bir klimatik oda test düzeneği içine yerleştirilerek farklı çalışma şartlarında kabin içi sıcaklık değişimi, kompressör dur-kalk süreleri üzerine olan etkileri incelenmiştir. Ayrıca, iç ve dış ortam sıcaklıkları koşullandırılarak yapılan testler sonucunda, ideal çalışma şartlarına göre oluşturulmuş datalarla karşılaştırıldığında soğuk oda içerisine FDM eklemenin soğutma sisteminin performans katsayısını etkisi incelenmiştir. Farklı çalışma şartlarını incelemek amacıyla dış ortam koşulları 30 °C, 20 °C ve 10°C olarak şartlandırılmıştır. Ayrıca kompresörün çalışma aralağı ayarlanarak kabin içi sıcaklığının belirlenen set değrerinden 2 °C, 4 °C ve 6 °C sıcaklık farkları için kompresör çalışma verileri ve iç hava sıcaklık değişim grafikleri elde edilmiştir. Çoğu senaryoda FDM eklenmesi ile compressor dur-kalk sayısını azaltarak compressor ömrünü uzatmaya katkı sağladığı gözlenmiştir. FDM'leri dondurmak için gerekli elektrik gücü de performans hesapları için hesaplanmıştır. FDM lerin sisteme katkısı hesaplanırken soğutma sistemi tarfından harcanan gücün telafi süresi de gözönüne alınmaktadır. Yapılan çalışmalara ek olarak güç kesintisi durumunda oda sıcaklığının FDM'nin gizli ısısı sayesinde ne kadar süre korunduğu ve oda sıcaklığının değişimi de incelenmiştir.

ABSTRACT

EXPERIMENTAL ANALYSIS OF REFRIGERATION SYSTEM USING PHASE CHANGE MATERIAL FOR ENERGY EFFICIENCY IMPROVEMENT

This study presents selection of the phase change materials (PCMs) placed inside of a cold storage room, and the effect of the addition of PCMs to the change in air temperature inside the room, the compressor on-off periods, the energy efficiency, temperature change during a power failure. The selection of the PCMs, which are synthesized and encapsulated for the experiments, is also done by a broad literature search and meticulous laboratory tests. In order to test them, PCM capsules were placed in a climatic room test rig formed by two chambers, and under different operating conditions their effects on the temperature change in the cabin and stop-start times of the compressor were examined. Moreover, according to the experimental results which are conducted in conditioned inner and outer zones, outcomes of adding PCMs to a cold room to the COP of the refrigeration system while comparing to the compressor ideal working data are analysed. To observe different operating conditions the outer zone is set 30 °C, 20 °C and 10°C, and also by adjusting the working range of the compressor, compressor operation data and indoor air temperature change graphs were obtained for the 2 °C, 4 °C and 6 °C temperature differences from the determined set value of the cabin. In most of the scenarios, it is observed that addition of the PCM reduces the number of compressor on-offs, which helps the compressor lifespan increase. The charge power required to freeze PCMs is also calculated for performance calculations. When calculating the contribution of PCMs to the system, the compensation time of the power consumed by the cooling system is also calculated. In addition to the studies conducted, in the case of power failure how long the room temperature is maintained due to the latent heat of the PCM and the change of the room temperature are also examined.

ABBREVIATIONS

USD : the United States of America Dollar

TES : Thermal Energy Storage

PCM : Phase Change Storage

CES : Cambridge Equation Solver

EES : Engineerig Equation Solver

AHP : Analytic Hierarchy Process

PP : Polypropylene

PS : Polystyrene

PET : Polyethylene terephthalate

HDPE : High-density polyethylene

AHU : Air Handling Unit

NTC : Negative Temperature Coefficient

ASHRAE :American Society of Heating, Refrigerating and Air-Conditioning Engineers

DSC : Differential Calorimetric Scanner

CMC : Carboxymethyl Cellouse

COP : Coefficient of Performance

SC : the Standard Condition

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The need for energy is increasing day by day with the needs of the developing world. In addition to finding alternative energy sources to meet the energy requirement, using existing energy in a 'smart' way is to respond to this energy need. Because no matter how much energy is produced, its inefficient consumption will, of course, lead to inadequacy. In addition, even if a large amount of production is made to respond to energy consumption, the negative impact of this energy on our world should be taken into consideration. Therefore, every energy produced should be consumed as efficiently as possible.

Approximated number of refrigeration system running around the world, including heat pumps and air conditioning systems, is 5 million and also its yearly market share is roughly 500 billion USD. The refrigeration sector has a major role in the world's electric consumption which is estimated as %20 of the overall [1]. Direct and indirect greenhouse emission of the refrigeration sector, along with air-conditioning and heat pumps, creates %7.8 of worldwide greenhouse emission [2]. These show the gravity of the refrigeration sector economically and environmentally. Hence taking action about the refrigeration sector's energy consumption is of great importance. One of the most convenient ways to succeed in energy efficiency and meet the increasing power demand is using thermal energy storage(TES) by phase change materials(PCMs).

Energy is stored in three ways: mechanical, electrical and thermal [3]. Thermal storage is classified into sensible heat, latent heat and thermochemical or a combination of these [4]. During a phase change, latent heat of PCMs is utilized. The temperature remains constant while the energy changes. This situation can be turned into an advantage in cold stores. Phase change materials may be utilized to prevent or delay the temperature change that may occur from heat gain during an electrical power failure, door opening or defrosting [5]. However, the choice of Phase Change Material plays a very important role. Because the features of the material such as phase change temperature, latent heat capacity, the tendency to supercooling or thermal conductivity, are crucial to adapt to the system. In addition, the container and the compatibility of the material should be considered. Otherwise, corrosion may occur between the material and the container or the

thermal conductivity may decrease due to the shape and material of the container. With all this in mind, the Phase Change Materials are classified according to many criteria [6] [7] [8] [9] [10] [11] [12]. Since the aim is for cold rooms, the studies suitable for subzero applications are scanned. PCMS and Types of PCMs will be introduced in detail in the next section.

1.1. Phase Change Materials

The latent heat of fusion of PCMs is utilized in many areas. Abhat [13]classified phase change materials according to their chemical structure. PCMs are mainly divided into three large families, organic, inorganic, and eutectics as seen in Figure 1.1 [14]. Although eutectics are nothing but organic or inorganic, they are seen in a different category. The following features are generally considered for the selection of materials [15]:

• Suitable phase change temperature and pressure close to atmospheric pressure for the desired application

• Large fusion heat with high heat storage density compared to sensible heat

• Cycle stability which allows materials to store and discharge energy many times: Phase segregation is a major problem in thermal storage. The energy storage capacity may be reduced when it is different from its initial phase.

• High thermal conductivity and low super-cooling

• Stable chemical property, low corrosion, low ozone depletion potential and low global warming potential

• Easy manufacturing and low cost

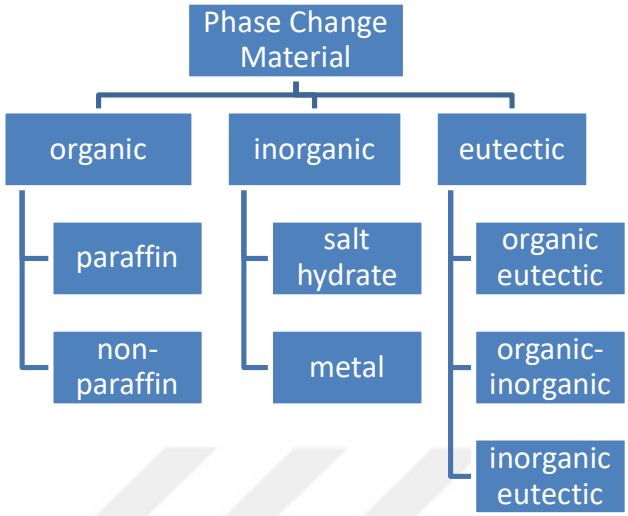

Figure 1.1. Classification of phase change materials [14]

The material that contains all these features is an excellent PCM. Unfortunately, there is no such PCM yet for subzero applications [15]. Nevertheless, there are ongoing efforts to improve their features. The comparison of organic and inorganic materials according to their advantages and disadvantages is shown in Table 1.1 [16]. Some may be compromised or some improvement may be made during material selection. Before starting to improvement works, the properties of the materials should be well known.

Table 1.1. The Comparison of Organics and Inorganics for Thermal Storage [16]

	Organics	Inorganics	Eutectics
Advantages	• Non-corrosive • No super-cooling or little • Chemical and thermal stability	• The high heat of fusion	• The high heat of fusion
Disadvantages	• Lower heat of fusion • Lower thermal conductivity • Flammability	• Super-cooling • Corrosion • Phase separation and phase segregation	• None (no disadvantages that found yet)

1.1.1. Organic Phase Change Materials

Organic PCMs are considered as paraffin and non-paraffin. Organic PCMs are generally materials which do not cause corrosion, do not overheat, and have material stability. However, fusion temperatures are lower than inorganic PCMs. They have low thermal conductivity, which makes it possible to delay the heat transfer to the desired environment while it is used as the thermal storage. Some species have flammable effects. Table 1.2 shows some of the thermal properties of paraffin [17].

Table 1.2. Thermal properties of paraffin [17]

PCM	Melting Temperature (°C)	Heat of Fusion(kj/kg)	Liquid Density (kg/m^3)	Volumetric Heat of Fusion(kj/cm^3)
$C_{10}H_{22}$	-29,6	201,8	730	147,3
$C_{11}H_{24}$	-25,5	141,9	740	105
$C_{12}H_{26}$	-9,5	216,2	748	161,7
$C_{13}H_{28}$	-5,3	154,5	756	116,8

As seen in Table 1.3, Li et al. listed the sub-zero cold storage materials in terms of melting temperatures, the heat of fusion and liquid densities of phase change materials [15].

Table 1.3. Thermal properties of alkenones [15]

PCM	Melting Temperature (°C)	Heat of Fusion(kj/kg)	Liquid Density (kg/m^3)	Volumetric Heat of Fusion(kj/cm^3)
2-Octanone ($C_8H_{16}O$)	-20,3	190,4	819	155,9
5-Nonanone ($C_9H_{18}O$)	-3,8	175,3	144,	144,8

1.1.2.Inorganic Phase Change Materials

Inorganic PCMs have a melting heat that is almost twice of organics. They have higher thermal permeability and lower costs [18]. However, corrosion of inorganic PCMs with metals shortens the working life and makes it more expensive [19]. In addition, salt and aqueous salts suffer from phase separation and super-cooling that affect their energy storage capacity [20].

1.1.3. Eutectic Phase Change Materials

The majority of the studies on PCM are on eutectic phase change materials. Because salty waters are easy to access high efficient PCMs. However, all the drawbacks mentioned for inorganic PCMs also are valid for salty waters which are inorganic eutectic PCMs as well. Zheng and Wu [21]'s study on salty water is shown in Table 1.4. In order to determine the heat storage per unit volume, density is also calculated.

Table 1.4. Thermal properties of eutectic solutions [21]

PCM	wt. % of salt	Melting Temperature (°C)	Heat of Fusion(kj/kg)	Volumetric Heat of Fusion(kj/cm^3)
$NaCl/H_2O$	0,22	-21,2	228,14	228,7
$(NH_4)_2SO_4/H_2O$	0,40	-18,5	187,75	188,3
$NaNO_3/H_2O$	0,37	-17,7	187,79	188,7
NH_4NO_3/H_2O	0,41	-17,35	186,29	186,8
NH_4Cl/H_2O	0,20	-16	258,18	258,4
$Ca(NO_3)_2/H_2O$	0,35	-16	199,35	200,4
K_2HPO_4/H_2O	0,37	-13,5	197,79	198,8
$Na_2S_2O_3/H_2O$	0,30	-11	219,86	220,3
KCl/H_2O	0,20	-10,7	253,18	253,7
$MnSO_4/H_2O$	0,32	-10,5	213,07	214,6
NaH_2PO_4/H_2O	0,32	-9,9	214,25	215,2
$BaCl_2/H_2O$	0,23	-7,8	246,44	248
$ZnSO_4/H_2O$	0,27	-6,5	235,75	237,4
$Sr(NO_3)_2/H_2O$	0,245	-5,75	243,15	244,3

$KHCO_3/H_2O$	0,17	-5,4	268,54	269,1
$MgSO_4/H_2O$	0,19	-3,9	264,42	265,3
Na_2SO_4/H_2O	0,13	-3,55	284,95	285,6
NaF/H_2O	0,04	-3,5	314,09	314,3
KNO_3/H_2O	0,10	-2,8	296,02	296,3
$NaOH/H_2O$	0,19	-2,8	265,98	266,6
Na_2CO_3/H_2O	0,06	-2,1	310,23	310,5
$FeSO_4/H_2O$	0,13	-1,8	286,81	287,8
$CuSO_4/H_2O$	0,12	-1,6	290,91	291,8

Commercial eutectic water-salt solutions shown in Table 1.5 are evaluated by Li et al. [15]. The energy storage capacity of several eutectic PCMs per unit volume was calculated in that work.

Table 1.5. Thermal properties of eutectic water-salt solutions

PCM	Melting Temperature (°C)	Heat of Fusion(kj/kg)	Liquid Density (kg/m^3)	Volumetric Heat of Fusion(kj/cm^3)
E-22	-22	234	1180	276,12
SN21	-21	240	1120	268,8
STL-21	-21	240	1120	268,8
E-21	-20,6	263	1240	326,12
E-19	-18,7	282	1125	317,25
SN18	-18	268	1210	324,28
E-15	-15	303	1060	321,18
SN15	-15	311	1020	317,22
E-14	-14,8	243	1220	296,46
E-12	-12,3	250	1110	277,5
SN12	-12	306	1060	324,36
E-11	-11,6	301	1090	328,09

STLN10	-11	271	1050	284,55
SN10	-11	310	1110	344,1
E-10	-10	286	1140	326,04
E-6	-6	275	1110	305,25
STL-6	-6	284	1070	303,88
SN06	-6	284	1070	303,88
E-4	-3,9	282	1060	298,92
E-3	-3,7	312	1060	330,72
STL-3	-3	328	1010	331,28
SN03	-3	328	1010	331,28
E-2	-2	306	1070	327,42
HS 23N	(-22) – (-24)	200	1180	236
HS 7N	(-7) – (-5)	230	1120	257,6

Mixtures of organic PCMs are also available, as well as the inorganic PCM mixtures. The studies of Yılmaz et al. [22] on this subject are shown in Table 1.6.

Table 1.6. Thermal properties of paraffin mixtures [22]

PCM	Melting Temperature (°C)	Heat of Fusion(kj/kg)	Liquid Density (kg/m^3)	Volumetric Heat of Fusion(kj/cm^3)
40:60 $C_{13}H_{28}$:$C_{12}H_{26}$ (wt.%)	-9,7	159	751,2	119,4
50:50 $C_{13}H_{28}$:$C_{12}H_{26}$ (wt.%)	-9,1	145	752	109
60:40 $C_{13}H_{28}$:$C_{12}H_{26}$ (wt.%)	-8	147	752,8	110,6

80:20 $C_{13}H_{28}$:$C_{12}H_{26}$ (wt.%)	-5,4	126	754,4	95
60:40 $C_{13}H_{28}$:$C_{14}H_{30}$ (wt.%)	-1,5	110	757,2	83,3

Guo et al. [23]studied multicomponent organic PCMs. These are shown in Table 1.7. In addition, the Renewable Alternative products of Thermester- (14) B and Thermester- (12) M [24] are also known as multi-component organic PCMs. These PCMs are called green technology composed of unutilised animal fats, vegetable waste oils which are not adequately evaluated [15].

Table 1.7. Thermal properties of multicomponent organic PCM [15]

PCM	Melting Temperature (°C)	Heat of Fusion(kj/kg)	Liquid Density (kg/m^3)	Volumetric Heat of Fusion(kj/cm^3)
Sodium formate/H_2O	-18	250,2	1184	296,24
Ethylene glycol/Sodium formate/H_2O	-25	173,1	1103	191
Glycerol/Sodium formate/H_2O	-23	174,5	1118,1	195,1
Ethylene glycol/Sodium acetate/H_2O	-19	118.5	1064,1	126
Glycerol/Sodium acetate/H_2O	-14	156.0	1078,9	168,3
Glycerol/Sodium lactate	-10	159.3	1044,3	166,35

Shen [25]conducted a hybrid PCM study involving inorganic and organic composition PCMs. This hybrid PCM is a good candidate for cold storage applications with temperature range and phase change temperature.

1.2. Selection of PCM

The selection of phase-change materials for thermal energy storage systems is based on many factors such as material properties, the storage capacity of the system, operating temperature, heat transfer and the design of heat exchangers [26]. The selection criteria are already defined as the criteria suggested by Li [15]. The proposed methodologies should be followed in terms of how to apply these selection criteria. These selection methods are mostly experimental [27] [28] [29] [30] [31],but may also be numerical simulations [32] [33]There is much software for selecting materials. Ramalhete et al. [38] researched this topic and found 87 databases and software. Fernandez et al[39] selected material for sensible heat storage using the Cambridge Engineering Selector (CES) software. In addition to this, Phase Change Material can be selected by using Multi-Criteria Decision-Making methods. Wang et al. [34]used the VIKOR Method for low-temperature thermal storage and found that the results agree with the experimental data. Similarly, Socaciu et al. [35]made the selection of PCM for thermal comfort in vehicles using the Analytic Hierarchy Process (AHP) method and stated that the test results were capable of leading to further studies.

1.3. Encapsulation of Phase Change Material

In the food or health sector, the PCM must not come into contact with the stored product. However, the coating method and shape used greatly affect the heat transfer rate. Maintaining PCM for this purpose is called encapsulation. The encapsulation methods are classified according to their size as follows [36]: 1) Macro (greater than 1 mm), 2) Micro (0–1000 mm) 3) Nano (0–1000 ηm) encapsulated PCM
Also, various encapsulation geometries are shown in Figure 1.2.

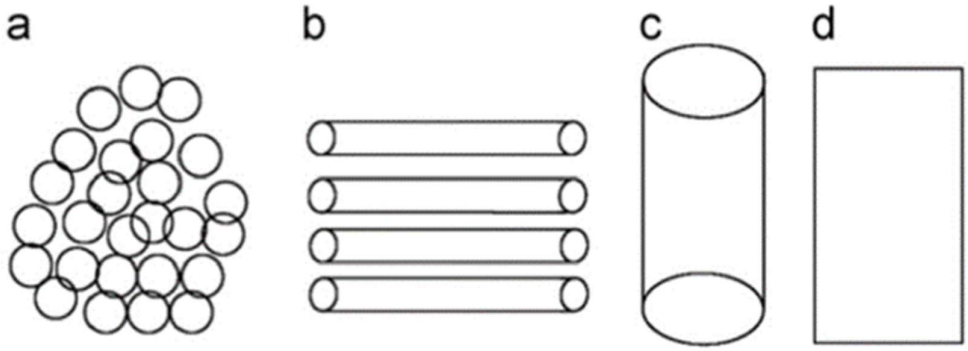

Figure 1.2. PCM Encapsulation Geometries: a. spherical b. tube c.cylindiracal d.rectangual [37]

1.3.1. Macroencapsulation

Macroencapsulation is the most widely used encapsulation method of PCMs. Simply placing the PCM in a container larger than 1 mm thick can be considered as macroencapsulation.

If the high heat transfer rate is a selection criterion, the metal capsule should be selected. If it is not, the plastic container with low thermal conductivity is preferred [37]. The two types of containers are also shown in Figure 1.3.

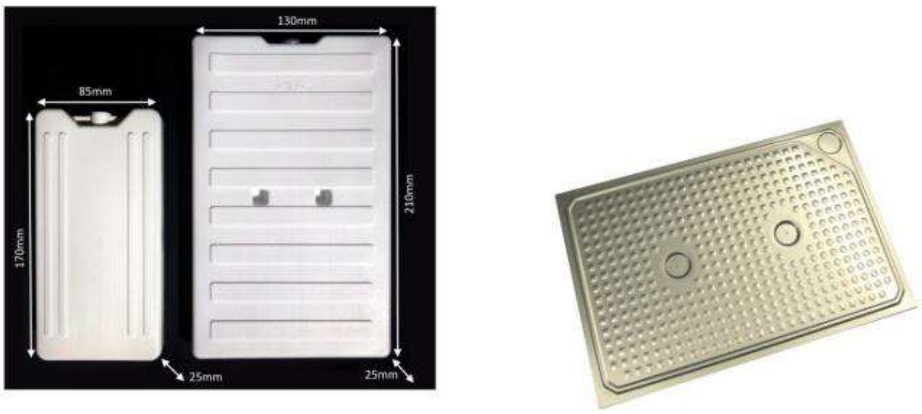

Figure 1.3. Macroencapsulated PCMs of Rubiterm: cooling accumulators(left), aluminium compact storage modules(right) [38]

1.3.2. Microencapsulation

A type of encapsulation in which the capsule containing the PCM is smaller than 1 mm is called microencapsulation. The microencapsulated PCM has a high heat transfer rate compared to the microencapsulated PCM. Because the microencapsulated FDM has a larger surface area to volume ratio and less chemical reaction with the material used as the shell. Sari et al proved that microencapsulated PCMs are more reliable, chemically and thermally more stable than macroencapsulated ones [39]. The preparation of these PCMs is carried out under laboratory conditions and the results are observed by scanning electron microscope (SEM).

1.3.3. Nanoencapsulation

This encapsulation method is also prepared in a professional environment such as microencapsulation. It gives better results than microcapsules and microcapsules due to the smaller dimensions. However, the cost of preparation is higher than others.

1.4. Performance Improvement

1.4.1. Super-cooling

Super-cooling means that the substance is in liquid form even when it is below freezing temperature. If the material does not change its state, latent heat cannot be utilized. This is a very important problem for the thermal storage system where it aims to benefit from latent heat. Super-cooling is generally experienced in inorganics (aqueous salts and brine solutions). There are several methods to overcome this obstacle. The first is to use a nucleating agent that is the material that initiates or accelerates the crystallization process [40]. The second solution is to use a cold finger. This device allows nucleation by keeping the temperature below the supercooling temperature [41].

1.4.2. Corrosion

Corrosion is important for the design of the container where the PCM is placed. Because a reaction between the PCM and the container will damage the structure of both, and the expected performance of the system cannot be obtained. There are varieties such as pitting corrosion, galvanized corrosion, erosion, vibratory wear, unalloying, hydrogen brittleness and oxidation [42]. Wear occurs when the anode-cathode relationship occurs between the PCM and the container [43]. Cabeza et al. put five types of metals commonly used with

various PCMs for wear testing [44] [45]. In addition, a similar experiment was conducted by Yılmaz et al. [46]. Based on these studies, the container to be used in inorganics should be stainless steel or plastic-based materials such as polypropylene(PP), Polystyrene (PS), Polyethylene terephthalate (PET) and High-density polyethylene (HDPE).

1.4.3. Phase Segregation

Phase segregation may occur in inorganic PCMs due to melting and freezing process. However, this does not occur in eutectic mixtures [47]. Kenisarin [48] has shown that the most promising compounds are double or triple eutectics, especially fluorinated and chlorinated varieties.

1.4.4. Thermal conductivity

In addition to the latent heat capacity of inorganic and organic-based PCMs, thermal conductivity is another factor to be considered. Although the thermal conductivity of inorganic substances is high, the whole system is affected if the thermal conductivity of the polymer-based shell used as a container is low. Hence polymers are generally modified to increase thermal conductivity [49]. There are several methods for these modifications.

1.4.4.1. Fins and Expanded Surfaces

Also known as finned surfaces, fins are one of the most common methods for increasing the heat transfer rate. Studies are suggesting that fin surfaces are also used in PCM containers. In the work of Hosseini [50], Rozenfeld [51], Rathod [52] and Gharebaghi [53], the performance of the horizontal fins were observed. Sciacovelli [54] found that heat transfer efficiency increased by 24% using Y type fin.

1.4.4.2. Addition of Particles with High Thermal Conductivity

Organic PCMs such as paraffin have low thermal conductivity. It has been considered that it is appropriate to add particles with high thermal conductivity to break the internal thermal resistance and increase the heat transfer rate. These particles are generally carbon-based materials [55] [56] [57].

1.4.4.3. Microencapsulated PCM

Microencapsulation, which is already mentioned, increases thermal conductivity. Likewise, nanoencapsulation can be utilized in this manner. Microencapsulation also

reduces the risk of corrosion and leakage. There are many positive studies on microencapsulated PCM [58] [59].

1.4.4.4. Multiple PCM Method

This PCM method was used in flow applications. The desired temperature value is maintained by latent heat extraction or oscillation at different temperatures. Many researchers have conducted studies on this method [60] [61].

1.4.4.5. Other Methods

Organic polymer containers used as shells have low thermal conductivity. They are therefore treated with graphene oxide grafting [62] or silver coating [63].

Veltage [64] and Ettouney [65] observed that the heat transfer rate increased by 20% by placing a metal body into the PCM. Abdollahzadeh [66] showed that by reducing the cohesion surface wavy, it reduces the solidification time by 60%. In addition, Omari [67] et al. examined the effect of various plate geometries on melting and concluded that rounded edges had a positive effect on efficiency.

2. METHODOLOGY

2.1. The Refrigeration System

The testing of the PCMs has occurred in Research and Development(R&D) Laboratory of Frigoblock Refrigeration Systems Company. The PCM experiments have been carried out in a cold storage unit to examine large amounts of PCM in a cold storage unit to examine large amounts of PCM in cold storage. To maintain the result as close as the real-life implementations, the whole system has been equipped as actual conditions.

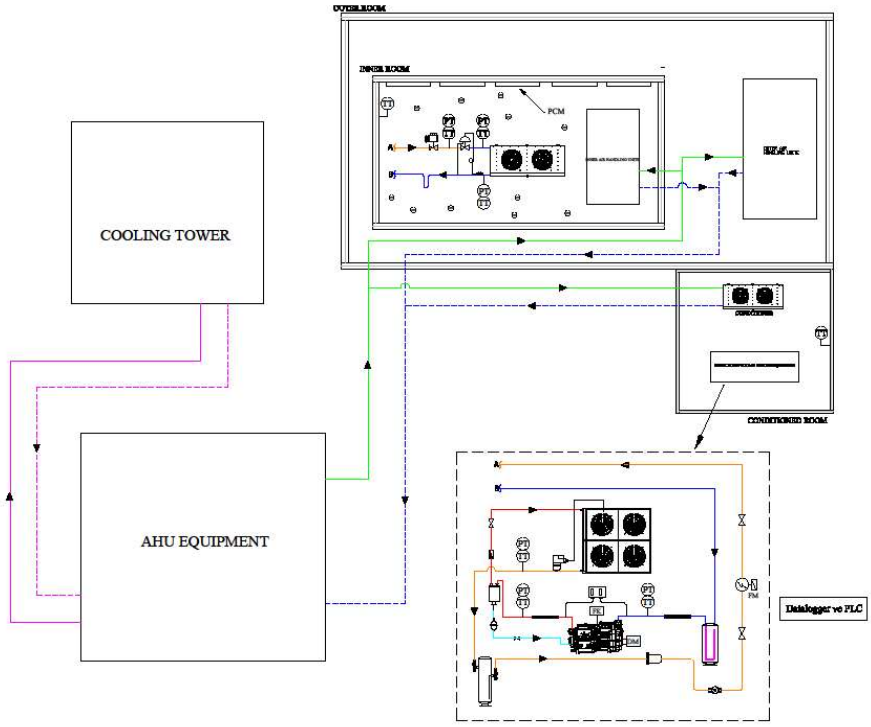

Figure 2.1. Simplified Scheme of the Experimental Setup

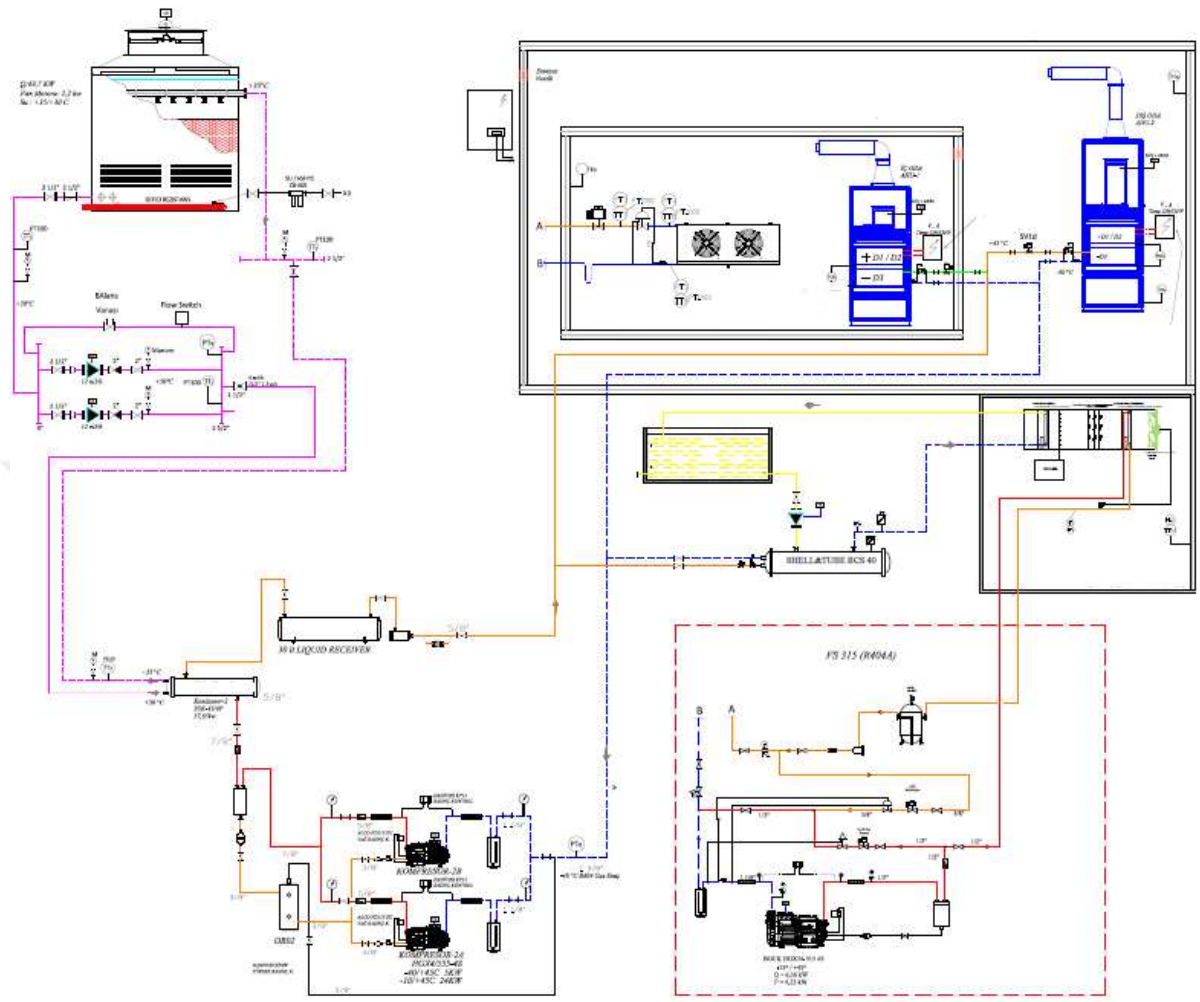

Figure 2.2.The Detailed Scheme of the Experimental Setup

The experimental setup with its components is shown in Figure 2.1. and Figure 2.2. The system consists of mainly 4 different units which are the inner room, the outer room, the conderser conditioning room, and the cooling system including cooling tower and AHU equipment to condition the outer room and the conditioned room. The first three rooms are mostly going to be discussed owing to their application in experiments.

The compressor of the system which is a GEA Bock HGX34-315 4S circulates R404A as the refrigerant. The refrigerant flows respectively through the evaporator, compressor, condenser and expansion valve of the cycle.

All sensors and electronic devices are connected to TelevisGo of ELIWELL data acquisition system to monitor and control the system. The logged and controlled within the run time interval of the experiments are as follows; the desired temperature for inner, outer, and conditioned rooms, the desired humidity for the conditioned room, the energy consumption of the compressor, temperature and pressure monitoring of the inlet and outlet pump line of main components.

2.1.1. The Inner Room

PCMs are located in the inner room as seen in Figure 2.2. This room consists of the evaporator with fan, an air handling unit(AHU) which is not used during the tests. Ten T-type thermocouples to measure PCM temperature from the surface of the PCM, 27 NTC temperature sensor to measure air temperature of the room are utilized. The volume of the inner room is 37,5 m^3.

2.1.2. The Outer Room

The outer room is built up to simulate the desired environmental conditions. It contains an AHU to maintain the desired temperature. This AHU consists of heating coils to heat the room and cooling fans which blow cool air that is contioned by a cooling tower.

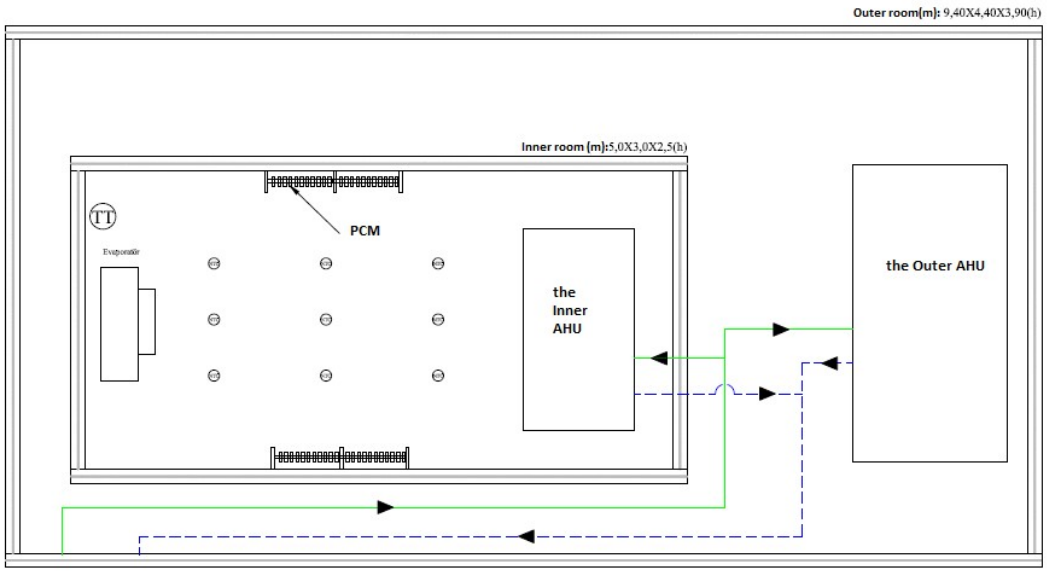

Figure 2.3.Outline of the Inner Room and the Outer Room

Figure 2.3. displays inner and outer rooms. The outer room is 161.5 m^3.

2.1.3. The Condenser Conditioning Room

This is the room where the condenser of the refrigeration system is placed. The surrounding environment where the condenser is located affects the efficiency and the performance of the system. Therefore, the condenser is put in a separate conditioned room to study the effect of ambient conditions. This conditioned room consists of the condenser with a fan, a humidifier to adjust the humidity, a heat exchanger with the water-glycol mixture to cool down the room air, number of humidity and temperature sensors to monitor the temperature and humidity of the room air.

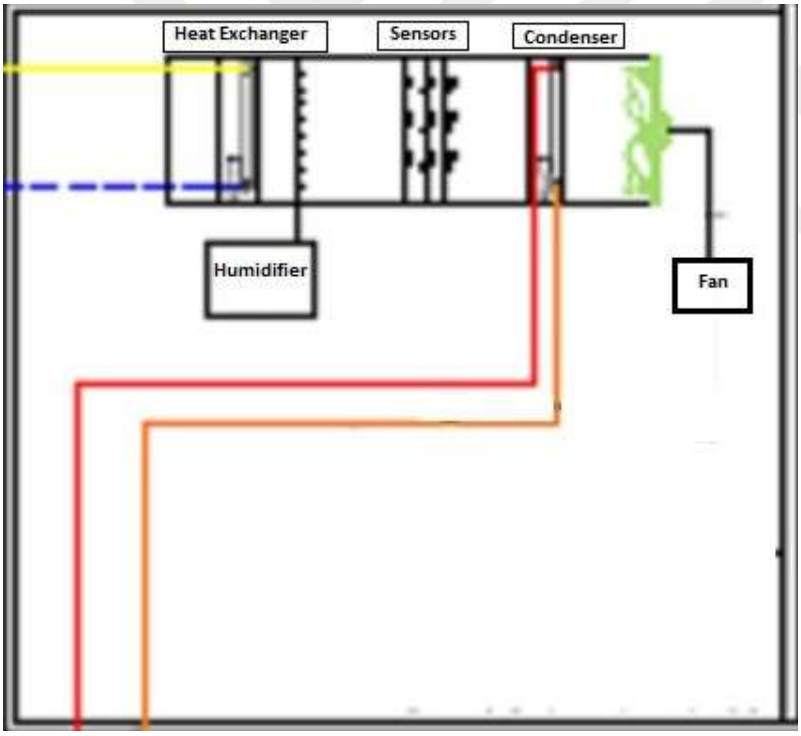

Figure 2.4.A Closer Look at The Condenser Conditioning Room

As seen in Figure 2.2 and Figure 2.4, the condenser room is connected to a water-glycol tank which is highlighted with yellow and a shell and tube heat exchanger. The heat-exchanger to cool the conditioned room down sends warm mixture to the water-glycol mixture tank and the tank sends it to the shell and tube to cool it down. The cooling water-

glycol mixture simply circulates between heat-exchanger of ceonderser room, mixture tank, and shell and tube heat-exchangers. The cooled refrigerant of the shell and tube is maintained by another system which contains 2 compressors, a cooling tower and a heat-exchanger to sustain shell and tube that cools water-glycol heat-exchanger.

2.2. Phase Change Material Selection

All the pros and cons of the PCM types are discussed in the introduction. Also, some of the selection methods are mentioned. To limit the number of candidates several criteria are considered. For example, the material must be cost-effective and eco-friendly. Because it is projected to be an industrial product to reproduce. And another desired aspect is having high thermal conductivity rate and latent heat value. When all the downsides and upsides are taken into account, the material is chosen to be an inorganic eutectic mixture.

According to the SC3 and SC4 [68] test conditions defined by ASHRAE, -18 °C and -25 °C room temperatures are set in experiments. Hence the phase change temperature of PCM must be close to these values due to work properly in the compressor on-off interval. According to previous studies mentioned in the introduction part, the number of salt candidates is narrowed down to 5. But choosing a salt-water mixture is not enough to produce a PCM since problems such as super-cooling, phase segregation, phase separation, etc. must be taken into account. To overcome these problems a nucleating agent and thickening or gelling agent should be added to the mixture. To select an appropriate PCM solution material, It is tested in two steps which are Differential Calorimeter Scanning (DSC) Tests and Freezing Tests.

2.2.3. Differential Calorimeter Scanning Tests

A new PCM solution is worked on since it is aimed to create a PCM answering the desired cold storage needs. To determine phase change temperatures and latent heats of this new solution, DSC tests are conducted. These tests are simply done by Chemical Engineering Lab of Istanbul University.

The upper part of Figure 2.5 shows the behaviour of the PCM solution during freezing. On the other hand, the lower part of it represents the melting of the PCM mixture. The peak points represent melting and freezing points. The melting and freezing points are observed at -30 ^{o}C and -24 ^{o}C respectively. During the freezing experiments, more than one peak is observed may be because of impurities in the solution. The temperature change continues through the phase change process rather than remaining still. This makes a problem in the implementation of PCMs because of the compressor on-off interval.

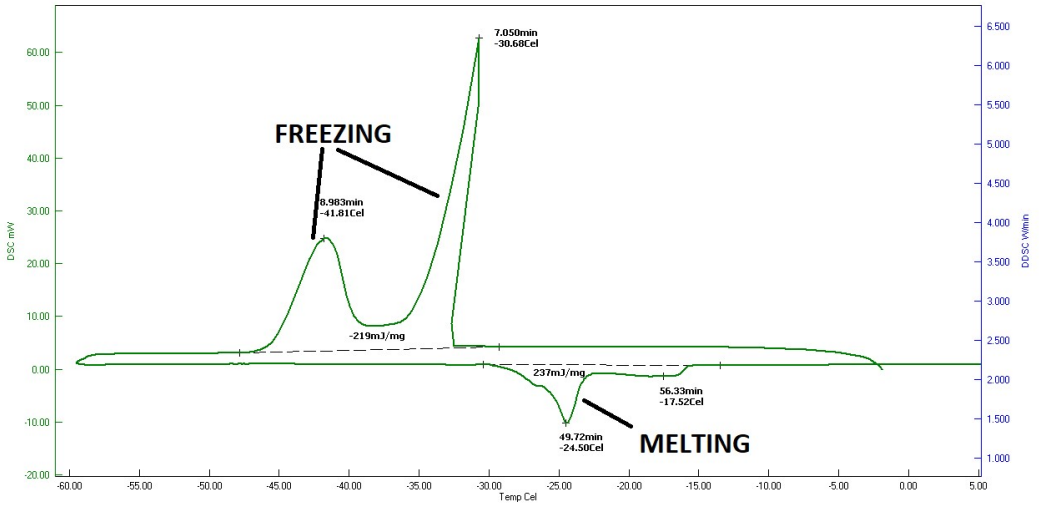

Figure 2.5.An Example of DSC Test Result

The elimination of the candidates via DSC test can not be the only consideration due to finding the perfect fit in a cooling application. Furthermore, the DSC tests may not reflect alone the correct behaviour of the mixture. So, the additional freezing-melting tests in a cold environment are required to observe whether the solution is frozen or not at the desired operating conditions.

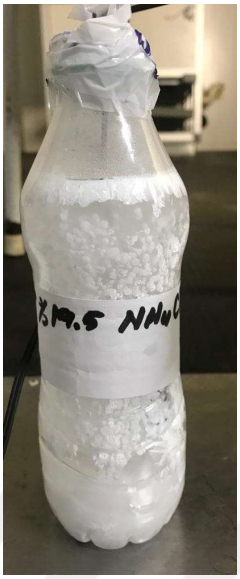

Figure 2.6.An Example of Sample Freezing

2.2.4. Freezing Tests

To observe how the mixtures are proper for the cold storage implementation, a little of the samples are placed into the inner room. The tests are simply done by examining the crystallization of mixtures and monitoring temperature change through a temperature probe that is immersed in the sample bottle. The surrounding environment is conditioned to the desired level and the phase change of the material has been observed and measured.

Figure 2.6. shows the capability of freezing one of the samples. The environment where the sample is placed is set to -18 °C.

2.3. The Encapsulation of the Phase Change Material

The PCM solution that will be used in the cold rooms should be encapsulated in a container. The geometry and the thermophysical properties of the container material are important for the performance of the PCM. Owing to cost-efficiency and feasibility aims, HDPE material is chosen as the material of the container [44] [45]. Figure 2.7. shows the shape of the PCM container which is designed by Frigoblock R&D Department. The

designed containers are produced by the blow molding process. The desired PCM will be easily filled in and closed by a lid which is shown in Figure 2.8.

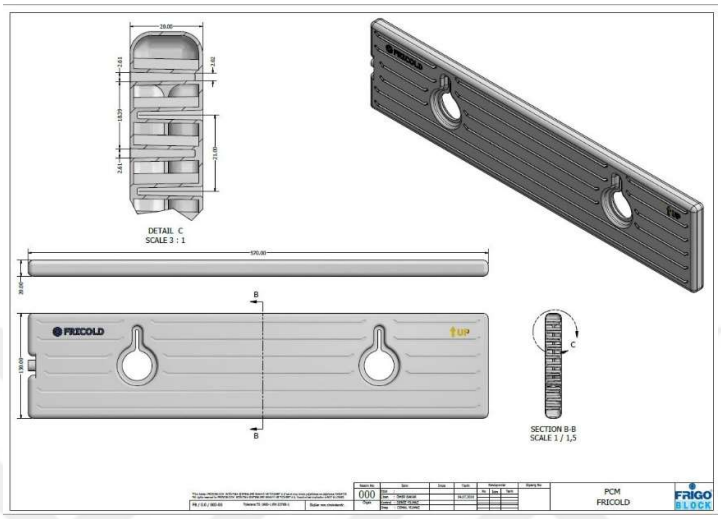

Figure 2.7.The Feature of the PCM Container

Depending on the cooling method of the HPDE material, 1% of the volume of PCM containers may vary. The internal volume is on average 0.625 litres. Since PCMs are water-based, it is predicted that they will experience expansion for freezing. It experiences 11% volumetric growth in comparison to freezing in + 4 ° C. However, this rate was found to be lower in PCM solutions that were examined by freezing. When there is 2% -3% safety percentage, the PCM remained within the safe limits.

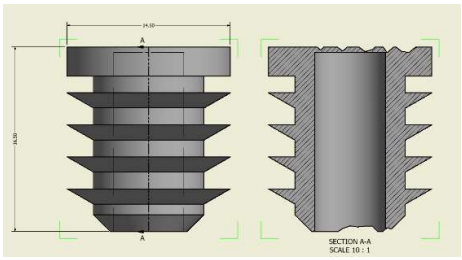

Figure 2.8.The Lid Design for PCM Container

2.4. The Experimental Setup

2.4.3. The Instalment of the PCM

The PCM containers are located vertically in the test room due to providing the most efficient natural convection when the compressor and the fans of the evaporator are off. Figure 2.9 shows a sample instalment method to create natural convection as in fins. In finned surfaces, while the gap between fins diminishes, the number of fins increases and the heat transfer area enlarges but this also causes decreasing of heat transfer coefficient. Hence it ought to be determined to an optimum gap between fins which represent PCMs [69].

Optimum distances between the PCM containers can be found using following relations;

$$S_{opt} = 2.714\left(\frac{S^3 L}{Ra_S}\right)^{0.25} = 2.714\frac{L}{Ra_L^{0.25}} \qquad \textbf{2.1}$$

$$Ra_S = \frac{g\beta(T_s - T_\infty)S^3}{v^2}\Pr \qquad \textbf{2.2}$$

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{v^2}\Pr \qquad \textbf{2.3}$$

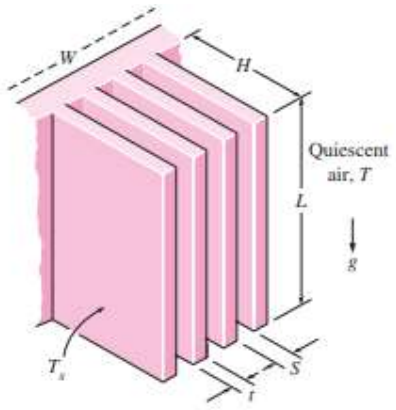

Figure 2.9.Finned Surface [69]

Owing to equations 2.1, 2.2, and 2.3 the optimum gap between fins conserving the boundary layer is calculated 16 mm while the length is 57 mm, the surface temperature is -18°C, and the ambient air is -16°C. The gap is taken as 5 cm to apply it easily.

Figure 2.10.The Implementation of PCMs on the Wall

Figure 2.10 shows the application of PCMs on the wall. Thanks to this placement, the heat gain through walls to the air will be diminished.

2.4.4. The Testing Conditions

The conditions of the experimental setup vary depending on the which aspects wanted to examine. The inner room temperature is initially set to -18 °C due to SC3 [68] but if the tested PCM has different phase change temperature from room conditions, the room conditions will be reset.

For the test the compressor on-off temperature is crucial. Usually, the system is set to 2 °C temperature difference. However, 2 °C temperature difference may not be large enough for PCM to have enough time to melt or to freeze. Hence different temperature gaps are tested for instances to maintain -24°C compressor off temperature and -18°C compressor on temperature, the temperature difference is set to 6 °C.

Another issue is to observe how the heat gains through walls due to different ambient conditions affect the PCM performance. To estimate the performance difference, several outer room temperatures are set such as 10 °C, 20°C, 30°C.

Whole test conditions are repeated with and without PCM in the inner room for comparison.

3. RESULTS

3.1. PCM Selection Results

Twelve eutectic or close to eutectic inorganic solutions to be PCM candidate are selected from the literature review and cold room experiments, which are to be explained in further steps of this chapter, based on the desired operating conditions.

PCM candidates are tested in DSC60 Shimadzu Differential Scanning Calorimetric device to measure their heat of fusion values, freezing and melting point temperatures during phase change. Therefore, it will be understood that whether the solution is suitable or not. The salt percentage is determined according to the eutectic point of the water-salt solutions. Nucleating and gelling agent percentages are determined from the literature [31] [70] [71].

The tests for PCM sample properties are conducted as follows; They are first cooled from 0°C to -60 °C with 5°C/min rate to determine freezing temperature and heat of solidification. Then, samples are held 2 minutes isothermally at -60 °C. Finally, they are heated to 20°C with 1°C/min rate so that heat of fusion values and melting temperatures are measured.

Table 3.1: PCM Candidates that are observed in DSC Test

PCM Candidate	Salt % (wt)	Nucleating Agent % (wt)	Gelling % (wt)	Water %(wt)
Sample 1	$Ca(NO_3)_2$ - 35%	NaCl - 2,5%	CMC - 1,5%	61%
Sample 2	NH_4Cl - 19%	NaCl - 2,5%	CMC - 1,5%	77%
Sample 3	NH_4NO_3 - 41%	NaCl - 2,5%	CMC - 1,5%	55%
Sample 4	$NaNO_3$ - 36%	NaCl - 2,5%	CMC - 1,5%	60%
Sample 5	NaCl - 15%	KNO_3 - 6 % C7H5NaO2 - 1%	CMC - 1,5%	76%

Sample 6	NaCl - 16%	Borax – 2%	CMC - 2%	80%
Sample 7	NaCl - 17%	Borax – 2%	CMC - 1,5%	79,5%
Sample 8	NaCl - 18%	Borax – 2%	CMC - 2%	78%
Sample 9	NaCl - 18%	-	CMC - 1,5%	80,5%
Sample 10	NaCl - 18%	-	-	82%
Sample 11	NH_4Cl - 21%	Borax – 2%	CMC - 1,5%	75,5%
Sample 12	NH_4Cl - 17%	Borax – 2%	CMC - 1,5%	79,5%

Table 3.1 shows all twelve solutions that were observed in DSC Device. But not all of them observed simultaneously. First 4 Samples have been conducted due to the literature review [21] and Sample 5 has been selected from a commercial PCM. Hence for the first step of selection tests, these 5 were observed.

Figures 3.1-3.5 show the heating and melting diagrams (thermograms) of the PCM candidates. The peaks observed in the figures refer to phase change points. Nevertheless, it is also seen that the phase change occurs in duration with large temperature gaps, not at a single point. Hence they are not helpful to indicate precise phase change temperature. But they may figure out the amount of the latent heat released or absorbed during phase change. It is also seen that the freezing and melting processes happen at different temperatures.

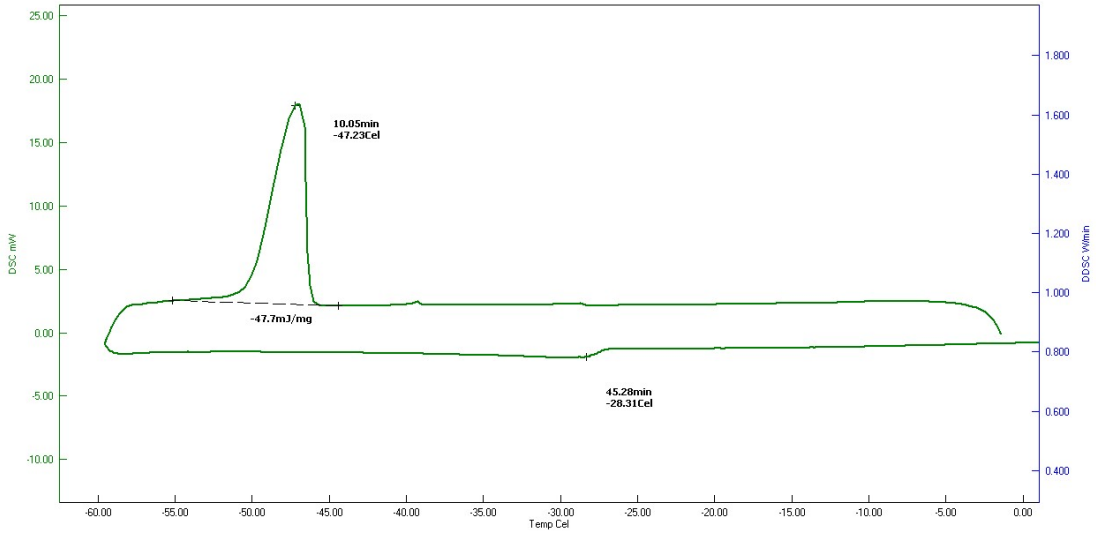

Figure 3.1. DSC Test Graph of Sample 1

As seen in Figure 3.1, Sample 1 has a freezing point at -47 °C and melting at -28 °C. Although its peak points are just one, the gap between them is very big. Tough it is not a pure eutectic solution, it has additives, its melting point should be close to melting temperature data in previous studies [21]. Unfortunately, it does not.

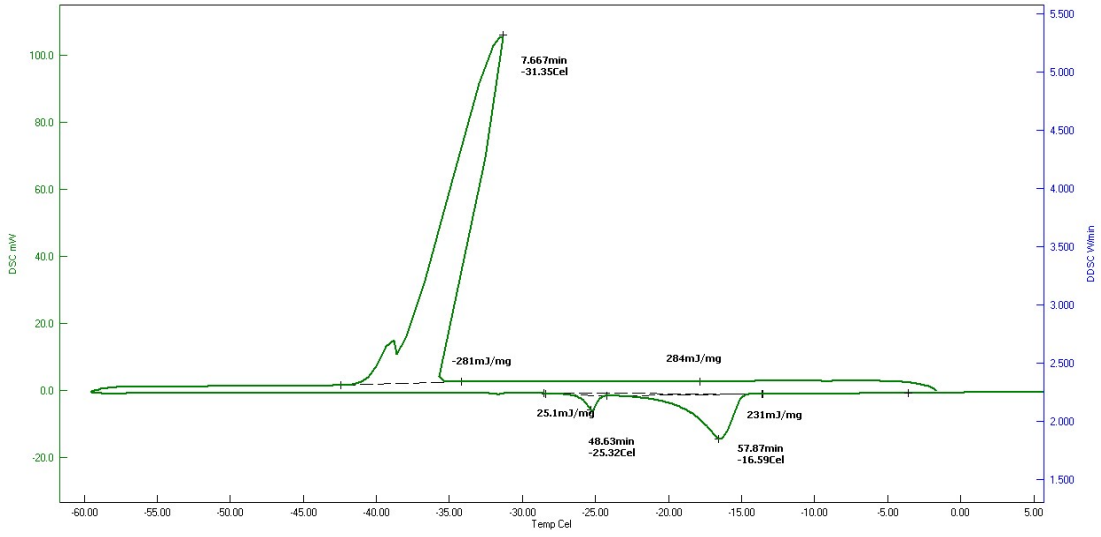

Figure 3.2. DSC Test Graph of Sample 2

In Figure 3.2, Sample 2 has a freezing point at -31 °C and meltings at -25 and -16,5 °C. Although it is not a pure eutectic solution, it has additives, its melting point should be

close to melting temperature data in previous studies. The melting point corresponds with previous data [21].

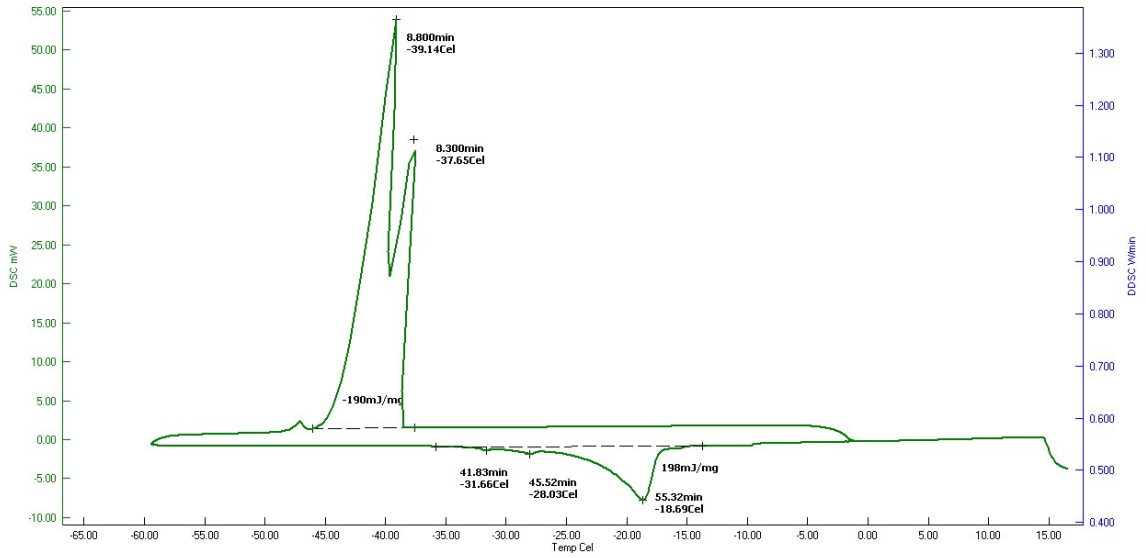

Figure 3.3:DSC Test Graph of Sample 3

In Figure 3.3, Sample 3 has a freezing point at -39 °C and -37,6 °C also, meltings at -18,7 °C. Although it is not a pure eutectic solution, it has additives, its melting point should be close to melting temperature data in previous studies. The melting point corresponds with previous data [21]. Nevertheless, its freezing makes two peaks due to impurities.

In Figure 3.4, Sample 4 has a freezing point at -39,6 °C also, meltings at -27,7 °C and -18,8 °C. Although it is not a pure eutectic solution, it has additives, its melting point should be close to melting temperature data in previous studies. Its second melting point corresponds with previous data [21]. Nevertheless, it makes two melting peaks which are undesirable for PCM applications.

In Figure 3.5, Sample 5 has a freezing point at -45 °C and -33,5°C also, meltings at -24,5 °C. Although it is not a pure eutectic solution, it has additives, its melting point should be

close to melting temperature data in previous studies. The melting point corresponds with previous data [71]. Nevertheless, its freezing makes two peaks due to impurities.

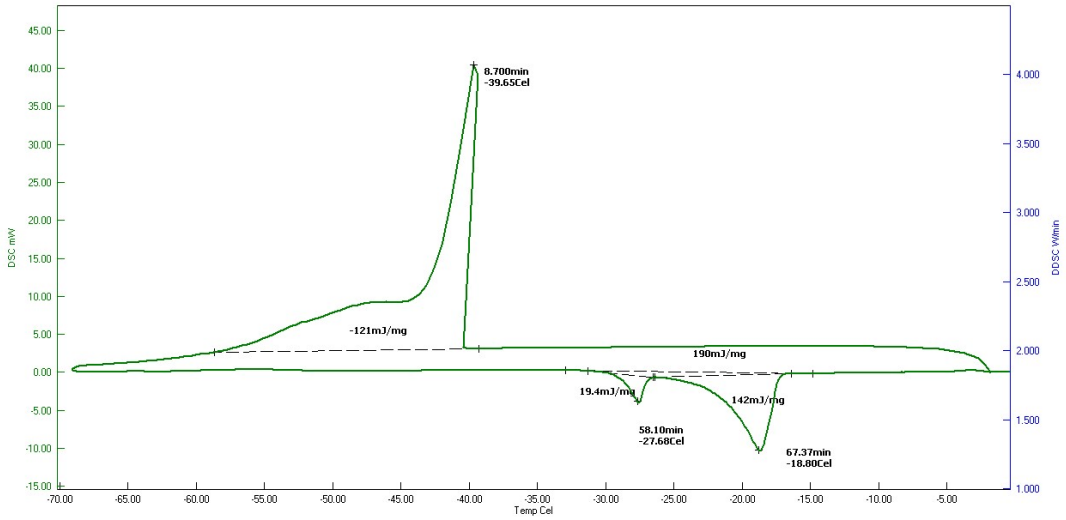

Figure 3.4:DSC Test Graph of Sample 4

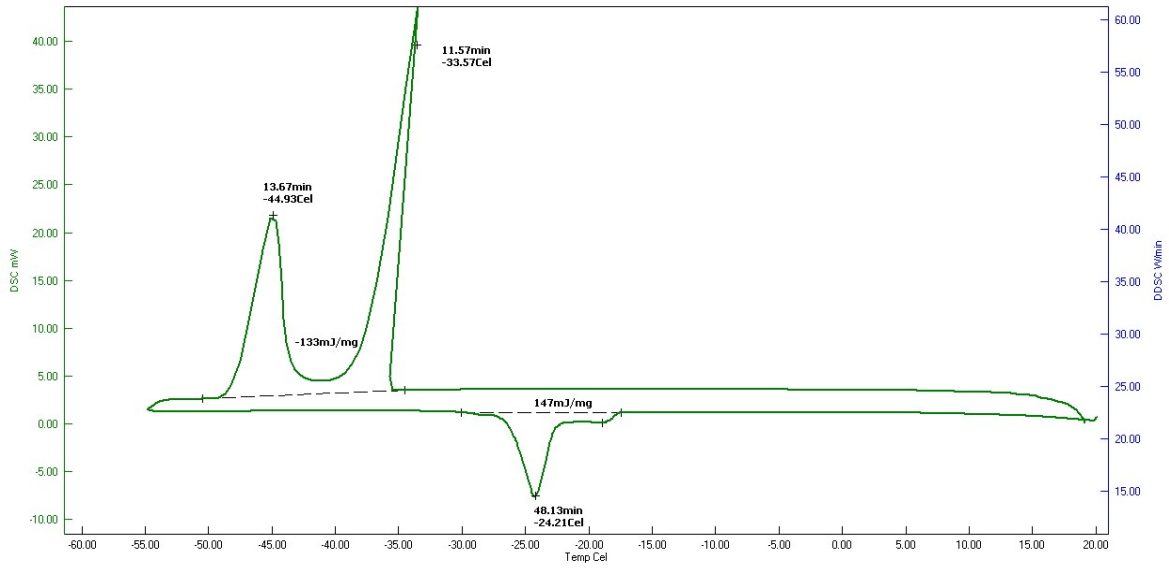

Figure 3.5:DSC Test Graph of Sample 5

The figures do not correspond to aimed phase change. It may occur due to the temperature change rate, which causes diverge on exact phase change temperature. The phase change temperatures may not represent the exact points, nevertheless, the latent heats are reasonable [21]. Hence they can be used during calculating the thermal storage capacity but not in determining the phase change temperature.

For further steps, to detect the melting and freezing points, the melting and freezing process of the samples should be observed. 5 different solution from 5 different salts makes the decision process hard. Furthermore, some additive such as gelling and nucleating agents are to be involved make it even harder. Hence it is decided to eliminate some of the salts owing to previous studies. Oró et al. [31] suggested that NH_4Cl based inorganic solution is promising, therefore NH_4Cl is chosen as a candidate. Moreover, a commercial product bought to examine consists of NaCl, so the second candidate is decided as NaCl.

Other than the base-salt, the inorganic solution must contain additives to resist problems such as super-cooling and phase segregation. Oró et al. [31] used AlF_3 and NaCl as the nucleating agents to resist super-cooling and carboxymethyl cellulose(CMC) as gelling to withstand to phase segregation.

The samples in the previous study [31], which are Sample 1, Sample 2, Sample 8, and Sample 14 of the previous study, are compounded from NH_4Cl for examining their freezing in the cold room. Sample 14 which is simply eutectic solution, Sample 8 with the nucleating agent, Sample 4 with a gelling agent, and Sample 1 which is close to the eutectic point also with a gelling and nucleating agent are recreated for this study.

Although it is known the commercial PCM consists of 15% NaCl, the previous study refers that may not be the right percentage for the -18°C condition [71]. For the desired condition 3 different percentage, 18%, 20%, 21%, were composed. The eutectic point of NaCl-water compound is 22%, hence these three compounds are sub-eutectic. To observe the effect of gelling a different 18%NaCl with CMC was compounded. It may be seen in Table 3.2 different solutions for the freezing-tests.

Table 3.2. PCM Compound Candidates for Cold Room and Their Features

Salt % (wt)	**Nucleating Agent % (wt)**	**Gelling% (wt)**	**Water %(wt)**	**Feature**
NH_4Cl -19.5%	-	-	80.5%	Eutectic
NH_4Cl - %22%	NaCl - 2.5%	-	75.5%	Super-eutectic, with nucleating agent
NH_4Cl - 22%	-	CMC - 1.5%	76.5%	Super-eutectic, with gelling
NH_4Cl -19%	NaCl-2,5%	CMC - 1,5%	77%	Close to eutectic, with both gelling and nucleating agent
NaCl - 21%	-	-	79%	Sub-eutectic
NaCl - 20%	-	-	80%	Sub-eutectic
NaCl - 18%	-	-	81%	Sub-eutecitc
NaCl - 18%	-	CMC - 1,5%	80.5%	Subeutectic, with gelling

According to Figure 19, it is seen that first, the room temperature dropped to -18°C and below. After this point, it started to show sine wave during compressor on-off period. While the compressor is off the temperature started to rise and while it is on, the temperature falls. This process continued awhile to examine the freezing point of the samples. Then, the compressor was completely shut down and the room temperature started to rise. It is assumed that freezings of the compounds have occurred when they started to show a horizontal temperature wave during freezing. And after the room temperature rose and intersected with the temperature lines od compounds, the meltings started.

As seen in the Figure 3.6, before the phase change proses temperatures of the compounds dropped below phase change temperature meaning super-cooling happened.

Of all compounds, these are completely freezed:

- NaCl(18%) + Water(82%),

- NaCl(18%) + CMC(1.5%) + Water(80.5%),
- NH4Cl (22%) + NaCl(2.5%)+Water(75.5%),
- NH4Cl (22%) + CMC(1.5%) + Water(76.5%),
- NH4Cl (19.5%) + Water(80.5%)

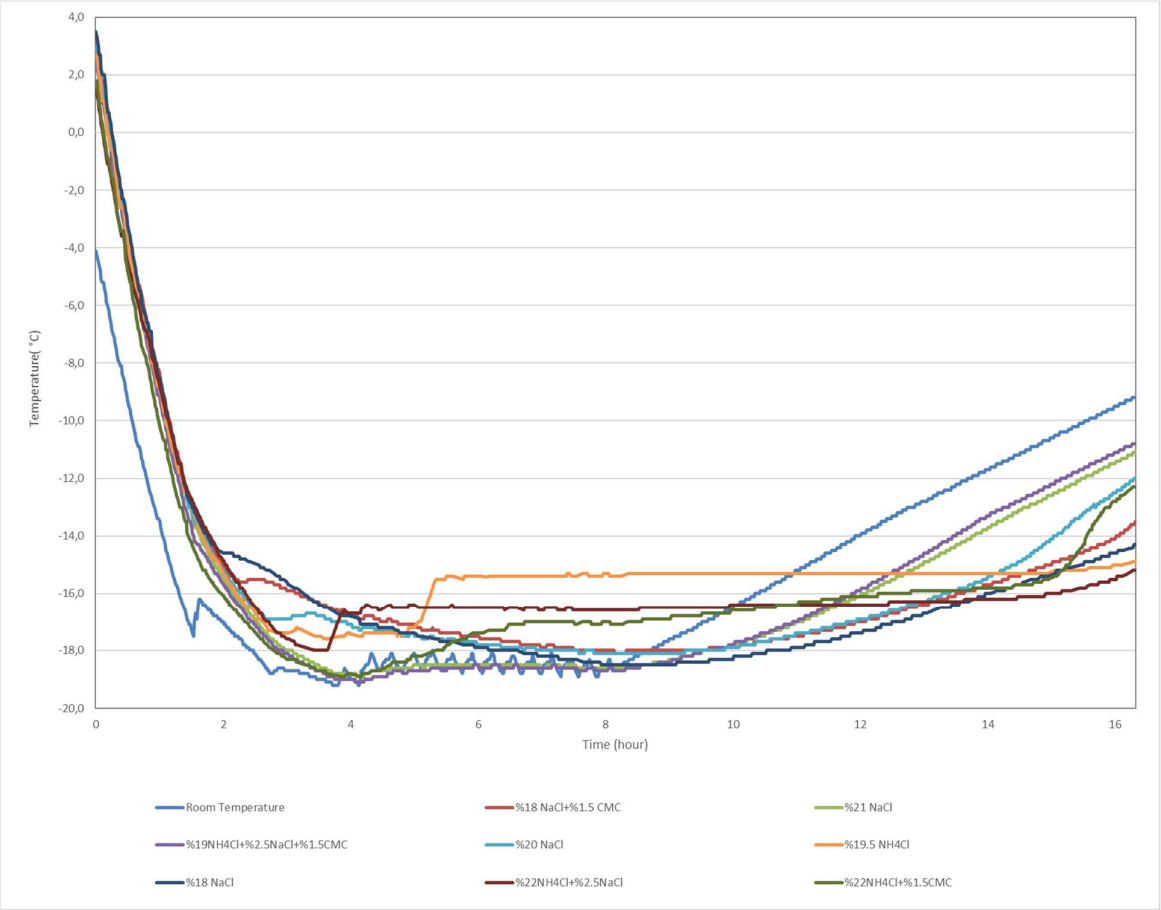

Figure 3.6. PCM Candidates During Freezing and Melting

These freezing-melting tests are run 10 times. After this runs, it was seen that NH_4Cl based compounds started to be decomposed which means phase-segregation happened. During melting-freezing, the salt within the compound may be sinking. This may lead to density changes and different melting-freezing points in the compound. Nevertheless, Oró

et al. [31] showed NH_4Cl water-based PCMs became more stable after 50 melting-freezing runs.

To diminish super-cooling, NaCl was used as a nucleating agent in NH_4Cl based compounds. But in NaCl based solution, it has not decided before the preliminary tests. It is suggested that sodium fluoride(NaF), sodium tetraborate decahydrate ($Na_2B_4.10H_2O$), titanium dioxide (TiO_2) are good nucleating agents [15] [70] [72].

Nucleating agents should be added in small amounts to make a homogenous distribution in solutions. Because the excess amount of nucleating agent may cause a difference in phase change temperature and latent heat, it is suggested that nucleating agent should be nearly 1% which can diminish super-cooling almost 90%. Nevertheless, it is also suggested that sodium tetraborate decahydrate, also known as borax, should be more than 2% [72].

CMC used as gelling agent increases viscosity however it decreases the latent heat. Furthermore, it maintains stability and prevents phase segregation. [70]. To determine the nucleating agent effect, the given solution down below are observed in the cold room.

- NaCl(18%)+ CMC(1.5%) + Borax (2.5%) + Water(78%)
- NaCl(18%)+ CMC(1.5%) + TiO_2 (1.5%) + Water(79%)
- NaCl(18%)+ CMC(1.5%) + NaF (1.5%) + Water (79%)

As the previous test, the samples are placed in -18°C and observed with NTC temperature sensor.

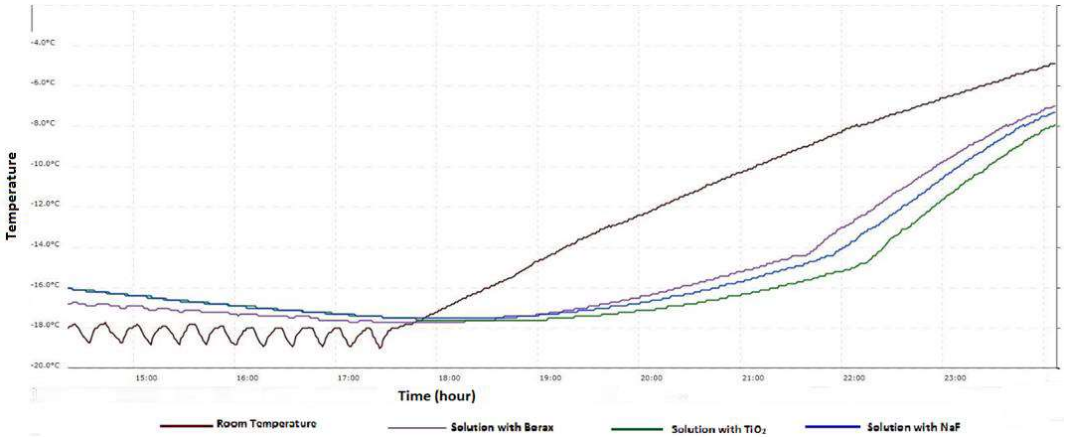

Figure 3.7. Phase and Temperature Change of Different Nucleating Agents in NaCl Solutions

According to the nucleating agent test in Figure 3.7 , it seems all three of them acts similarly. Although the solution with borax reacts more promptly.

Even though for NaCl-water solution the right percentage, 18%, determined, when the CMC and nucleating agent addition is considered, the percentage may differ. Hence it is decided to change percentage.

Whilst preparing PCM candidates, it was seen there is sediments of borax. Therefore the CMC percentage is lowered to 2%. In the next step, the solutions down below were observed in the cold room.

- NaCl 17% +CMC% (1.5) + Borax (2%)
- NaCl 16%+ CMC% (1.5) + Borax (2%)
- NaCl 19 %+ CMC% (1.5) + Borax (2%)
- NaCl 20% + CMC % (1.5) + Borax (2%)
- NH_4Cl 17% + CMC % (1.5) + Borax (2%)
- NH_4Cl 21% + CMC% (1.5) + Borax (2%)

Among all these seven solutions, NaCl 16%+ CMC% (1.5) + Borax (2%) and NH_4Cl 17% + CMC % (1.5) + Borax (2%) showed the most decent freezing which is more stable and low. Nevertheless, to make the final decision the rest of the candidates in Table 9 are tested in DSC device.

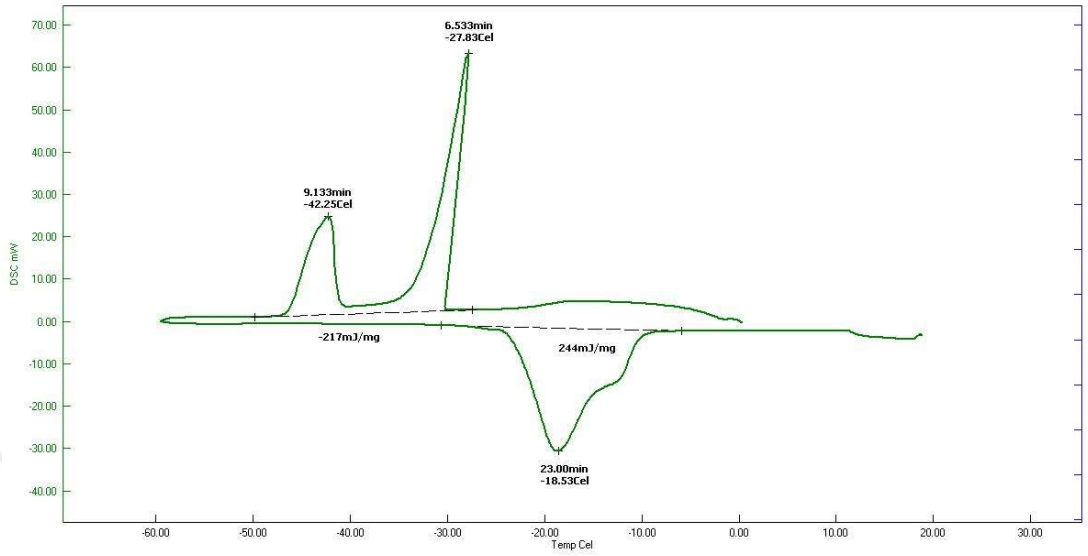

Figure 3.8. the DSC Graph of Sample 6

Figure 3.8 shows the melting and freezing graph of Sample 6 according to DSC device.

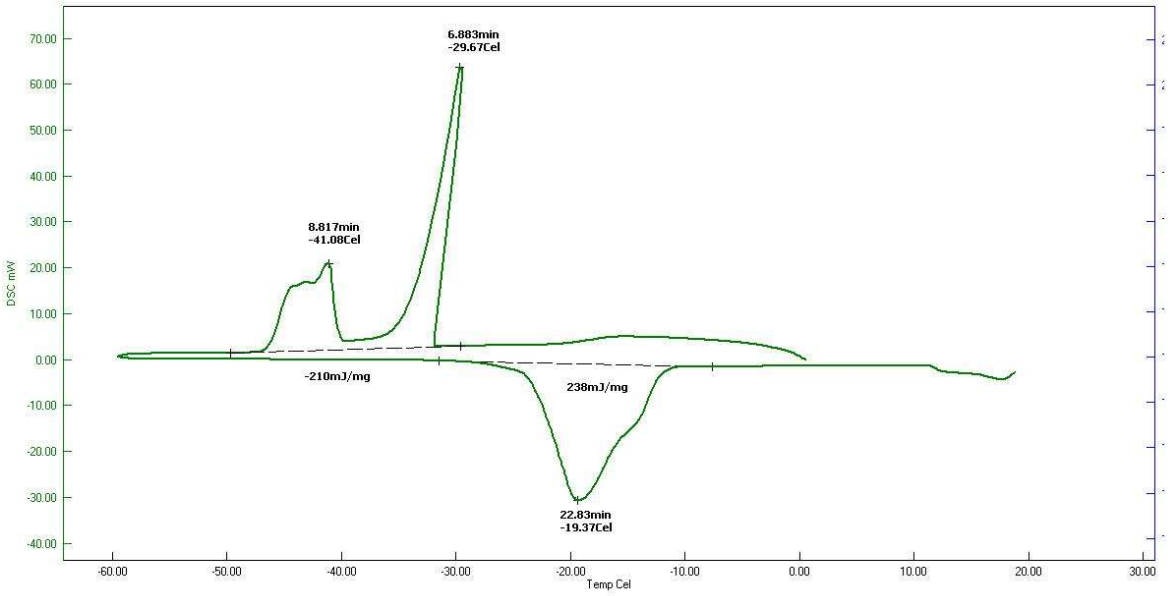

Figure 3.9. the DSC Graph of Sample 7

Figure 3.9 shows the melting and freezing graph of Sample 7 according to DSC device.

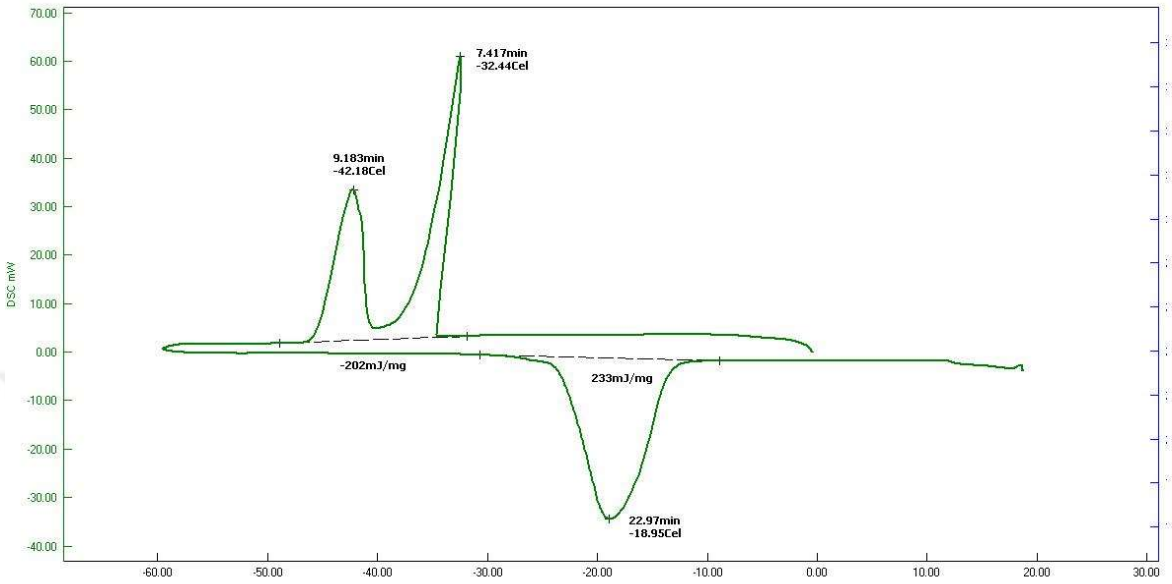

Figure 3.10. the DSC Graph of Sample 8

Figure 3.10 shows the melting and freezing graph of Sample 8 according to DSC device.

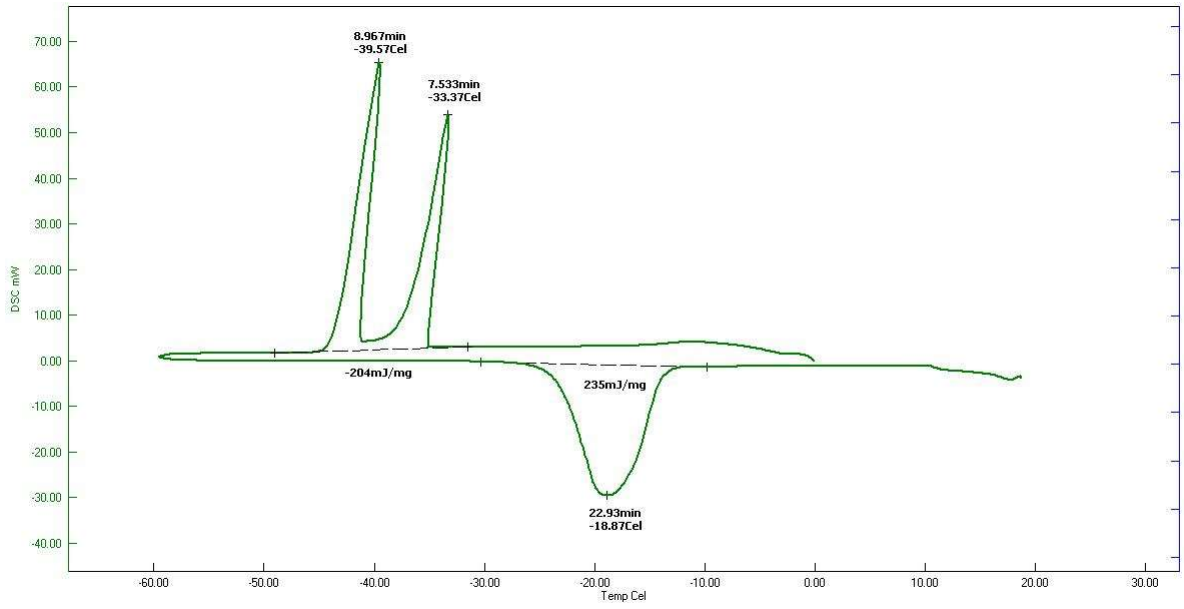

Figure 3.11. the DSC Graph of Sample 9

Figure 3.11 shows the melting and freezing graph of Sample 9 according to DSC device.

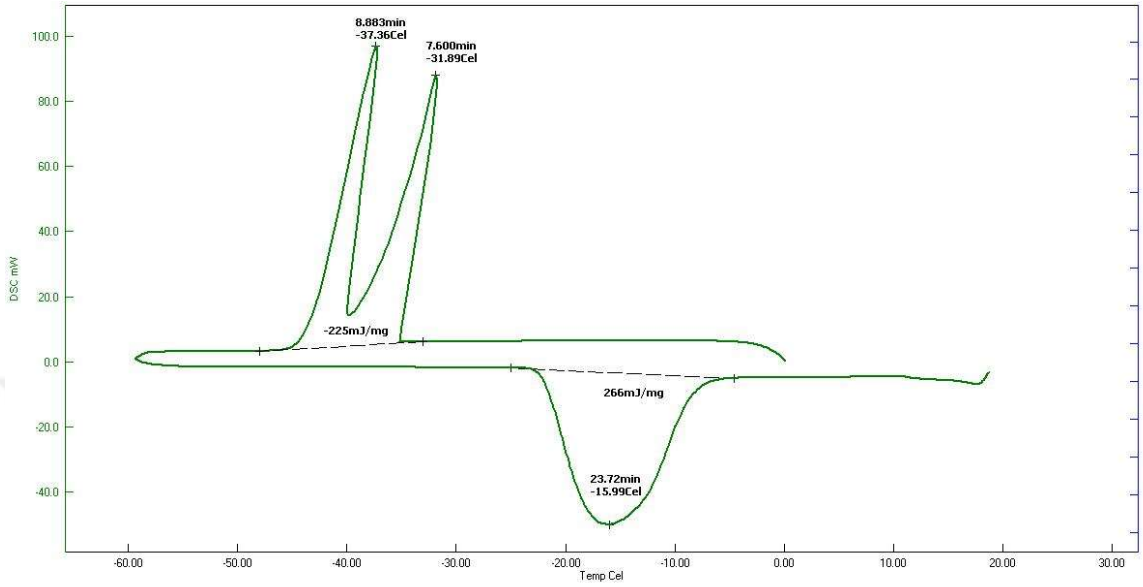

Figure 3.12. the DSC Graph of Sample 10

Figure 3.12 shows the melting and freezing graph of Sample 10 according to DSC device.

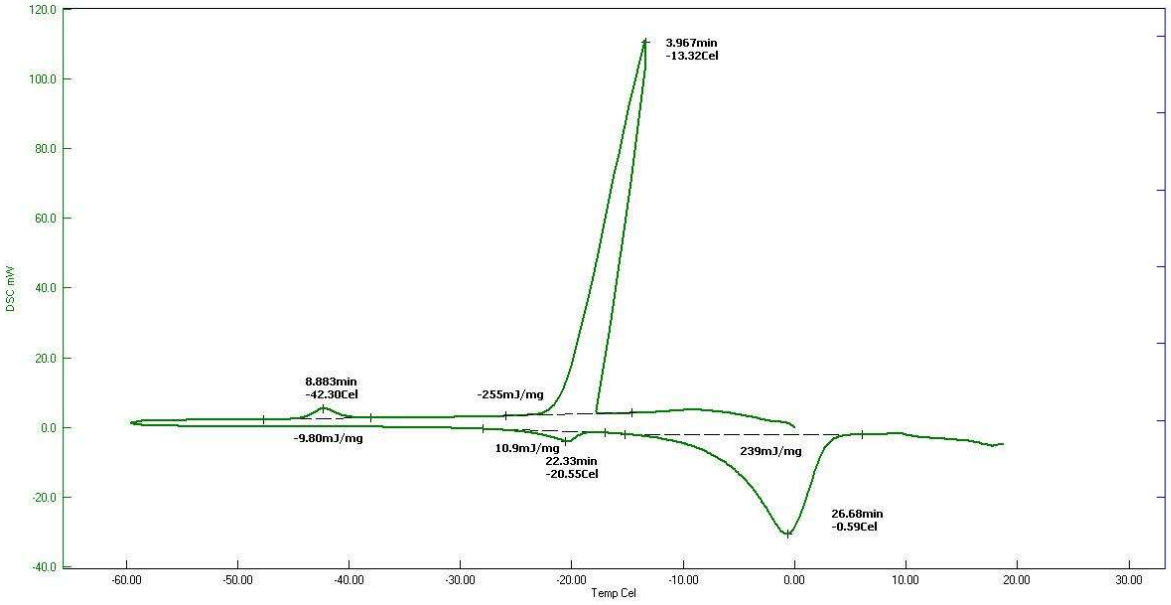

Figure 3.13. the DSC Graph of Sample 11

Figure 3.13 shows the melting and freezing graph of Sample 11 according to DSC device.

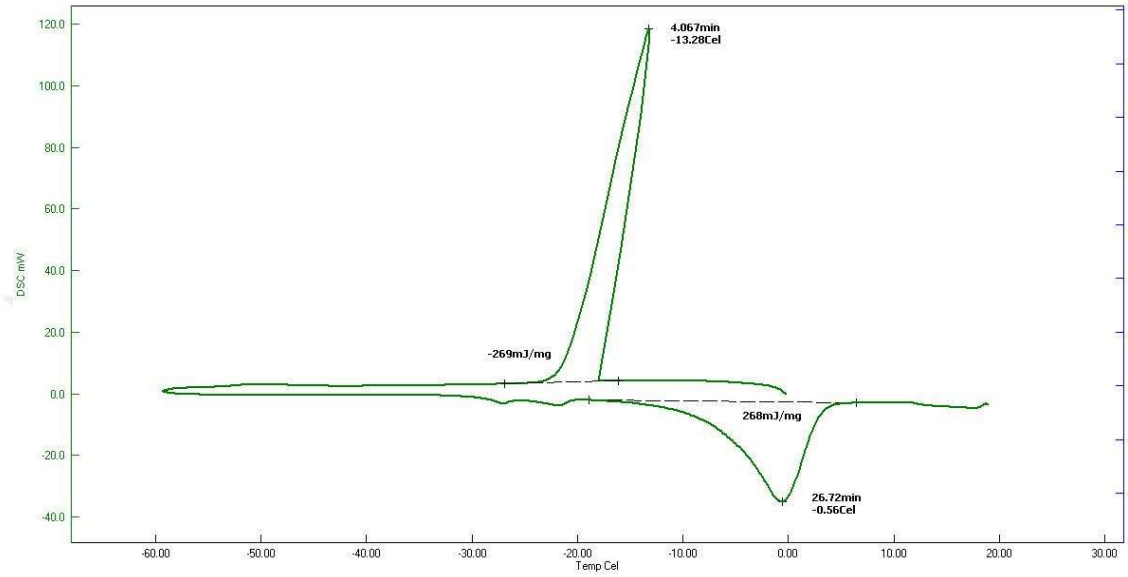

Figure 3.14. the DSC Graph of Sample 12

Figure 3.14 shows the melting and freezing graph of Sample 12 according to DSC device.

In Table 3.3, the latent heats of the samples from the DSC graphs between Figure 3.8-3.14 is given. The highest latent heats belong to Sample 6, Sample 10 and Sample 12. Since Sample 10 does not consist of nucleating agent and gelling, it is in danger of supercooling and phase segregation. Hence Sample 6 and Sample 12 is decided to be used in the cold room experiments.

Table 3.3. Enthalpies of the PCMs tested in DSC

PCM	Entalpy (kj/kg)
Sample 6	244

Sample 7	238
Sample 8	233
Sample 9	235
Sample 10	266
Sample 11	239/10,9
Sample 12	268

Sample 6 and Sample 12 was produced 100 litres each. It is estimated that the room with 100 litre PCM requires 1.24 kW to decrease the temperature from +25°C to -18°C.

Even though the volume of each PCM capsules differs 1% compared to others due to the cooling method of HDPE, the inner volume is approximately 0.625 litre. Since PCMs are water-based, it is estimated that expansion in the capsules may occur. Distilled water enlarges 11% when it freezes. However, during the melting-freezing test, it was observed that the expansion was nearly between 2%-3%.

Table 3.4: Densities of the PCMs in the Cold Storage Room

PCM	**Density (kg/m^3)**
Sample 6	1127.9
Sample 12	1018.8

Since Sample 6 and Sample 12 is filled to capsules in %98 fullness, due to densities in Table 3.4, Sample 6 and Sample 12 inside a PCM weighs 0.69 kg and 0.624, respectively.

3.2. The Cold Room Implementations

The performance of the PCMs is observed on several accounts. The main aim is to extrapolate power save and coefficient of performance (COP) improvement. Furthermore, diminishing on-off cycles of the compressor are also anticipated for the sake of increasing compressor life. Additionally, it is known that PCMs are useful during a power shortage, defrosting and door opening. Owing to their latent heat, the product kept in the cold environment, such as a cold room or refrigerator, can maintain its temperature a while or diminish its temperature increase.

The observations and inference are done throughout this study are shown and discussed in further branches.

3.2.1. The Coefficient of Performance

After PCM solutions had been composed, they were filled into capsules. Thus they can be placed and replaced in the room. To conduct to experiment several temperature and pressure sensor are placed in refrigeration cycle.

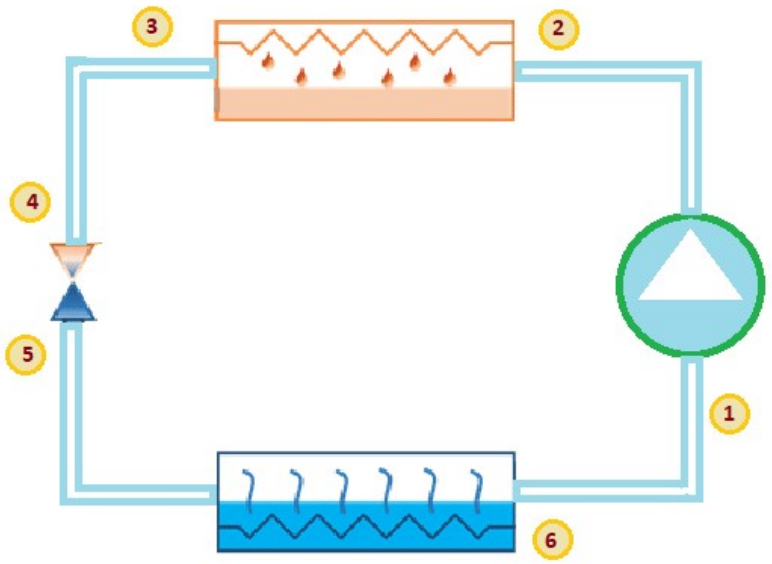

Figure 3.15: Simplified Refrigeration Cycle of the Cold Room

Figure 3.15 shows the components of the refrigeration cycle and the points which sensor are placed. Furthermore, to determine flowrate The FLOMEC Stainless Steel flowmeter is placed before the expansion valve, point 4. And the power that consumed in the compressor is measured from Entes Energy Analyzer. The COP is calculated with Engineering Equation Solver(EES).

The PCM had been placed to the room, the system ran 24 hours to obtain steady-state. After the first 24 hours, it continued to run another 24 hours to observe its steady-state behaviour.

3.2.1.1. The COP of NaCl based PCM

The average temperature and pressure according to points in Figure 3.15 are shown in Table 3.5

Table 3.5: Measured Temperatures, Pressures and Calculated Entalpies

	Temperature(°C)	*Pressure(bar)*	*Entalpy*
1	6,09	2,342	231,5
2	59,44	18,53	357,8
3	34,48	17,49	104,1
4	13,85	16,87	73,21
5			73,21
6	-21,84	2,597	207

$h_1 = enthalpy(T_1, P_1)$

$h_2 = enthalpy(T_2, P_2)$

$h_3 = enthalpy(T_3, P_3)$

$h_4 = enthalpy(T_4, P_4)$

$h_5 = h_4$

$h_6 = enthalpy(T_6, P_6)$

To calculate the COP the equations down below are applied.

$q_L = h_6 - h_5$

$q_H = h_2 - h_3$

$d = density(T_3, P_3)$

$\dot{m} = d * \dot{V}$

$\dot{Q}_L = q_L * \dot{m}$

$COP_R = \dot{Q}_L / \dot{W}$

The missing values of $\dot{V}$ and $\dot{W}$, which are measured from flowmeter and analyzer, are 0,0000645 m^3/s and 4,082 kW, respectively. COP_R is calculated as 2,106.

According to VAP [73] for Stationary Applications of GEA Group, the COP of the compressor is 1.99 for similar conditions with cold room. Hence COP improvement is %5.5

3.2.1.2 The COP of NH_4Cl based PCM

The average temperature and pressure according to points in Figure 3.15 are shown Table 3.6.

Table 3.6. Measured Temperatures, Pressures and Calculated Enthalpies

	Temperature(°C)	***Pressure(bar)***	***Enthalpy***
1	3,43	2,346	229,2
2	57,47	18,53	255,4
3	34,05	17,47	103,5
4	12,41	16,53	71,15
5			71,15
6	-21,68	2,613	207,1

To calculate the COP the equations above are applied.

The missing values of $\dot{V}$ and $\dot{W}$, which are measured from flowmeter and analyzer, are 0,00007 m^3/s and 4,213 kW, respectively. COP_R is calculated as 2,255.

According to VAP [73] for Stationary Applications of GEA Group, the COP of the compressor is 1.99 for similar conditions with cold room. Hence COP improvement is %13.

3.2.2. Power Consumption and Compressor On-Off Period of the Cold Room

The power consumption and on-off period of the compressor are observed with certain changes in variables, such as temperature difference and ambient temperature. Hence the

number of experiments increased proportionally. To diminish the number of experiments this part of the study is done by only NH_4Cl based PCM.

Throughout the study, it is seen that NH_4Cl based PCM is more suitable for -24 °C rather than -18°C, which means it is more suitable for a room in SC4 than SC3. Therewith compressor is shut down at -24 °C. Afterwards, while the temperature of the room rises, the compressor starts over. The start temperature depends on the temperature difference between shut down temperature. Hence 3 different temperature difference is chosen to observe, which are 2 °C, 4 °C, and 6 °C.

Furthermore, the ambient temperature is also shifted to observe how an ambient affects the compressor on-off cycle and which ambient temperature is more suitable for the PCM. Hence the outer room and condenser room temperature temperatures changed to 30°C, 20°C, and 10°C.

3.2.2.1. Temperature Change of the Cold Room without PCM

The cold room without PCM installation worked in different scenarios.

Figure 3.16 shows compressor power consumption during temperature changes between -24 °C and -18 °C. The outer room and condenser room temperatures are 30 °C. According to the compressor on-off period in Figure 3.16, the compressor makes 7 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 29 on-offs.

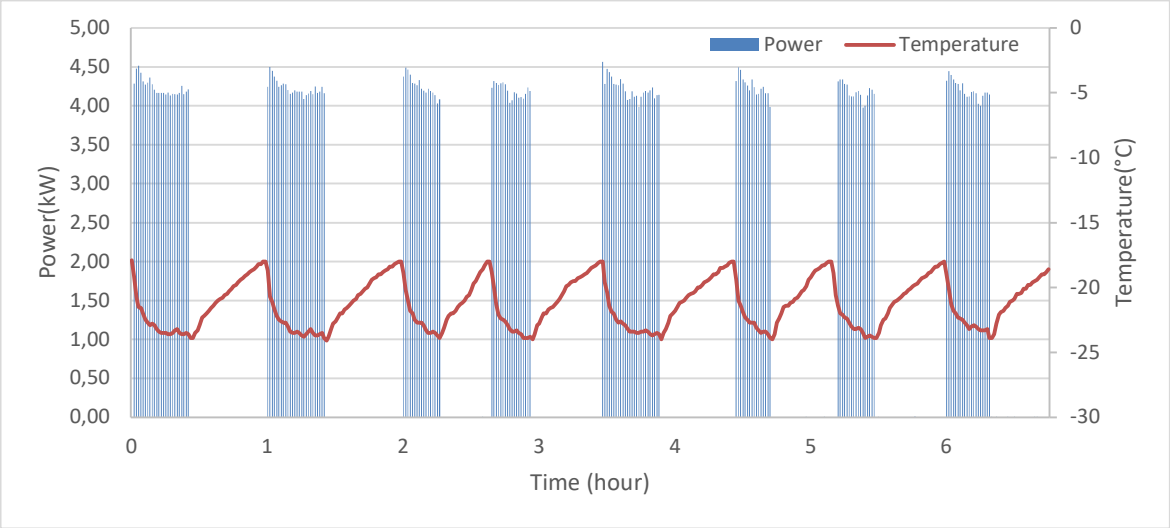

Figure 3.16: 6 °C Temperature Difference (between -24 °C and -18 °C) and 30 °C Ambient Air Temperature

Figure 3.17 shows compressor power consumption during temperature changes between -24 °C and -20 °C. The outer room and condenser room temperatures are 30 °C. Since the temperature is difference 4 K (between -24 °C and -20 °C), on-offs of the compressor increases compared to 6 K scenario. According to the compressor on-off period in Figure 3.17, the compressor makes 7 times on and offs in 4 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 43 on-offs.

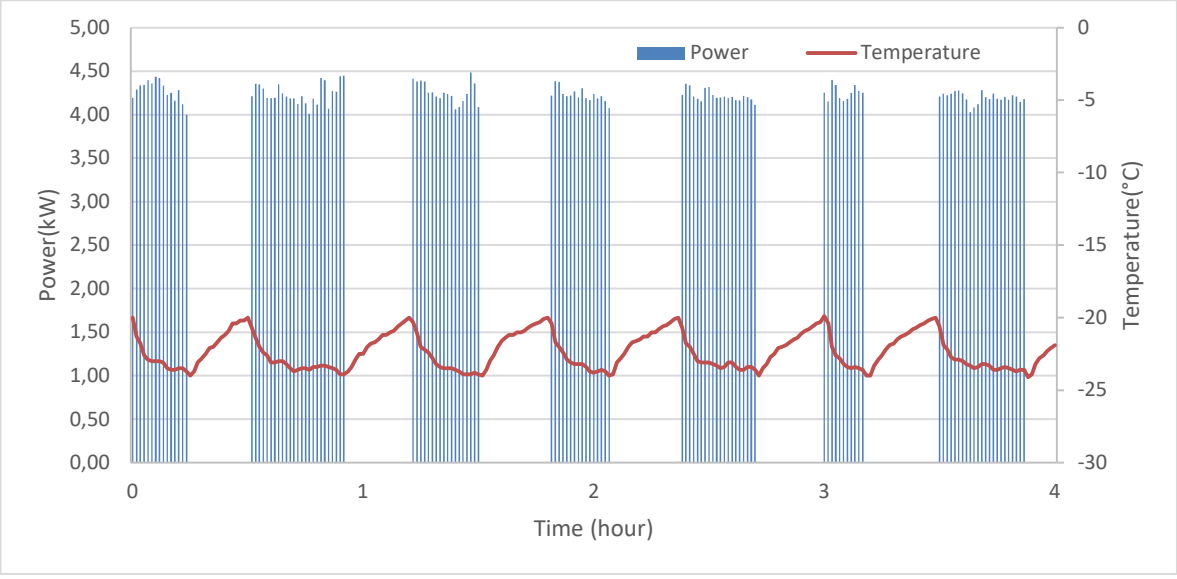

Figure 3.17: 4 °C Temperature Difference (between -24 °C and -20 °C) and 30 °C Ambient Air Temperature

Figure 3.18 shows compressor power consumption during temperature changes between -24 °C and -22 °C. The outer room and condenser room temperatures are 30 °C. The on-offs are prominently more than the other scenarios. According to the compressor on-off period in Figure 3.18, the compressor makes 34 times on and offs in 4 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 204 on-offs.

Figure 3.19 shows compressor power consumption during temperature changes between -24 °C and -18 °C. The outer room and condenser room temperatures are 20 °C. According to the compressor on-off period in Figure 3.19, the compressor makes nearly 8 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 31 on-offs.

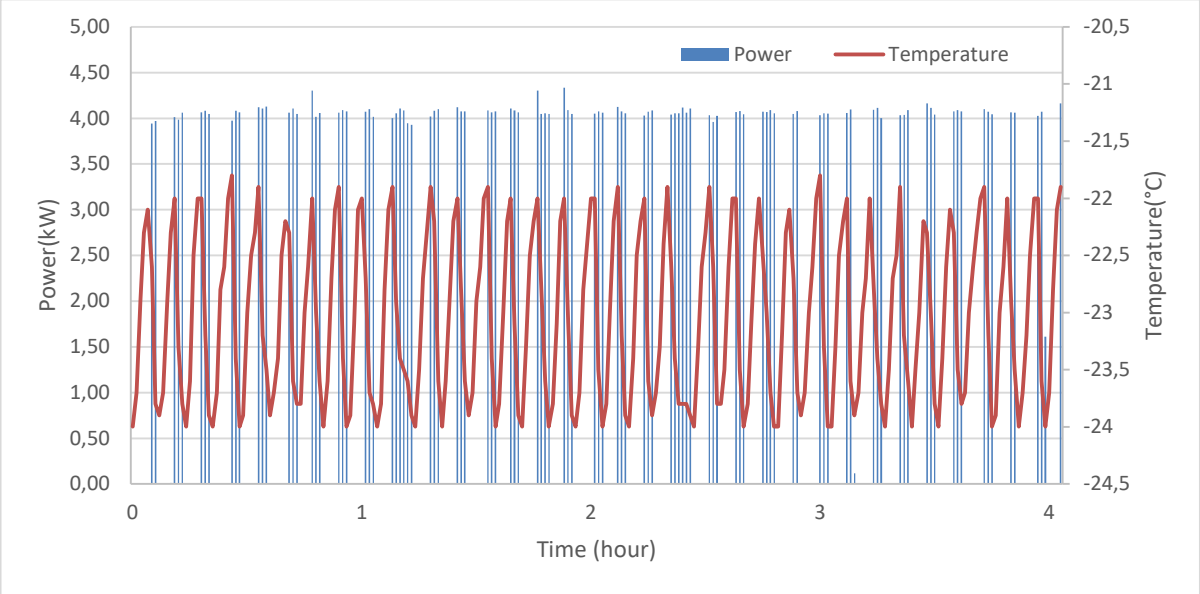

Figure 3.18: 2 °C Temperature Difference (between -24 °C and -22 °C) and 30 °C Ambient Air Temperature

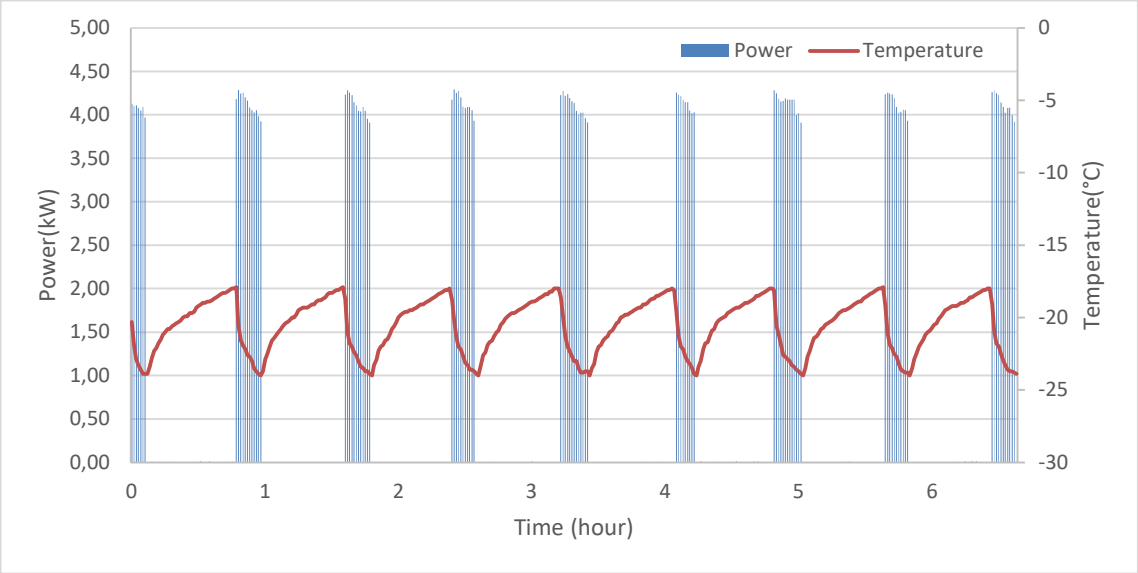

Figure 3.19: 6 °C Temperature Difference (between -24 °C and -18 °C) and 20 °C Ambient Air Temperature

Figure 3.20 shows compressor power consumption during temperature changes between -24 °C and -20 °C. The outer room and condenser room temperatures are 20 °C. Since the temperature is difference 4 K (between -24 °C and -20 °C), on-offs of the compressor increases compared to 6 K scenario at 20 °C. According to the compressor on-off period in Figure 3.20, the compressor makes nearly 15 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 59 on-offs.

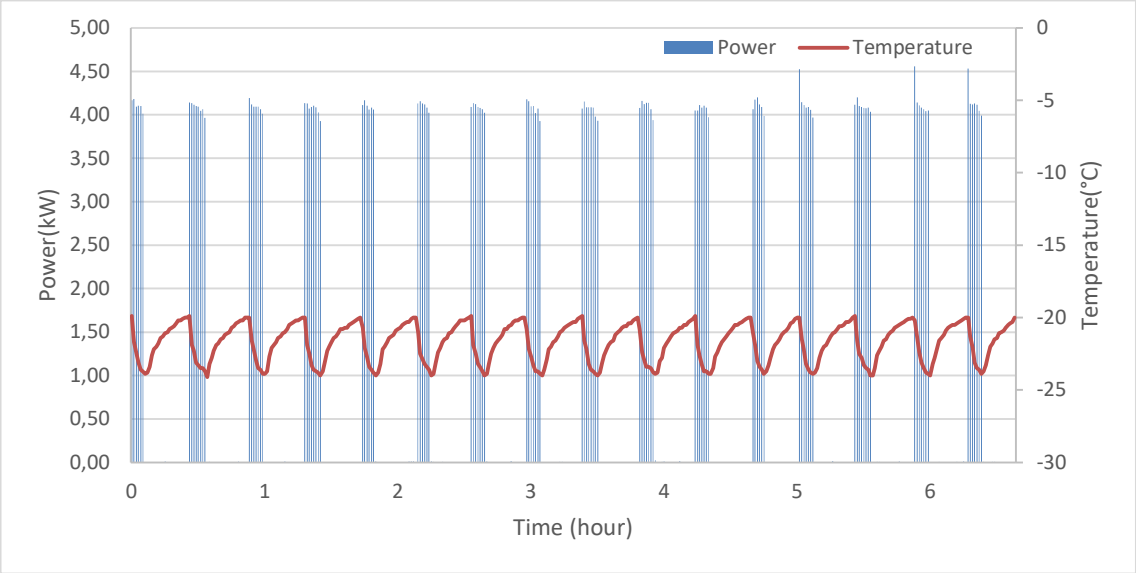

Figure 3.20: 4 °C Temperature Difference (between -24 °C and -20 °C) and 20 °C Ambient Air Temperature

Figure 3.21 shows compressor power consumption during temperature changes between -24 °C and -22 °C. The outer room and condenser room temperatures are 20 °C. The on-offs are prominently more than the other scenarios at 20 °C. According to the compressor on-off period in Figure 3.21, the compressor makes nearly 49 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 199 on-offs.

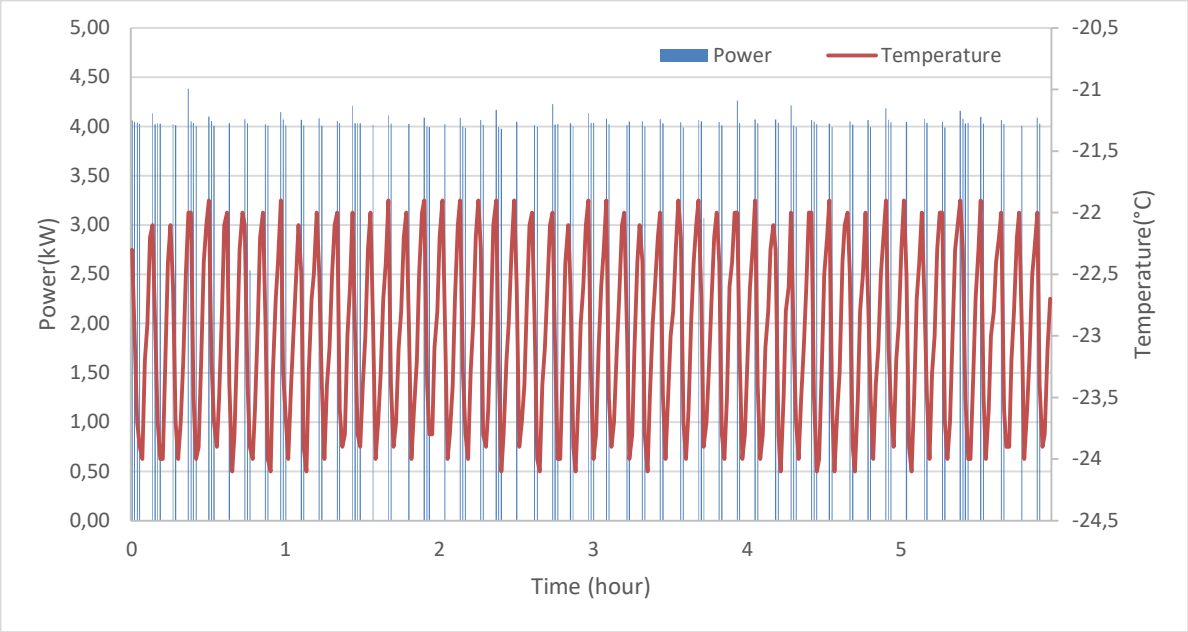

Figure 3.21: 2 °C Temperature Difference (between -24 °C and -22 °C) and 20 °C Ambient Air Temperature

Figure 3.22 shows compressor power consumption during temperature changes between -24 °C and -18 °C. The outer room and condenser room temperatures are 10 °C. According to the compressor on-off period in Figure 3.22, the compressor makes nearly 7 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 26 on-offs.

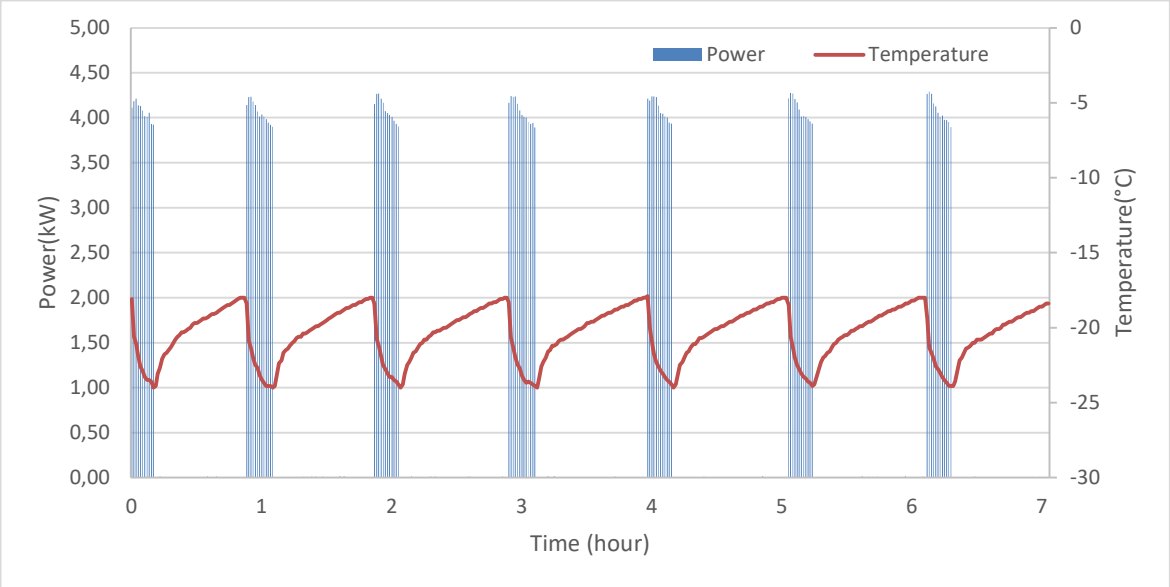

Figure 3.22: 6 °C Temperature Difference (between -24 °C and -18 °C) and 10 °C Ambient Air Temperature

As is seen while the temperature difference in the room decreases, the compressor on-off increases. But it is hard to comment on the compressor on-offs while outer room temperature decreases.

3.2.2.2. Temperature Change of the Cold Room with PCM

The cold room with PCM installation worked in different scenarios.

Figure 3.23 shows compressor power consumption during temperature changes between -24 °C and -18 °C. The outer room and condenser room temperatures are 30 °C. The compressor on-off period can be seen. According to the compressor on-off period in Figure 3.23, the compressor makes nearly 7 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 26 on-offs.

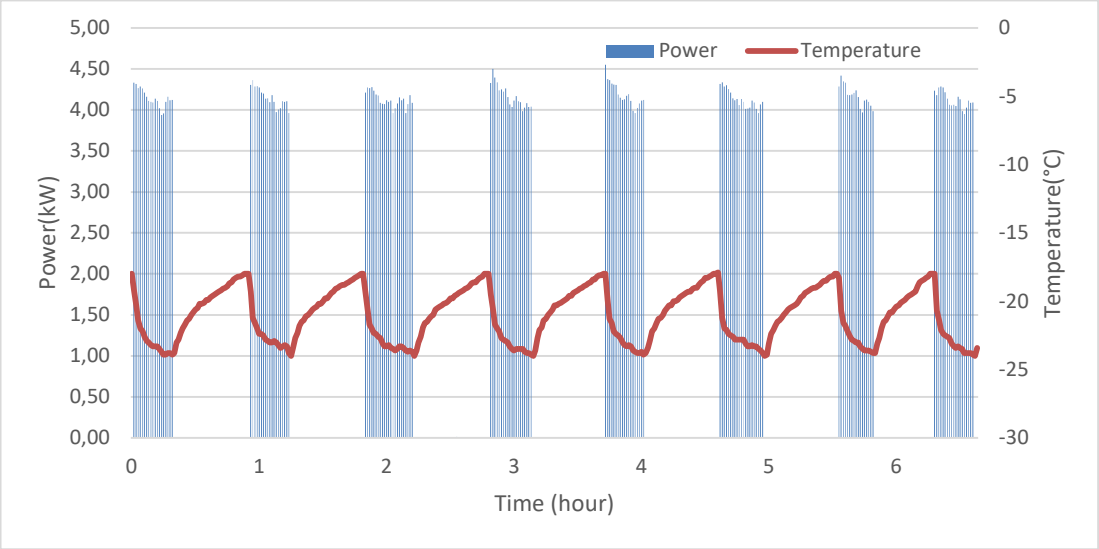

Figure 3.23: 6 °C Temperature Difference (between -24 °C and -18 °C) and 30 °C Ambient Air Temperature

Figure 3.24 shows compressor power consumption during temperature changes between -24 °C and -20 °C. The outer room and condenser room temperatures are 30 °C. Since the temperature is difference 4 K (between 24 °C and -20 °C), on-offs of the compressor increases compared to 6 K scenario. According to the compressor on-off period in Figure 3.24, the compressor makes nearly 12 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 49 on-offs.

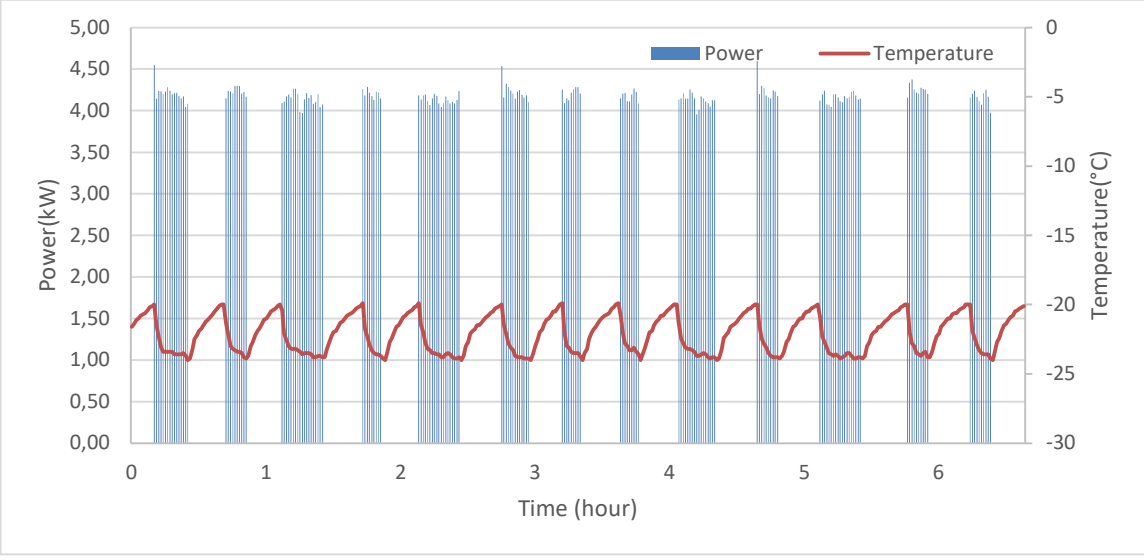

Figure 3.24: 4 °C Temperature Difference (between -24 °C and -22 °C) and 30 °C Ambient Air Temperature

Figure 3.25 shows compressor power consumption during temperature changes between -24 °C and -22 °C. The outer room and condenser room temperatures are 30 °C. The on-offs are prominently more than the other scenarios in the room with PCM at 30 °C. According to the compressor on-off period in Figure 3.25, the compressor makes nearly 45 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 176 on-offs.

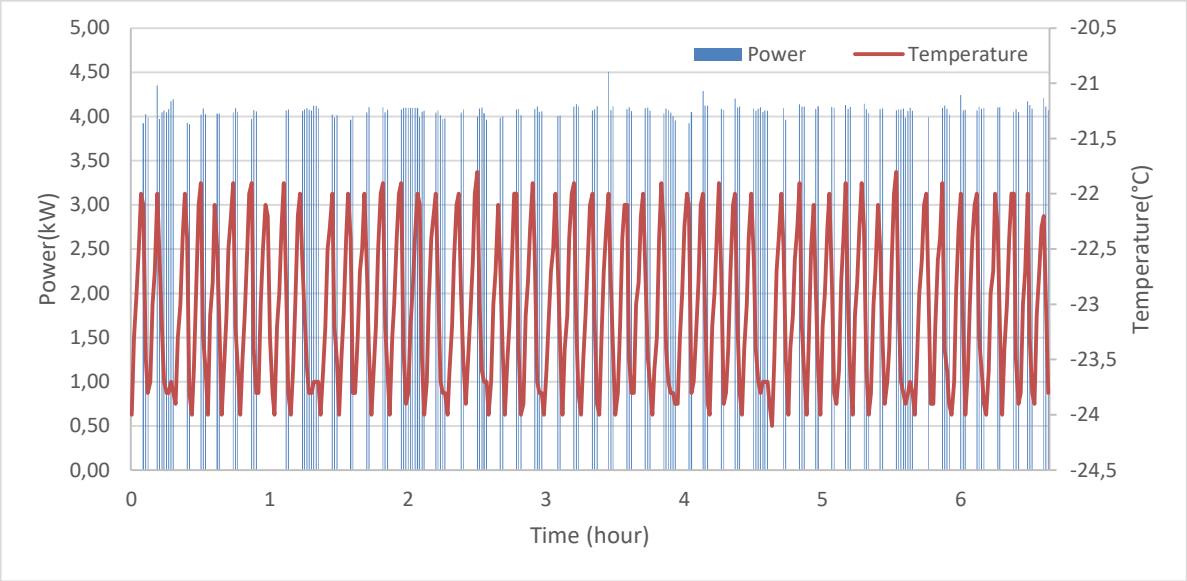

Figure 3.25:2 °C Temperature Difference (between -24 °C and -22 °C) and 30 °C Ambient Air Temperature

Figure 3.26 shows compressor power consumption during temperature changes between -24 °C and -18 °C. The outer room and condenser room temperatures are 20 °C. In 24 hours, it makes 27 times on-offs. According to the compressor on-off period in Figure 3.26, the compressor makes nearly 7 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 27 on-offs.

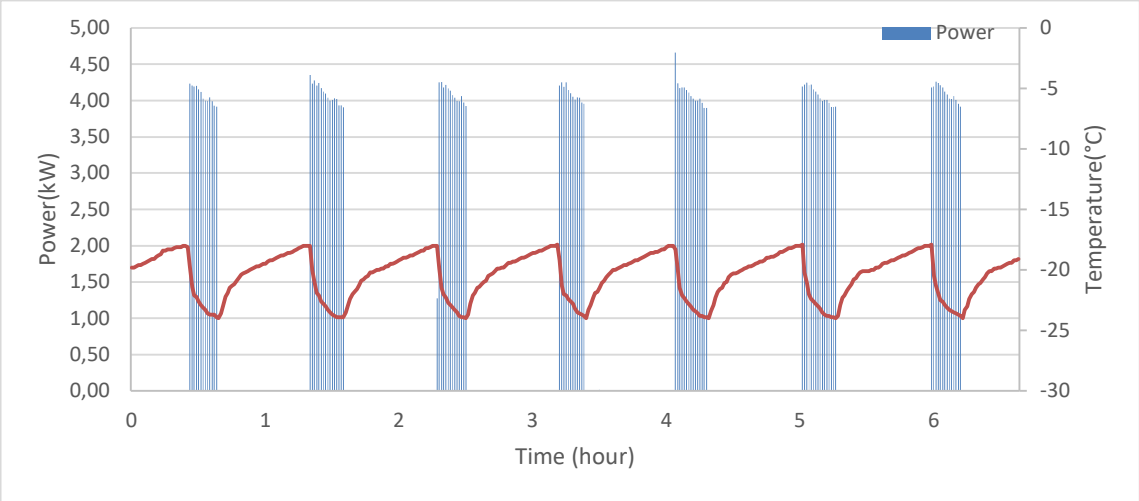

Figure 3.26:6 °C Temperature Difference (between -24 °C and -18 °C) and 20 °C Ambient Air Temperature

Figure 3.27 shows compressor power consumption during temperature changes between -24 °C and -20 °C. The outer room and condenser room temperatures are 20 °C. Since the temperature is difference 4 K (between -24 °C and -20 °C), on-offs of the compressor increases compared to 6 K scenario at 20 °C. According to the compressor on-off period in Figure 3.27, the compressor makes nearly 14 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 56 on-offs.

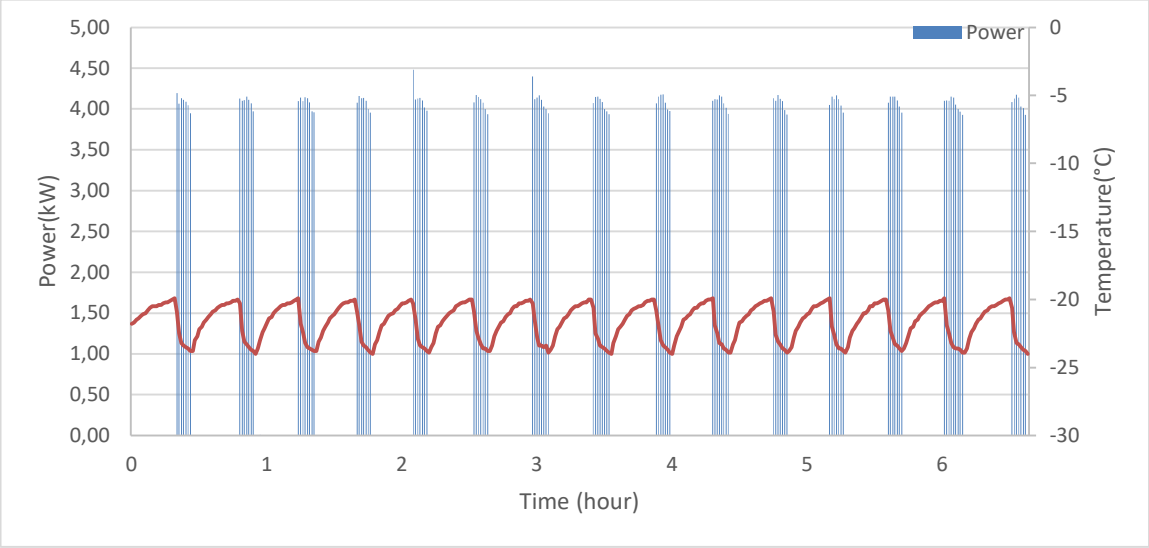

Figure 3.27:4 °C Temperature Difference (between -24 °C and -20 °C) and 20 °C Ambient Air Temperature

Figure 3.28 shows compressor power consumption during temperature changes between -24 °C and -22 °C. The outer room and condenser room temperatures are 20 °C. The on-offs are prominently more than the other scenarios at 20 °C. According to the compressor on-off period in Figure 3.28, the compressor makes nearly 51 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 204 on-offs.

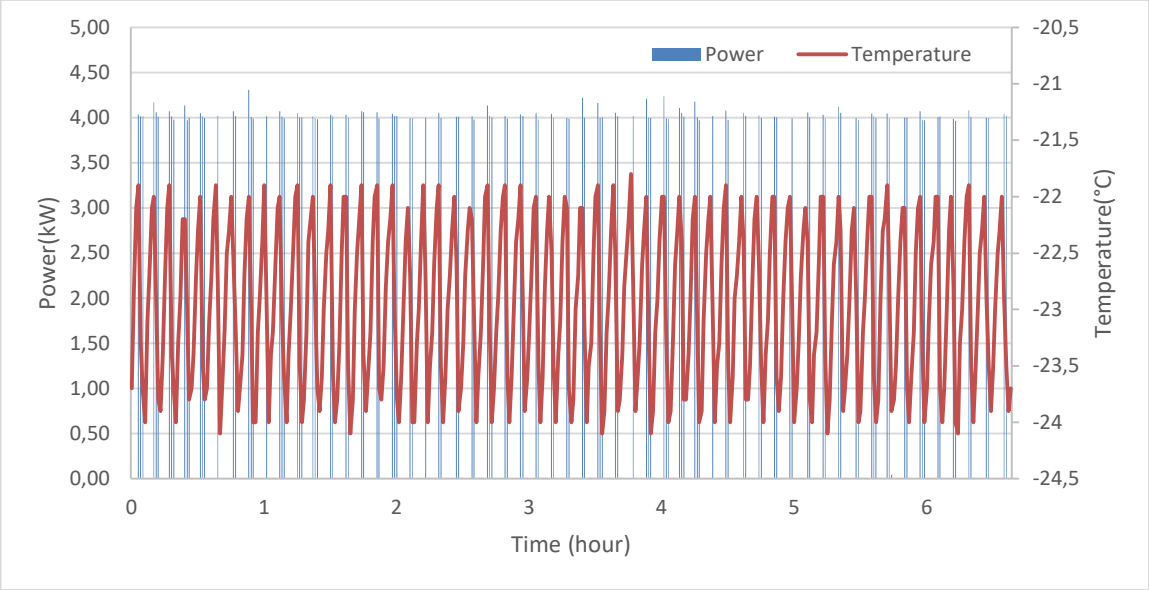

Figure 3.28:2 °C Temperature Difference (between -24 °C and -12 °C) and 20 °C Ambient Air Temperature

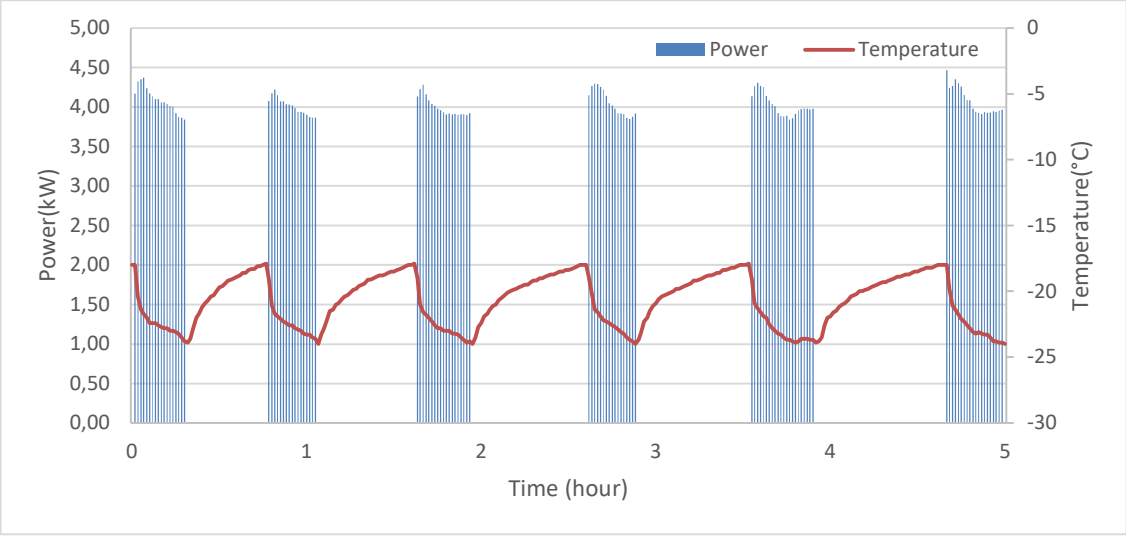

Figure 3.29:6 °C Temperature Difference (between -24 °C and -18 °C) and 10 °C Ambient Air Temperature

Figure 3.29 shows compressor power consumption during temperature changes between -24 °C and -18 °C. The outer room and condenser room temperatures are 10 °C. According to the compressor on-off period in Figure 3.29, the compressor makes nearly 5 times on and offs in 5 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 28 on-offs.

Figure 3.30 shows compressor power consumption during temperature changes between -24 °C and -20 °C. The outer room and condenser room temperatures are 10 °C. Since the temperature is difference 4 K (between -24 °C and -20 °C), on-offs of the compressor increases compared to 6 K scenario at 20 °C. According to the compressor on-off period in Figure 3.30, the compressor makes nearly 10 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 43 on-offs.

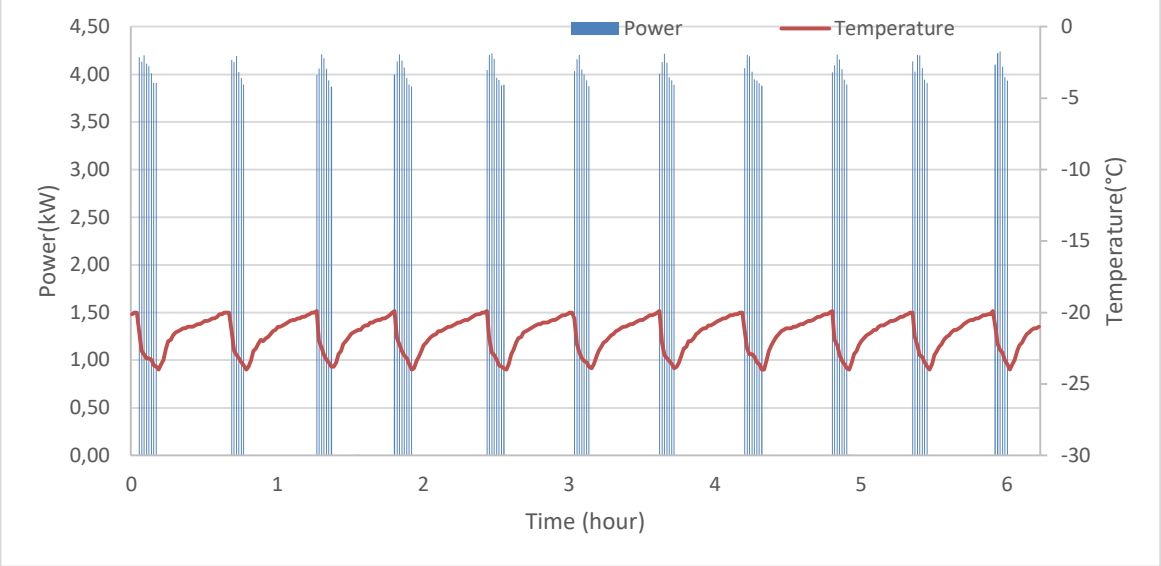

Figure 3.30: 4 °C Temperature Difference (between -24 °C and -20 °C) and 10 °C Ambient Air Temperature

Figure 3.31 shows compressor power consumption during temperature changes between -24 °C and -22 °C. The outer room and condenser room temperatures are 10 °C. The on-offs are prominently more than the other scenarios at 10 °C. According to the compressor on-off period in Figure 3.31, the compressor makes nearly 44 times on and offs in 6 hours duration. It is calculated that, in 24 hours, the compressor presumably makes 162 on-offs.

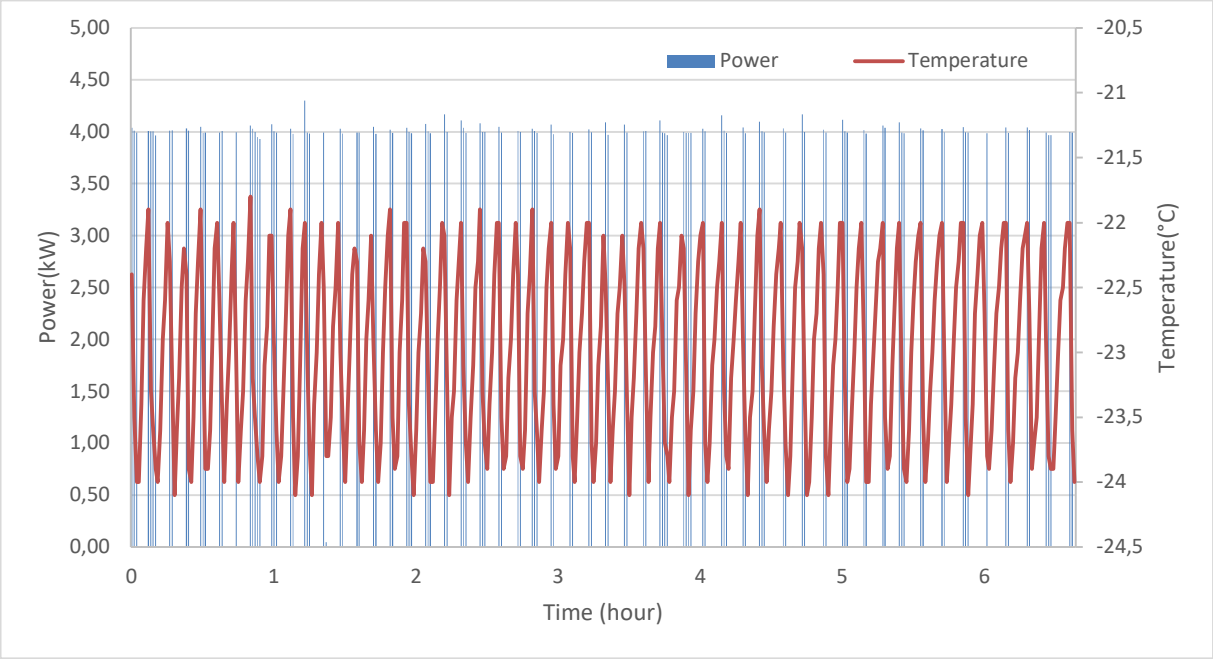

Figure 3.31: 2 °C Temperature Difference (between -24 °C and -22 °C) and 10 °C Ambient Air Temperature

3.2.2.3. The Comparison of the Room with and without PCM

Figure 3.32 shows the power consumptions of the cold room with and without PCM between -24 °C and – 18 °C at 30 °C outer room and condenser rooms temperatures. It is already known that the one without PCM and the one with PCM make 29 and 26 times on-offs, respectively, in 24 hours.

Figure 3.33 illustrates temperature fluctuation between -24 °C and – 18 °C at 30 °C outer room and condenser rooms temperatures. It is seen that while the temperature rises, the one with PCM is more inclined which means long compressor off time.

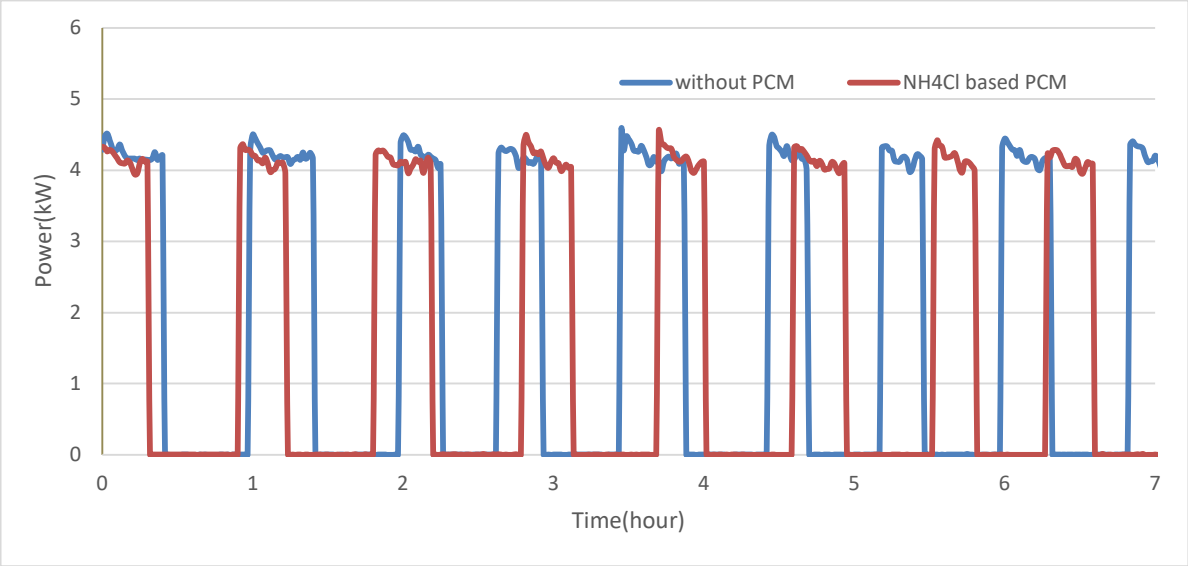

Figure 3.32: Power Consumption at 30 °C Ambient Air Temp. and 6 °C Temperature Difference (between -24 °C and -18 °C)

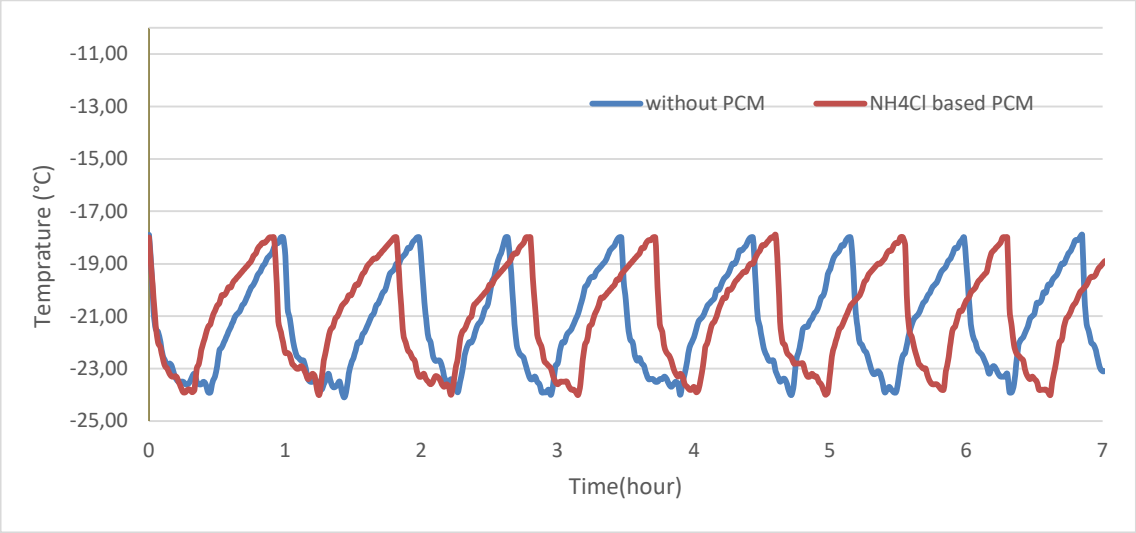

Figure 3.33: Temperature Change at 30 °C Ambient Air Temp. and 6 °C Temperature Difference (between -24 °C and -18 °C)

Figure 3.34 display the power consumptions of the cold room with and without PCM between -24 °C and – 20 °C at 30 °C outer room and condenser rooms temperatures. It is

known that the one without PCM and the one with PCM make 44 and 49 times, respectively, in 24 hours.

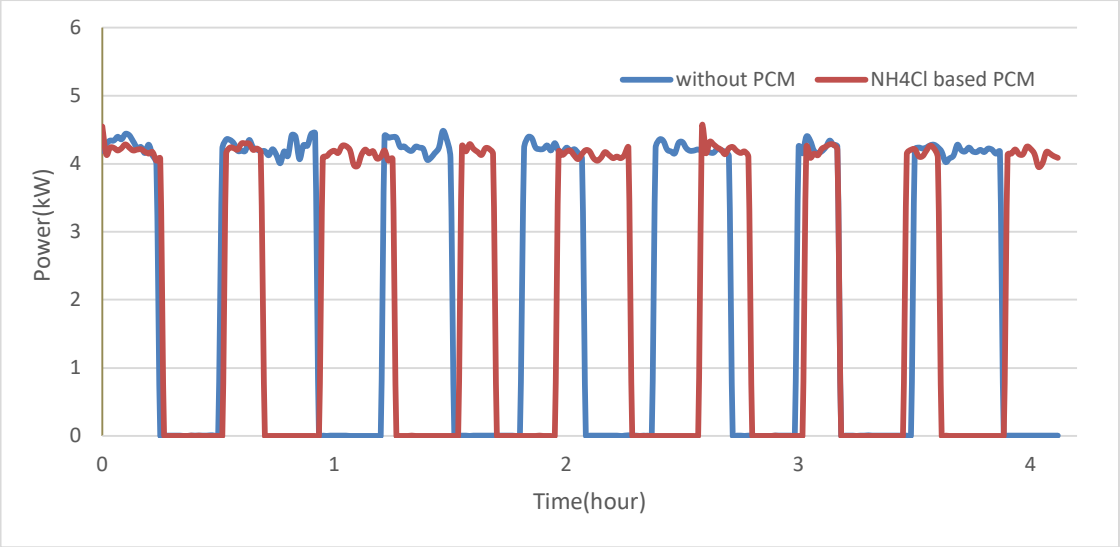

Figure 3.34: Power Consumption at 30 °C Ambient Air Temp. and 4 °C Temperature Difference (between -24 °C and -20 °C)

Figure 3.35 demonstrates temperature fluctuation between -24 °C and – 18 °C at 30 °C outer room and condenser rooms temperatures. The temperature rise slopes show no difference between NH_4C based PCM and without PCM.

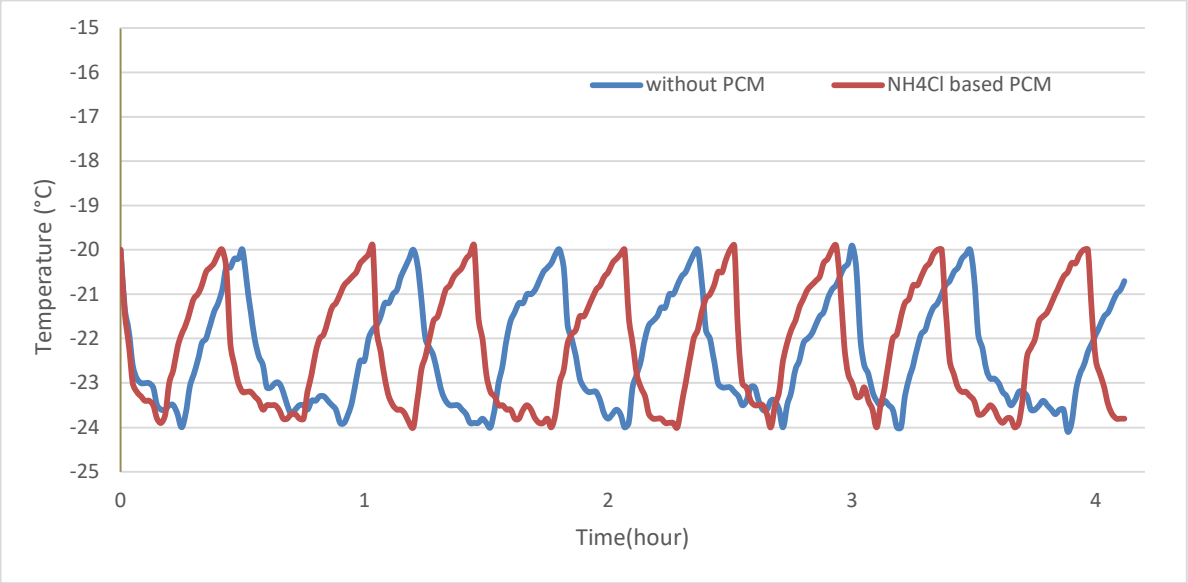

Figure 3.35: Temperature Change at 30 °C Ambient Air Temp. and 4 °C Temperature Difference (between -24 °C and -20 °C)

Figure 3.36 shows the power consumptions of the cold room with and without PCM between -24 °C and – 22 °C at 30 °C outer room and condenser rooms temperatures. It is known that the one without PCM and the one with PCM make 204 and 156 times, respectively, in 24 hours. PCM evidently provides development in on-offs in this scenario.

Figure 3.37 illustrates temperature fluctuation between -24 °C and – 22 °C at 30 °C outer room and condenser rooms temperatures. The temperature rise slopes show no difference between NH_4C based PCM and without PCM.

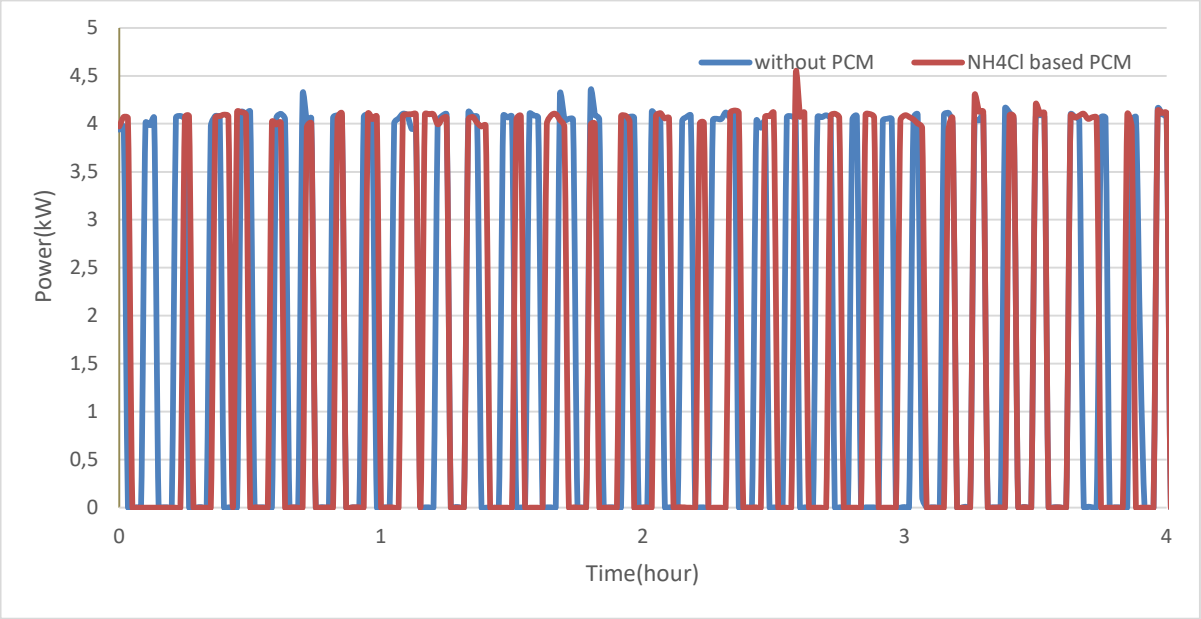

Figure 3.36: Power Consumption at 30 °C Ambient Air Temp. and 2 °C Temperature Difference (between -24 °C and -22 °C)

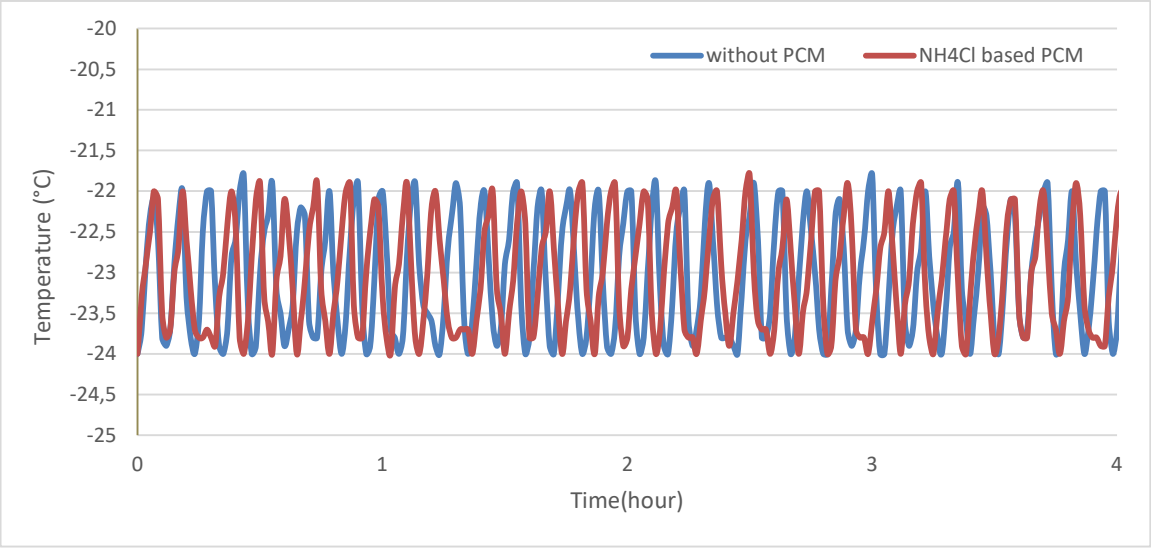

Figure 3.37: Temperature Change at 30 °C Ambient Air Temp. and 2 °C Temperature Difference (between -24 °C and -22 °C)

Figure 3.38 shows the power consumptions of the cold room with and without PCM between -24 °C and – 18 °C at 20 °C outer room and condenser rooms temperatures. As is seen from the Figure 48 the one with PCM makes fewer on-offs. It is also known that

the one without PCM and the one with PCM make 31 and 27 times, respectively, in 24 hours.

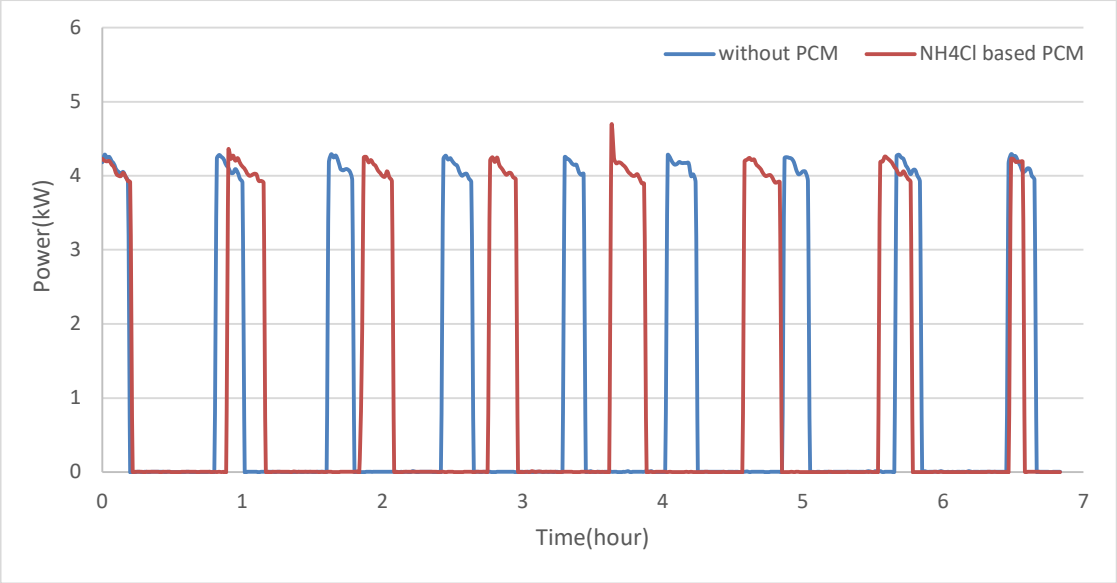

Figure 3.38: Power Consumption at 20 °C Ambient Air Temp. and 6 °C Temperature Difference (between -24 °C and -18 °C)

Figure 3.39 demonstrates temperature fluctuation between -24 °C and – 18 °C at 20 °C outer room and condenser rooms temperatures. The temperature rise slope of the NH_4Cl based PCM is more inclined compared to without PCM.

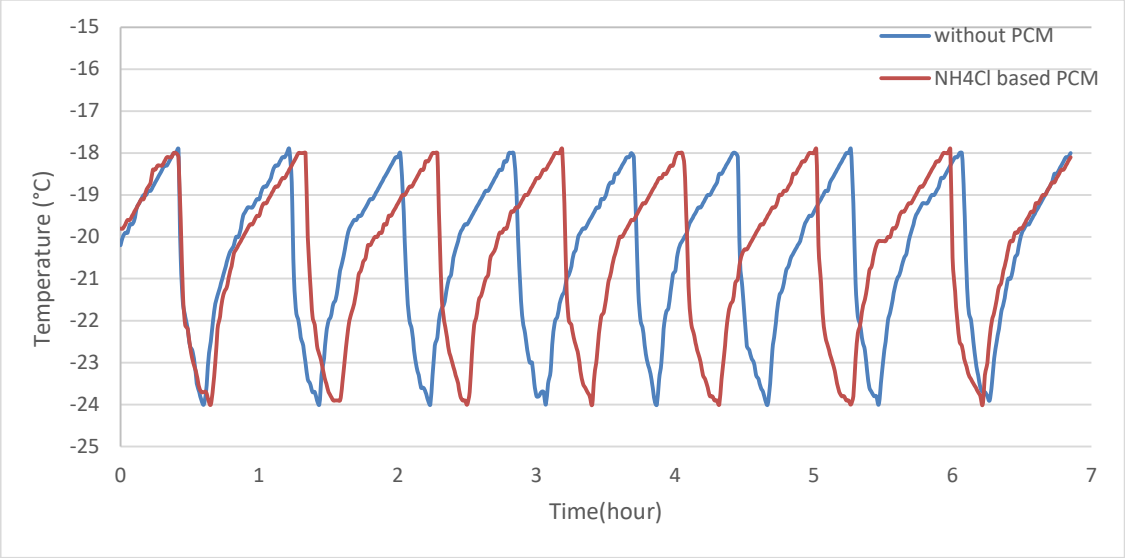

Figure 3.39: Temperature Change at 20 °C Ambient Air Temp. and 6 °C Temperature Difference (between -24 °C and -18 °C)

Figure 3.40 illustrates the power consumptions of the cold room with and without PCM between -24 °C and – 20 °C at 20 °C outer room and condenser rooms temperatures. Even though the lines are interlaced at the beginning of the graph, the line of NH_4Cl based PCM shifts right which means fewer on-off of the compressor. It is also known that the one without PCM and the one with PCM make 59 and 56 times, respectively, in 24 hours.

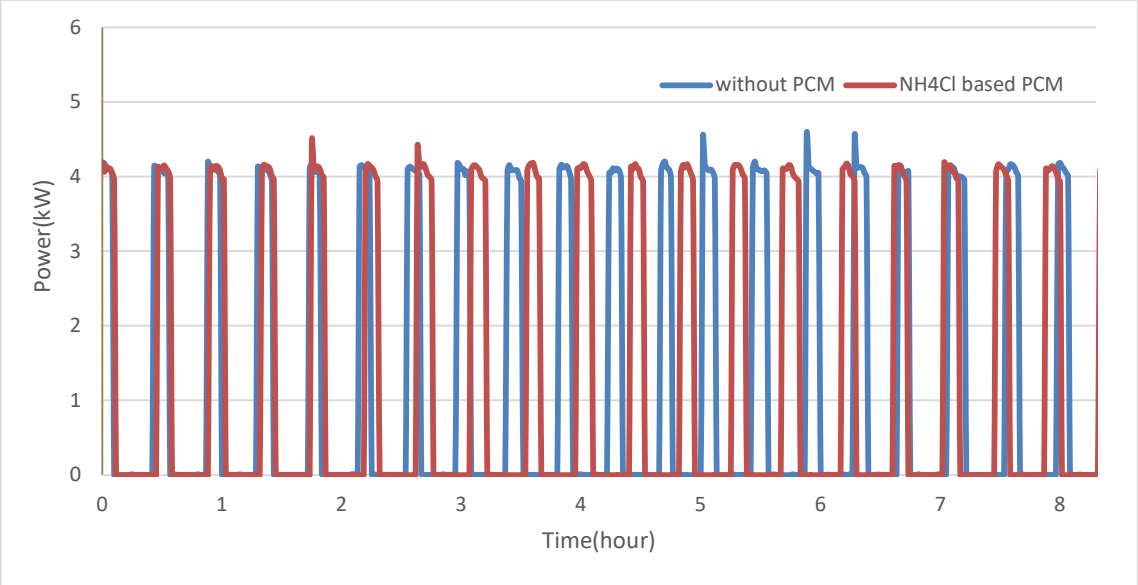

Figure 3.40: Power Consumption at 20 °C Ambient Air Temp. and 4 °C Temperature Difference (between -24 °C and -20 °C)

Figure 3.41 temperature fluctuation between -24 °C and – 20 °C at 20 °C outer room and condenser rooms temperatures. The slopes of the lines show no apparent difference.

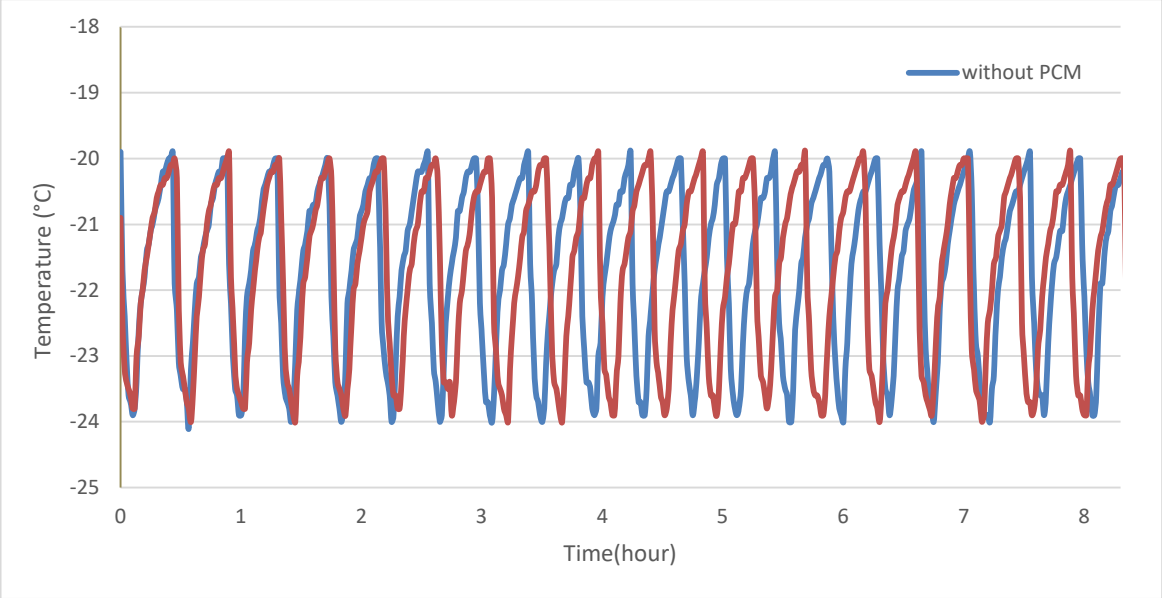

Figure 3.41: Temperature Change at 20 °C Ambient Air Temp. and 4 °C Temperature Difference (between -24 °C and -20 °C)

Figure 3.42 illustrates the power consumptions of the cold room with and without PCM between -24 °C and – 22 °C at 20 °C outer room and condenser rooms temperatures. As is seen from the graph, it seems there is no positive effect of the PCMs. The data of on-off periods present compressor of the room without PCM makes 199 times on-offs while the one with PCM makes 204 times in 24 hours.

Figure 3.43 temperature fluctuation between -24 °C and – 22 °C at 20 °C outer room and condenser rooms temperatures. The slopes of the lines show no obvious difference.

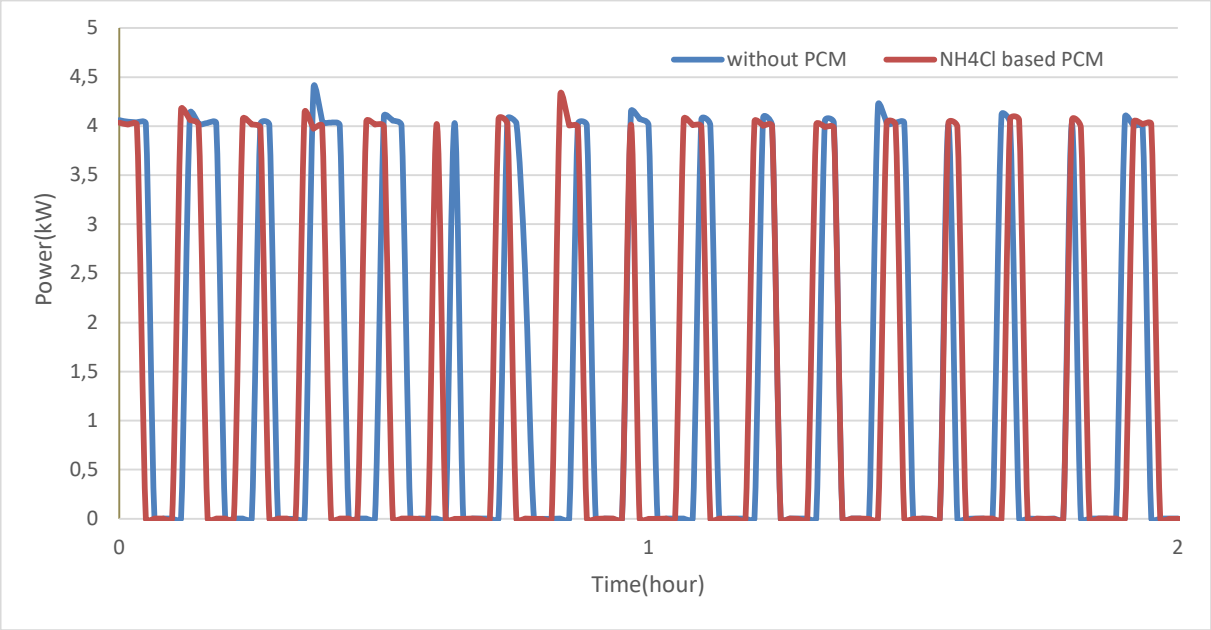

Figure 3.42: Power Consumption at 20 °C Ambient Air Temp. and 2 °C Temperature Difference (between -24 °C and -22 °C)

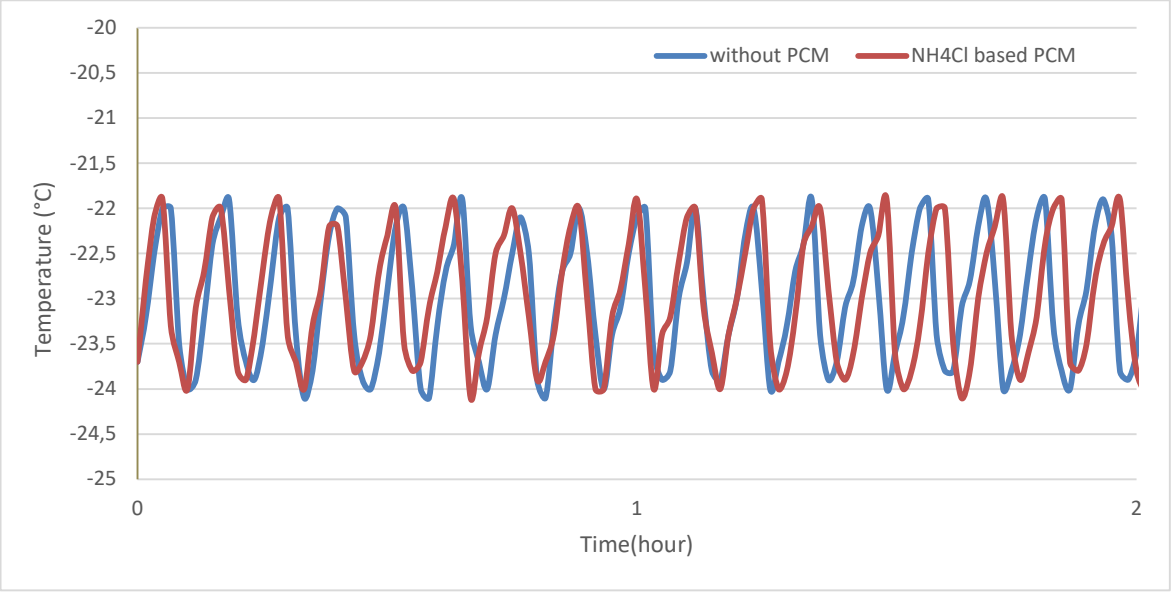

Figure 3.43: Temperature Change at 20 °C Ambient Air Temp. and 2 °C Temperature Difference (between -24 °C and -22 °C)

3.2.2.4. *Cumulative Power Consumption*

Total power consumptions of the cold rooms with and without PCM is demonstrated in this section. Consumption in compressor on period added to one before, and it continues cumulatively.

In the start points, the power consumption to reach -24 °C from 13 °C are taken, which are 916,92 kW and 665,77 kW. The power difference grows out of PCM charge meaning PCM freezing energy.

Figure 3.44 shows cumulative power consumption between -24 °C and -18 °C at 30 °C ambient air temperature. The equations of the trend lines of these data can also be seen.

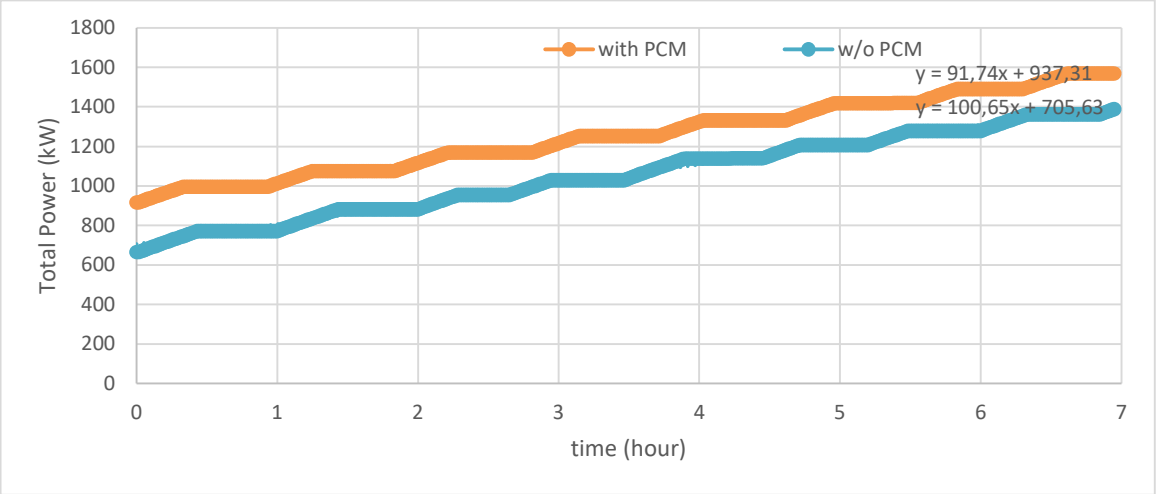

Figure 3.44: Cumulative Power Consumptions at 30 °C Ambient Air Temp. and 6 °C Temperature Difference (between -24 °C and -18 °C)

Figure 3.45 illustrates the equations given in Figure 3.44. The lines intersect at 26th hour meaning PCM compensates charging energy in 26 hours.

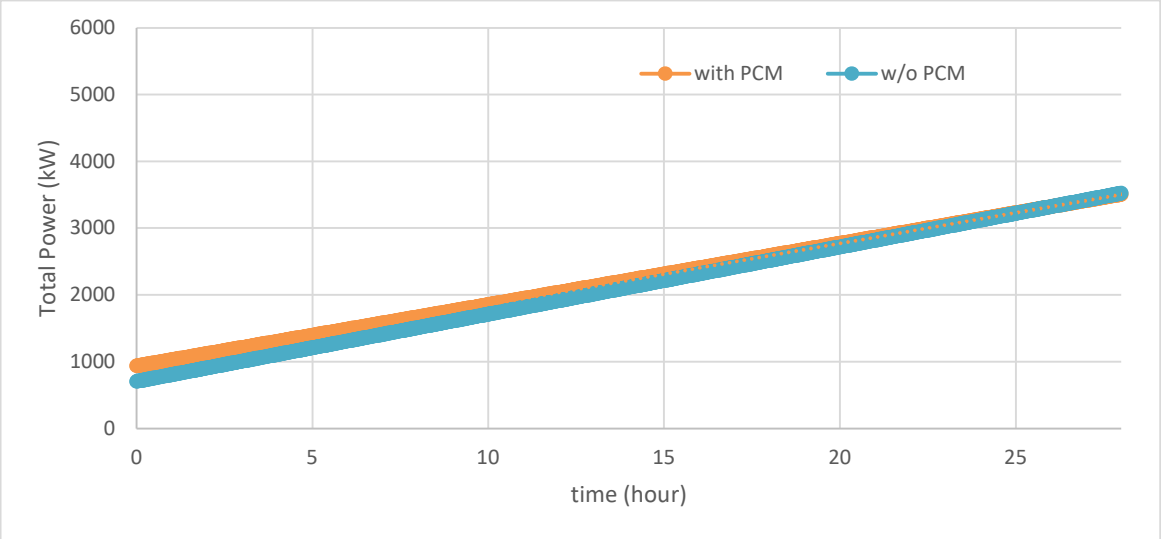

Figure 3.45: Graph of the Linear Equations in Figure 3.44

Figure 3.46 shows cumulative power consumption between -24 °C and -20 °C at 30 °C ambient air temperature. The equations of the trend lines of these data can also be seen.

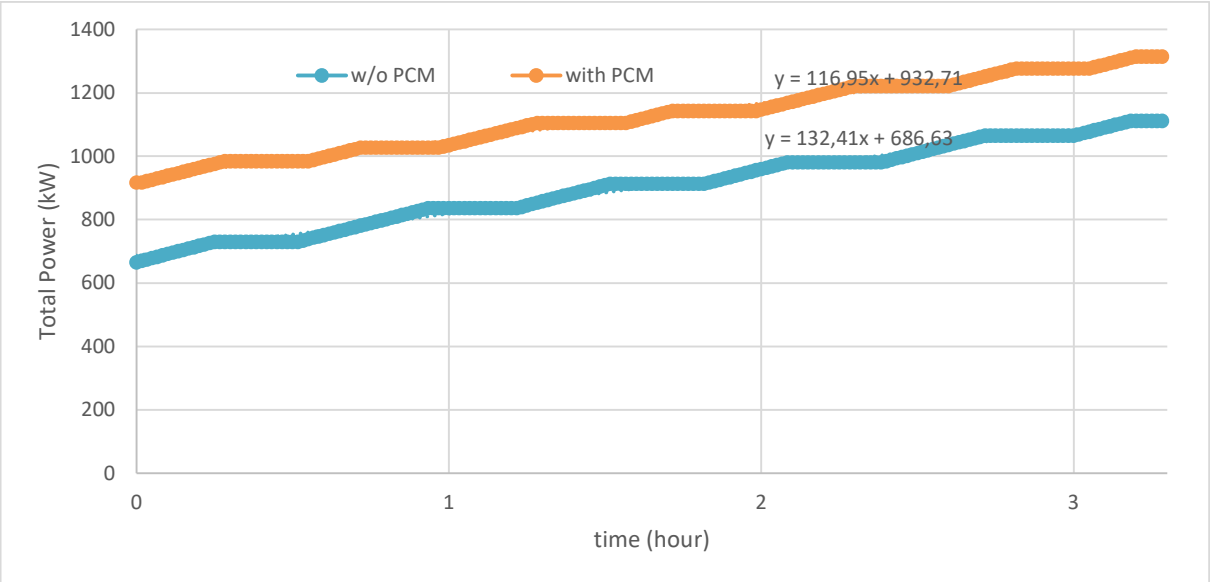

Figure 3.46: Cumulative Power Consumptions at 30 °C Ambient Air Temp. and 4 °C Temperature Difference (between -24 °C and -20 °C)

Figure 3.47 illustrates the equations given in Figure 3.46. The lines intersect at 16th hour meaning PCM compensates charging energy in 16 hours.

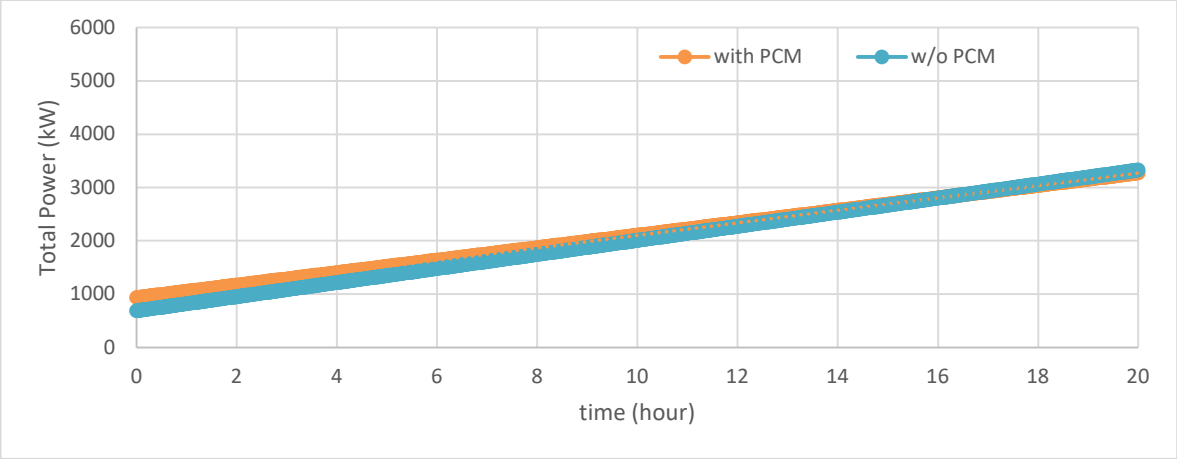

Figure 3.47: Graph of the Linear Equations in Figure 3.46

Figure 3.48 shows cumulative power consumption between -24 °C and -22 °C at 30 °C ambient air temperature. The equations of the trend lines of these data can also be seen.

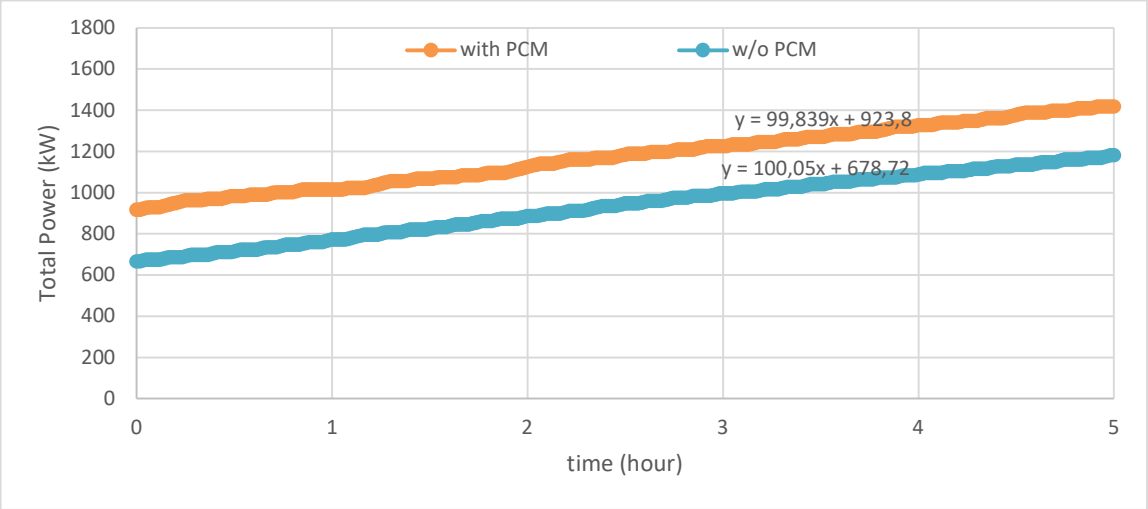

Figure 3.48: Cumulative Power Consumptions at 30 °C Ambient Air Temp. and 2 °C Temperature Difference (between -24 °C and -22 °C)

Figure 3.49 illustrates the equations given in Figure 3.48. As seen from the graph, the lines seem the same but they move nearly parallel and intersects at hour 1161,5 which nearly makes 49 days.

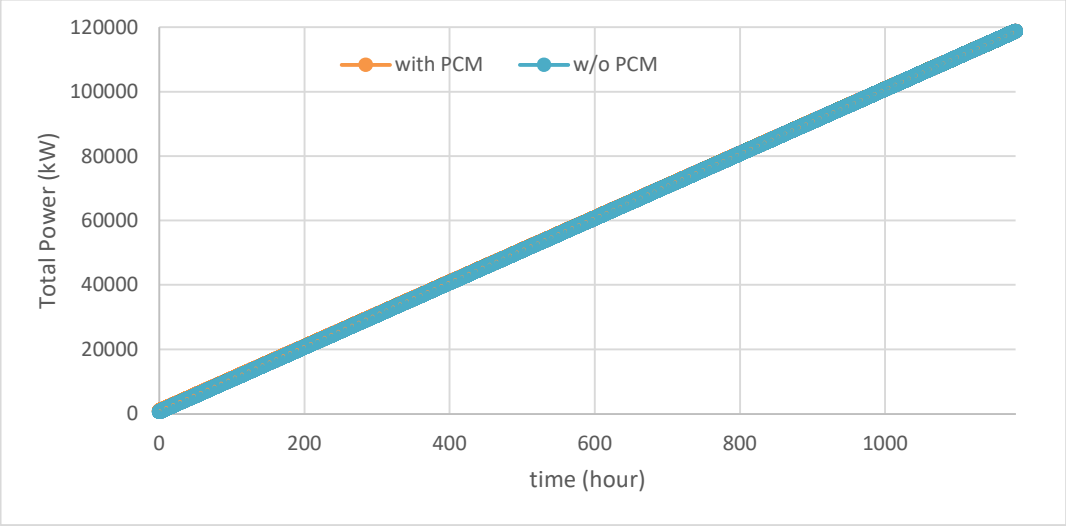

Figure 3.49: Graph of the Linear Equations in Figure 3.48

Figure 3.50 shows cumulative power consumption between -24 °C and -18 °C at 20 °C ambient air temperature. The equations of the trend lines of these data can also be seen.

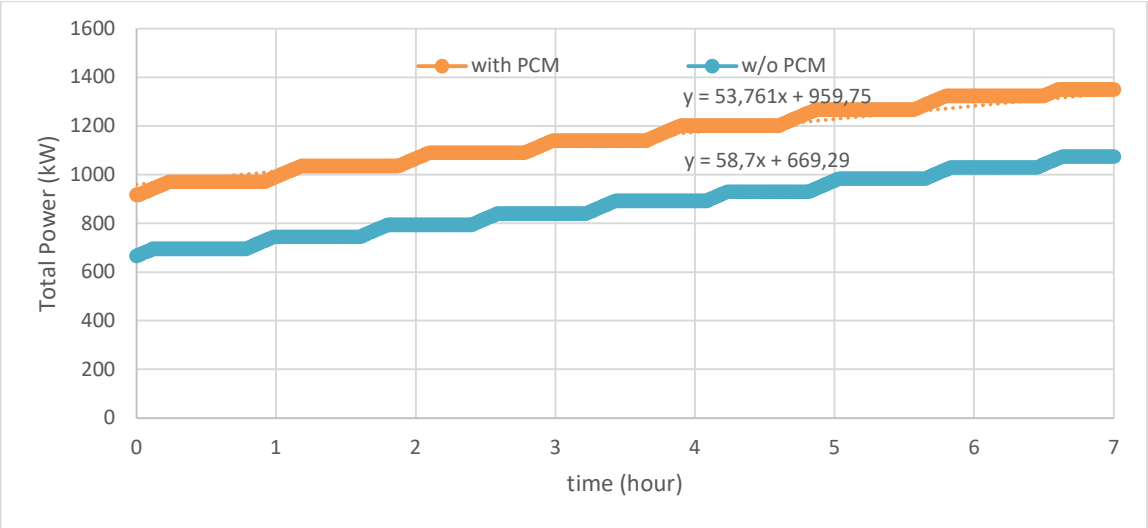

Figure 3.50: Cumulative Power Consumptions at 20 °C Ambient Air Temp. and 6 °C Temperature Difference (between -24 °C and -18 °C)

Figure 3.51 illustrates the equations given in Figure 3.50. The lines intersect at 59th hour meaning PCM compensates charging energy in nearly 59 hours.

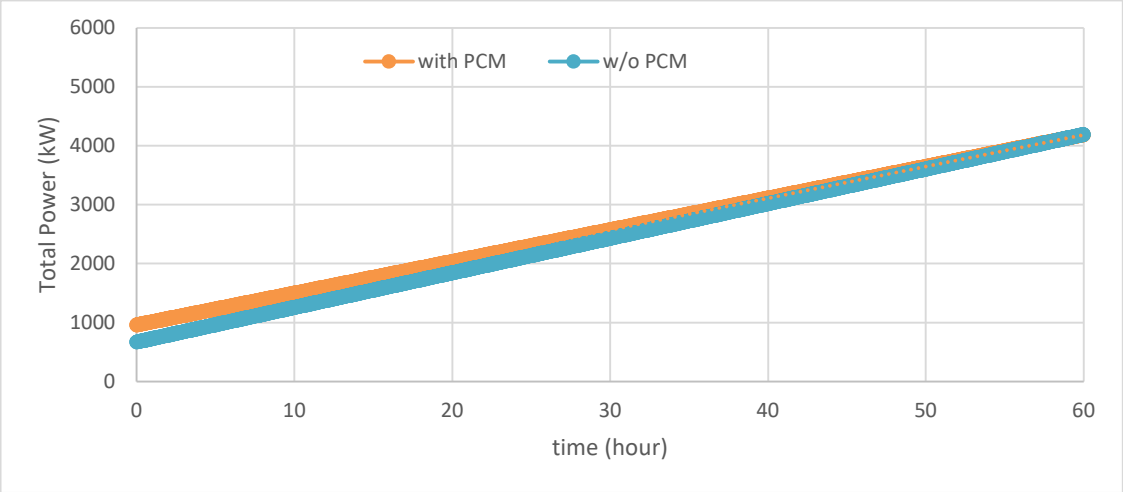

Figure 3.51: Graph of the Linear Equations in Figure 3.50

Figure 3.52 shows cumulative power consumption between -24 °C and -20 °C at 20 °C ambient air temperature. The equations of the trend lines of these data can also be seen.

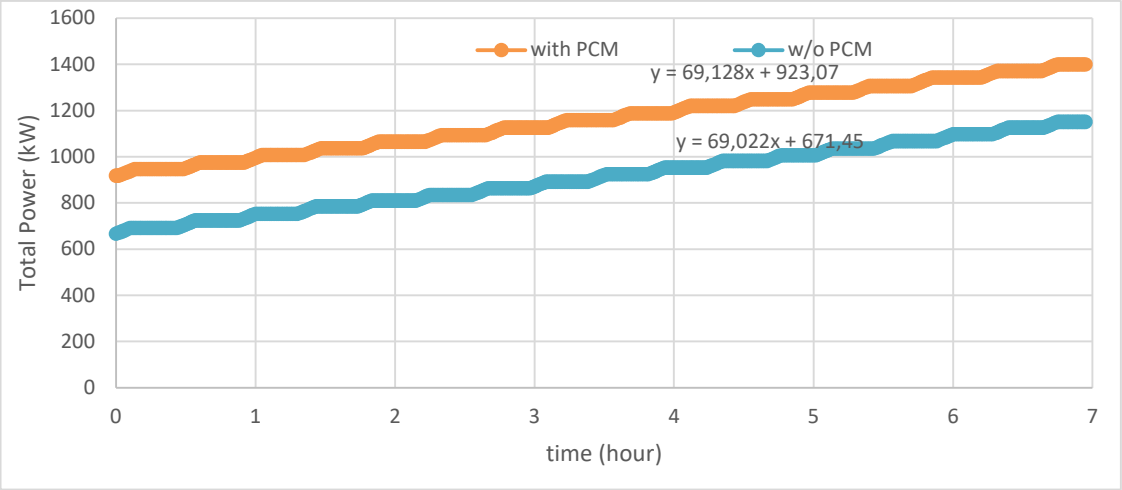

Figure 3.52:Cumulative Power Consumptions at 20 °C Ambient Air Temp. and 4 °C Temperature Difference (between -24 °C and -20 °C)

Figure 3.53 illustrates the equations given in Figure 3.52. The lines do not intersect.

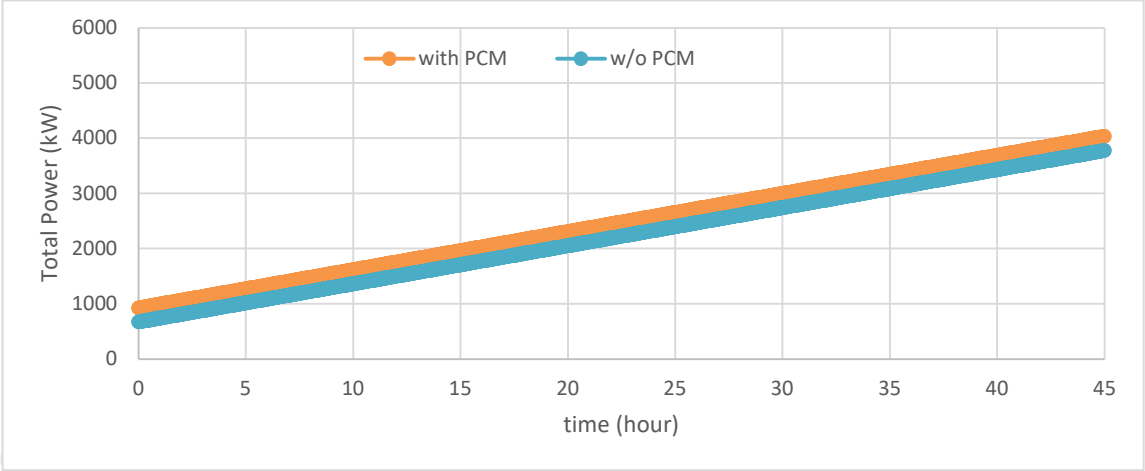

Figure 3.53:Graph of the Linear Equations in Figure 3.52

Figure 3.54 shows cumulative power consumption between -24 °C and -22 °C at 20 °C ambient air temperature. The equations of the trend lines of these data can also be seen.

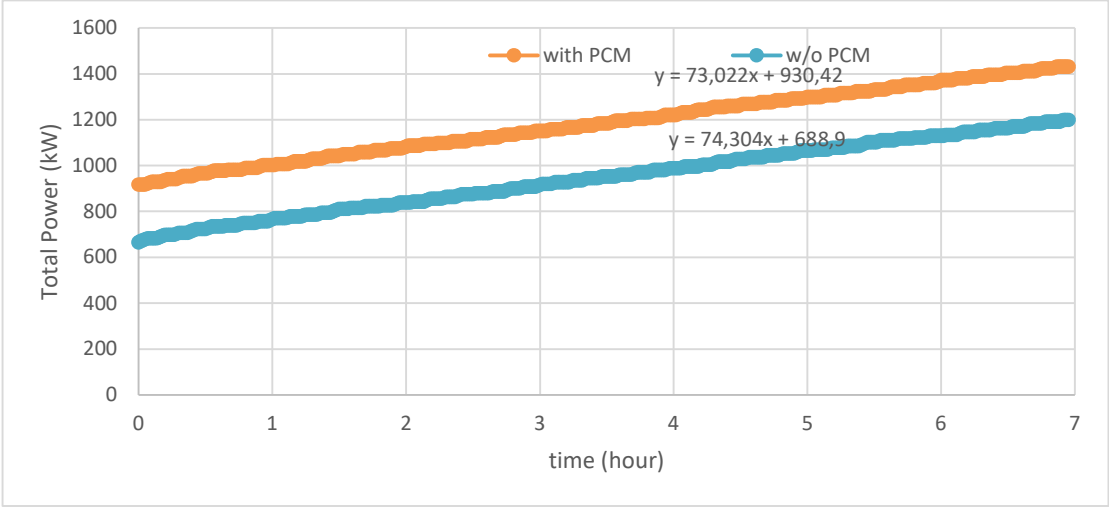

Figure 3.54: Cumulative Power Consumptions at 20 °C Ambient Air Temp. and 2 °C Temperature Difference (between -24 °C and -22 °C)

Figure 3.55 illustrates the equations given in Figure 3.54. The lines intersect at 189th hour meaning PCM compensates charging energy in nearly 189 hours.

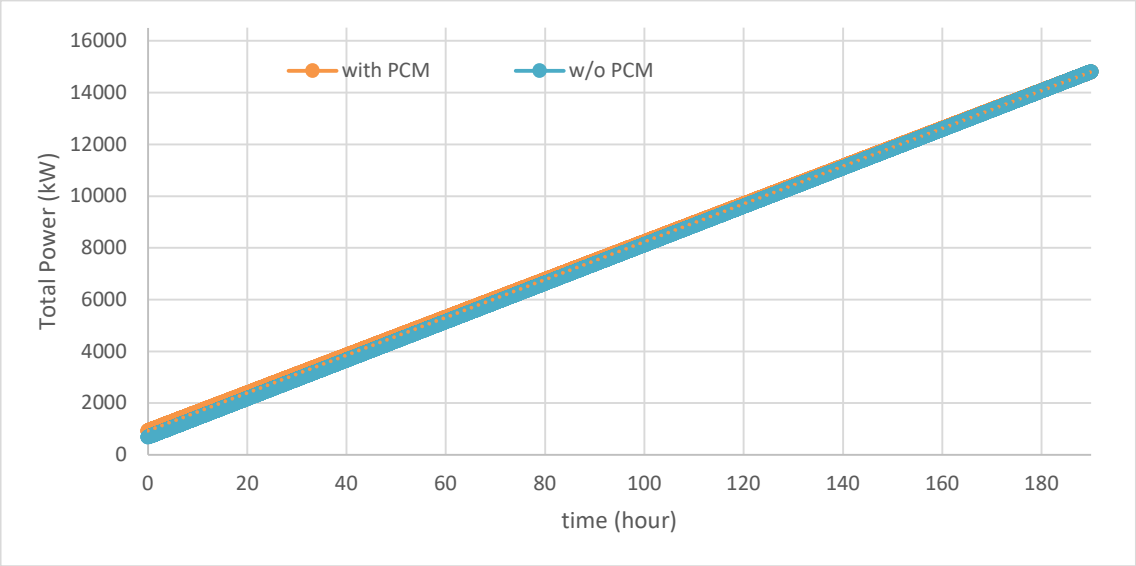

Figure 3.55: Graph of the Linear Equations in Figure 3.54

3.2.3. Temperature Variation During Power Failure

One of the benefits of the PCMs is that they can be utilized as cold battery. During long compressor off times like power failure, PCM can maintain temperature or diminish temperature rising rate.

Figure 3.56 illustrates temperature change from -24 ºC to -13.5 ºC while the compressor is off. These data are experimental. Owing to equations of the lines, it can be detected what will the room temperatures be at any given time.

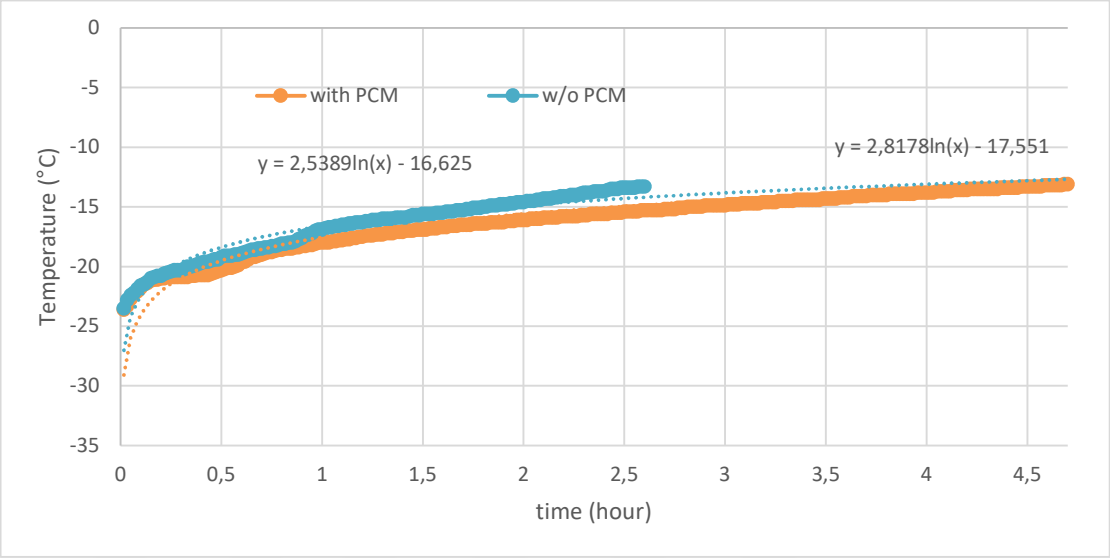

Figure 3.56: Temperature Change Comparison During Power Failure

According to the trend of the lines in Figure 3.56, temperature rising behaviour of the rooms can be predictable. Figure 3.57 shows the temperature rise of the room with PCM and the room without PCM due to given trend equations. Temperatures reach -10 °C at 13 hours and 22,6 hours, respectively.

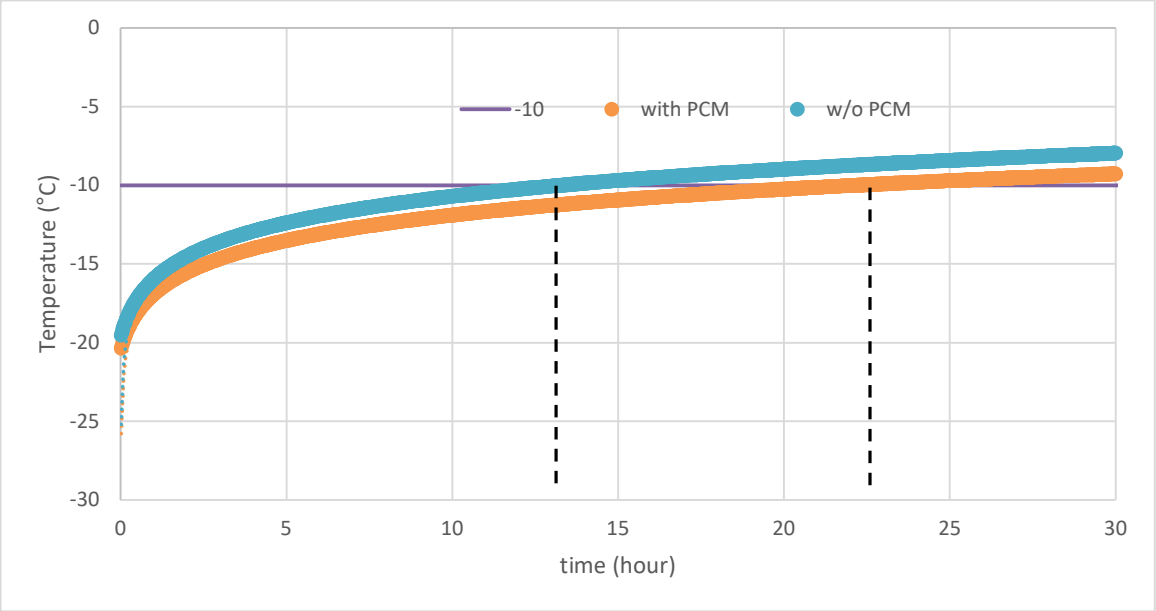

Figure 3.57. Temperature Change Comparison due to Trends in Figure 3.56

4. CONCLUSIONS

The study aimed to observe the effects of PCM in a cold room. Previous studies about PCM implementations mostly focused on small spaces such as refrigerators and cabinets. Hence this study aims to study effect of PCM integration to a cold room having moderately larger volume.

The utilized PCM was developed for the study. Appropriate PCM solutions were selected based on their high latent heat that was measured from the differential calorimetric scanner(DSC) and their melting freezing temperature that was obtained from the cold room tests. Two different PCM were produced, which are NaCl and NH_4Cl based, but they both are the inorganic solutions. At first, it was intended that they are to be inorganic-eutectic solutions. However, in order to prevent some problems such as phase segregation and supercooling, some additives were used. Hence both PCMs are close to the eutectic-inorganic solution with CMC as a gelling, and Borax as a nucleating agent.

Encapsulation of the PCM was chosen to be macroencapsulation owing to its application ease. The material of the encapsulant is high-density polyethylene(HDPE) due to its lightweight, reusability, non-corrosiveness and cost-efficiency.

The COPs of the PCMs are observed as 2,1 and 2,25 for NaCl-based and NH4Cl-based PCMs. According to VAP [73] for Stationary Applications of GEA Group, the COP of the compressor is 1.99 for similar conditions with cold room. Hence COP improvements of 5.5% and 13% were obtained by addition of PCMs, respectively.

To extend compressor lifespan, it is aimed to reduce its number of on-off periods during working. The comparison between 30 °C and 20 °C of the outer room temperature is done while changing temperature difference in the inner room air for 6 °C, 4 °C, 2 °C. Most of the cases it is seen that PCM has a positive effect on lowering the number of compressor on-off cycles. While doing 2 °C temperature difference experiments it was observed that the compressor made an excessive amount of on-offs. The data acquisition system records data in one minute periods. Hence the data acquisition system of the setup may not be adequate for 2 °C scenario. Since 2°C experiments are reliable, in overall, at 30 °C outer temperature with 6 °C difference shows the best result. Moreover, it is seen that the implementation of PCM affects the compressor's on-off cycles in a better way.

Utilizing PCM requires freezing it before application. During charging of PCMs, the compressor consumes more power than without PCM case. It is expected that PCM compensates this power while the operation of the cold room. Cumulative power consumption of the compressor with and without PCM are compared. Duration of the experiments is inadequate to comment about compensation time. Hence according to the obtained line trends and equations, the PCM compensation time for charging power is predicted. After the compensation, PCM implementation improves energy-efficiency of the system. The most rapid scenario that obtained is 30 °C outer temperature with 4 °C temperature difference which is compensated at 16^{th} hour.

One of the benefits of PCM is providing heat extraction from the environment with melting. Hence once the room temperature rises above the PCM melting temperature, PCM starts to melt and decelerate the room temperature rise. According to results the room with PCM reaches -10 °C in 22,6 hours while the room without PCM reaches in 13 hours. During power failure experiment, it is seen that the room temperature rises much slower in the room with PCM.

In conclusion, in most of the scenarios, PCM is beneficial in cold storage. Further studies, more outer room and inner room temperature difference scenarios can be tested. During experiments, there was no load in the cold room. In future, the room can be loaded to observe COP, compressor on-offs, and power failure temperature rise. In the present study, there was no door opening situation, in a future study, door openings on temperature change and compressor power consumption may also be observed.

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