MARMARA UNIVERSITY

INSTITUTE FOR GRADUATE STUDIES

APPLICATION OF DIFFERENT PHASE CHANGE MATERIALS TO IMPROVE THE PERFORMANCE OF A COOLING SYSTEM

SINEM UNAL TEKER

MASTER THESIS

Department of Chemical Engineering

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ISTANBUL, 2024

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May, 2024 **Sinem UNAL TEKER**

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ÖZET

BİR SOĞUTMA SİSTEMİNİN PERFORMANSINI ARTTIRMAK İÇİN FARKLI FAZ DEĞİŞTİREN MADDELERİN KULLANIMI

Dondurucular sıcaklığa duyarlı ve kolay bozulabilen gıda maddelerinin korunmasında gerekli olan sıcaklığı sağlamaları nedeniyle yaygın olarak kullanılmaktadırlar. Dondurucu iç hava sıcaklığı teorik olarak -18°C'ye ayarlansada genellikle sistem sıcaklığı tavsiye edilen sıcaklığın üstünde kaydedilmiştir. Bu dondurulmuş ürünlerde kalite kaybına ve ayrıca gerekli sıcaklık değerine ulaşmak için büyük enerji tüketimine neden olabilmektedir. Dolayısıyla bu istenmeyen sonuçların önlenmesi için soğutma sistemleri genellikle faz değiştiren malzemeler (FDM'ler) ile çalıştırılmaktadırlar.

Bu çalışmada tavsiye edilen sıcaklık değerinden daha yüksek sıcaklıklarda (-5°C ile -13°C) çalışan bir dondurucuyu simüle eden bir soğutma sistemi performansı FDM'siz ve FDM'lerle test edilmiştir. Sodyum klorür (NaCl) çözeltileri uygun faz değiştirme sıcaklığı nedeniyle FDM olarak seçilmiştir. Bu ötektik çözeltilere jelleştirici ajan olarak karboksimetil selüloz (CMC) ve nükleasyon ajanı olaraksa boraks eklenmiştir. İlk olarak; NaCl (ağırlıkça %4,0 ve 16,0), CMC'nin (ağırlıkça %0,0-1,5) ve boraks'ın (ağırlıkça %0,0-2,0) ve farklı konsantrasyonlarının etkisi deneysel olarak soğutma sisteminde incelenmiştir. Tüm sonuçlar, dondurucu performansının hem NaCl hem de ajanların konsantrasyonlarına önemli ölçüde bağlı olduğunu ortaya koymuştur. En uygun FDM'nin ağ. %4,0 NaCl-ağ. % 1,0 CMC-ağ. %1,0 boraks çözeltisi olduğu belirlenmiştir. Ayrıca bu çalışmada önerilen sıcaklığın üzerinde çalışan bir dondurucunun enerji tüketimini en aza indirmek için optimal FDM formülasyonunun belirlenmesine de odaklanılmıştır. Karboksimetil selüloz (ağ. %0,5-1,5) ve Boraks (ağ. %0,0-2,0) içeren sodyum klorür (ağ. %4,0-8,0)-su ikili sistemine dayalı bir dizi FDM formülasyonu -5°C ile -13°C arasında çalışan bir dondurucuyu simüle eden soğutma sisteminde test edilmiştir. Deney sonuçları Box-Behnken tasarımına dayanan Yanıt Yüzey Metodolojisi (RSM) ile değerlendirilmiştir. Böylelikle, bir dondurucunun enerji tüketimini en aza indirecek optimal FDM formülasyonu belirlenmiş ve ayrıca yanıt (çalışma süresi yüzdesi) ile bağımsız değişkenler (bileşenlerin konsantrasyonları) arasındaki ilişkiyi ortaya koyan ikinci dereceden bir polinom denklemi (R^2=0,9521) türetilmiştir. Sonuç olarak, dondurucuların uzun süre az enerji ile çalıştırılmasına olanak sağlayabilecek maliyeti düşük, kolay bulunabilen ve toksik olmayan alternatif bir FDM önerilmiştir.

***Anahtar Kelimeler*:** Dondurucular, faz değiştiren maddeler, enerji tüketimi, Box-Behnken Tasarımı

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ABSTRACT

APPLICATION OF DIFFERENT PHASE CHANGE MATERIALS TO IMPROVE THE PERFORMANCEOF A COOLING SYSTEM

Freezers are widely used for the preservation of temperature-sensitive and perishable food items due to their ability to maintain the required temperature Although the theoretical internal air temperature of the freezer is set to -18°C, it is often recorded above the recommended temperature. This deviation can lead to a loss of quality in frozen products and may result in significant energy consumption to achieve the required temperature. Therefore, to prevent these undesirable results, the operation of cooling systems frequently involves phase change materials (PCMs).

In this study, the performance of a cooling system simulating a freezer operating at temperatures higher than the recommended temperature (-5°C to -13°C) was tested both with and without PCMs. As PCM, sodium chloride (NaCl) solutions were utilized due to its suitable phase change temperature, and different concentrations of carboxymethyl cellulose (CMC) as thickening and borax as nucleating agents were mixed with these solutions. Firstly, the experimental effects of different concentrations of NaCl (4.0 and 16.0 weight %), CMC (0.0-1.5 weight %) and borax (0.0-2.0 weight %), was investigated for this cooling system. All results indicate that the freezer performance is significantly dependent on both NaCl and agent concentrations. 4.0 wt.% NaCl -1.0 wt.% CMC-1.0 wt.% borax solution was determined as the more suitable PCM. In addition, this study aimed to identify the optimum PCM for minimizing the energy consumption of a freezer. A set of PCM formulations based on sodium chloride (4.0-8.0 wt.%)- carboxymethyl cellulose (0.5-1.5 wt.%) and water binary system including borax (0.0-2.0 wt.%) were tested for the cooling system simulating a freezer operating between -5°C and -13°C. The experimental results were evaluated by Response Surface Methodology (RSM) based on the Box-Behnken design. Thus, the optimum PCM formulation was determined and also a second-order polynomial equation (R^2=0.9521) was developed to establish the relationship between response (running time percentage) and the independent variables (concentrations of components). In conclusion, a cost-effective, easily accessible, and non-toxic alternative FDM has been proposed that could enable freezers to operate for an extended period with minimal energy.

***Keywords*:** Freezers, phase change materials, energy consumption, Box-Behnken design

SYMBOLS

ΔH/Δq **:** Enthalpy of fusion/latent heat of fusion [J/kg]

J **:** Joule

Q_s **:** Storage capacity (of a system; J)

t_m **:** Melting temperature (ºC)

C_{ps} **:** Average specific heat of the solid phase [kJ/kg·K]

C_{pl} **:** Average specific heat of the liquid phase [J/kg·K]

f **:** Melt fraction

t_i **:** Initial temperature of the storage material (ºC)

t_f **:** Final temperature of the storage material (ºC)

wt.% : Weight percentage

t : Time [h]

t_{on} : Compressor on time [min]

t_{off} : Compressor off time [min]

T : Temperature [°C]

V : Volume (mL)

W_{PCM} : Total energy consumption with PCM [kJ]

W : Total energy consumption without PCM [kJ]

W(t) : Compressor energy consumption [kJ]

W : Power [kW]

ABBREVIATIONS

PCM : Phase Change Materials

OECD **:** Organization for Economic Co-operation and Development

GHG : Greenhouse Gas

TES **:** Thermal Energy Storage

COP **:** Coefficient of Performance

CMC : Carboxymethyl Cellulose

VCC **:** Vapor Compression Cooling

THS **:** Thermochemical Heat Storage

LHS : Latent Heat Storage

SHS **:** Sensible Heat Storage

SSPCM **:** Shape Stabilized Phase Change Material

HSC **:** Heat Storage Condenser

CSE **:** Cold Storage Evaporator

DES **:** Dual Energy Storage

CCD **:** Central Composite Design

RSM **:** Response Surface Methodology

SAP **:** Super Absorbent Polymer

MEG **:** Modified Expanded Graphite

DSC **:** Differential Scanning Calorimetry

DOE : Design of Experiments

BBD : Box-Behnken Design

wt : Weight

w/PCM : With phase change material

wo/PCM : Without phase change material

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1.INTRODUCTION

1.1 General Information and Objectives

There is an ever-increasing energy demand and consumption as the consequences of climate change and incessant growth of population (the world population is projected to reach 10 billion by 2060) as well as the advancement of technology (OECD, 2022, Global Plastics Outlook: Policy Scenarios to 2060; Economic Projections to 2060, https://www.oecd-ilibrary.org/environment/global-plastics-outlook_aa1edf33-en). Energy consumption causes climate change through greenhouse gas (GHG) emissions, environmental pollution, and the increasing use of fossil fuels. Nowadays, one of the main reasons of the energy demand and consumption are household applications such as cooling systems, heat pumps, and air conditioners. Heat pumps, air conditioners, and cooling systems, such as refrigerators and freezers, are widely used on both household and industrial scales due to their providing suitable temperature conditions. Consequently, cooling systems, by being so prevalent, are responsible and related to a large amount of global energy consumption. By 2015, refrigerators, freezers, heat pumps, and air conditioners accounted for approximately 30% of the global energy consumption, and this is projected to surge 33-fold by 2100 (Yang et al., 2021). Household appliances such as refrigerators and freezers continuously operate throughout the day and are responsible for 7.2% of the total domestic energy consumption (Chen et al., 2022). Therefore, energy-saving solutions for refrigerators/freezers are needed to reduce environmental concerns in both households and industry.

Refrigerators and freezers have several parameters related to energy consumption, such as ambient temperature, set-point temperatures, thermal load, the material(s) used for thermal insulation, design and efficiency of the condenser, evaporator and compressor, thermostat setting, door opening frequency, and the type of refrigerant utilized (Marques et al., 2014; Bista et al., 2018; Dandotiya and Banker, 2017). In literature, it is indicated that the ambient temperature is a significant element of cooling systems' energy consumption (Geppert and Stamminger, 2013) with increases in ambient temperature leading to higher energy consumption, the condenser temperature, and the compressor running time (Björk and Palm, 2006). To achieve the energy saving and performance increase possible, there are some main aspects that have been focused on in literature as follows: the enhancement of compressor efficiency, improvement of the heat transfer in the condenser and evaporator, applying advanced circulation, and development of thermal insulation of the system by increasing the

thickness of the insulation or applying advanced thermal insulation materials (Bakhshipour et al., 2017). There are various studies related to the compressors of refrigerators and freezers due to their total energy consumption by 80% (Joybari et al., 2015). Therefore, an alternative method has been proposed in the literature to minimize the energy consumption of these systems. Phase Change Materials are integrated into the systems to reduce the compressor's on-off cycle during the cooling system's running period, maximizing energy savings. PCMs, having a large energy storage capacity, are used in latent heat storage systems. As thermal energy storage (TES) materials, PCMs are utilized for various applications such as food preservation, transportation, electronic cooling, showcases, and heating-cooling for buildings (Vikram et al., 2018; Ilongovan et al., 2022). During phase transition at constant temperature, PCMs remain thermally stable, absorbing or releasing thermal energy during the melting or freezing process, respectively. (Mona et al 2022; Omara and Mohammedali, 2020a). The latent heat storage systems include the following types of phase change: solid-solid, solid-gas, liquid-gas, and solid-liquid. Among these types of phase change, solid-liquid transitions are the most common and studied applications (Yang et al., 2021). PCMs can be classified into three groups: organic, inorganic and eutectic. To enhance the performance of cooling systems and obtain energy-efficient systems, PCMs must have certain chemical, physical, and economic properties and integrate suitable locations in the system. The chemical, physical, and economic properties of PCMs include compatibility with other materials, low vapour pressure, small volume change, suitable phase change temperature, significant change in enthalpy, substantial specific heat capacity, low price, and abundance *etc*. (Khan, 2016; Akeiber et al., 2016; Omara and Abuelnour, 2019; Omara, et al., 2020b). In the literature, applications of PCMs in cooling systems include integrating on the condenser, compressor, cabinet or between condenser and expansion valve, and evaporator (Riffat et al., 2022). The composition and integration variations of PCMs are of different effects on the compressor's on/off cycle time period, the coefficient of performance (COP), the maximum/minimum temperature values of the system parts, and the temperature fluctuations (Sonenrein et al., 2020; Selvnes et al., 2021; Suamir et al., 2019; Sun et al., 2023; Javadi et al., 2020). Thus, the optimal combination of PCM formulation and integration location needs to be designed to maximize system performance and energy efficiency.

Although there are many studies in the literature where different compounds and/or mixtures are used as PCMs, studies examining the use of PCMs in low temperature applications are limited. Therefore, the aim of this experimental study is to propose an alternative and promising

eutectic PCM solutions to be used in a freezer with the operating condition between -13°C and -5°C. A set of PCM formulations based on sodium chloride-water binary system including borax and carboxymethyl cellulose were tested for a freezer. A suitable solution was proposed as a PCM to minimize the energy consumption of a freezer operating at higher temperature values than the desired value. An experimental design study was also performed to reveal the optimal PCM. The experimental results were evaluated using the Response Surface Methodology (RSM) based on the Box-Behnken design. In summary, a cost-effective, easily accessible, and non-toxic alternative FDM has been proposed that could enable freezers to operate for an extended period with minimal energy.

1.2 Cooling Systems

Cooling systems are utilized for maintaining the ambient and/or indoor temperature by exchanging heat/energy with the system environment. Cooling systems can be thermal-driven, electricity-driven, or solar-driven in order to make the heat flow from colder to warmer. Heat transfer occurs through refrigerants within the cooling systems (Sleiti et al., 2020).

Cooling systems such as freezers, refrigerators, air-conditioners, heat pumps employ various cooling technologies: 1) Vapor compression cooling system (VCC), 2) Absorption cooling system, 3) Adsorption cooling system, 4) Ejector cooling system, 5) Evaporative cooling system, 6) Solid and liquid desiccant system, 7) Thermoelectricity cooling system, 8) Thermomechanical compressor system, 9) Stirling cycle system, 10) Air cycle system, 11) Tri-generation system, 12) The organic Rankine cycle system, and 13) Hybrid systems. Since the early 20th century, vapour compression systems have been widely applied by cooling system applications owing to their low cost and high-efficiency properties. However, environmental damage and high energy consumption lead to alternative cooling technologies and the replacement and improvement of conventional VCC systems. In this regard, the use of PCMs is one of the prominent methods for developing VCC systems (Tassou et al., 2010; Kojok at al., 2016; Sleiti et al., 2020; Gado et al., 2021).

1.2.1 Refrigeration Cycle of Cooling Systems

Conventionally, the single stage vapor compression refrigeration cycle is generally utilized in cooling systems and the efficiency of this systems is characterized by the theoretical efficiency of the Carnot cycle. An ideal refrigeration cycle and its *T*-*s* diagram are shown in **Figure 1.1**. Nowadays, ideal refrigeration cycle and its *T*-*s* diagram is revised, modified and improved

constantly depending on the applications and requirements. Cooling systems consist primarily of compartment, evaporator, condenser, thermal insulation layer, machinery space where compressor, suction line heat exchanger (or internal heat exchanger), discharger pipe, and filter drier are located. (Arora, 2003; Moran and Shapiro, 2006; Ahamed et al., 2011; Wang et al., 2014; Yang et al., 2015; Belman-Flores et al., 2015; Chen et al., 2016; Yan et al., 2019; Fang et al., 2019; Yang et al., 2023).

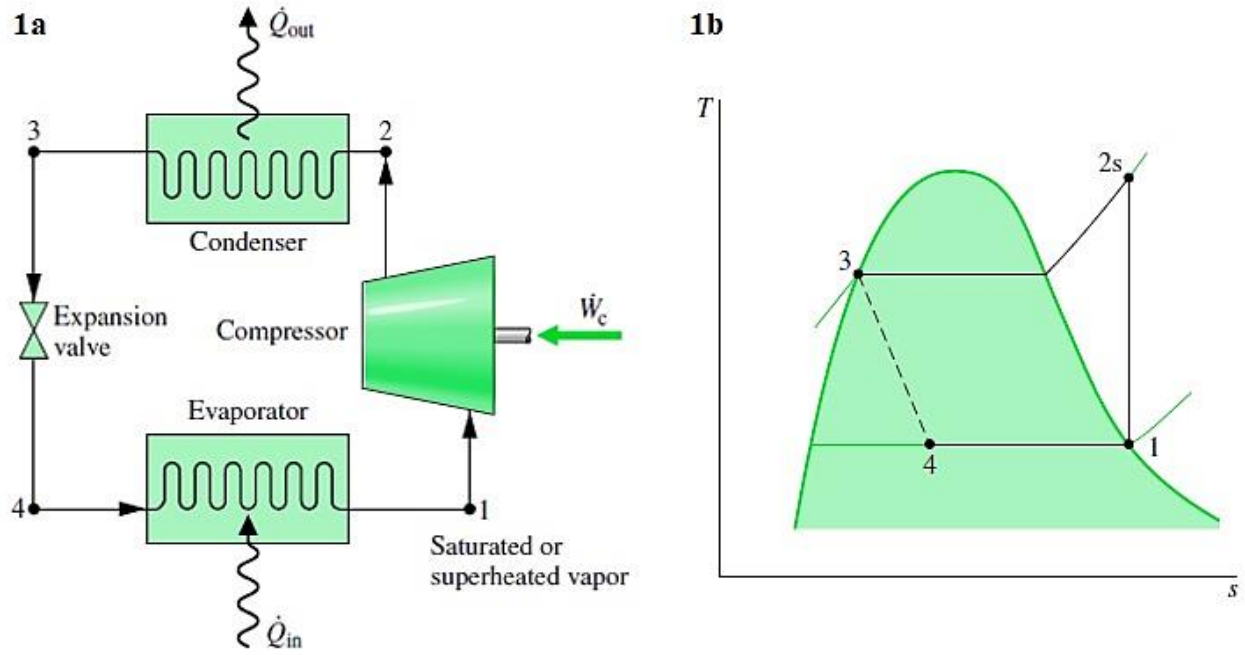

Figure 1.1 Ideal refrigeration cycle and *T-s* diagram for the cooling systems.
W_c, input power; Q_{in} and Q_{out}, heat transfer from and to the ambient, respectively. Processes signify the following: Process 1 to 2s is the isentropic compression of the refrigerant to the condenser pressure at state 2s; Process 2s to 3 is the heat transfer from the refrigerant while flowing through condenser at constant pressure; Process 3 to 4 is the throttling process at the expansion 5 valve; Process 4 to 1 is the heat transfer to the refrigerant while flowing through evaporator at constant pressure (Moran and Shapiro, 2006).

1.2.2 Freezers

Freezers have a variety of applications including domestic and commercial food storage, scientific research, biomedical, ocean fishing, transportation, *etc.* with the temperature range between -1 and -100 °C (Mota-Babiloni et al., 2020). Even though there are examples as to the modifications of cycle and system components of freezers in order to improve the system performance (Yang et al., 2015; Hou et al., 2017; Sarkar, 2017; Chen et al., 2017; Fang et al.,

2019; Lu et al., 2020; Wang et al., 2020), freezers and the refrigeration cycle to be based on generally have the four main components, which are the compressor, condenser, expansion valve, and evaporator, as seen in **Figure 1.1a**. The systems also consist of a refrigerant performing phase change reversibly to procure the cooling effect. The compressor pressurizes the intermittent flow of fluids (refrigerant and secondary fluid) and control the circulation of these fluids through its on/off process. The refrigerant having the high temperature and pressure flows to the condenser. The condenser propagates to the ambient the latent heat generated during the condensation of refrigerant vapor and thus, the refrigerant condenses. In the evaporator, heat exchange occurs again while the evaporator absorbs the heat from cold ambient, and the refrigerant vaporizes. The expansion valve facilitates pressure reduction. Among these components, the compressor is the most important part by being responsible for the majority of the use of the energy consumption and determining the life-cycle expectancy of any given system. As it is of in the scope of this study, reducing the compressor cycle frequency and energy consumption can be achieved through the PCM use for the freezers (Arora, 2003; Moran and Shapiro, 2006; Ahamed et al., 2011; Wang et al., 2014; Yang et al., 2015; Belman-Flores et al., 2015; Kiran-Yildirim, 2022).

1.2.3 Refrigerants

Refrigerants are one of the major components within a freezer affecting the system performance, thereby the energy consumption. Therefore, they are a key parameter to consider during system design. During the compressor on-time, the refrigerant absorbs the ambient heat through conduction process. The density of the refrigerant is directly proportional to the temperature and pressure of the evaporator having the PCM. Consequently, vaporized refrigerant enters the compressor, and the higher refrigeration capacity and COP can be achieved (Nguyen et al., 2023).

Over time, the use of refrigerants has been subject to change in accordance with the emergence of environmental concerns related to greenhouse gases and ozone depletion. The refrigerants are classified as the following order by their detrimental effects: 1) Chlorofluorocarbons (CFCs), 2) Hydrochlorofluorocarbons (HCFCs), 3) Hydrofluorocarbons (HFCs), 4) Carbon dioxide (CO_2), natural hydrocarbons (HCs), and ammonia (NH_3). Having settled on by Montreal Protocol in 1987, the use of these refrigerants would be terminated gradually or rapidly depending on their several impacts. Currently, HCs, HFCs, and CO_2 alongside their mixtures, have been used widely (Mohanraj et al., 2011; Sarbu, 2014; Belman-Flores et al.,

2015; Roy and Halder, 2020; Pabon et al., 2020). In addition, new alternative mixtures containing nanoparticles have been studied as well (Belman-Flores et al., 2015; Sharif et al., 2018). In this study, R404A was used as refrigerant. R404A is a HFC mixture of R125, R134a, and R143a (Roy and Halder, 2020).

1.3 Thermal Energy Storage (TES)

Utilizing renewable energy sources and the storage of the energy are the most sustainable solutions for meeting ever-increasing global energy consumption and preventing ever-deteriorating environment. However, the replacement of fossil fuels by renewable energy sources would take a considerable time. TES systems have significant advantages, such as facilitating a more consistent and stable demand-supply balance, enhancing the performance of the current energy systems, recycling the low-grade thermal energy and reducing the greenhouse gas emission (Alva et al., 2018; Gude, 2015). Thus, the storage of thermal energy derived from fossil fuels and/or renewable energy sources stands out as both effective and sustainable solution. Currently, TES has various energy storage technologies such as compressed air energy storage, flywheel energy storage, pumped hydro energy storage, battery energy storage, hydrogen storage, and Carnot battery (Sun et al., 2023). TES systems typically involve a substance, known as the storage medium, used to store cold or hot thermal energy for later use (Guelpa and Verda, 2019). TESs store the thermal energy in the off-peak time period and release that energy in order to balance intermittent energy demand (Vikram et al., 2018). TES classification is divided into three categories and is shown in **Figure 1.2** (Khan et al., 2017; Zare and Mikkonen, 2023).

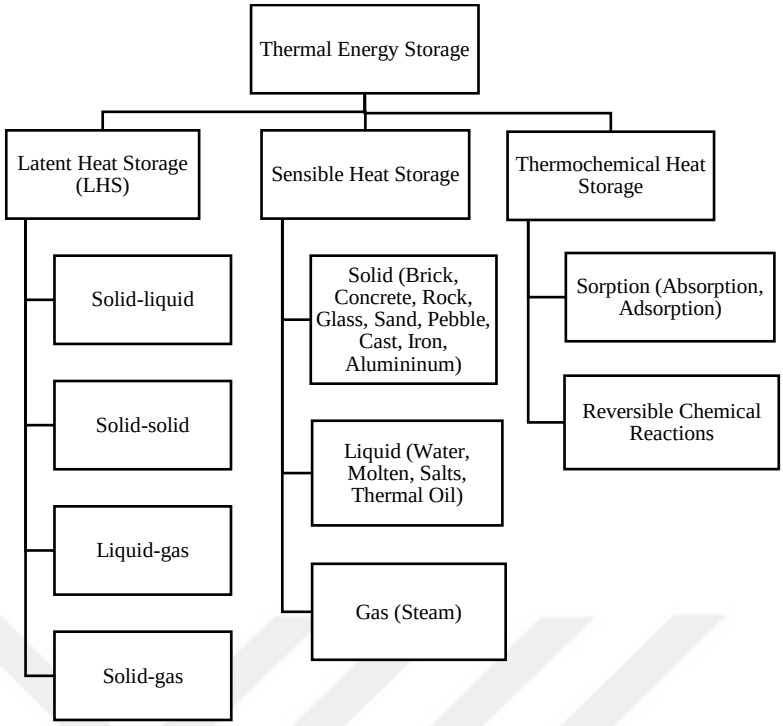

Figure 1.2 Thermal Energy Storage classification.

Thermochemical heat storage (THS) uses reversible chemical reactions to store energy. THS consists of three steps. In the first step an endothermic reaction charges the storage unit, in the second step energy storage happens, and in the third step an exothermic reaction discharges the storage unit. Despite having higher storage capacity than latent heat storage (LHS) and sensible heat storage (SHS), THS being also expensive and difficult has chemical instability during the process. SHS is related with the mass, temperature change of the medium, and the specific heat capacity of the material. SHS is the simplest and cost-efficient system and is already commercially on the market. During the heat storage process, the temperature of the storage medium increases/decreases to store or release heat. In comparison, LHS based on the phase transition has a more substantial energy storage density than SHS. In the initial and late stages of heat storage, as it is of the SHS, as the temperature of the heat storage medium (PCM) increases, the heat absorbed gradually increases. When the temperature reaches the phase transition point, PCM continues to absorb heat at relatively constant temperature during phase transition process. A common PCM application, a solid-liquid phase transition principle, can be seen in the **Figure 1.3**. There is sensible heat in the initial and late stages of heat storage, but the whole process is dominated by the enthalpy of fusion value ΔH (or Δq; J/kg), and the storage capacity Qs of the LHS system having a PCM can be calculated by **Equation 1.1** (Hinojosa et

al., 2023; Sun et al., 2023; Zare and Mikkonen, 2023; Sarkar et., 2022; Shchukina et al., 2018; Patel et al., 2017).

$$Q_S = \int_{ti}^{tm} mcp\Delta t - mf\Delta q - \int_{tm}^{tf} mcp\Delta t \quad (1.1)$$

$$Qs = m[c_{ps}(t_m - t_i) - f\Delta q - c_{pl}(t_i - t_m)]$$

Where t_m (ºC) is the melting temperature; t_i is the initial temperature of the storage material (ºC); t_f is the final temperature of the storage material (ºC); m (kg) is the mass of PCM; c_{ps} (kJ/kg·K) is the average specific heat of the solid phase between t_i and t_m; c_{pl} (J/kg·K) is the average specific heat of the liquid phase between t_m and t_f; f is the melt fraction; Δq (J/kg) is the latent heat of fusion (Sarbu and Sebarchievici, 2018).

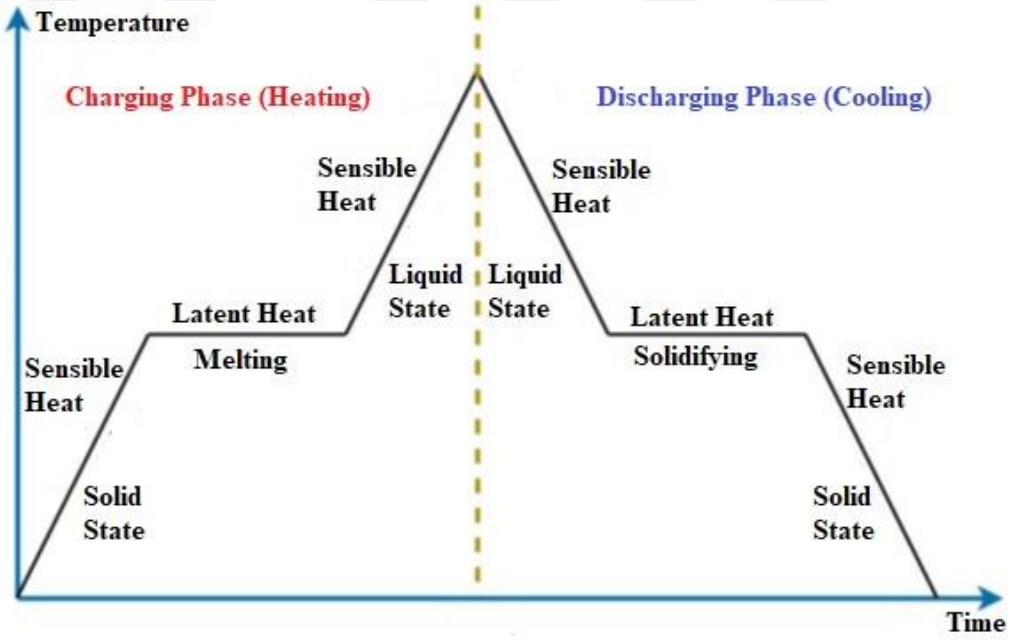

Figure 1.3 The solid-liquid PCM application principle.

1.4 Phase Change Materials (PCM)

Phase change materials (PCMs) are also known as latent heat storage tank due to their ability to absorb or release latent heat. PCMs provide advantage in terms of keeping temperature at a desired values by absorbing and releasing a huge amount of latent thermal energy through the process of phase change (charging and discharging process). The heat absorbed or released during process is related to the latent heat of the PCM. PCMs assist in maintaining

compartment/indoor ambient temperature within a particular temperature range which is close to the melting/freezing temperature of the PCM. In comparison to the SHS, PCMs have higher energy storage capacity with a minimum volume change and therefore, less material amount and volume are required for the application (Du et al., 2018; Sangwan et al., 2022).

The stability of Phase Change Materials (PCMs) significantly affects their freezing/melting cycles, thereby extending their lifetime. Thus, PCM applications require consideration of two important aspects; the integration of the material and interaction with the system environment. Also, the temperature at which phase transition occurs in PCMs, PCM type, quantity and thickness of PCMs, and location in the system influence the performance of any given PCM and before the selection of the material, these features have to be assessed (Frahat et al., 2023). **Table 1.1** provides a summary of experiments conducted by various researchers exploring the application of PCM in refrigeration. These aspects will be discussed and detailed in the following sections through classification, properties and literature applications of PCMs.

Table 1.1 A summary of experiments conducting the application of PCM in refrigeration (Cheng et al., 2011; Rahman et al., 2013; Abhilash et al, 2015; Azzouz et al., 2005; Azzouz et al., 2009; Onyejekwe et al., 1989; Marques et al., 2014; Gin and Farid, 2010; Khan et al., 2013; Elarem et al., 2017; Subramanium et al., 2010; Yuan and Cheng, 2014; Wang et al., 2017)

Ref.	PCM Type			Location			Phase	PCM	Thermal Load	
	Water	Eutectic	Paraffin	Evaporator	Condenser	Compartment	Change Temp	Thickness	Ambient Temp	Evaporation Temp
Cheng et al.			✓		✓					
Rahman et al.	✓			✓						
Abhilash et al.				✓						
Azzouz et al.		✓		✓			✓		✓	
Azzouz et al.		✓		✓			✓	✓	✓	
Azzouz et al.	✓	✓		✓				✓	✓	
Onyejekwe et al.		✓		✓				✓	✓	
Marques et al.	✓			✓				✓	✓	✓
Gin and Farid		✓								
Khan et al.	✓	✓		✓		✓				✓
Elarem et al.				✓		✓				✓
Subramanium et al.				✓						
Yuan and Cheng			✓		✓					
Wang et al.		✓		✓	✓					

1.4.1 Properties of Phase Change Materials

The phase change temperature determines the application of any PCM so that the system can be designed properly and accurately. The heat/energy amount stored or released in the phase change process is related to the latent heat of the PCM. Having higher melting enthalpy indicates storing or releasing a larger amount of energy. Regardless of their classification, PCMs must have to necessary properties summarized in **Table 1.2**. Although it is very unlikely for a solid-liquid PCM to have all of these properties, by taking into consideration these properties, an optimum and invaluable TES system in the freezers can be constituted by selecting the appropriate PCM alongside the application location of the PCM (Sarbu and Sebarchievici, 2018).

Table 1.2 Due properties of PCMs (Nguyen et al., 2023; Selvnes et al., 2021; Khan et al., 2016; Li et al., 2013; Oro et al., 2012a).

Category	Properties
Physical	Favorable phase equilibrium; Reproducible phase change (cycling stability); High density; Small volume change; Low vapor pressure at melting temperature; High thermal conductivity
Chemical	Long term chemical stability; Compatibility with other materials; No toxicity; No corrosiveness; Non-flammable; Non-explosive
Kinetic	No supercooling; Sufficient crystallization rate; High nucleation rate
Thermal	Suitable phase change temperature; High latent heat capacity; Good heat transfer characteristics; High heat of fusion
Economic and Environmental	Abundant; Commercially available; Cost-effective; Good recyclability; Non-polluting

Various of PCMs and their mixtures have been studied extensively in the literature for their potential applications covered in Section 1.6. Besides, they have been reviewed in literature for their various application areas such as cooling and heating systems (refrigerators-freezers, air-conditioners, refrigerated truck trailers, food refrigerated display cabinets, heat pumps and heat exchangers), automotive sector, low-grade waste heat recovery, solar energy storage (solar thermal collectors, solar dryers, solar photovoltaic and desalination systems), textile,

showcases, electronic devices, life science applications, building industry as a passive energy storage (integration into the floors, windows, roofs, ceilings *etc.*), and an active energy storage (utilizing a mechanical system) (Pielichowska and Pielichowski, 2014; Verghese et al., 2015; Heier et al., 2015; Alzuwaid et al., 2016; Akeiber et al., 2016; Purohit and Dasgupta, 2020; Nie et al., 2020; Pahamli and Valipour, 2021; Radouane, 2022; Zhang et al., 2021; Taher et al., 2022; Sarkar et al., 2022; Wang et al., 2022; Maghrabie et al., 2022; Rashid et al., 2023; Hinojosa et al., 2023).

1.4.2 Classification of PCMs

PCMs are classified into four categories which are solid-liquid, solid-solid, solid-gas, and liquid-gas. Among these, the latent heat of solid-solid transition is usually much lower than of the solid-liquid transition. The volume change before and after phase transition in the solid-gas and liquid-gas transitions is excessive, hence the applications in the industry are limited. The solid-liquid transition having a large value of latent heat, a small volume change during phase change and a wide range of phase changing temperature is commonly investigated and used. Solid-liquid PCMs can be further classified as organic, inorganic, and eutectic to be seen in the **Figure 1.4**. (Hinojosa et al., 2023; Diaconu et al., 2022; Hussain et al., 2020; Akeiber et al., 2016; Su et al., 2015).

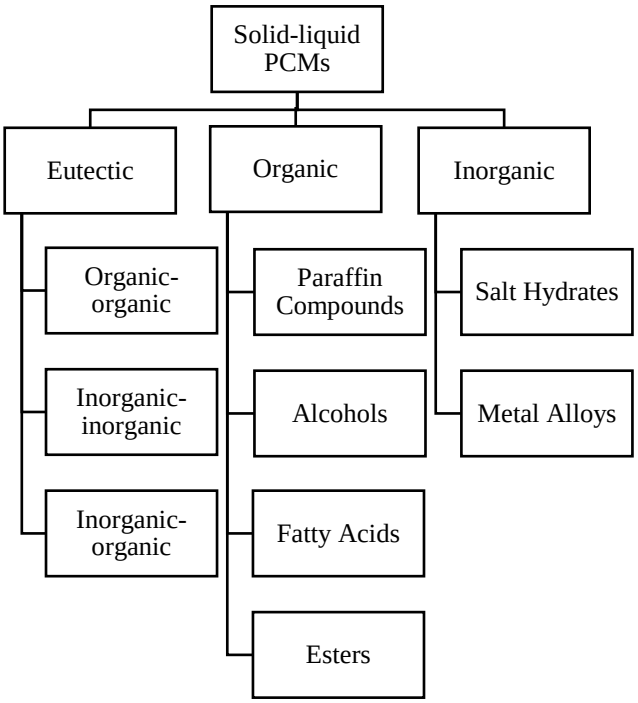

Figure 1.4. The classification of solid-liquid PCMs.

1.4.2.1 Organic PCMs

Organic PCMs usually are classified into two categories as paraffin compounds and non-paraffin compounds (alcohols, fatty acids, glycols, and esters). Phase change temperature mostly varies between -200ºC – 150ºC for organic PCMs (Cabeza et., 2011; Yang et al., 2021). Organics PCMs have some general advantages and disadvantages. Crystallization with no or very low supercooling, melting and freezing many times without phase seperation and deterioration of latent heat of fusion, being non-corrosive, having stable and inert chemical properties, low cost are the main and common advantages. Having low thermal conductivity (therefore a larger surface area is needed to provide the required heat transfer rate), moderate flammability, low energy storage density are the main and common disadvantages (Aluyor and Ori-Jesu, 2009; Sharma et al., 2009; Yongsheng et al., 2010; Cabeza et., 2011; Oro et al., 2012a; Huang et al., 2014; Yibo et al., 2016; Yang et al., 2018; Omara and Mohammedali, 2020a; Yang et al., 2021).

The most widely studied organic PCMs are paraffin compounds and fatty acids. Hydrogen and carbon structures having different chain length form paraffin or n-alkane compounds. Their melting point and latent heat increase with the length of the carbon chain. Paraffin compounds are reliable, chemically stable and inert, non-corrosive, available in a wide range of temperatures (5ºC – 80ºC). In comparison to pure paraffin waxes, technical-grade paraffin is preferred because of their low prices. Fatty acids can be efficiency from vegetable and animal oils and hence, they are regarded as food-grade. Melting point and latent heat of fusion increase as the length of the fatty acid chains such as paraffin compounds. They have almost the same thermo-physical properties as paraffin compounds (Schaink et al., 2007; Mehling and Cabeza, 2008; Sharma et al., 2009; Bica et al., 2011; Oro et al., 2012a; Li et al., 2013; Hyun et al., 2014; Yuan et al., 2014; Su et al., 2015; Shao et al., 2015; Vakhshouri, 2020; Mishra et al., 2022; Guo et al., 2022).

1.4.2.2 Inorganic PCMs

Inorganic PCMs consist of mainly salt hydrates and metallic compounds. Phase change temperature mostly varies between -100ºC – 1000ºC for inorganic PCMs (Romdhane et al., 2020; Javadi et al., 2020; Zhang et al., 2021). Inorganic PCMs have also some general advantages and disadvantages. High thermal conductivity, high energy storage for higher enthalpies per volume, and cost-efficiency and non-flammability are the main and common

advantages. Being corrosive, having a high supercooling effect and chemical instability, and showing phase segregation are the main and common disadvantages. (Yibo et al., 2016; Wahid et al., 2017; Omara et al., 2019; Li et al., 2019; Fang et al., 2019; Romdhane et al., 2020; Nie et al., 2020; Nguyen et al., 2023)

Salt hydrates, containing water and inorganic salt, can be formed by hydrating or dehydrating a salt. The hydrating or dehydrating of a salt amount to the freezing or melting process in thermodynamics. Alongside supercooling, the common disadvantage of salt hydrates is the incompatible melting, which causes the solution to be supersaturated by losing water molecules. In order to prevent these issues, adding thickening agents, adding water, mechanical stirring, or encapsulating the PCM are the main methods to be benefited. However, their thermal conductivity is twice that of pure paraffin, and they have high latent heat of fusion per unit volume. Metallic PCMs consist of low-melting metals and metal alloys. Property of low-melting enthalpy per unit weight constraints metallic PCMs to be used in TES systems (Gasanaliev and Gamataeva, 2000; Sharma et al., 2009; Noro et al., 2014; Hyun et al., 2014; Kumar, 2018; Rajagopalan et al., 2021; Purohit and Sistla, 2021; Ribezzo et al., 2022).

1.4.2.3 Eutectic PCMs

Eutectic PCMs are the composition of two or more organic and/or inorganic components with similar freezing and melting points, without exhibiting phase segregation of the material during the freezing/melting process. They are classified as organic-organic, inorganic-inorganic, and inorganic-organic. Phase change temperature mostly varies between -86ºC – 30ºC for eutectic PCMs in cold TES applications (Sharma et al., 2004; Shen et al., 2019; Oro et al., 2012a). However, there are some commercial eutectic PCMs having the phase change temperature as low as -114 ºC (Selvnes et al., 2021). Eutectic PCMs have high volumetric energy storage density and thermal conductivity as advantages. In addition to having limited availability and considerably higher cost in comparison to organic and inorganic PCMs, eutectic PCMs have low latent and specific heat capacities, which are disadvantages. By changing the weight proportion of component, a desired phase change temperature can be controlled and managed with the properties of lower melting temperature, stable and specific phase change temperature. Consequently, eutectic PCMs can be utilized for different applications (Baetens et al., 2010; Raj and Velraj, 2010; Li et al., 2013; Akeiber et al., 2016; Wahid et al., 2017; Abuelnuor et al., 2018; Wong-Pinto et al., 2020; Javadi et al., 2020; Zhao et al., 2020; Zhang et al., 2021).

There is considerable research in the literature on the different mixtures of eutectic PCMs conceived and used for cold storage applications. **Table 1.3** shows the eutectic PCM solutions having the potential of use for the cold storage applications.

Table 1.3 Eutectic PCM mixtures investigated in the literature for cold storage applications (Oro et al., 2012a; Li et al., 2013; Khan and Afroz, 2013a; Xie et al., 2017; Mo et al., 2017; Sze et al., 2018; Suamir et al., 2019; Cong et al., 2019; Faraj et al., 2020; Zhao et al., 2020).

Composition	Type of the Eutectic Solution	Melting Temperature (°C)	Latent Heat of Fusion (kJ/kg)
24.8 weight % HCl	Water–salt	-86	-73.77 (kJ/mol)
24 weight % LiCl	Water–salt	-67	-36.26 (kJ/mol)
$ZnCl_2/H_2O$ (0.51 wt %)	Water–salt	-62	116.84
$FeCl_3/H_2O$ (0.331 wt %)	Water–salt	-55	155.52
$CaCl_2/H_2O$ (0.298 wt %)	Water–salt	-55	164.93
30.5 weight % $CaCl_2$	Water–salt	-49.5	-76.81 (kJ/mol)
Sodium lactate/H_2O (85.15:14.85 wt%)	Organic	-49	28.3
Sodium acetate/H_2O (23.96:76.04 wt%)	Organic	-43	29.7
$CuCl_2/H_2O$ (0.36 weight %)	Water–salt	-40	166.17
Ethylene glycol/H_2O (50:50 weight %)	Organic	-37.1	41.59
K_2CO_3/H_2O (0.396 weight %)	Water–salt	-36.5	165.36
$MgCl_2$-H_2O-MWCNTs (-)	Water–salt	-34.54	146.9
$MgCl2/H_2O$-1 (0.171 weight %)	Water–salt	-33.6	221.88
21.01weight % $MgCl_2$	Water–salt	-33.5	-36.30 (kJ/mol)
$Al(NO_3)_3$ (30.5 weight %) - H_2O	Water–salt	-30.6	131.5
$Mg(NO_3)_2//H_2O$ (0.346 weight %)	Water–salt	-29	186.93
$Zn(NO_3)2/H_2O$ (0.394 weight %)	Water–salt	-29	169.88
NH_4F/H_2O (0.323 weight %)	Water–salt	-28.1	187.83
$NaBr/H_2O$ (0.403 weight %)	Water–salt	-28	175.69
NaCl-$NaNO_3$-H_2O	Water–salt	-27	50-150
Ethylene glycol/Sodium formate/H_2O (1:1:8 weight%)	Organic	-25	173.1
NaCl-KCl- H_2O	Water–salt	-23	260
Glycerol/Sodium formate/H_2O (1:1:8 weightt%)	Organic	-23	174.5
Corn-oil ester/Tap water (30:70 vol%)	Organic	-23	78.6
27.9 weightt% Li_2SO_4	Water–salt	-23	-26.10 (kJ/mol)
KF/H_2O (0.215 weight %)	Water–salt	-21.6	227.13
NaCl (22.4 weight %) - H_2O	Water–salt	-21.2	222
23.3 weight % NaCl	Water–salt	-21.2	233 (5.0) (kJ/mol)
NaCl- Na_2SO_4-H_2O	Water–salt	-21	200

(**Table 1.3** continued)

TMP-NH_4Cl-H_2O-TiO_2-PAAS (-)	Water–salt	-19.9	246.8
$MgCl_2/H_2O$-2 (0.25 weight %)	Water–salt	-19.4	223.10
$(NH_4)_2SO_4/H_2O$ (0.397 weight %)	Water–salt	-18.5	187.75
Sodium formate/H_2O (1:4 weight%)	Water–salt	-18	250.2
$NaNO_3/H_2O$ (0.369 weight %)	Water–salt	-17.7	187.79
NH_4NO_3/H_2O (0.412 weight %)	Water–salt	-17.35	186.29
$Ca(NO_3)_2/H_2O$ (0.35 weight %)	Water–salt	-16	199.35
NH_4Cl/H_2O (0.195 weight %)	Organic	-16	248.44
$C_3H_8O_3$-CH_3COONa-H_2O (1:01:08)	Water–salt	-14	172
K_2HPO_4/H_2O (0.368 weight %)	Water–salt	-13.5	197.79
$Na_2S_2O_3/H_2O$ (0.3 weight %)	Water–salt	-11	219.86
19.7 weight % KCl	Water–salt	-10.6	18.43 (kJ/mol)
$MnSO_4/H_2O$ (0.322 weight %)	Water–salt	-10.5	213.07
20 weight % KCl	Organic	-10	284
Diethylene glycol	Water–salt	-10	247
NaH_2PO_4/H_2O (0.324 weight %)	Nanofluid PCM	-9.9	214.25
$TiO_2/BaCl_2/H_2O$ (TiO_2 0.283 vol%)	Nanofluid PCM	-8.6	258.3
$TiO_2/BaCl_2/H_2O$ (TiO_2 0.167 vol%)	Water–salt	-8.5	279.5
22.1 weight % $BaCl_2$	Organic	-7.7	-10.2 (kJ/mol)
Corn-oil ester/Tap water (10:90 vol%)	Water–salt	-7.5	171.7
$ZnSO_4/H_2O$ (0.272 weight %)	Water–salt	-6.5	235.75
$Sr(NO_3)_2/H_2O$ (0.245 weight %)	Water–salt	-5.75	243.15
$KHCO_3/H_2O$ 0.1695 weight %)	Water–salt	-5.4	268.54
10 weight % NaCl	Organic	-5	289
12% Ethylene glycol/H_2O (vol.%)	Water–salt	-4.9	281
18.63 weight % $MgSO_4$		-4.8	-84.96 (kJ/mol)
Calcium lactate-NH_4Cl (50:50)	Water–salt	-4.3	265.2
$NiSO_4/H_2O$ (0.206 weight %)	Organic	-4.15	258.61
Tetradecane - octadecane	Water–salt	-4.02	227.52
$MgSO_4/H_2O$ (0.19 weight %)	Water–salt	-3.9	264.42
Na_2SO_4/H_2O (0.127 weight %)	Water–salt	-3.55	284.95
NaF/H_2O (0.039 weight %)	Organic	-3.5	314.09
Corn-oil ester/Tap water (5:95 vol%)	Water–salt	-3.5	227.8
C_5H_7COOK-KCl (85.72:14.28)	Water–salt	-2.8	254.6
$NaOH/H_2O$ (0.19 weight %)	Water–salt	-2.8	265.98
KNO_3/H_2O (0.097 weight %)	Water–salt	-2.8	296.02
Na_2CO_3/H_2O (0.059 weight %)	Water–salt	-2.1	310.23
$FeSO_4/H_2O$ (0.1304 weight %)	Water–salt	-1.8	286.81
$CuSO_4/H_2O$ (0.119 weight %)	Water–salt	-1.6	290.91
6.49 weight % $KsSO_4$	Water–salt	-1.55	26.88 (kJ/mol)

Several studies have been conducted on binary mixtures characterized by varying concentrations. The sodium chloride solution (NaCl– H_2O) is a salt solution that has been extensively researched. Yilmaz et al. (2010), examined and investigated the use of aqueous salt solutions containing NaCl and potassium chloride (KCl) as phase change materials (PCM) in cooling applications and cold storage systems. Cycle tests were conducted within a temperature range of -24°C to -10°C. Subcooling was seen in all of the solutions examined in **Table 1.4**.

Table 1.4. Freezing-melting temperature range and subcooling for aqueous NaCl and KCl solutions (Kumano, Asaoka and Saito, 2009)

Solutions	Subcooling	Freezing Temperature (°C)	Melting Temperature (°C)	ΔT (freezing point depression)
5% NaCl	3.87	-3.87/-4.27	-4.87/-3.18	3.04
10% NaCl	6.28	-7.60/-7.70	-7.80/-6.10	6.56
15% NaCl	5.30	-15.19/-15.29	-10.40/-9.20	10.88
20% NaCl	2.79	-18.22/-17.92	-18.92/-14.62	16.45
21% NaCl	2.20	-18.46/-18.36	-18.86/-18.26	17.77
22% NaCl	1.60	-21.95/-21.85	-20.15/-19.65	19.17
23% NaCl	0.20	-20.89/-21.39	-22.39/-20.89	20.66
24% NaCl	0.30	-20.19/-19.79	-22.08/-19.59	-
5% KCl	1.59	-3.38/-3.58	-3.28/-2.08	2.32
10% KCl	7.48	-6.60/-7.10	-11.79/-6.00	4.80
15% KCl	4.40	-12.80/-13.20	-11.40/-9.60	-
20% KCl	5.59	-12.93/-13.13	-10.23/-9.43	-
21% KCl	4.80	-10.35/-10.65	-10.15/-9.65	-
22% KCl	6.90	-10.45/-11.25	-10.95/-9.15	-
23% KCl	7.48	-12.12/-12.82	-12.32/-9.38	-
24% KCl	5.10	-10.80/-11.10	-11.10/-9.10	-

Han et al. (2006), conducted a study in which they analyzed the latent heat during the phase change of the NaCl- H_2O binary mixture using differantial scanning calorimeter (DSC) at different concentrations. They observed two different endothermic peaks, one indicating

eutectic melting at around -22°C and the other for ice. DSC results for different NaCl concentrations in water are shown in **Figure 1.5**. According to the figure, it was concluded that the eutectic mixture was the best mixture.

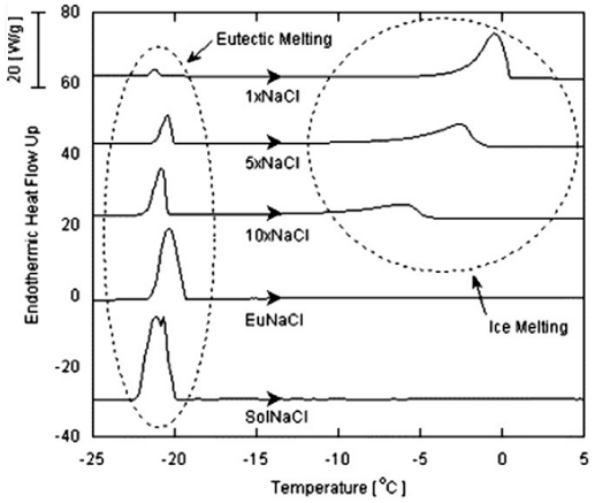

Figure 1.5. DSC thermograms for some concentrations of NaCl - H_2O mixture (Han et al., 2006)

In this study, it is also focused on a eutectic PCM. NaCl solution were chosen as PCM due to their being non-toxic, easily accessible and cheap. A good comprehension of M- H_2O binary phase diagrams can aid in the choice of a salt hydrate as a phase change material (PCM) (Zief and Wilcox, 1967). The compound binary phase diagram for sodium chloride (NaCl) and water (H_2O) is seen in **Figure 1.6**. In this figure, E represents the eutectic point of the solution.

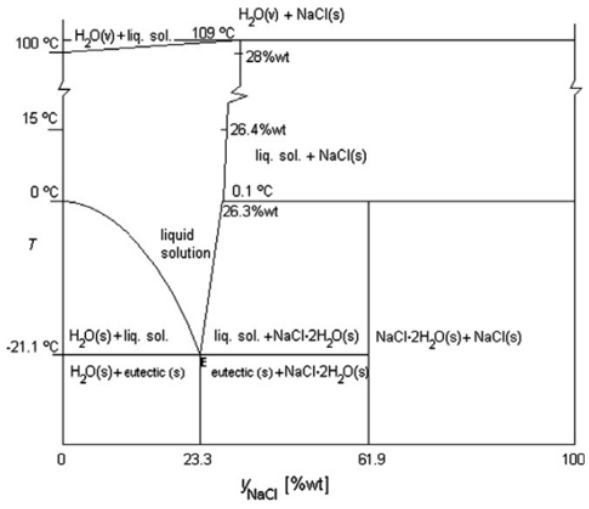

Figure 1.6. Binary phase diagram for NaCl - H_2O (Oro et al, 2012a)

The effect of NaCl, CMC and borax concentrations on the melting point was investigated and the results are presented in **Table 1.5.** (Kurtbogan, 2020)

Table 1.5. The effect of NaCl, CMC and borax concentrations on the melting point (Kurtbogan, 2020)

PCM Candidate	Salt % (wt)	Nucleating Agent % (wt)	Gelling Agent % (wt)	Water %(wt)	Melting Point	Freezing Point
Sample 6	NaCl – 16%	Borax – 2%	CMC – 2%	80%	-18.53°C	-42.25°C/-27.83°C
Sample 7	NaCl – 17%	Borax – 2%	CMC – 1.5%	79.5%	-19.37°C	-41.08°C/-29.67°C
Sample 8	NaCl – 18%	Borax – 2%	CMC – 2%	78%	-18.95°C	-41.18°C/-32.44°C
Sample 9	NaCl – 18%	-	CMC – 1.5%	80.5%	-18.87°C	-39.57°C/-33.37°C
Sample 10	NaCl – 18%	-	-	82%	-16.99°C	-37.36°C/-31.89°C

According to the **Table 1.5**, the melting and freezing points are highly depending on the concentration of all components.

1.5 Response Surface Methodology (RSM)

Response Surface Methodology (RSM) provides a valuable approach for optimizing variable conditions to achieve desired responses when dealing with multiple quantitative factors. It involves the detection of variable interactions, formulation of model equations, and measurement of factors to enhance the understanding of the process under study. In RSM, the responses, which are typically performance measures or quality characteristics, are dependent variables, while the independent variables or factors are utilized for prediction (Myers, 2002). Through empirical modelling techniques, RSM aims to accurately establish the relationship between dependent variables and the influencing independent variables (Demir et al., 2017).

Essentially, the purpose of RSM is to analyze the impact of factors on response variables, predict the factor values needed to achieve desired responses and identify the optimal working range for the product's process. (Eriksson et al., 2008).

It is advisable to limit the inclusion of more than 5 factors to prevent excessive trials and to create models with greater statistical significance and more robust prediction capabilities. Thus, prior to proceeding with the RSM design for optimizing the formulations, the number of components must be decreased using a statistical elimination design. Model equations need to be developed to predict response variable values more precisely and reliably based on inputs. The model equations might be either first or second-order (Demir et al., 2017).

Once the model equation is established, a suitable experimental design is selected. The significant experimental designs are Central Composite, Box-Behnken, Taguchi, Plackett-Burmann, full factorial, partial factorial, random, and Latin squares. These designs help establish the circumstances and number of experiments required for optimization. The centripetal compound experimental design consists of cube points, star points, and centre points (Myers, 2002; Berthouex and Brown, 2002; Box and Draper, 2007; Dean and Voss, 1999).

1.5.1 Box Behnken Design

Box-Behnken Design, established in 1960 by Box and Behnken, represents a non-linear model of Response Surface Methodology developed as an experimental design (Tekindal et al., 2012).

Box-Behnken Design creates an empirical matrix necessary to incorporate process parameter conditions (Agarwal et al., 2014; Yue, 2016). Box-Behnken Design consists of three-level designs where all design points are positioned in the middle of the edges of a cube or hypercube, which can be seen in Figure **1.7**, and these points are all situated on the surface of a sphere. In these designs, 1st and 2nd order model coefficients can be estimated effectively. However, for this design to be used, at least three factors must be quantitative (Demir et al., 2017). Factors are represented as x1, x2, and x3.

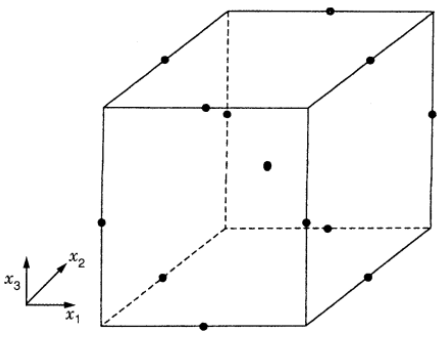

Figure 1.7. Box-Behnken design for 3-level factor (Myers, Montgomery and Anderson-Cook, 2009)

1.5.2 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a method for analyzing data from experimental designs that compare two or more variables simultaneously and is the most effective tool for analyzing more complex data sets with different sources of variation (Winer, Brown and Michels, 1991).

Analysis of variance is categorized into several types based on experimental design and relies on a basic, totally randomized design. ANOVA tests are classified into two types: one-way and two-way. One-way ANOVA involves one independent variable or factor and examines group means to estimate the population mean of the independent variable. Two-way ANOVA test is a method that examines the effect of different categorical independent variables on a dependent variable and allows the simultaneous testing of both components. (Molugaram and Rao, 2017).

ANOVA techniques should examine variance homogenity for all measurement types graphically and numerically (Montgomery, 2009). This procedure is necessary to guarantee the correct application of tests for comparison of mean values and should always indicate the probability (p-value) of the test in text, tables or figures. When the standard deviation of the parameter is at least 10% lower than the corresponding parameter value and the parameters of a model are statistically significant, the model is considered to fit the experimental data. A statistically significant relationship between variables is assumed when the probability value of the correlation coefficient is less than 0.05 (Granato et al., 2014).

In this study, the performance of a cooling system simulating a freezer operating at temperatures higher than the recommended temperature (-5°C to -13°C) was tested both with and without PCMs. NaCl solution was chosen as PCM due to its non-toxic, easily accessible, and cheap nature, as well as its suitable phase change temperature. NaCl solution was modified with different concentrations of carboxymethyl cellulose (CMC) as thickening and borax as nucleating agents. Firstly, the experimental effects of different concentrations of NaCl (4.0 and 16.0 weight %), CMC (0.0-1.5 weight %) and borax (0.0-2.0 weight %), was investigated for this cooling system. All results indicate that the freezer performance is significantly dependent on both NaCl and agent concentrations. Secondly, the Response Surface Methodology (RSM) based on the Box-Behnken design was applied to determine the optimum PCM formulation that would provide maximum energy savings.

1.6 Literature Review

PCM selection is the key step for achieving an optimal and efficient TES system. Phase change temperature, heat of fusion, thermal conductivity, and storage density are the main properties for any given PCM to be chosen and investigated for theoretical and commercial applications. Sarbu and Sebarchievici (2018) stated that any LHS system has to hold at least three main features: 1) a convenient PCM having a melting point in the desired temperature range, 2) a convenient heat exchange surface, 3) a convenient PCM container. There are several studies in the literature covering the integration of PCMs into cooling systems (Zare and Mikkonen, 2023). However, the use of PCMs in cooling systems as cold thermal energy storage applications is still limited, which is mostly attributed to their poor thermal conductivity, super-cooling, and leakage during phase change as drawbacks and challenges (Zhang et al., 2021; Nie et al., 2020). More importantly, eutectic PCMs account for a significantly small portion of the current research articles. Lawag and Ali (2022) indicated that 81%, 15%, and 4% are the percentages of the research articles investigating organic PCMs, inorganic PCMs, and others, respectively (Diaconu et al., 2022). In the literature, it is pointed out that paraffins, salt hydrates, fatty acids, water, and eutectic solutions stand out as the most applied PCMs. Among these, water and eutectic solutions are especially implemented in the cooling systems. Among these, water and eutectic solutions are especially implemented in the cooling systems. The maximum and minimum operating temperatures of the refrigerators and freezers generally range between 2-5°C (fresh food) and -18°C (frozen food), respectively. The most important properties of water and eutectic solutions that are used for low-temperature applications are a convenient phase change temperature and a large heat of fusion. Even though water has the advantages of being safe, eco-friendly, low cost, high density, high latent heat capacity, and high specific heat, water is not a suitable option as the sole PCM for below 0°C applications. Instead, eutectic solutions, especially salt-water solutions, are used at temperatures below 0°C. In recent years, studies have also been conducted by involving composite PCM solutions containing nucleating agents, thickeners, and containment methods in order to avoid super-cooling, phase separation, and poor thermal conductivity and sustain the chemical and physical stability (Li et al., 2013; Pirvaram et al., 2019; Omara and Mohammedali, 2020a; Javadi et al., 2020).

The selection of the appropriate PCM is the foundation of any LHS system. However, this also depends on where the PCM will be placed within the system. In terms of the freezer/refrigerator applications, PCMs can be utilized for either heat storage or cold storage. For cold storage, a PCM is integrated into the evaporator part of the freezer/refrigerator; for heat storage, a PCM

is integrated into the condenser part of the freezer/refrigerator. As it is applied within the scope of this study, the effects of integration of a PCM into the evaporator are also going to be reviewed in this section. When PCM is placed around/into the evaporator, it efficiently stores a significant amount of the heat generated by the cabinet while the compressor is not running. This stored heat is then transferred to the refrigerant when the compressor is running, facilitated by the process of conduction. Having a high enthalpy of fusion and high thermal capacity, PCM provides higher evaporation temperature and pressure and extends the compressor off-time during phase change. Increasing evaporation temperature and pressure also causes an increase in the vapour density of refrigerant, which gets into the condenser and leads to a higher refrigeration capacity. Consequently, the phase change temperature of a given PCM controls the evaporation temperature and pressure. If the PCM's phase change temperature is higher than the compartment's temperature, the compressor off/on cycle is more frequent because of the high thermal resistance at the evaporator. If the compartment temperature is adjusted to a lower degree, extra heat is going to be absorbed from the compartment, evaporation temperature is going to reduce, and the system is going to run more longer requiring more energy. In conclusion, increasing evaporating temperature and pressure leads to an increase in COP and a decrease in energy consumption. Also, PCM integration at evaporator facilities maintains cold temperatures in the compartment in case of power failure, enters higher refrigerant density, more temperature control at the compressor inlet, and more stable conditions in the cases of thermal load variations. Differently, the main disadvantage of PCM integration into an evaporator is the causing higher condensation temperature (Azzouz et al., 2008; Azzouz et al., 2009; Subramaniam et al., 2010; Oro et al., 2012c; Khan and Afroz, 2013a; Rahman et al., 2013; Marques et al., 2014; Visek et al., 2014; Joybari et al., 2015; Bista et al., 2018; Nguyen et al., 2023). In the literature, it is stated that there is limited research as regards utilizing PCMs with phase change temperatures below 0°C in cooling systems, especially in the freezers (Xie et al., 2020). Alzuwaid et al. (2015) investigated the effect of PCM integration on energy consumption and product and cabinet temperatures. This study utilized water gel in different compositions as PCM, together with a refrigerated open-type multi-deck display cabinet. The system is equipped with two separate plate radiators. The system was designed with two single plate radiators, including water gel PCM. PCM integration made for energy saving by 5%, and the product and the cabinet temperatures decreased. In addition, defrost time as the most affected parameter increased at a rate of 70% of the original defrost time. Elarem et al. (2017) carried out an experimental and numerical study in order to examine the performance improvement of household refrigerators with the addition of PCM. A Plus-Ice was used as PCM

having the phase change temperature of 4°C alongside the different arrangements of the PCM. Energy consumption was reduced by 12% and COP increased by 8% with addition of PCM. Also, the numerical simulation showed that adding PCM on the evaporator, walls and racks of the compartments had a substantial impact on stabilizing and homogenizing the temperature. Sonnenrein et al. (2015) evaluated the effects of various heat storage materials including water, paraffin and copolymer-bound PCM, and diverse macro-encapsulations methods (such as high-density polyethylene (PE-HD) foil and aluminium-composite film) on energy consumption. The energy consumption was reduced by 10% with the integration of copolymer-bound compound. Sonnenrein et al. (2020) used a leak proof and transparent polymer-bound PCM having a melting temperature of around 9°C on commercially available refrigerator and refrigerator-freezer combined systems by studying the effects of PCM on daily energy consumption, cooling capacity, and temperature rise time. They concluded that integrating PCM increased the cooling capacity and temperature rise time by 33% and 145%, respectively without any negatively effecting on energy consumption. Bakhsipour et al., (2017) examined the effects of PCM thickness, refrigerant property (mass flow rate and type), and geometrical property (tube diameter and length of the PCM heat exchanger) on the refrigerant temperature and COP of the refrigeration cycle. As PCM, N-Octadecane with a phase change temperature of 21°C was used and the PCM was placed between the condenser and the expansion valve. The results indicated an increase in COP by 9.58% due to decreasing condenser outlet temperature. Cheng et al., (2017) investigated the efficacy and energy conversation results of four refrigerator systems: conventional, with a heat storage condenser (HSC), with a cold storage evaporator (CSE), and the novel dual energy storage (DES) system comprising both HSC and CSE. They integrated SSPCM into the condenser and evaporator part of the refrigerator. Energy saving percentages were 0, 12%, 16%, and 32%, respectively and the refrigerator cycle time values were 60, 38, 260, and 222 minute, respectively. The authors revealed that the DES refrigerator system had the best heat transfer and operational performance. Azzouz et al. (2009) investigated the effects of incorporating the PCM into a domestic refrigerator model in order to see the performance without a power supply. Water and an eutectic aqueous solution (the temperature at which a substance freezes is -3°C) were used as PCM. The results compared with an original refrigerator. Longer and continuous operation was facilitated (5-9 h) with the integration of the PCM in comparison to experiment without the PCM (1-3 h). Also, depending on the thermal load, coefficient of system performance (COP) increases between 10-30% was procured. Gin et al. (2010) investigated the impact of door opening, defrost running period, and power failure effect on a domestic freezer. Having reduced

the temperature variations with the integration of PCM, the energy consumption decreased by 8% and 7% during the defrost cycle and door openings, respectively. The loss of power experiment showed that reaching an air temperature of -3°C with and without PCM took 11 and 4.4 hours, respectively. The eutectic aqueous ammonium chloride (NH4Cl) solution with a phase change temperature of 15.4°C was used in the experiment with the composition of 19.5% NH4Cl salt in water. Due to its good thermal conductivity, anodized aluminum used to store the PCM in order to prevent the corrosive effect of the chosen PCM and anodized aluminum layers was placed against the freezer walls (cabin). Pavitran et al. (2021) performed a numerical study focusing on the effects of PCM integration into the refrigerator, and different arrangements of PCM in the refrigerator were applied to reveal the effects on the system temperature. The results indicated that maintaining temperature during compressor off-mode was attainable. Another result deduced from the study was the percentage of area coverage of PCM and arrangements of PCM had a substantial effect on temperature maintenance. Cheng and Yuan (2013) numerically investigated the effect of replacing a conventional condenser with a heat storage condenser with shape-stabilized PCM (SSPCM) for a household refrigerator. For the novel refrigerator with -18°C as freezer temperature, the energy saving and the increase in COP are 12% and 19%, respectively. Yusufoglu et al. (2015) studied five different PCMs on two different refrigerator models. PCMs were integrated into the evaporator tubes of the refrigerator and packed with polymer lined aluminum metallic film in order to enable higher thermal conductivity. The melting temperatures of PCMs were -2.5, -4.4, and -3.6°C for PCM1, PCM2, and PCM3, respectively. They found that energy savings were 8.8% (water as PCM) and 9.4% (for PCM1) for the refrigerators 1 and 2, respectively. The compressor off-time was increased from 39 to 133 minutes in PCM1-refrigerator2 combination and 105 to 215 minutes for the water-refrigerator1 combination. They also concluded that increasing condenser surface area by 20% improved the effect of PCM. Marques et al. (2013) investigated the integration of water and eutectic mixtures having the melting temperatures of -2 and -6°C for a natural convection thermal energy storage refrigerator. It is found that eutectic mixtures having a melting temperature as close to 0°C as possible were more efficient at maintaining compartment temperature. They also tested the impact of PCM positioning and concluded that combining horizontal and vertical eutectic PCMs in a compartment of full height or by separating the compartment into two drawers and utilizing a horizontal PCM in every drawer enabled lower compartment temperature. Marques et al. (2014) investigated the performance of a domestic refrigerator with a PCM (water). The PCM was integrated as a slab with a 5mm thickness, and it was found that in power failure conditions, the refrigerator continued to operate for 3-5 hours

with the PCM. In addition, they reached the conclusion that the larger compressors were more efficient by replacing the 4 cm3 with the 8 cm3 compressor. Wang et al. (2007a, 2007b) investigated the effects of the integration of eutectic PCMs into the different locations in the refrigeration cycle experimentally and in a dynamic simulation model. They used PCMA, PCMB, and PCMC, with melting temperatures of 21, 21, and 8°C, respectively. PCMA placed between the compressor and condenser, PCMB placed between the condenser and expansion valve, and PCMC placed between the evaporator and condenser. For the A and B configurations, the COP value was increased by 6% and 8%, respectively. COP increase of 6% was the result of lower pressure and temperature in the condenser; COP increase of 8% was the result of higher super-cooling effect. The dynamical simulation model was congruent with their experimental results. Khan and Afroz (2013a) studied water and eutectic mixture having the phase change temperatures of 0°C and -5°C. Based on the thermal load and PCM amount, between 20-27% COP improvement was attained. They also found that the reduction of average compressor running time was between 2-36% compared to the case without PCM. They concluded that eutectic mixture is a better option, showing higher COP and compressor running time savings at low thermal load compared to water. Pirvaram et al. (2019) used varying weight percentages of eutectic mixtures of polyethylene glycol (PEG) 100 and 600 as PCM to investigate the performance of a household refrigerator. PCM solutions were integrated into the condenser part of a household refrigerator. They designed a novel system integrating two PCMs in a cascade configuration. Consequently, the condenser surface temperature, the compressor work time and energy consumption of the system decreased and heat transfer performance of the condenser increased. Energy saving was 13.38% with cascade configuration in comparison to the case of single PCM with the value of 8.72%. Pirvaram et al. (2020) used two eutectic mixture of PEGs as PCMs. In this study, different compositions of PEG 200 and 300 were utilized and phase change temperatures of -10, -15, -18, and -20°C were chosen. By introducing a novel household freezer, PCMs having different melting points arranged in a cascade configuration so as to minimize temperature fluctuations and decrease energy consumption. PCMs were placed into six trays inside the interior compartment of the freezer. In order to optimize the phase change temperatures and the amount of two PCMs, a three-level, three-factor CCD consisting of 18 experiments was used as RSM. The impact of three independent factors (PCMs' amounts and melting temperature of selected PCM as PCM2) on two responses (energy consumption and temperature fluctuation) inside the freezer were investigated. In order to minimize the required experiments, the melting temperature of PCM1 was kept at constant -18°C. Three PCM packs weighing 1.5 kg each, with a melting point of -18°C, were positioning

on the upper trays, and positioning another three PCM packs of the same weight with a melting point of -20°C on the lower trays of the freezer. The results showed a significant reduction in energy consumption of 13.42%. The application of Response Surface Methodology (RSM) in conjunction with a Central Composite Design (CCD) of the experiment enabled the identification of variables influencing energy consumption and temperature fluctuations. This was achieved by determining the influences and statistical significance of experimental conditions, as well as by predicting optimal values. The numerical optimization showed that the optimal amount of PCM1 was 1.97 kg and the optimal amount and melting temperature of PCM2 were 1.57 kg and -20 °C respectively. It was indicated that the rates of energy consumption reduction and temperature fluctuation reduction were 12.31% and 39.90%, respectively. Abdolmaleki et al. (2020) used eutectic mixtures of PEG 200 and 300 in order to minimize energy consumption and temperature fluctuations of household freezers. The phase change temperatures of PCMA, PCMB, and PCMC were -10, -15, and -20°C, respectively. PEG200 and PEG300 weight percentages were different for each PCM solution. PCM solutions were integrated into a novel freezer system. Response surface methodology (RSM) based on central composite design (CCD) was applied to determine the optimum phase change temperature and the amount of PCM used inside the freezer. Two independent variables (temperature as x_1 and mass of PCM as x_2), with three levels, and four center points applied in the CCD method. By analyzing the response surface contour plot and solving the regression equation, the optimal values of the variables were determined. A second-order polynomial equation model was constructed to predict the optimal point between the response variables (reduction of energy consumption and temperature fluctuations) and the independent variables. PCMC of 1.5 kg enabled the system to reach energy saving value of 8.37%, and PCMC of 2.0 kg reduced the temperature fluctuations by 40.59%. PCM with a phase change temperature of -20°C and an amount of 1.61 kg was revealed to be optimum. Liu et al. (2017) used an air-cooled frost-free household refrigerator. A water/super absorbent polymer (SAP)/diatomite mixture was used with phase change temperature of 0.41°C and placed in the fresh food chamber of the refrigerator, on the air duct foam. A NaCl/SAP/diatomite eutectic mixture was used with a phase change temperature of -18.98°C and placed in the freezer. The authors investigated the temperature fluctuations of freezer and fresh-food compartments, energy consumption during off-peak time with PCM, and compressor on-time. They found that energy consumption and the compressor on-time ratio were reduced by 18.6% and 13.6%, respectively. Thus, a frost-free refrigerator with PCM under the original control type showed favourable results in terms of energy consumption and food quality. Cofre-Toledo et al. (2018) modified

of a household refrigerator evaporator with two eutectic PCMs, PLUSICE E-10 and NH4Cl aqueous solution, having melting temperatures of -11.20 and -15.60°C, respectively. In the study, the results showed that the average temperatures of the fresh-food and fast-cooling compartments were reduced using E-10 by 37.2% and 56.9%, respectively, using NH4Cl aqueous solution by 37.8% and 49%, respectively. Besides, energy consumption was reduced by 1.74% with E-10 and 5.81% with an aqueous mixture of NH4Cl. Oro et al. (2012b) studied the thermal analysis of a low-temperature, and non-refrigerated storage food chamber with the commercial eutectic PCMs, Climsel C-18 and E-21, having transition temperatures of -18°C and -21°C, respectively. The thermal response of the low-temperature storage unit (freezer cabin), including PCMs, was examined in the case of refrigeration system failure/without refrigeration cycle. In conclusion, the temperature of interior air could be kept at lower values with PCMs. They also indicated that the E-21 performed better at maintaining lower temperature. Oro et al. (2013) used a set of eutectic solutions based on ammonium chloride (NH4Cl) and a water binary system. Also, in order to reduce the super-cooling (during solidification) and modify the phase change temperature (during melting), aluminum fluoride (AlF3) or sodium chloride (NaCl) was added as an additive, and oxyethylmethylcellulose added as a thickening agent in order to increase the viscosity of PCM. It was put forward in the study that a higher water-to-salt ratio would make for an increase in the freezing temperature with a wider phase change temperature range, and different concentrations of all components were introduced with varying formulas. It was indicated that all of the PCMs tested performed well in terms of thermal and chemical stability, reaching 100 phase change cycles, and oxyethylmethylcellulose enhanced their stability. Xin et al. (2019) used a novel eutectic PCM by mixing sodium sulfate decahydrate (Na2SO4.10H2O) and disodium hydrogen phosphate dodecahydrate (Na2HPO4.12H2O) and also modified with nucleating (nano aluminum nitride and borax) and thickening (hydroxyethyl cellulose, sodium alginate and sodium polyacrylate) agents in order to enhance the performance of cooling systems. Suamir et al. (2018) used tap water and corn-oil ester (as the nucleating agent) mixture with different concentrations as PCM. The results indicated that mixtures including 5 to 35% corn-oil ester had a phase change temperature of -3.5 to -27°C with minimum or no super-cooling effects. Xie et al. (2020) developed a composite PCM of dipotassium hydrogen phosphate trihydrate (K2HPO4.3H2O)-sodium dihydrogen phosphate dihydrate (NaH2PO4.2H2O)- sodium thiosulfate pentahydrate (Na2S2O3.5H2O)- water (H2O) eutectic salt solution together with modified expanded graphite (MEG) having a phase temperature of -5.3°C. It was stated that the thermal conductivity of composite PCM was 13.3 times higher than pure eutectic salt solution, in

addition to better thermal cycling performance. Husainy et al. (2019) performed an experimental study in order to improve the cooling performance and reduce the temperature fluctuations during the energy power-off case. Nano-PCMs containing copper oxide - potassium chloride (CuO - KCl) or CuO - NaCl with water as base fluid and different concentrations were prepared to integrate into the system. The outcomes demonstrated that the use of eutectic Nano-PCMs kept the evaporator temperature between 3 to 9°C for 5 to 7 hours during energy power-off. By improving the heat transfer rate, 16% of COP enhancement was facilitated with Water - KCl - CuO mixture. Kiran-Yildirim (2022) used water, and sodium sulphate (Na2SO4) eutectic solutions with different concentrations as PCMs in a system simulating the operating conditions of a household refrigerator. In order to improve the heat transfer, PCM solutions were placed into an Al foil bags and aligned horizontally on the evaporator. The 1.0 weight % Na2SO4 solution showed the best performance enabling a minimum running time percentage of 21.7%, a maximum energy saving of 14.3%, a 2-hour of time interval, and a number of compressor cycles of 5.3. In addition, the use of eutectic solution prevented the cabinet air temperature from quickly (9 hours) reaching 20°C in comparison to water (~6 hours).

2.MATERIALS AND METHODS

2.1 Test Set-up

The schematic design of experimental test set up, built in a previous study (Kiran-Yildirim et al., 2021) is shown in Figure 2.1. The main equipments of the system are an evaporator, a compressor, a condenser, and an expansion valve. The system was tested at temperature of between -5°C and -13°C both without PCM and with different PCMs.

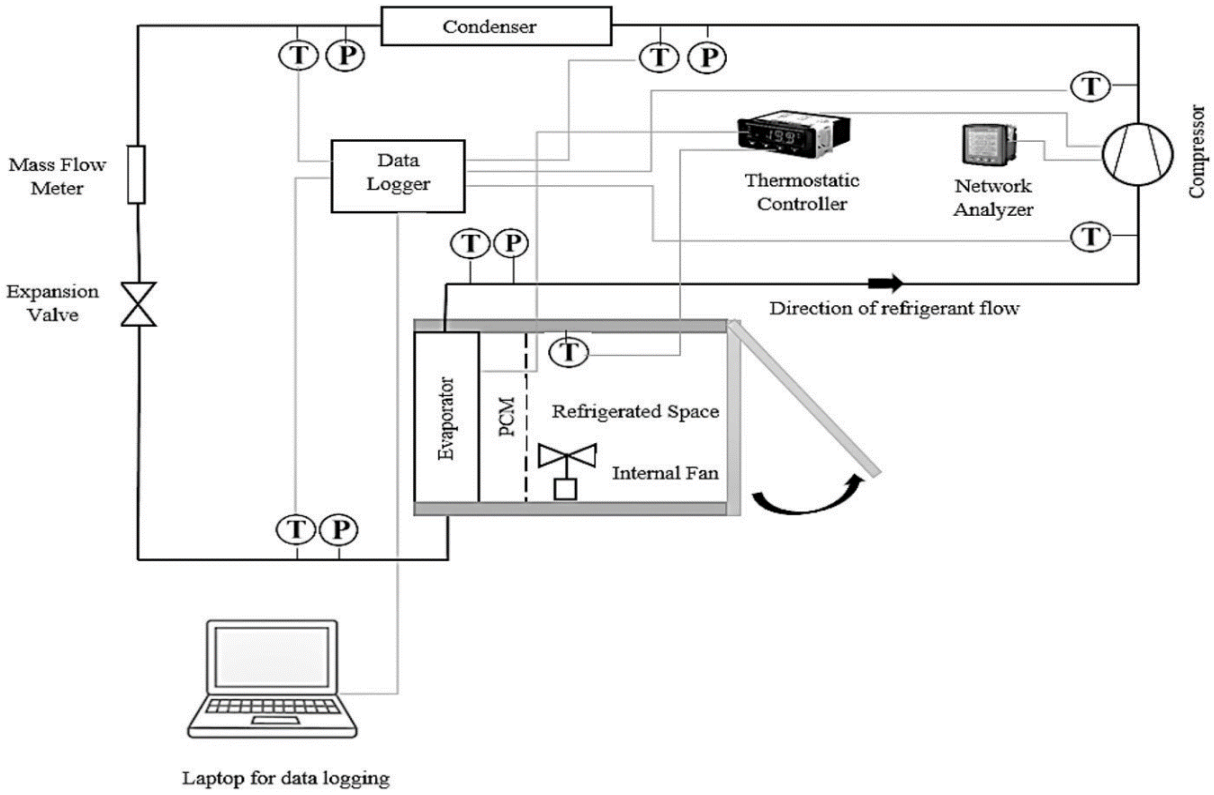

Figure 2.1. Schematic view of the experimental test set-up

The evaporator was placed on the inner back wall of the cabinet and PCMs were located on the evaporator surface. A fan was mounted on the side wall of the cabinet to facilitate the circulation of the air flow inside the cabinet. The cabinet with an inner volume of 72 liters, had dimensions of 0.435 m x 0.390 m x 0.425 m. The refrigerant used in the system was R404A as a HFC mixture of R125, R134a, and R143a (Roy and Halder, 2020).

The system's evaporator and condenser were both free convection heat exchangers. The compressor was a hermetic reciprocating compressor. A data logging unit records the refrigerant mass flow rate as well as the evaporator, compressor, and condenser temperatures

every minute with ± 0.5% accuracy. Power consumption measured every minute by the network analyzer device with ± 1.0-digit accuracy. The cabinet air temperature was measured by the thermostatic controller with ± 1.0-digit accuracy.

2.2. Test Procedure

The experiments conducted in a closed room with an air conditioner that kept the temperature almost constant at 18°C. The cabin air temperature was set at -5°C with an average value of -9°C. The PCM solutions were prepared in a volume of 600ml, which has indicated as the suitable amount in the literature (Kiran-Yildirim, 2022). NaCl solution with a weight concentration of 16.0% was prepared as PCM. Subsequently, CMC and borax were added to solution as thickening and nucleating agents, respectively, with weight concentration of 1.0-1.5%, and 0.0-2.0%, respectively. PCM was frozen horizontally in the aluminum zip foil bags in a freezer at -80°C. Aluminum zip foil bags were placed into the evaporator surface on the inside back wall of the cabinet.

The data was recorded after the system reached equilibrium. All experiments were repeated at least three times and the mean values were used for calculations. The running time (%) values were calculated by using Equation 2.1.

$$Running\ time\% = \frac{t_{on}}{t_{on}+t_{off}} x100 \quad (2.1)$$

where t_{on} and t_{off} (minute) are on-time and off-time of the compressor, respectively. In addition, the energy consumption of the compressor, W(t), was determined according to Equation 2.2.

$$W(t) = \int_{t=0h}^{t=24h} \dot{W}\,(t)dt \quad (2.2)$$

The energy saving (%) was also determined according to with Equation 2.3.

$$Energy\ saving\ \% = \frac{W_{PCM}-W}{W} x100 \quad (2.3)$$

In Eq. 2.3; W_{PCM} is total energy consumption with PCM, while W is total energy consumption without PCM.

The system was also operated in the case of without and with PCMs during a power failure. The time required for reaching cabin air temperature to 18°C was recorded and compared for all cases.

2.3. Design of experiments

A design of experiments (DOE) was carried out for optimizing the concentration of PCM components (NaCl, H_2O, CMC and borax). Box-Behnken Design (BBD) was chosen for selecting the experimental design for RSM. It should be noted that the use of the RSM is very common and beneficial by reducing experimental costs and time and optimizing the experiments by providing interaction effects and predicting optimal levels (Khuri and Mukhopadhyay, 2010; Kazemian et al., 2021; Manojkumar et al., 2022; Veza et al., 2023; Lu et al., 2023).

The BBD method was considered for three independent variables, with three levels and 5 center points. The range and levels of variables used in the experimental design are represented in **Table 2.1**.

Table 2.1. Level of independent variables

Variables	**Range and levels**		
	-1	0	1
A: NaCl Concentration (weight %)	4	6	8
B: Carboxymethylcellulose (CMC) Concentration (weight %)	0.5	1.0	1.5
C: Borax Concentration (weight %)	1.0	1.5	2.0

The combined effects of NaCl, CMC and borax concentrations on the compressor running time (%) were examined by BBD. The experimental data were analyzed by fitting to a quadratic model. The significance of this model was determined by performing the analysis of variance (ANOVA) and lack-of-fit test.

3.RESULTS AND DISCUSSIONS

A laboratory-scale cooling system, simulating a freezer was tested without PCM and with different PCMs. The experiments were carried out in three steps. First, the results were compared for the case without PCM and with 16.0 wt.% NaCl solution PCM due to its proper melting point. Secondly, 16.0 wt.% NaCl solution was prepared with CMC and borax, and the effect of CMC and borax concentrations was examined in terms of both running time (%) and energy saving (%). Subsequently, the effect of NaCl concentration was investigated at a certain level of CMC and borax concentrations. Lastly, the optimum PCM formulation was determined by applying BBD.

3.1 System performance evaluation with and without PCM

3.1.1 Running time and power failure periods without PCM

The experiment was carried out for 4 hours without PCM in order to determine the running time (%) and energy consumption of the compressor. The system was also operated in the case of without PCM during a power failure period.

Effect of PCM on the cabin air temperature

The cabin air temperature fluctuation with time in the case of without PCM is presented in Figure 3.1.

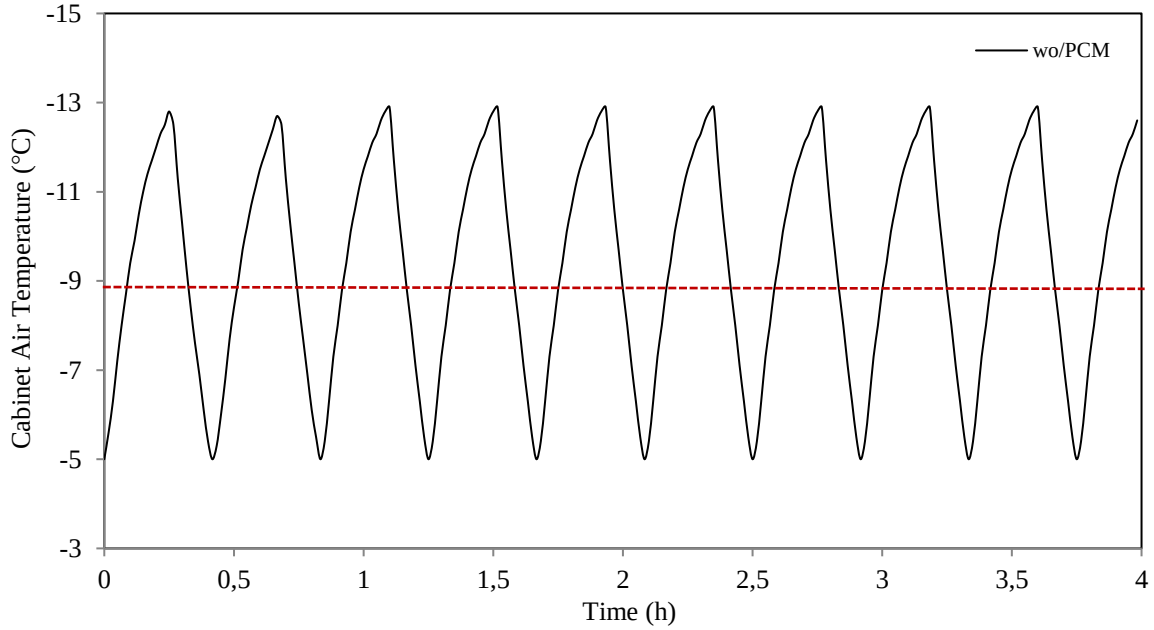

Figure 3.1 The profile of cabin air temperature in the case of without PCM.

As seen in Figure 3.1, the cabin air temperature fluctuated within the range of -5°C to -13°C. The cycle time was calculated 25 min, while the compressor on-time and off-time was determined to be 16 min., and 9 min., respectively. The numbers of cycles without PCM was found to be 9.6.

The running time (%) was calculated to be 64.00% in the case of without PCM by using Equation 2.1.

Effect of PCM on the compressor power consumption

The power consumption variation over time in the case of without PCM is presented in Figure 3.2.

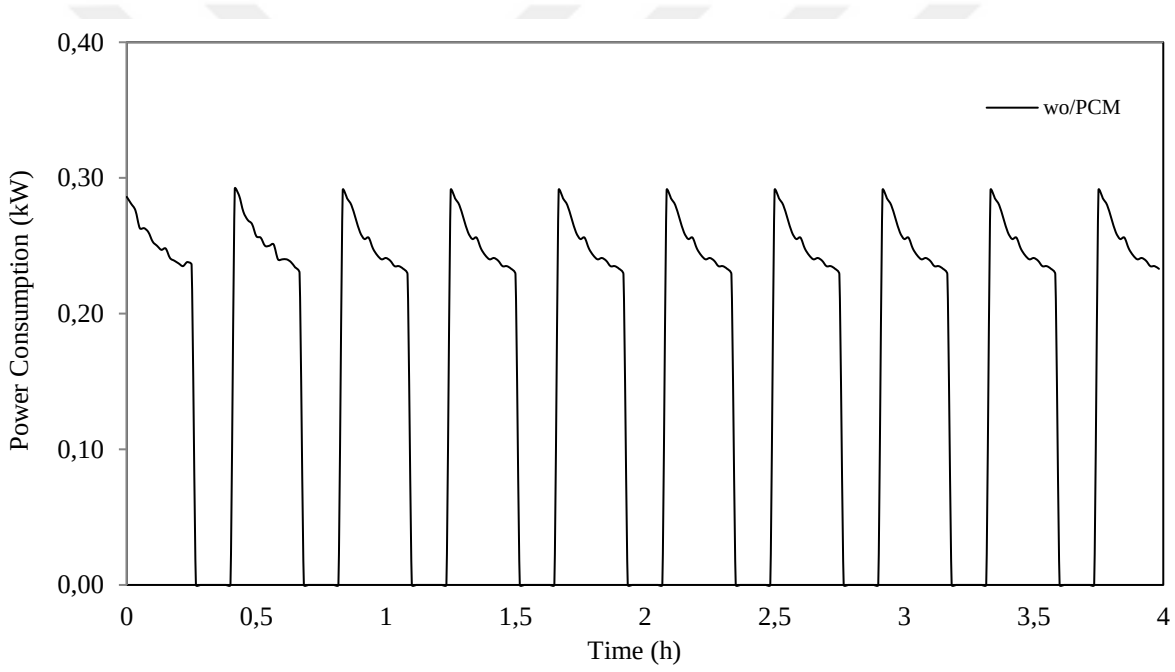

Figure 3.2 Compressor power consumption versus time in the case of without PCM.

The total energy consumptions during the compressor running periods of 4 hours were calculated to be 40.22 kJ without PCM by using Equation 2.2. The minimum and maximum power consumption values were measured to be 0.229 kW and 0.292 kW respectively.

Effect of PCM on the cabin air temperature during the power failure period

The system was also tested during a power failure without PCM. The time required for reaching the cabin air temperature to the ambient temperature of 18°C was determined during a power

failure. The cabin air temperature fluctuation with time in the case of without PCM during a power failure period is presented in Figure 3.3

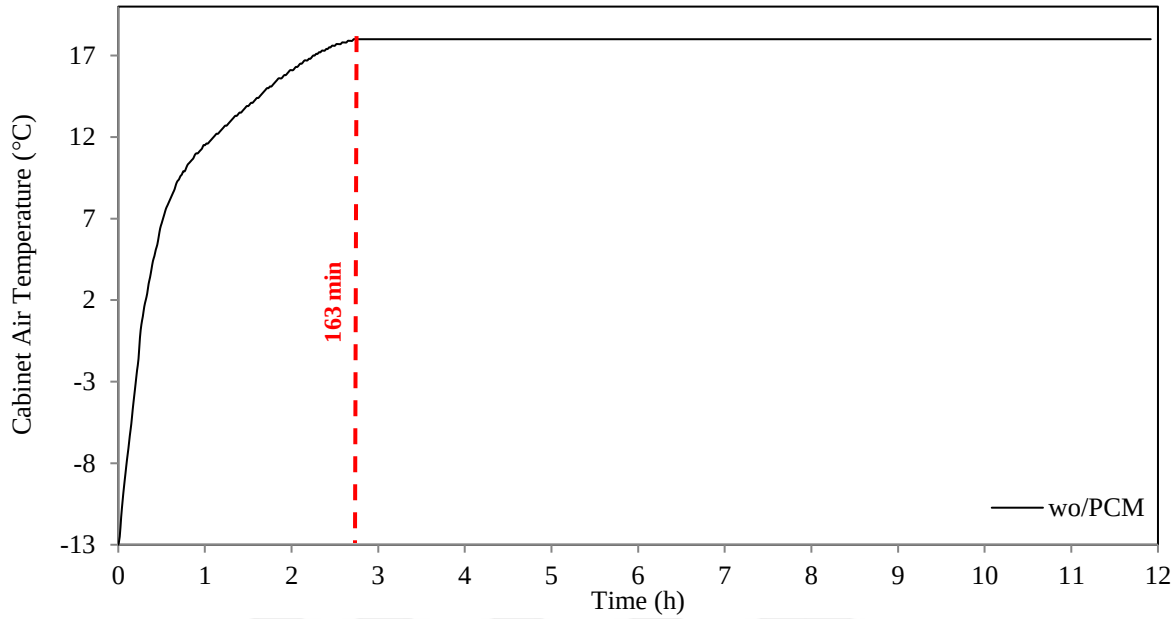

Figure 3.3 Temperature of cabinet air – time in the power failure period without PCM.

The cabin air temperature reached 18.0℃ in 163 minutes in the case of without PCM.

3.1.2 Running time and power failure periods with different PCMs

Firstly, the system was tested with 16.0% NaCl solution as PCM due to its proper melting point. Secondly, 16.0% NaCl solution was prepared with CMC and borax, and the effect of CMC concentration (1.0-1.5%) and borax concentration (0.0-2.0%) was examined in terms of both running time (%) and energy saving (%). Subsequently, the effect of NaCl concentration was investigated at a certain level of CMC and borax concentrations.

3.1.3 Effect of integrating 16.0 wt.% NaCl solution as PCM on the system performance

The experiments were carried out for 4 hours with 16.0% NaCl solution as PCM in order to determine the running time (%) and energy consumption of the compressor. The system was also operated in the case of with 16.0% NaCl solution as PCM during a power failure period.

Effect of PCM on the cabin air temperature

The cabin air temperature fluctuation with time in the case of 16.0% NaCl solution as PCM is presented in Figure 3.4.

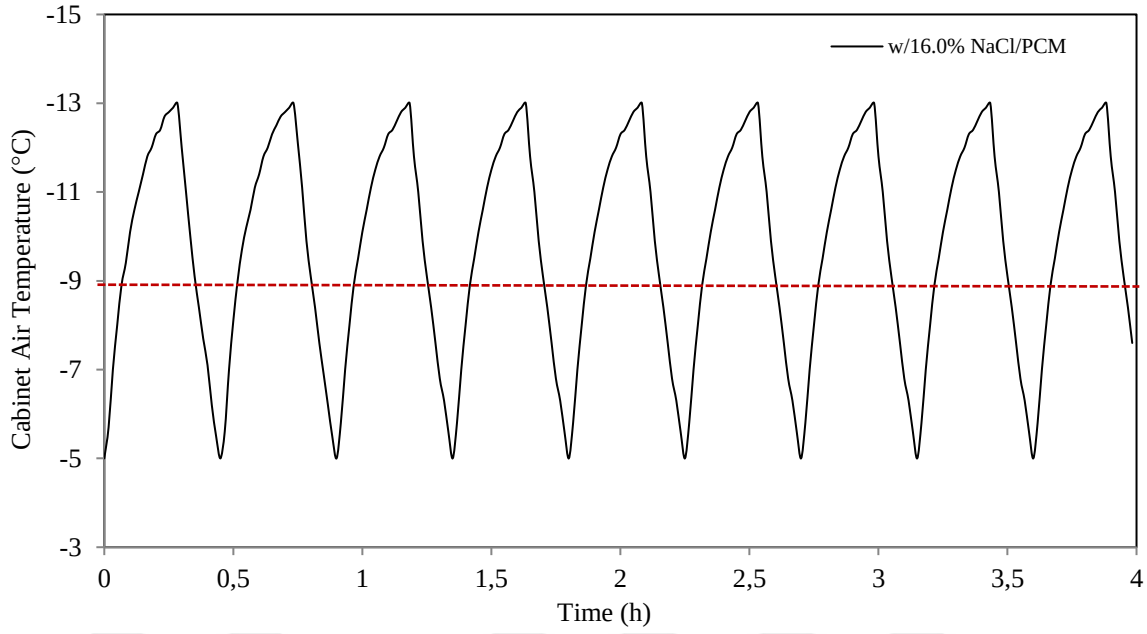

Figure 3.4 The profile of cabin air temperature in the case of with 16.0% NaCl solution.

As seen in Figure 3.4, the cabin air temperature fluctuated within the range of -5°C to -13°C. ,The cycle time was calculated 27 min, while the compressor on-time and off-time was determined to be 17 min., and 10 min., respectively. The numbers of cycles with 16.0% NaCl solution as PCM was found to be 8.8.

The running time (%) was calculated to be 62.96% in the case of with 16.0% NaCl solution as PCM by using Equation 2.1.

The compressor on time and off time values were increased with 16.0% NaCl solution. The increase in the compressor off time positively affected influenced the running time, slightly decreased from 64.00% to 62.96% compared to case without PCM.

Effect of PCM on the compressor power consumption

The power consumption variation over time in the case of with 16.0% NaCl solution is presented in Figure 3.5.

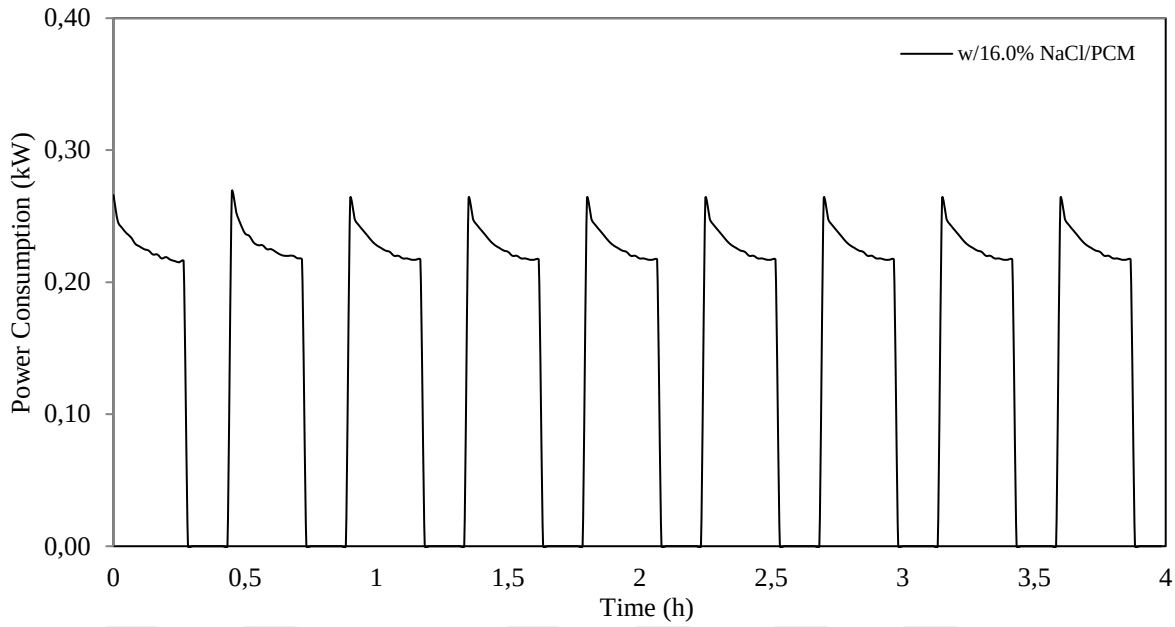

Figure 3.5 Compressor power consumption versus time in the case of with 16.0% NaCl solution.

The total energy consumptions during the compressor running periods of 4 hours were calculated to be 34.99 kJ with 16.0% NaCl solution as PCM by using Equation 2.2. The minimum and maximum power consumption values were measured to be 0.216 kW and 0.266 kW, respectively.

Effect of PCM on the cabin air temperature during the power failure period

The system was also tested during a power failure with 16.0% NaCl solution as PCM. The time required for reaching the cabin air temperature to the ambient temperature of 18°C was determined during a power failure. The cabin air temperature fluctuation with time in the case of with 16.0% NaCl solution as PCM during a power failure period was represented in Figure 3.6.

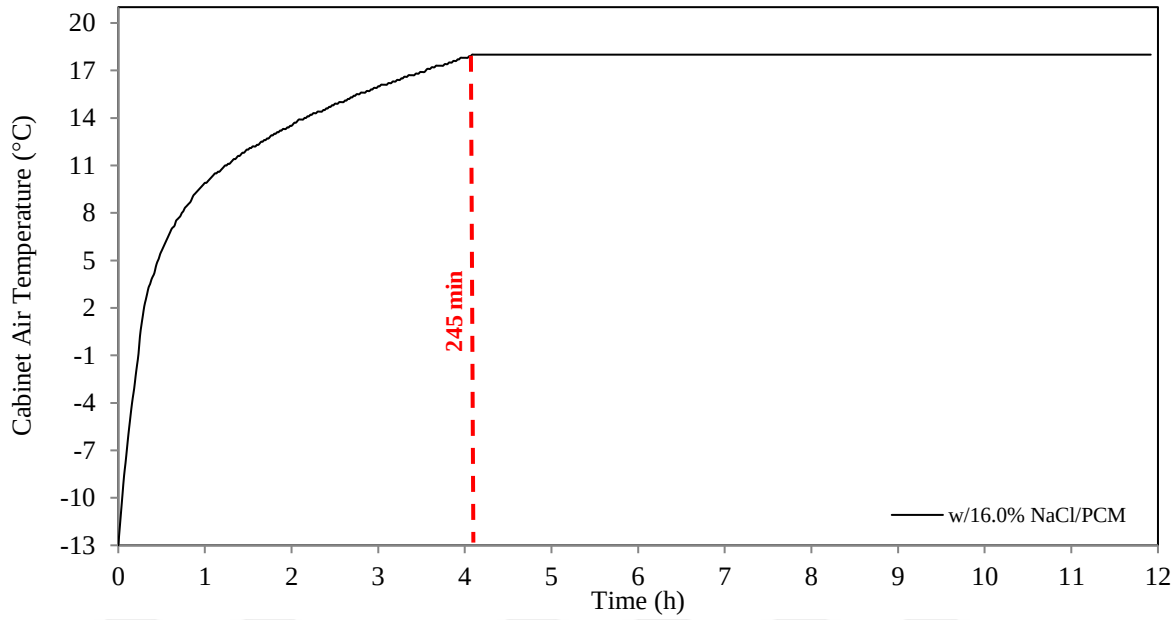

Figure 3.6 Temperature of cabinet air – time in the power failure period with 16.0% NaCl solution.

The cabin air temperature reached 18.0°C in 245 minutes with 16.0% NaCl solution as PCM. The 16.0% NaCl solution as PCM maintained the temperature much longer than the case of without PCM.

3.1.4 Examination of different concentrations of nucleating and thickening agents on the effect of 16.0 wt.% NaCl solution as PCM

The experiments were performed by adding different concentrations of nucleating and thickening agents on the 16.0% NaCl solution. The prepared solutions as PCM were 16.0% NaCl - 1.5% CMC solution, 16.0% NaCl – 1.5% CMC – 1.0% borax solution, 16.0% NaCl – 1.5% CMC – 2.0% borax solution, 16.0% NaCl – 1.0% CMC – 1.0% borax solution.

Effect of PCM on the cabin air temperature

The cabin air temperature fluctuation with time in the case of with different PCMs are presented in Figures 3.7-3.10. All results are shown in Figure 3.11

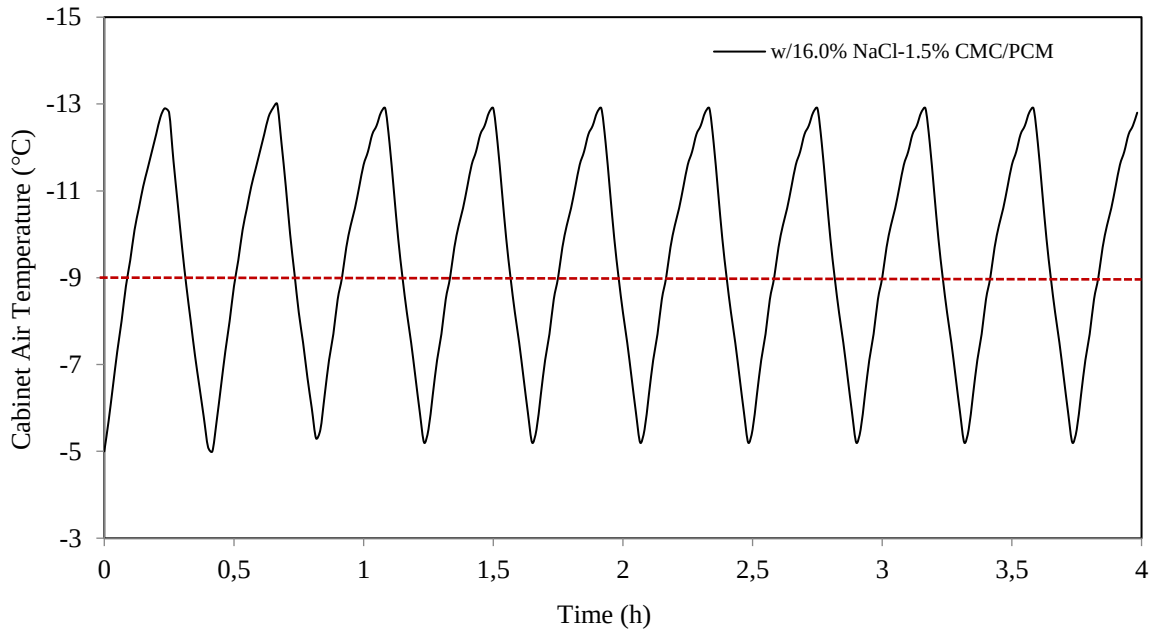

Figure 3.7 The profile of cabin air temperature in the case of with 16.0% NaCl – 1.5% CMC solution.

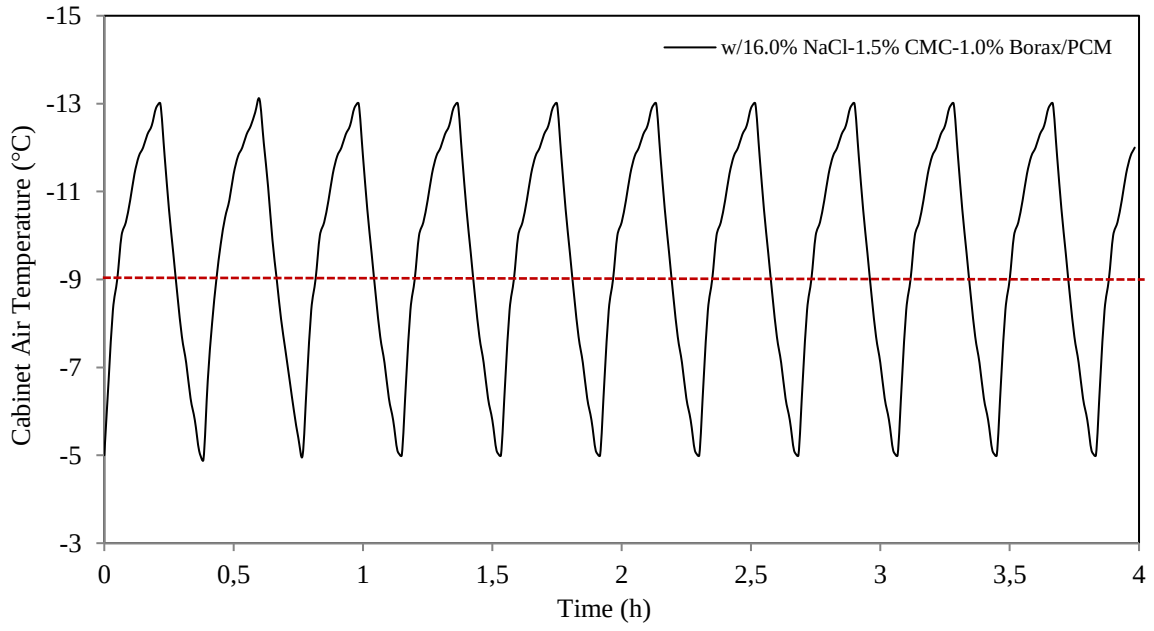

Figure 3.8 The profile of cabin air temperature in the case of with 16.0% NaCl – 1.5% CMC – 1.0% borax solution.

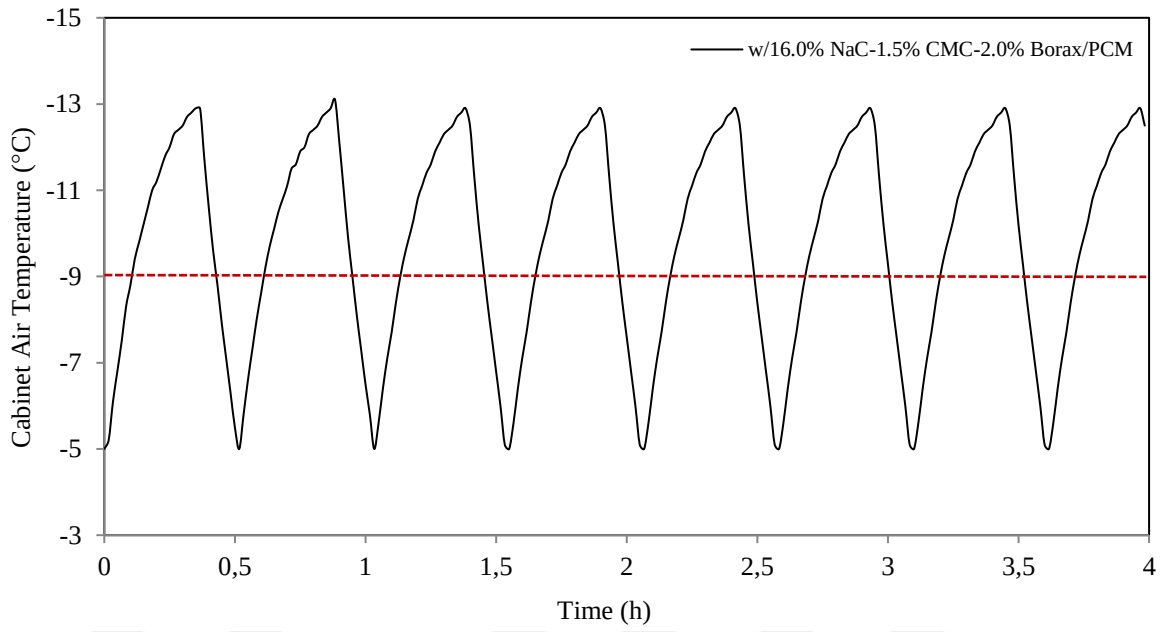

Figure 3.9 The profile of cabin air temperature in the case of with 16.0% NaCl – 1.5% CMC – 2.0% borax solution.

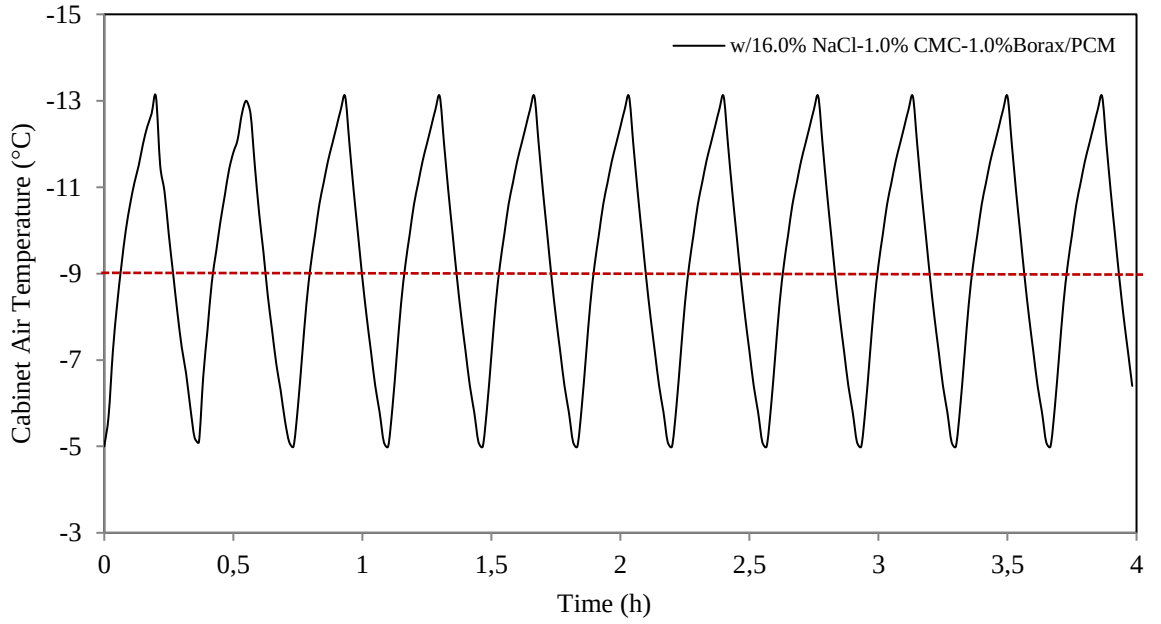

Figure 3.10 The profile of cabin air temperature in the case of with 16.0% NaCl – 1.0% CMC – 1.0% borax solution.

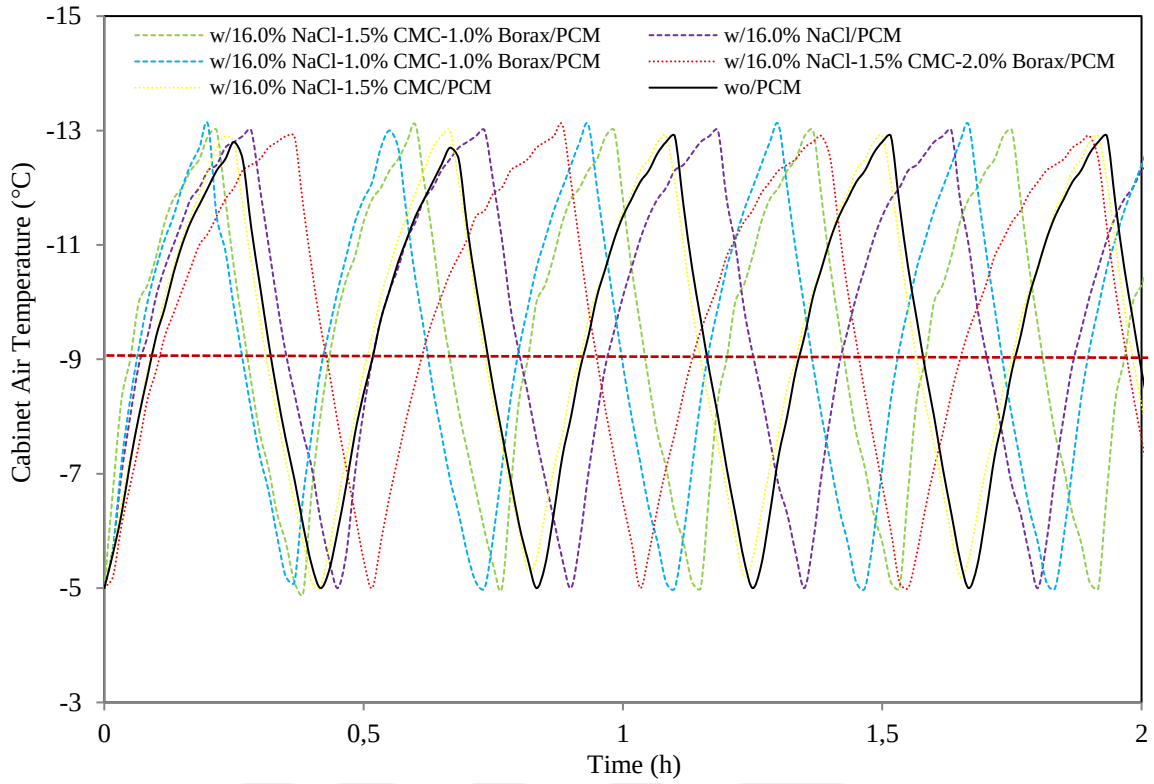

Figure 3.11 The profile of cabin air temperature in the case of without PCM and with different PCMs.

As seen in Figure 3.11, the cabin air temperature fluctuated within the range of -5°C to -13°C. The running time (%) was calculated with Equation 2.1, using the data of the compressor on-time (t_{on}) and off-time (t_{off}) for 4 hours of a running period and the results can be seen in the Table 3.1.

Table 3.1 The compressor on-time (t_{on}) and off-time (t_{off}) values for running periods of 4 hours in the case of without and with NaCl (16.0 wt.%)- CMC-borax solutions as PCMs.

PCM	**Cycle Time $t_{on}+t_{off}$ (min)**	**Compressor on time, t_{on}(min)**	**Compressor off-time, t_{off} (min)**	**Running Time (%)**
without PCM	25	16	9	64.00
16.0% NaCl	27	17	10	62.96
16.0% NaCl – 1.5% CMC	25	15	10	60.00
16.0% NaCl – 1.5% CMC – 1.0% borax	23	13	10	56.52
16.0% NaCl – 1.5% CMC – 2.0% Borax	31	22	9	70.97
16.0% NaCl – 1.0% CMC – 1.0% borax	22	12	10	54.55

The running time (%) was calculated to be 64.00% without PCM, 62.96% with 16.0% NaCl , 60.00% with 16.0% NaCl – 1.5% CMC solution, 56.52% with 16.0% NaCl – 1.5% CMC –

1.0% borax solution, 70.97% with 16.0% NaCl – 1.5% CMC – 2.0% borax solution, 54.55% with 16.0% NaCl – 1.0% CMC – 1.0% borax solution as PCM by using Equation 2.1.

The minimum running time percentage was determined to be 54.55% for 16.0% NaCl - 1.0% CMC - 1.0% borax solution. Consequently, the running time percentage was reduced from 64.00% to 54.55% in comparison to the case of without PCM. This decrease indicates an improvement of the compressor lifespan and energy saving.

Effect of PCM on the compressor power consumption

The power consumption variations over time in the case of with different PCMs are presented in Figures 3.12-3.15. All results are shown in Figure 3.16.

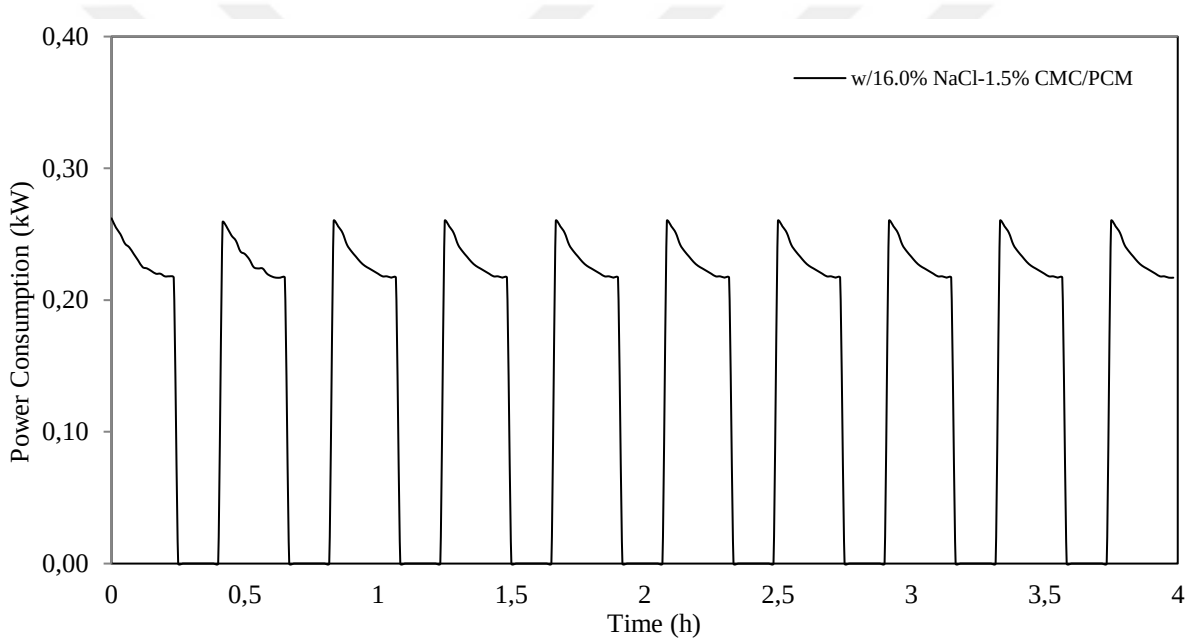

Figure 3.12 Compressor power consumption versus time in the case of with 16.0% NaCl – 1.5% CMC solution.

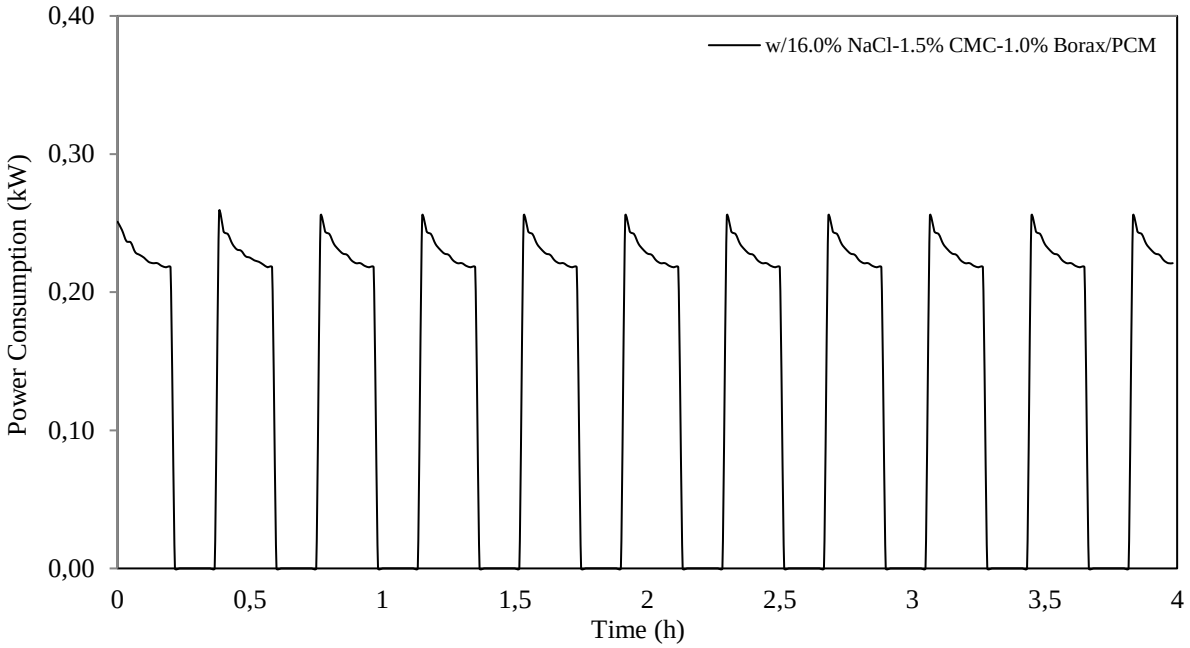

Figure 3.13 Compressor power consumption versus time in the case of with 16.0% NaCl – 1.5% CMC – 1.0% borax solution.

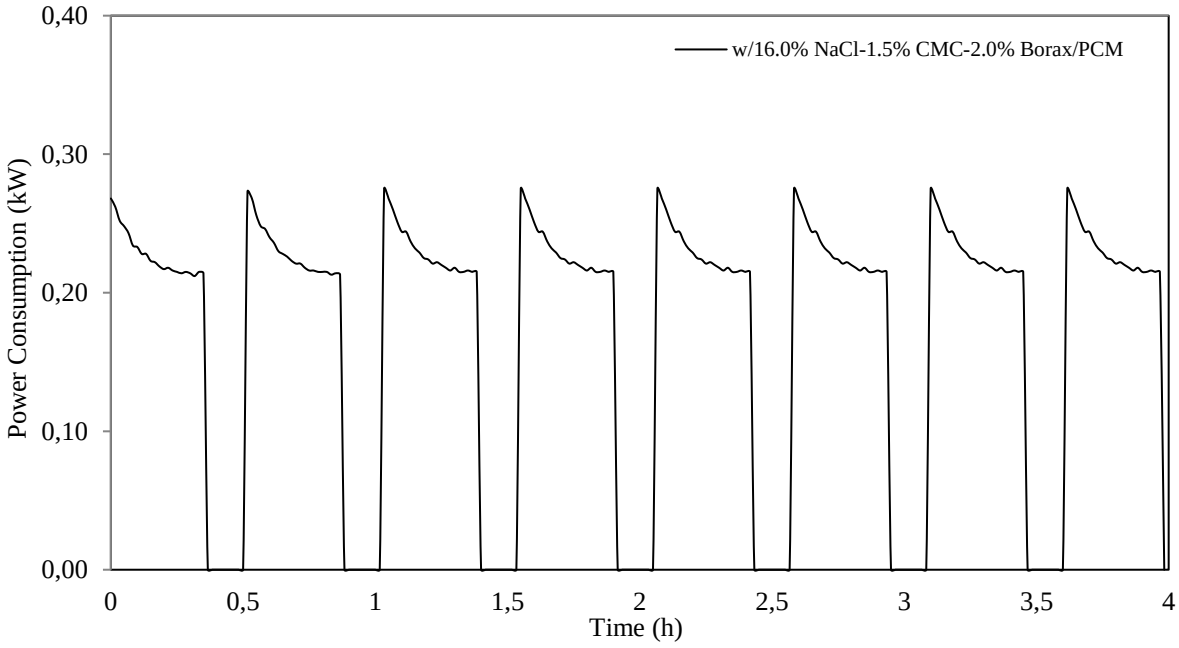

Figure 3.14 Compressor power consumption versus time in the case of with 16.0% NaCl – 1.5% CMC – 2.0% borax solution.

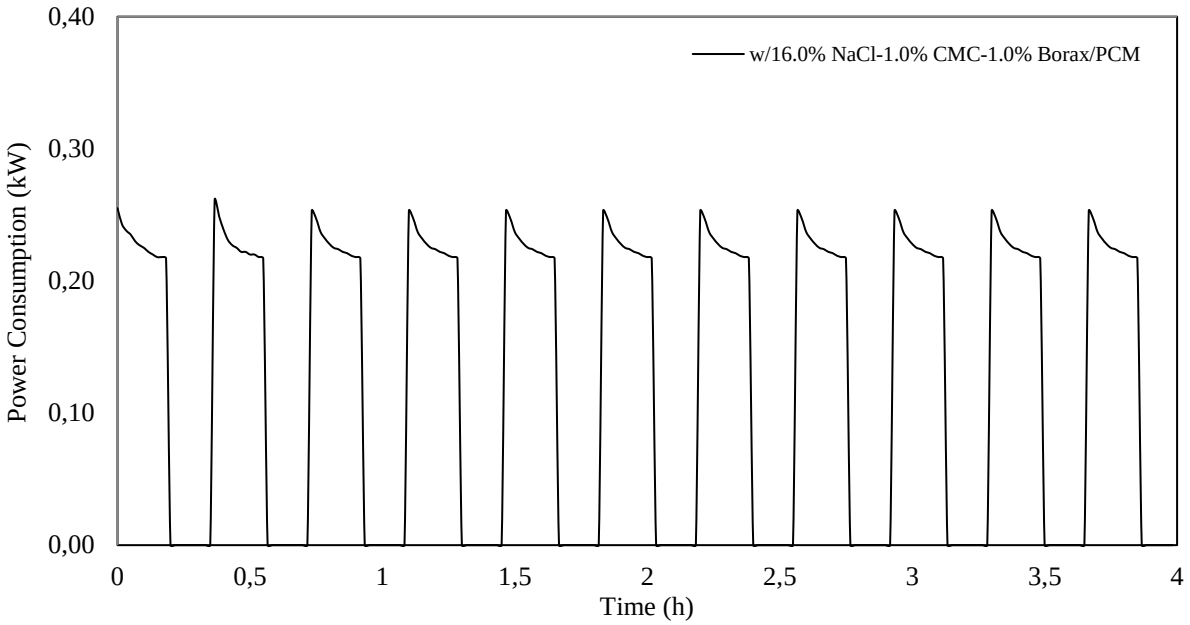

Figure 3.15 Compressor power consumption versus time in the case of with 16.0% NaCl – 1.0% CMC –1.0% borax solution.

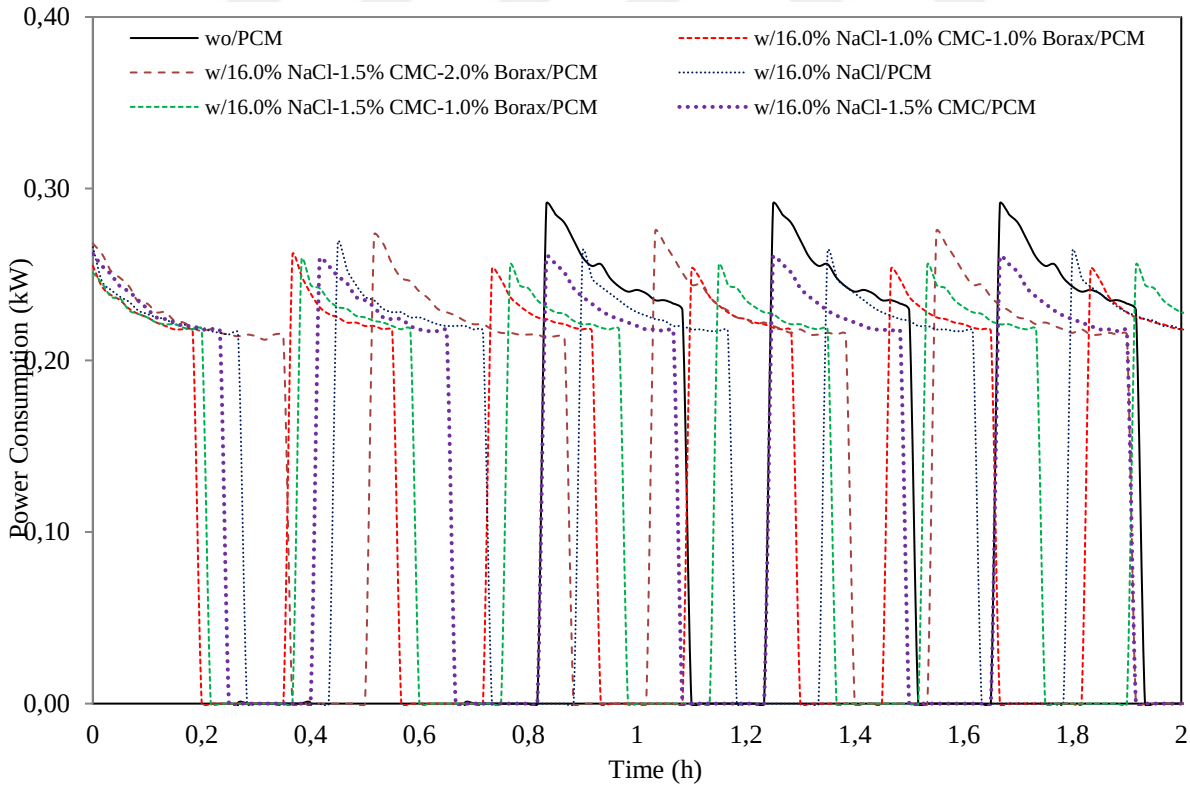

Figure 3.16 Compressor power consumption versus time in the case of without PCM and with different PCMs.

The total energy consumptions during the compressor running periods of 4 hours were calculated to be 40.22 kJ without PCM, 34.99 kJ with 16.0% NaCl solution, 34.71 kJ with 16.0% NaCl – 1.5% CMC solution, 32.14 kJ with 16.0% NaCl – 1.5% CMC – 1.0% borax solution, 40.54 kJ with 16.0% NaCl – 1.5% CMC – 2.0% borax solution, 30.19 kJ with 16.0% NaCl – 1.0% CMC – 1.0% borax solution by using Equation 2.2. The minimum and maximum power consumption values were measured to be 0.229 kW and 0.292 kW without PCM, 0.216 kW and 0.266 kW with 16.0% NaCl solution, 0.217 kW and 0.262 kW with 16.0% NaCl – 1.5% CMC solution, 0.218 kW and 0.258 kW with 16.0% NaCl – 1.5% CMC – 1.0% borax solution, 0.215 kW and 0.274 kW with 16.0% NaCl – 1.5% CMC – 2.0% borax solution, 0.217 kW and 0.261 kW with 16.0% NaCl – 1.0% CMC – 1.0% borax solution, respectively.

Effect of PCM on cabin air temperature during power failure period

The system was also tested during a power failure with different PCMs solutions. The time required for reaching the cabin air temperature to the ambient temperature of 18°C was determined during a power failure. The cabin air temperature fluctuation with time in the case of with different PCMs during a power failure period are represented in Figures 3.17-3.20. All results are shown in Figure 3.21.

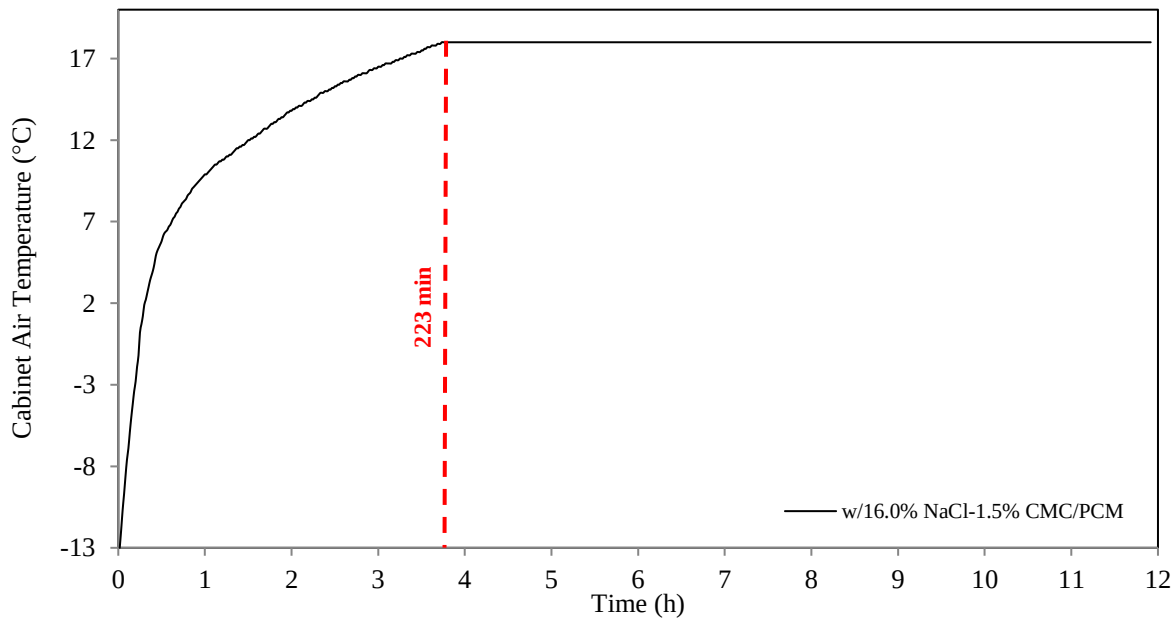

Figure 3.17 Temperature of cabinet air– time in the power failure period with 16.0% NaCl – 1.5% CMC solution.

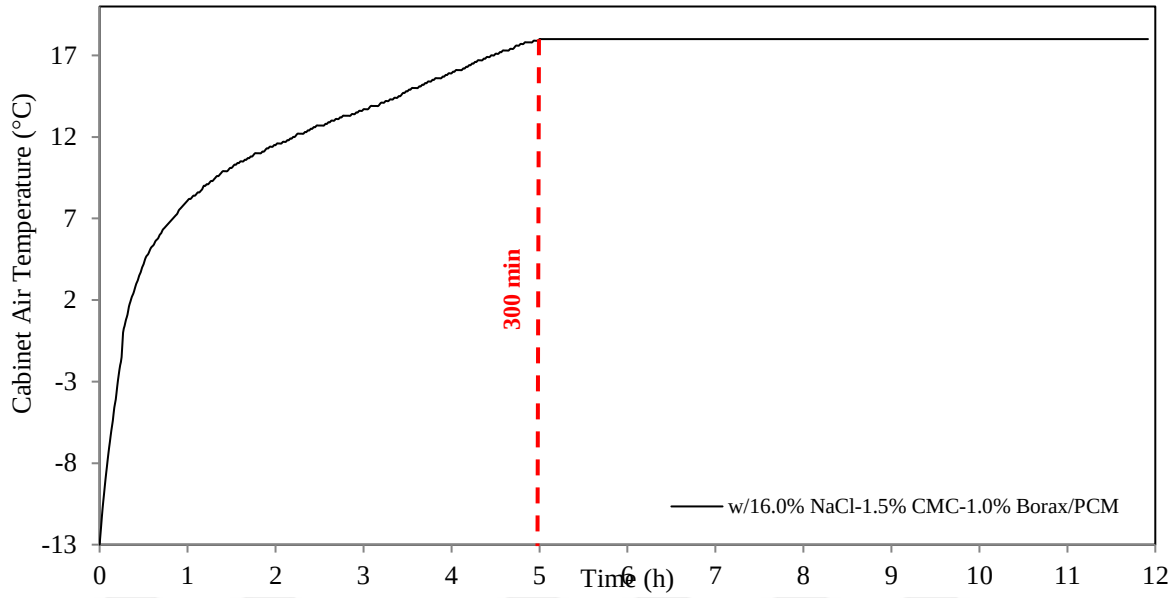

Figure 3.18 Temperature of cabinet air – time in the power failure period with 16.0% NaCl – 1.5% CMC – 1.0% borax solution.

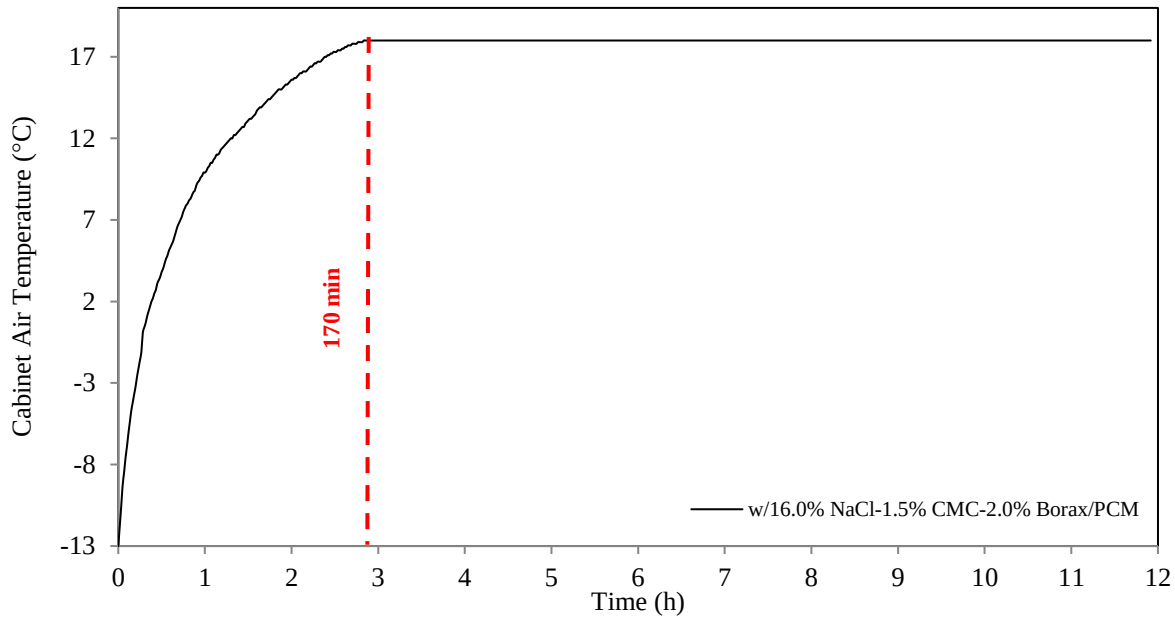

Figure 3.19 Temperature of cabinet air– time in the power failure period with 16.0% NaCl – 1.5% CMC – 2.0% borax solution.

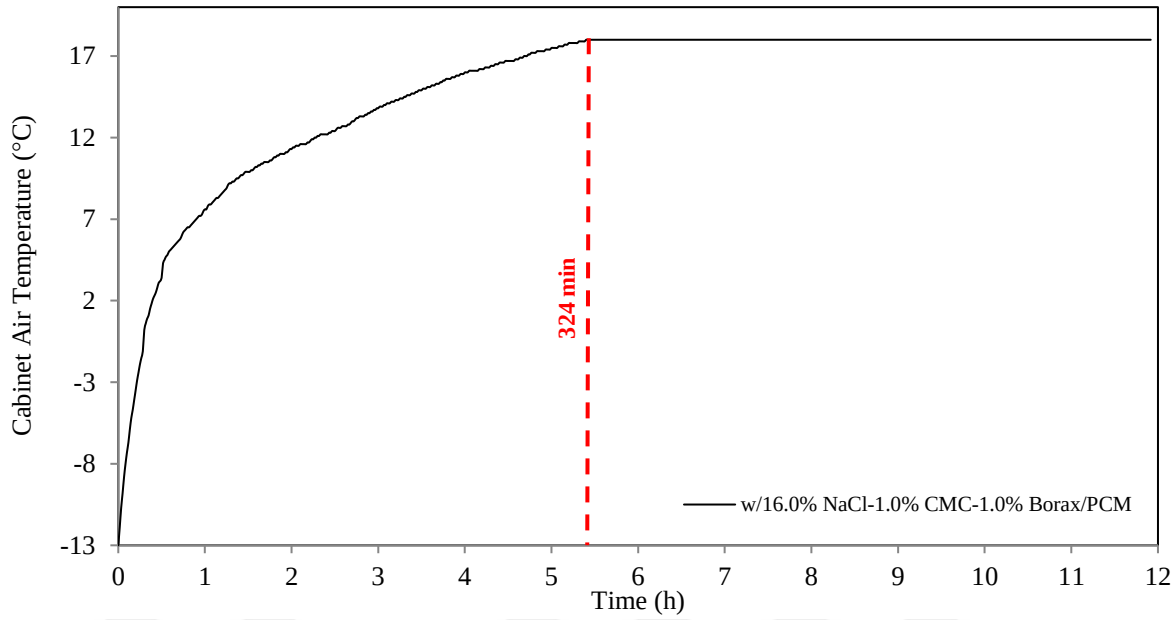

Figure 3.20 Temperature of cabinet air– time in the power failure period with 16.0% NaCl – 1.0% CMC – 1.0% borax solution.

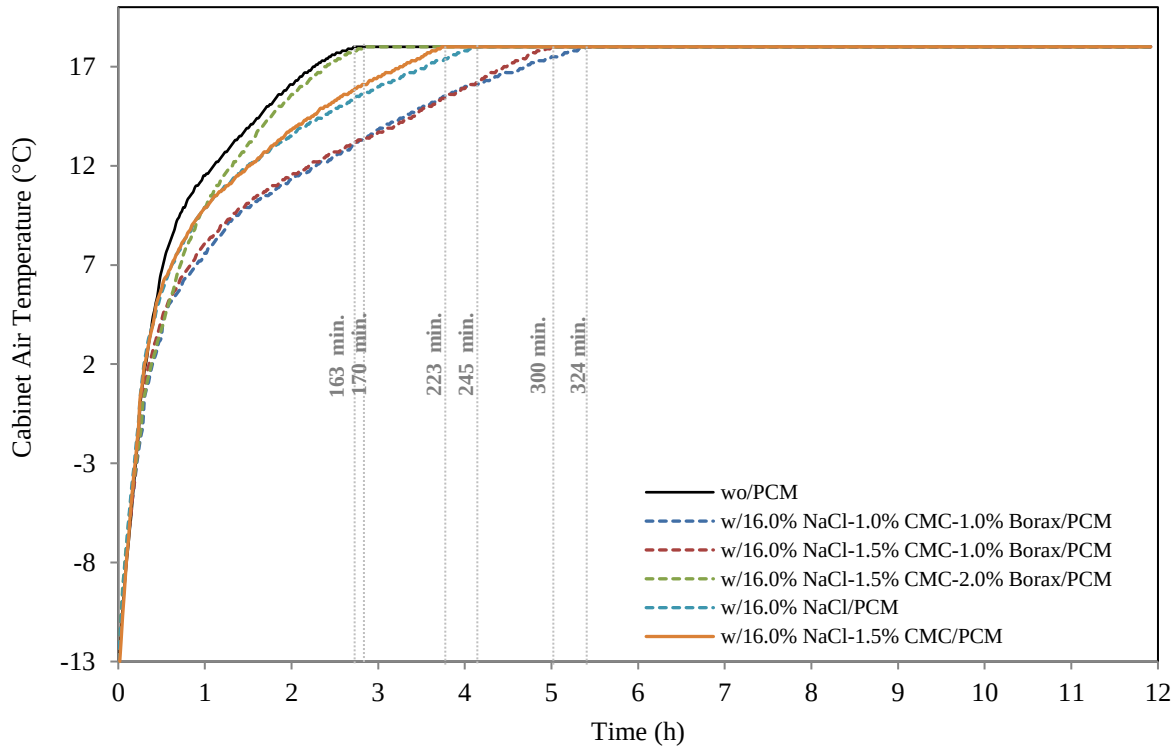

Figure 3.21 Temperature of cabinet air– time in the power failure period without PCM and with different PCMs.

The cabin air temperature reached 18.0℃ in 163 min. without PCM, in 245 min. with 16.0% NaCl solution, in 223 min. with 16.0% NaCl – 1.5% CMC solution, in 300 min. with 16.0% NaCl – 1.5% CMC – 1.0% borax solution, in 170 min. with 16.0% NaCl – 1.5% CMC – 2.0% borax solution, in 324 min. with 16.0% NaCl – 1.0% CMC – 1.0% borax solution.

The results indicate that PCM integration into a freezer could keep the cabinet air temperature at low values for a longer time. When compared to case of without PCM, the integration of the 16.0% NaCl – 1.0% CMC – 1.0% borax solution has an advantage by maintaining the cabinet air temperature for a longer time period.

The evaluation of energy consumption for running periods of 4 hours and power failure values in the case of without and with NaCl (16.0 wt.%)- CMC-borax solutions as PCMs can be seen in the Table 3.2.

Table 3.2. Energy consumption for running periods of 4 hours and power failure values in the case of without and with NaCl (16.0 wt.%)- CMC-borax solutions as PCMs.

PCM	Total Power Consumption (4h), (kJ)	Energy Saving (%)	Power Failure (min)
without PCM	40.22	-	163
16.0% NaCl	34.99	-13.01	245
16.0% NaCl – 1.5% CMC	34.71	-13.69	223
16.0% NaCl – 1.5% CMC – 1.0% borax	32.14	-20.09	300
16.0% NaCl – 1.5% CMC – 2.0% borax	40.54	0.79	170
16.0% NaCl – 1.0% CMC – 1.0% borax	30.19	-24.93	324

3.1.5 Effect of NaCl concentrations of PCM on the system performance

Effect of PCM on the cabin air temperature

The cabin air temperature fluctuation with time in the case of 4.0% NaCl – 1.0% CMC – 1.0% borax solution as PCM is presented in Figure 3.22.

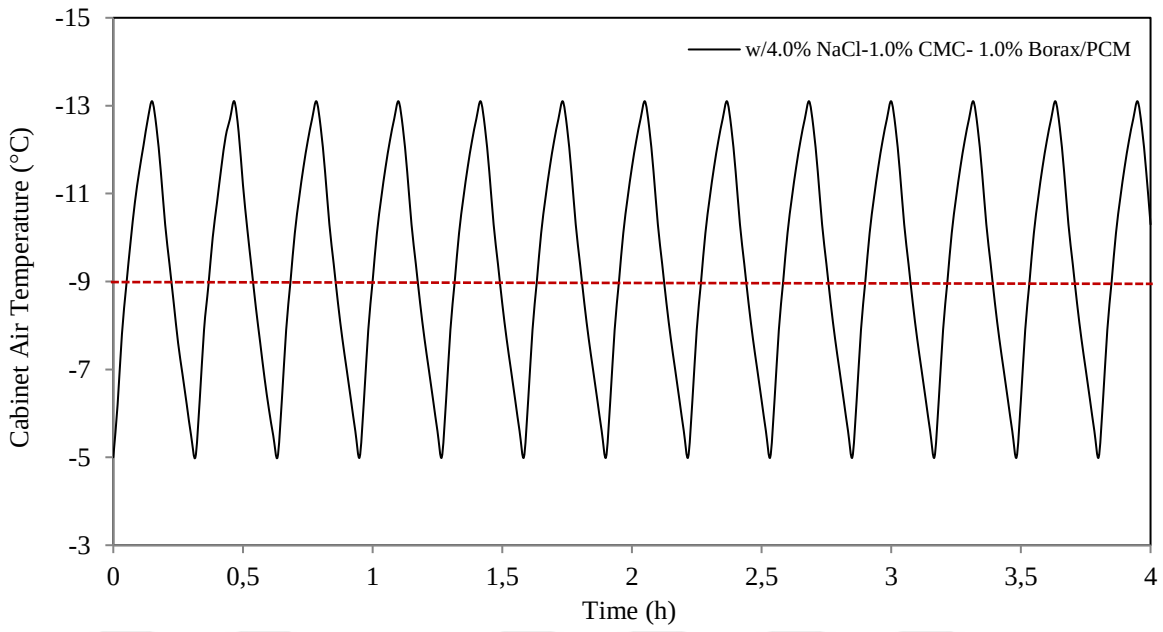

Figure 3.22 The profile of cabin air temperature in the case of with 4.0% NaCl – 1.0% CMC – 1.0% borax solution.

As seen in Figure 3.22, the cabin air temperature fluctuated within the range of -5°C to -13°C. The cycle time was calculated 19 min, while the compressor on-time and off-time was determined to be 9 min., and 10 min., respectively. The numbers of cycles with 4.0% NaCl – 1.0% CMC – 1.0% borax solution as PCM was found to be 12.6. The running time (%) was calculated to be 47.37% in the case of with 4.0% NaCl – 1.0% CMC – 1.0% borax solution as PCM by using Equation 2.1.

Effect of PCM on the compressor power consumption

The power consumption variation over time in the case of with 4.0% NaCl – 1.0% CMC – 1.0% borax solution is presented in Figure 3.23.

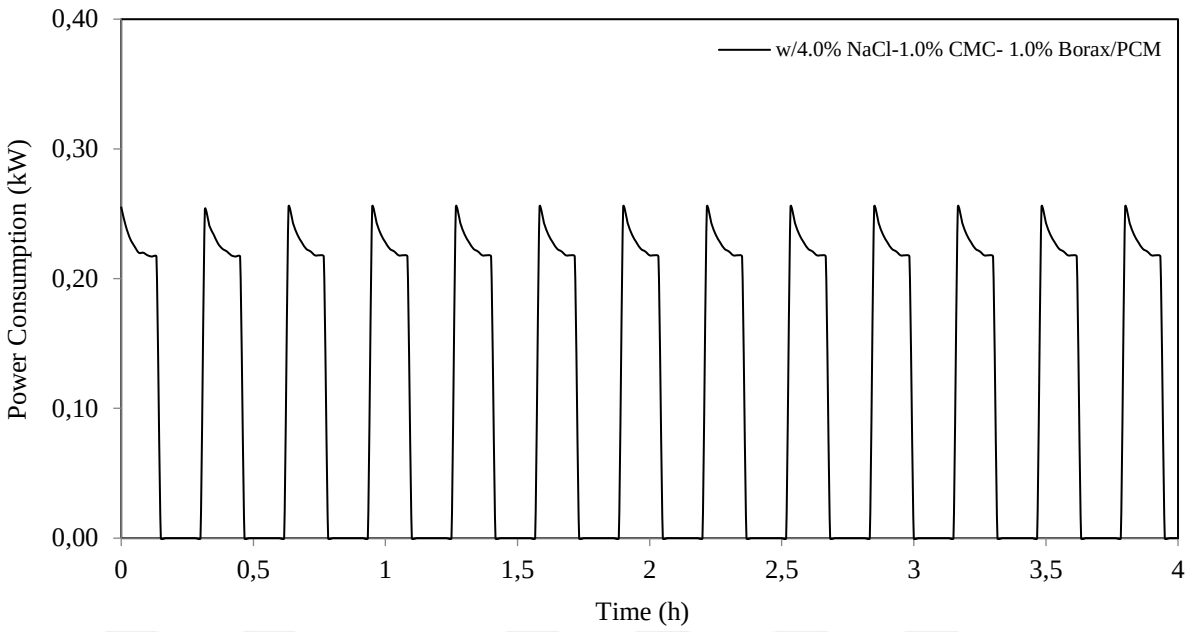

Figure 3.23 Compressor power consumption versus time in the case of with 4.0% NaCl – 1.0% CMC – 1.0% borax solution.

The total energy consumptions during the compressor running periods of 4 hours were calculated to be 26.72 kJ with 4.0% NaCl – 1.0% CMC – 1.0% borax solution as PCM by using Equation 2.2. The minimum and maximum power consumption values were measured to be 0.217 kw and 0.255 kW, respectively.

The NaCl concentration impact on the total energy consumption was investigated by decreasing its concentration from 16.0% to 4.0%. The total energy consumption was calculated to be 30.19 kJ with 16.0% NaCl - 1.0% CMC - 1.0% borax solution. The results showed a 12.98% reduction in the total energy consumption with decreasing NaCl concentration.

Effect of PCM on the cabin air temperature during the power failure period

The system was also tested during a power failure with 4.0% NaCl – 1.0% CMC – 1.0% borax solution as PCM. The time required for reaching the cabin air temperature to the ambient temperature of 18°C was determined during a power failure. The cabin air temperature fluctuation with time in the case of with 4.0% NaCl – 1.0% CMC – 1.0% borax solution as PCM during a power failure period was represented in Figure 3.24

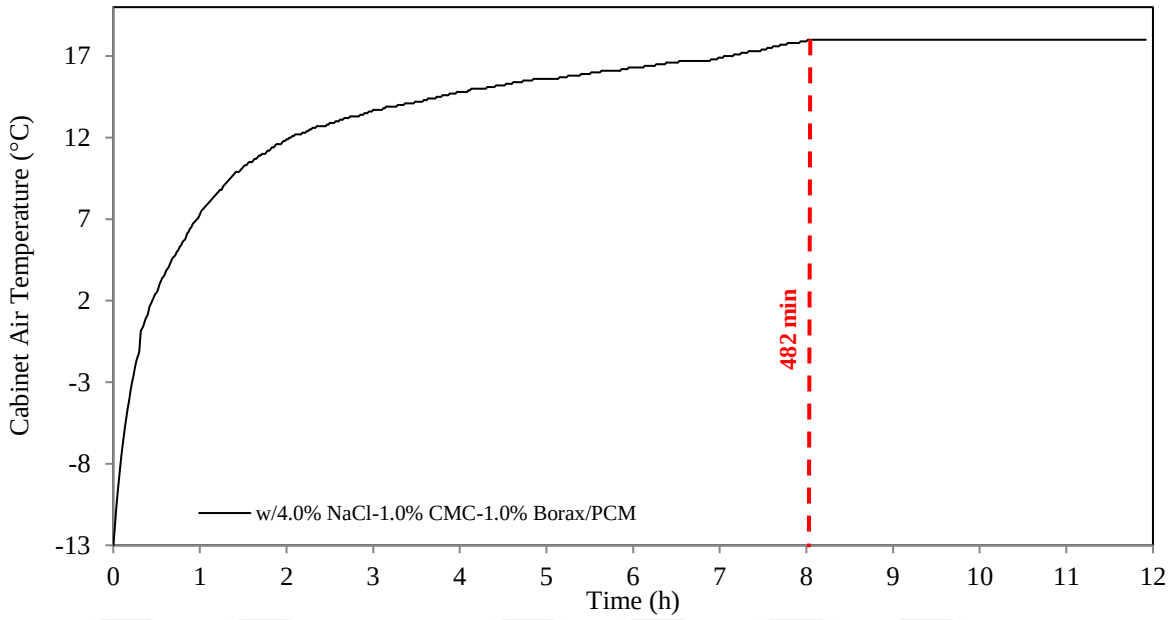

Figure 3.24 Temperature of cabinet air – time in the power failure period with 4.0% NaCl – 1.0% CMC – 1.0% borax solution.

The cabin air temperature reached 18.0°C in 482 minutes with 4.0% NaCl – 1.0% CMC – 1.0% borax solution as PCM. It took 3 times more hours than that of the case without PCM.

3.2 Optimization of PCM formulation

RSM was applied to reveal the optimal PCM based on Box Behnken design (BBD). Based on the experimental design analysis, 17 runs were needed for the selection of the optimum PCM **(see Table 3.3).** A set of PCM formulations based on sodium chloride (4.0-8.0 wt.%)-carboxymethyl cellulose (0.5-1.5 wt.%) and water binary system including borax (0.0-2.0%) were tested for the cooling system simulating a freezer operating between -5°C and -13°C.

The experimental results from the combination of all the factors were presented in **Table 3.3**.

Table 3.3. The Box-Behnken design matrix for variables along with the actual responses

Run	Actual level of factors			Response
	NaCl Concentration (weight %)	**(CMC) Concentration (weight %)**	**Borax Concentration (weight %)**	**Running Time (%)**
1	6.0	0.5	2.0	57.14
2	6.0	1.5	2.0	47.37
3	8.0	1.0	0.0	55.00
4	6.0	1.0	1.0	43.75
5	8.0	1.0	2.0	52.63
6	6.0	0.5	0.0	78.57
7	4.0	1.0	2.0	61.54
8	4.0	1.5	1.0	42.11
9	8.0	0.5	1.0	55.56
10	6.0	1.0	1.0	43.75
11	6.0	1.5	0.0	47.06
12	4.0	1.0	0.0	56.52
13	6.0	1.0	1.0	43.75
14	4.0	0.5	1.0	70.00
15	6.0	1.0	1.0	43.75
16	6.0	1.0	1.0	43.75
17	8.0	1.5	1.0	50.00

3.2.1 Effect of integrating 4.0 wt.% NaCl solution as PCM on the system performance

The experiments were carried out for 4 hours by using different PCMs; 4.0% NaCl - 1.0% CMC solution, 4.0% NaCl - 1.0% CMC - 2.0% borax solution, 4.0% NaCl - 0.5% CMC - 1.0% borax solution, 4.0% NaCl - 1.5% CMC - 1.0% borax solution respectively.

Effect of PCM on the cabin air temperature

The cabin air temperature fluctuation with time in the cases of with different PCM solutions containing 4.0% NaCl are presented in Figures 3.25-3.28. All results are shown in Figure 3.29.

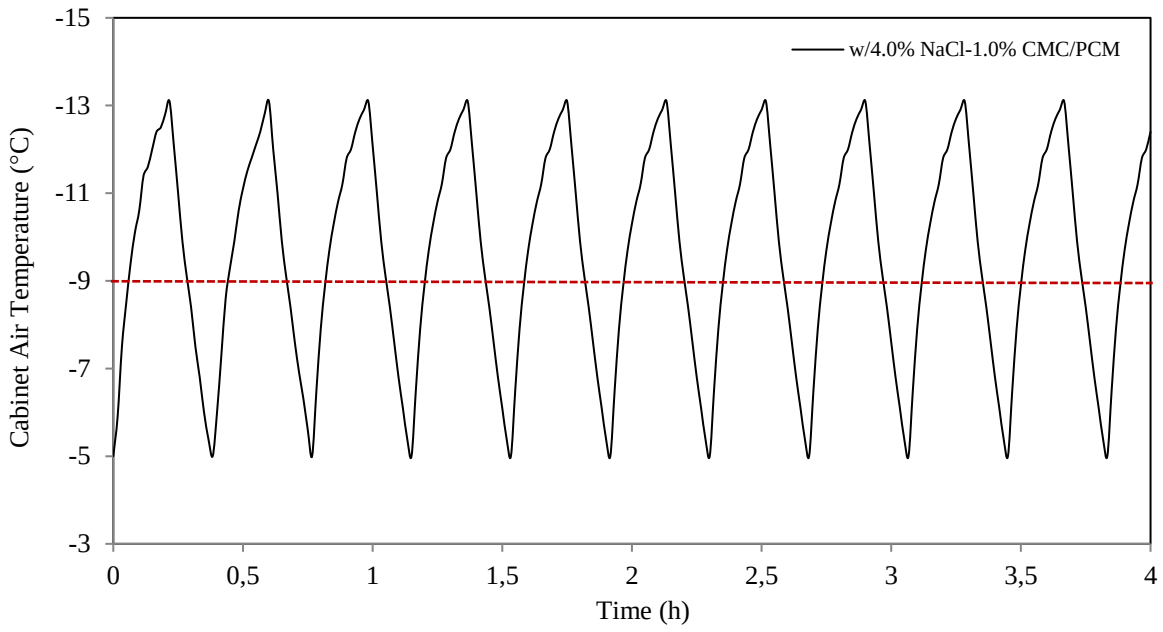

Figure 3.25 The profile of cabin air temperature in the case of with 4.0% NaCl - 1.0% CMC solution.

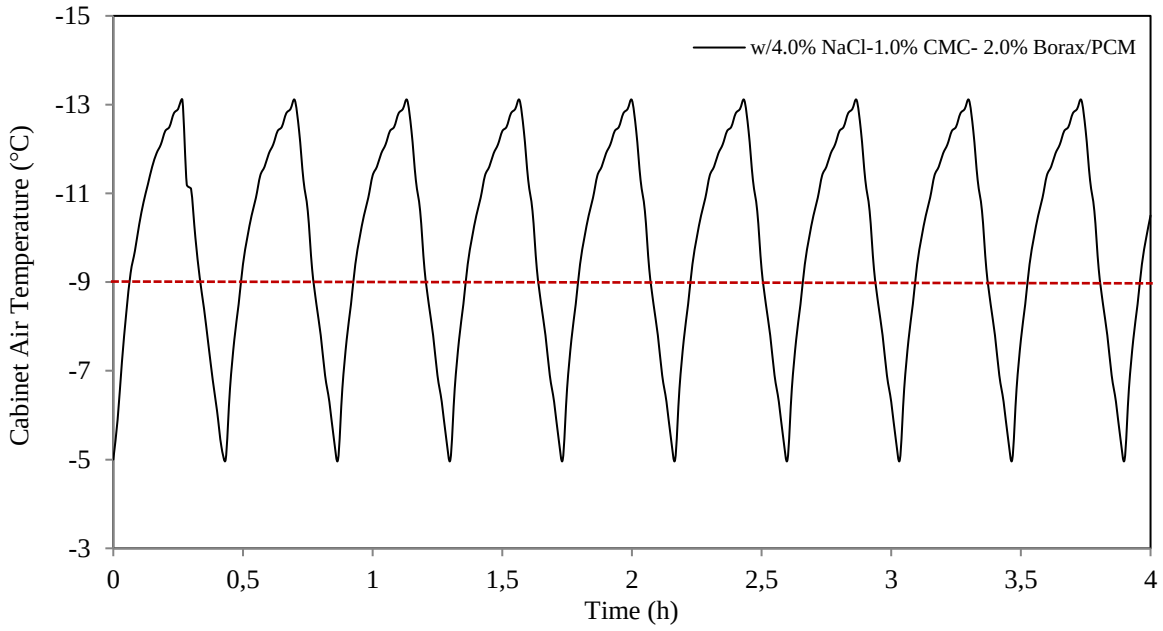

Figure 3.26 The profile of cabin air temperature in the case of with 4.0% NaCl - 1.0% CMC - 2.0% borax solution.

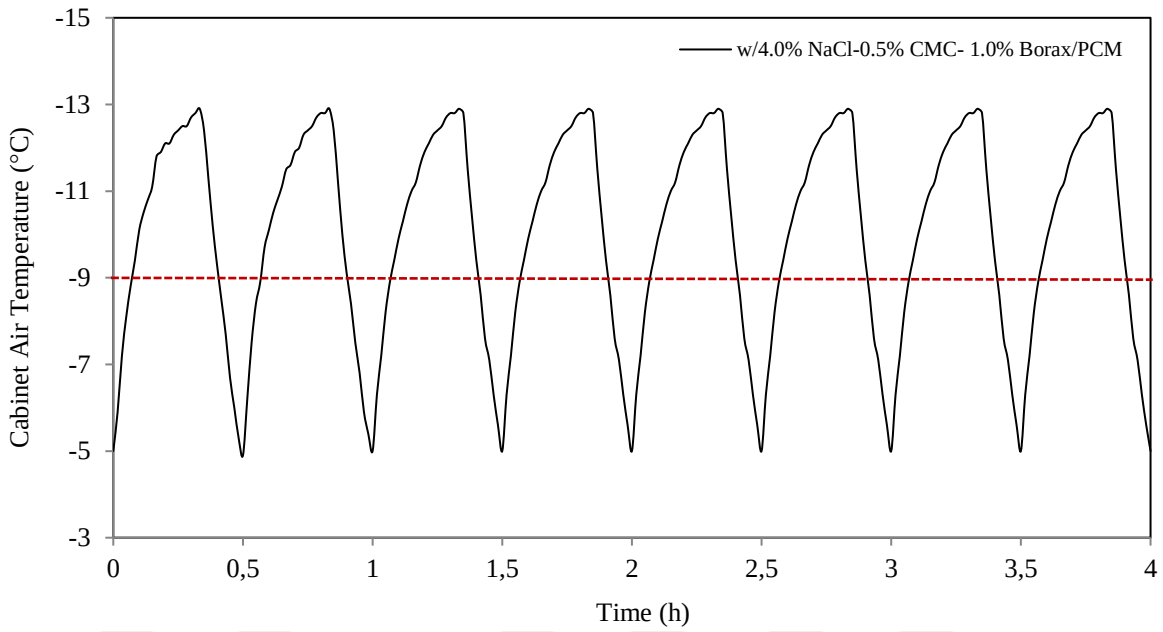

Figure 3.27 The profile of cabin air temperature in the case of with 4.0% NaCl - 0.5% CMC - 1.0% borax solution.

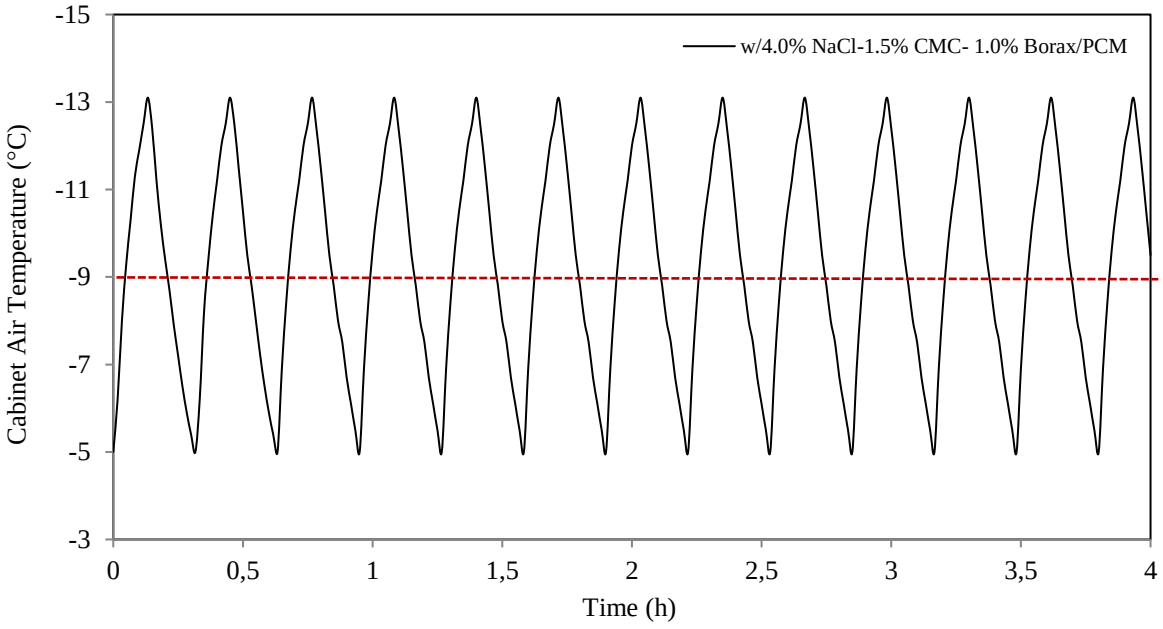

Figure 3.28 The profile of cabin air temperature in the case of with 4.0% NaCl - 1.5% CMC - 1.0% borax solution.

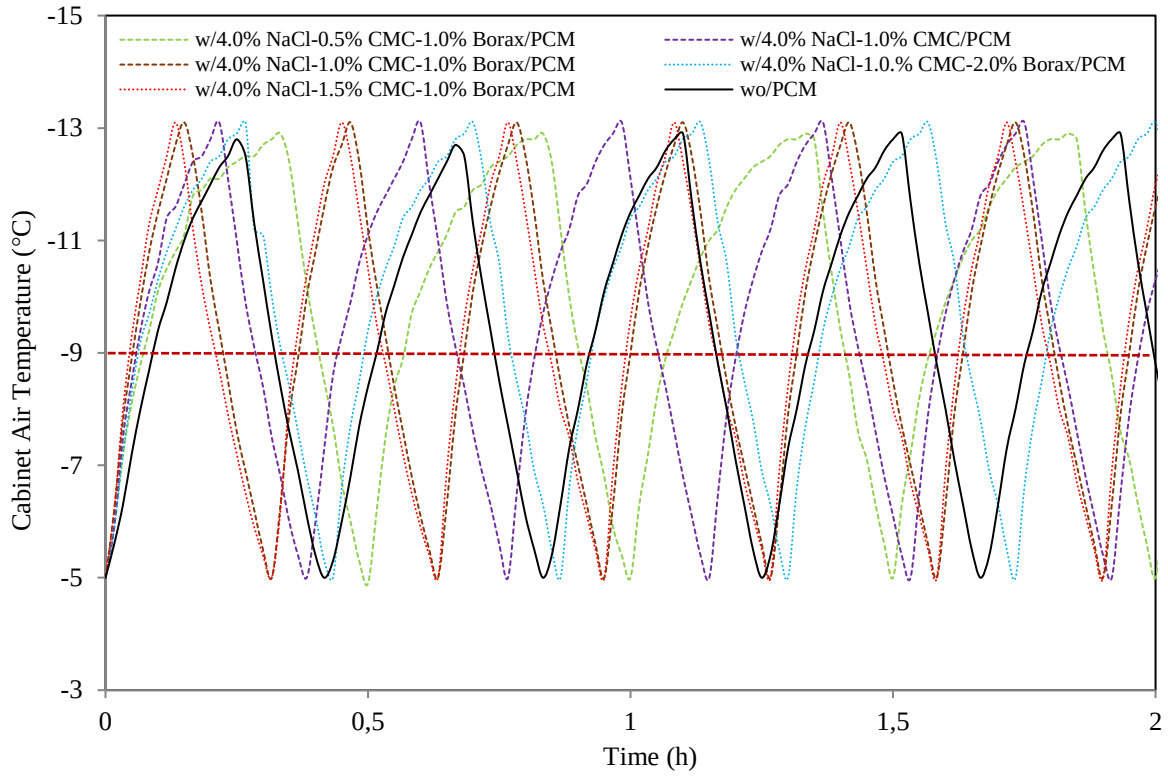

Figure 3.29 The profile of cabin air temperature in the case of without PCM and with different PCMs.

As seen in Figure 3.29, the cabin air temperature fluctuated within the range of -5°C to -13°C. The running time (%) was calculated with the Equation 2.1, using the data of the compressor on-time (t_{on}) and off-time (t_{off}) for 4 hours of a running period and the results can be seen in the Table 3.4.

Table 3.4 The compressor on-time (t_{on}) and off-time (t_{off}) values for running periods of 4 hours in the case of without and with NaCl (4.0 wt.%)- CMC-borax solutions as PCMs.

PCM	**Cycle Time $t_{on}+t_{off}$ (min)**	**Compressor on time, t_{on}(min)**	**Compressor off-time, t_{off} (min)**	**Running Time (%)**
without PCM	25	16	9	64.00
4.0% NaCl – 1.0% CMC – 1.0% borax	19	9	10	47.37
4.0% NaCl – 1.0% CMC	23	13	10	56.52
4.0% NaCl – 1.0% CMC – 2.0% Borax	26	16	10	61.54
4.0% NaCl – 0.5% CMC – 1.0% borax	30	21	9	70.00
4.0% NaCl – 1.5% CMC – 1.0% borax	19	8	11	42.11

The running time (%) was calculated to be 64.00% without PCM, 47.37% with 4.0% NaCl – 1.0% CMC – 1.0% borax solution 56.52% with 4.0 wt. % NaCl – 1.0 wt.% MC solution, 61.54% with 4.0% NaCl – 1.0% CMC – 2.0% borax solution, 70.00% with 4.0% NaCl – 0.5%

CMC – 1.0% borax solution, 42.11% with 4.0% NaCl – 1.5% CMC – 1.0% borax solution as PCM by using Equation 2.1.

Effect of PCM on the compressor power consumption

The power consumption variation over time in the cases of with different PCMs are presented in Figures 3.30-3.33. All results are shown in Figure 3.34.

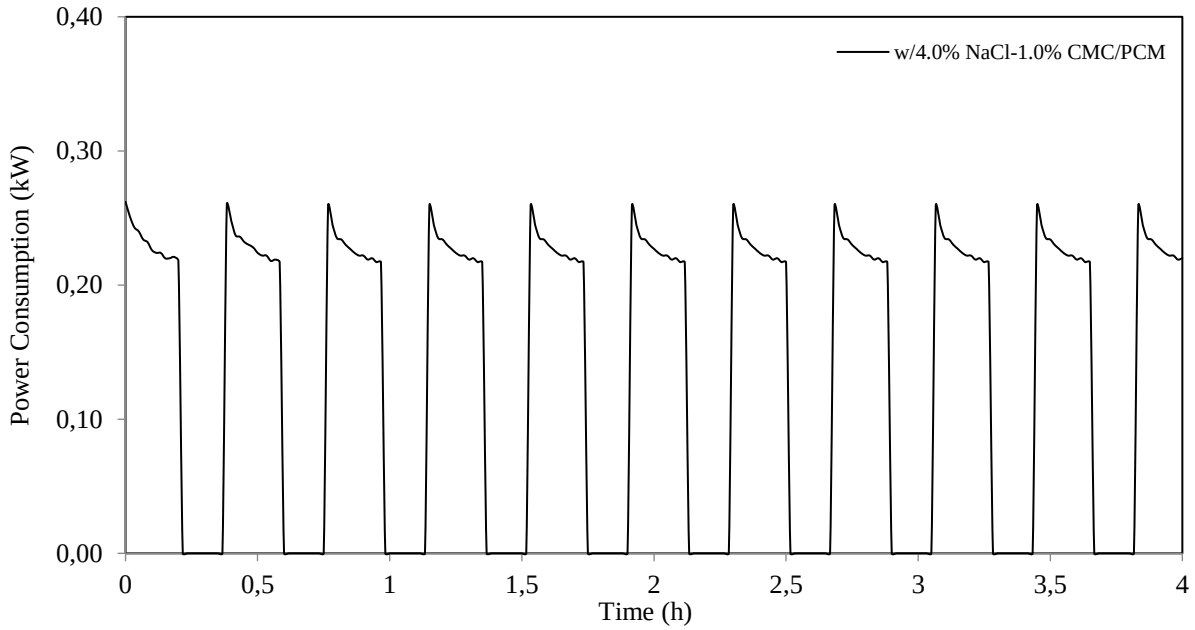

Figure 3.30 Compressor power consumption versus time in the case of with 4.0% NaCl - 1.0% CMC solution.

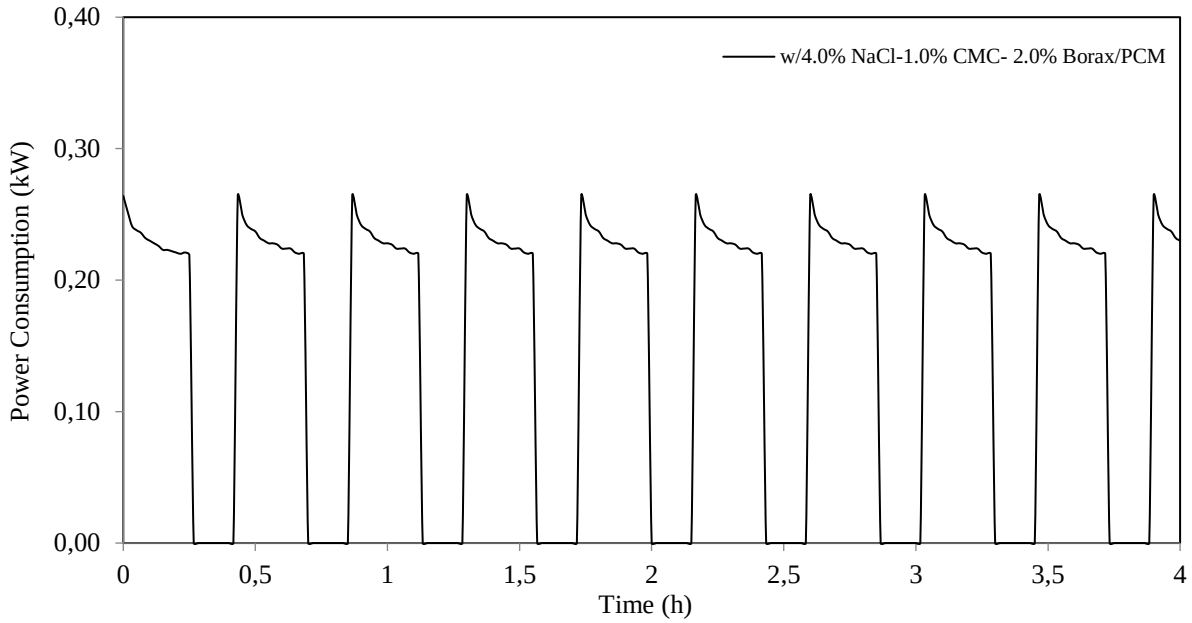

Figure 3.31 Compressor power consumption versus time in the case of with 4.0% NaCl - 1.0% CMC - 2.0% borax solution.

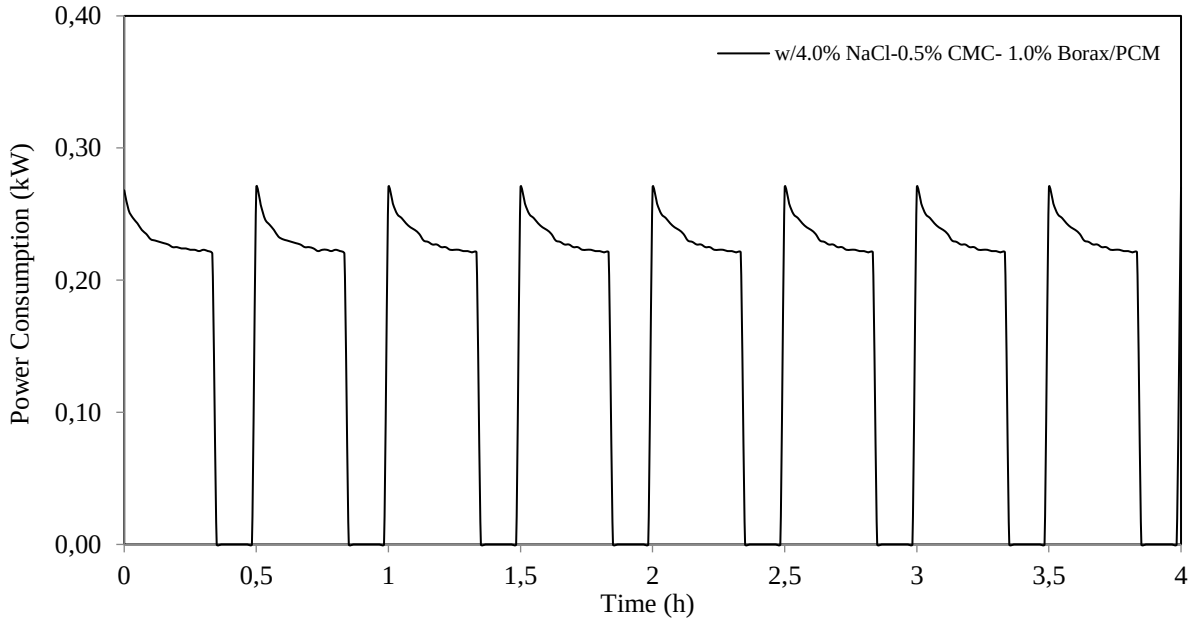

Figure 3.32 Compressor power consumption versus time in the case of with 4.0% NaCl - 0.5% CMC - 1.0% borax solution.

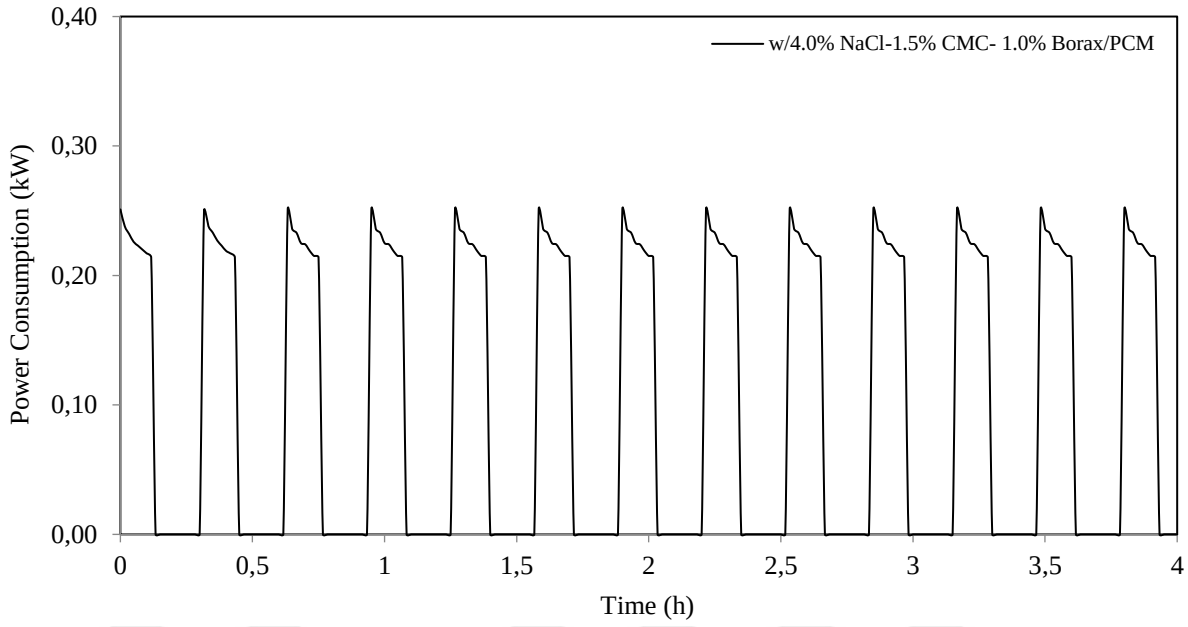

Figure 3.33 Compressor power consumption versus time in the case of with 4.0% NaCl - 1.5% CMC - 1.0% borax solution.

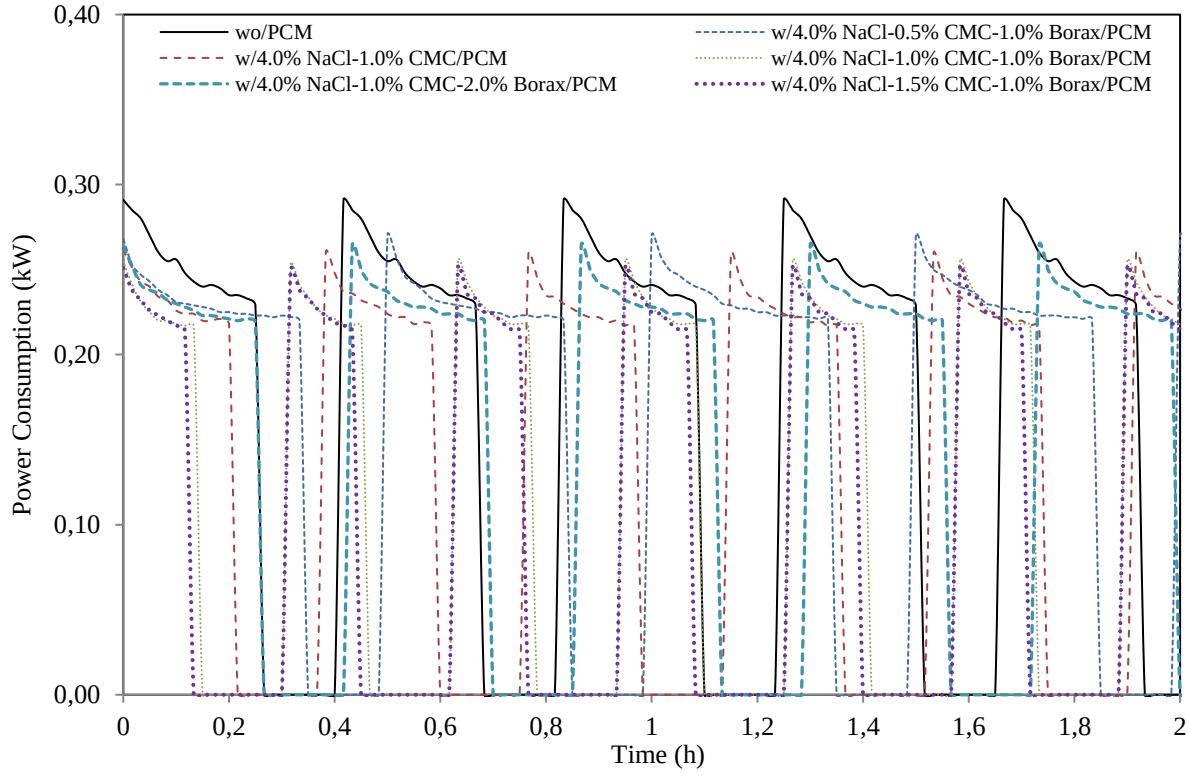

Figure 3.34 Compressor power consumption versus time in the case of without PCM and with different PCMs.

The total energy consumptions during the compressor running periods of 4 hours were calculated to be 40.22 kJ without PCM, 26.72 kJ with 4.0 wt. % NaCl - 1.0% CMC - 1.0% borax solution 32.31 kJ with 4.0% NaCl - 1.0% CMC solution, 35.07kJ with 4.0 wt. % NaCl - 1.0% CMC - 2.0% borax solution, 39.11 kJ with 4.0% NaCl - 0.5% CMC - 1.0% borax solution, 23.69 kJ with 4.0% NaCl - 1.5% CMC - 1.0% borax solution by using Equation 2.2.

The minimum and maximum power consumption values were measured as 0.229 kW and 0.292 kW without PCM, 0.217 kW and 0.255 kW with 4.0 wt. % NaCl - 1.0% CMC - 1.0% borax solution, 0.217 kW and 0.262 kW with 4.0% NaCl - 1.0% CMC solution, 0.219 kW and 0.264 kW with 4.0 wt. % NaCl - 1.0% CMC - 2.0% borax solution, 0.220 kW and 0.270 kW with 4.0% NaCl - 0.5% CMC - 1.0% borax solution, 0.214 kW and 0.251 kW with 4.0% NaCl - 1.5% CMC - 1.0% borax solution.

Effect of PCM on cabin air temperature during power failure period

The system was also tested during a power failure with different PCMs. The time required for reaching the cabin air temperature to the ambient temperature of 18°C was determined during a power failure. The cabin air temperature fluctuation with time in the cases of with different PCMs during a power failure period are represented in Figures 3.35-3.38. All results are shown in Figure 3.39.

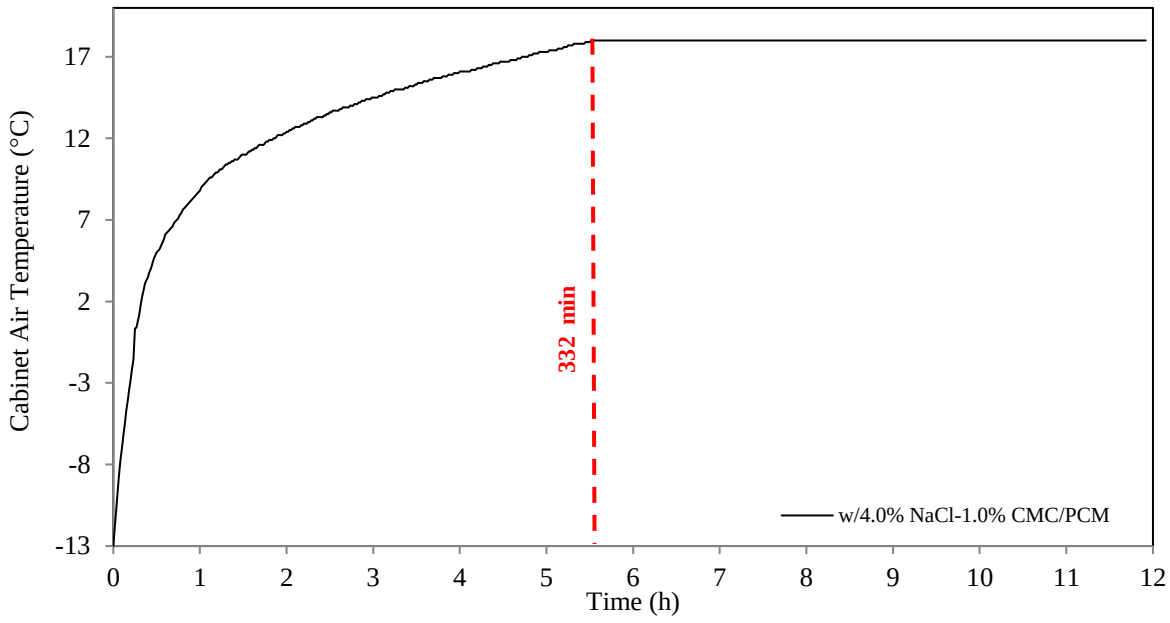

Figure 3.35 Temperature of cabinet air– time in the power failure period with 4.0% NaCl - 1.0% CMC solution.

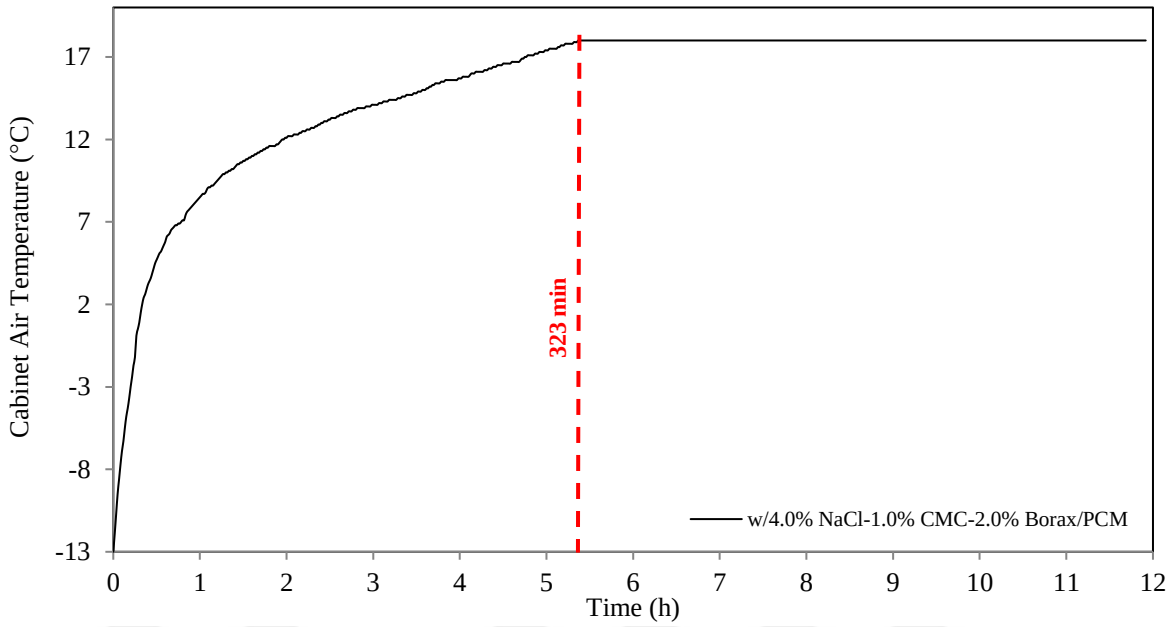

Figure 3.36 Temperature of cabinet air– time in the power failure period with 4.0% NaCl - 1.0% CMC - 2.0% borax solution.

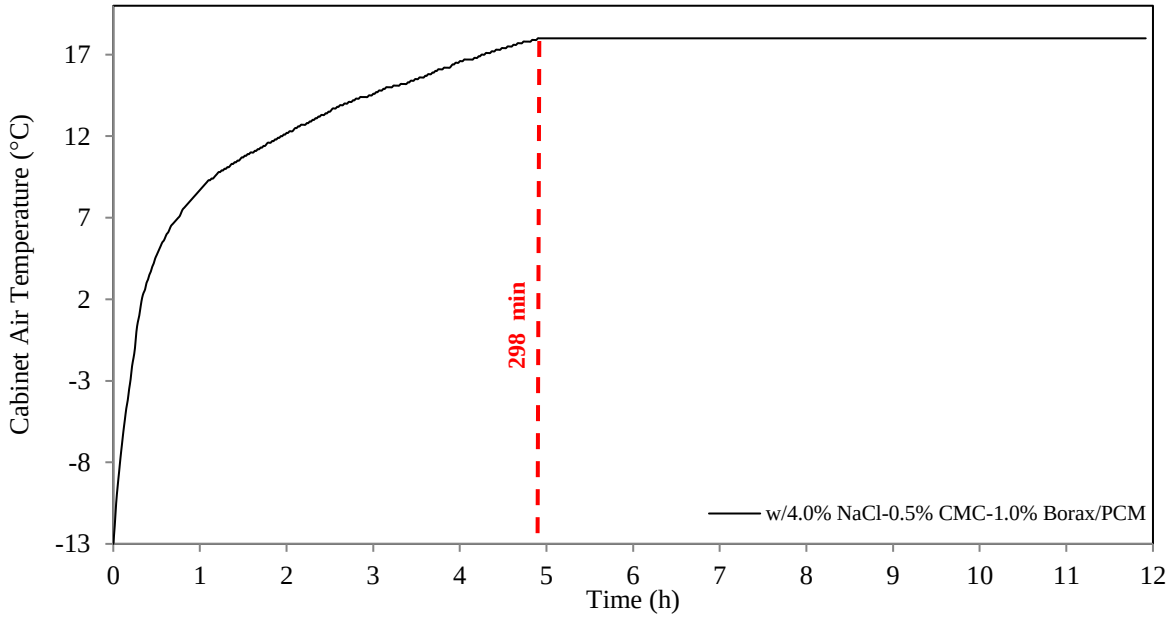

Figure 3.37 Temperature of cabinet air– time in the power failure period with 4.0% NaCl - 0.5% CMC - 1.0% borax solution.

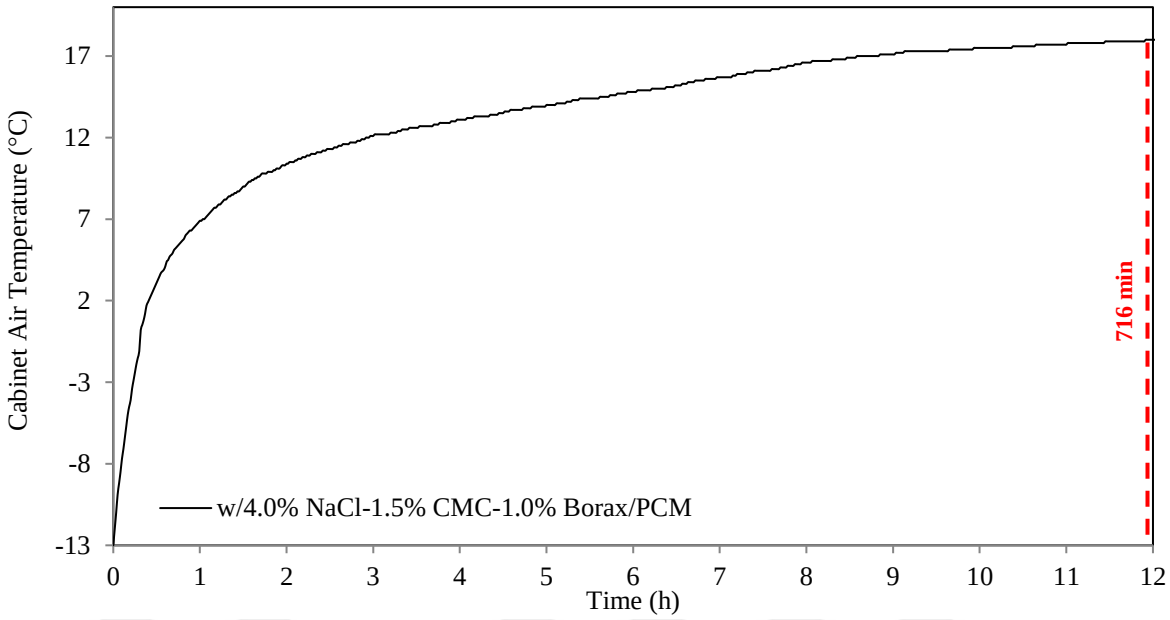

Figure 3.38 Temperature of cabinet air– time in the power failure period with 4.0% NaCl - 1.5% CMC - 1.0% borax solution.

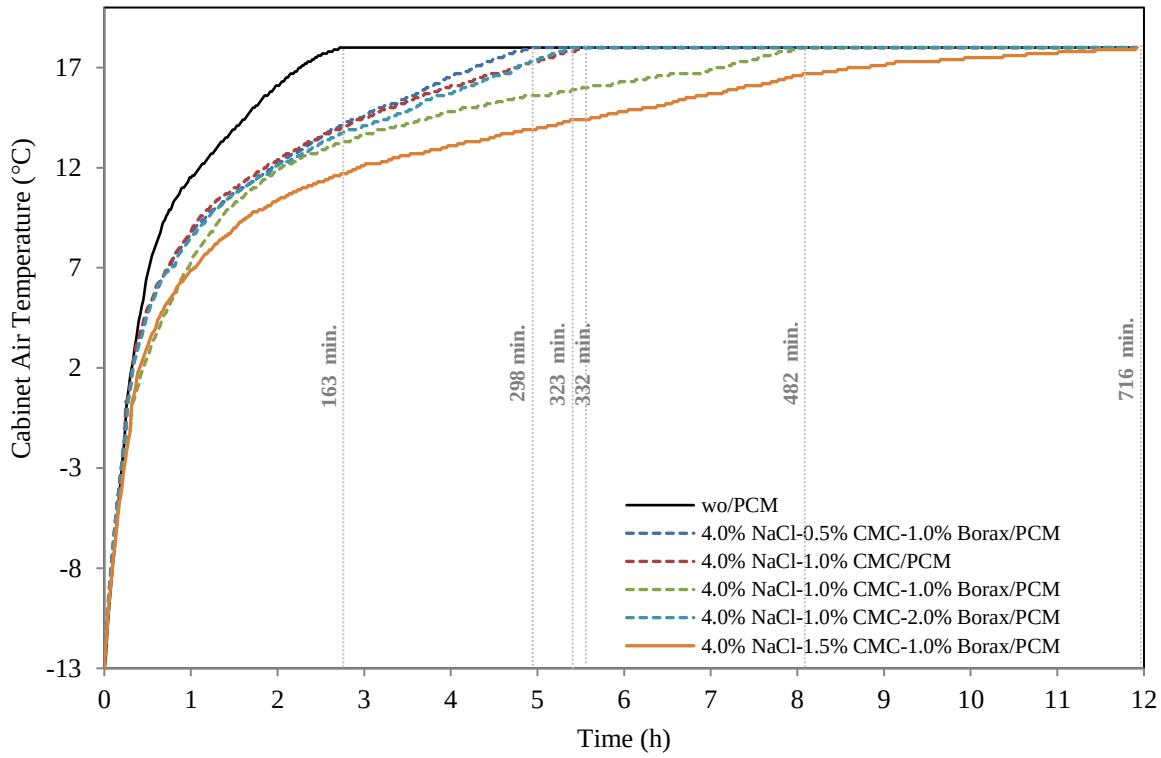

Figure 3.39 Temperature of cabinet air– time in the power failure period without PCM and with different PCMs.

The cabin air temperature reached 18.0℃ in 163 min. without PCM, in 482 min. with 4.0% NaCl - 1.0% CMC – 1.0% borax solution, in 332 min. with 4.0% NaCl - 1.0% CMC solution, in 323 min. with 4.0% NaCl - 1.0% CMC - 2.0% borax solution, in 298 min. with 4.0% NaCl - 0.5% CMC - 1.0% borax solution, in 716 min. with 4.0% NaCl - 1.5% CMC - 1.0% borax solution.

The results indicate that the integration of PCM into the domestic freezer could maintain the cabinet air temperature at certain temperature values for a longer time period. In comparison to the case of without PCM, integration of the 4.0% NaCl - 1.5% CMC - 1.0% borax solution has a considerable advantage by maintaining the cabinet air temperature at certain temperature values for a longer time period.

The evaluation of energy consumption for running periods of 4 hours and power failure values as in the case of without and with NaCl (4.0 wt.%)- CMC-borax solutions as PCMs can be seen in the Table 3.5.

Table 3.5. Energy consumption for running periods of 4 hours and power failure values in the case of without and with NaCl (4.0 wt.%)- CMC-borax solutions as PCMs.

PCM	Total Power Consumption (4h), (kJ)	Energy Saving (%)	Power Failure (min)
without PCM	40.22	-	163
4.0% NaCl – 1.0% CMC – 1.0% borax	26.72	-33.57	482
4.0% NaCl – 1.0% CMC	32.31	-19.64	332
4.0% NaCl – 1.0% CMC – 2.0% borax	35.07	-12.80	323
4.0% NaCl – 0.5% CMC – 1.0% borax	39.11	-2.76	298
4.0% NaCl – 1.5% CMC – 1.0% borax	23.69	-41.10	716

3.2.2 Effect of integrating 6.0 wt.% NaCl solution as PCM on the system performance

The experiments were carried out for 4 hours with different PCMs; 6.0% NaCl - 1.0% CMC - 1.0% borax solution, 6.0% NaCl - 1.5% CMC - 2.0% borax solution, 6.0% NaCl - 0.5% CMC solution, 6.0% NaCl - 0.5% CMC - 2.0% borax solution, 6.0% NaCl - 1.5% CMC solution.

Effect of PCM on the cabin air temperature

The cabin air temperature fluctuation with time in the cases of with different PCM solutions containing 6.0% NaCl is presented in Figures 3.40-3.44. All results are shown in Figure 3.45.

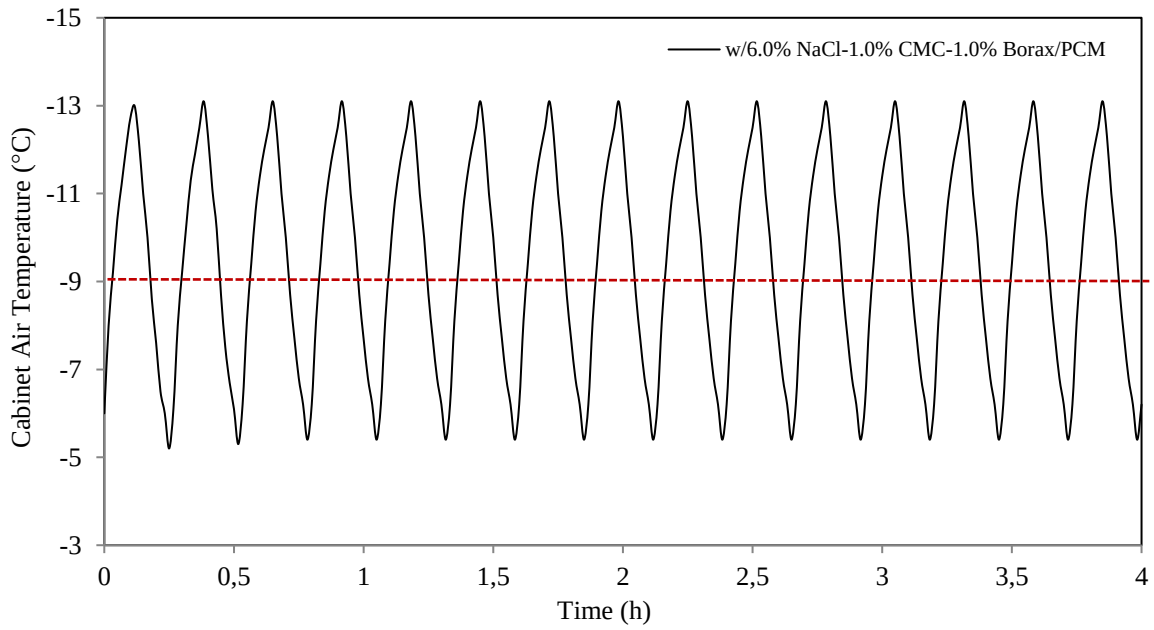

Figure 3.40 The profile of cabin air temperature in the case of with 6.0% NaCl - 1.0% CMC - 1.0% borax solution.

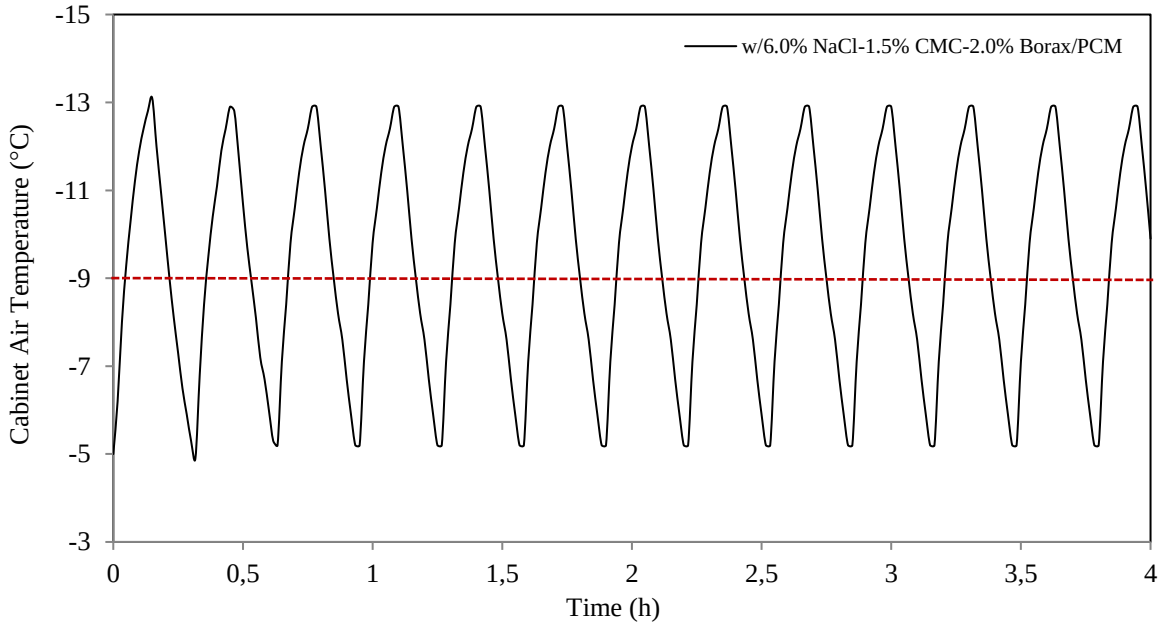

Figure 3.41 The profile of cabin air temperature in the case of with 6.0% NaCl – 1.5% CMC – 2.0% borax solution.

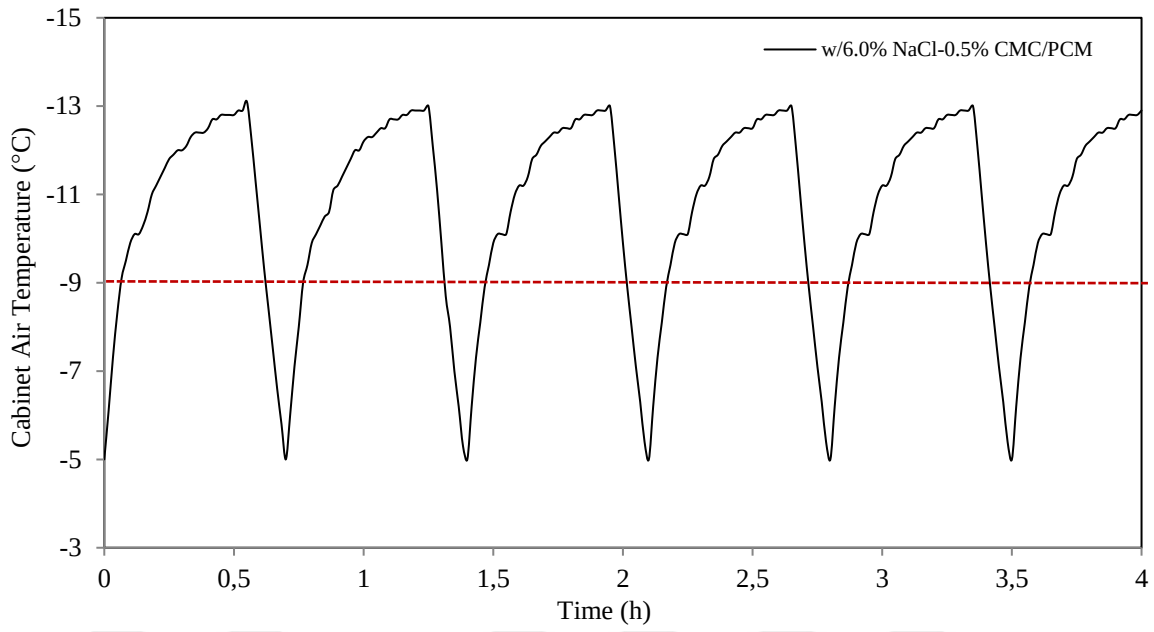

Figure 3.42 The profile of cabin air temperature in the case of with 6.0% NaCl – 0.5% CMC solution.

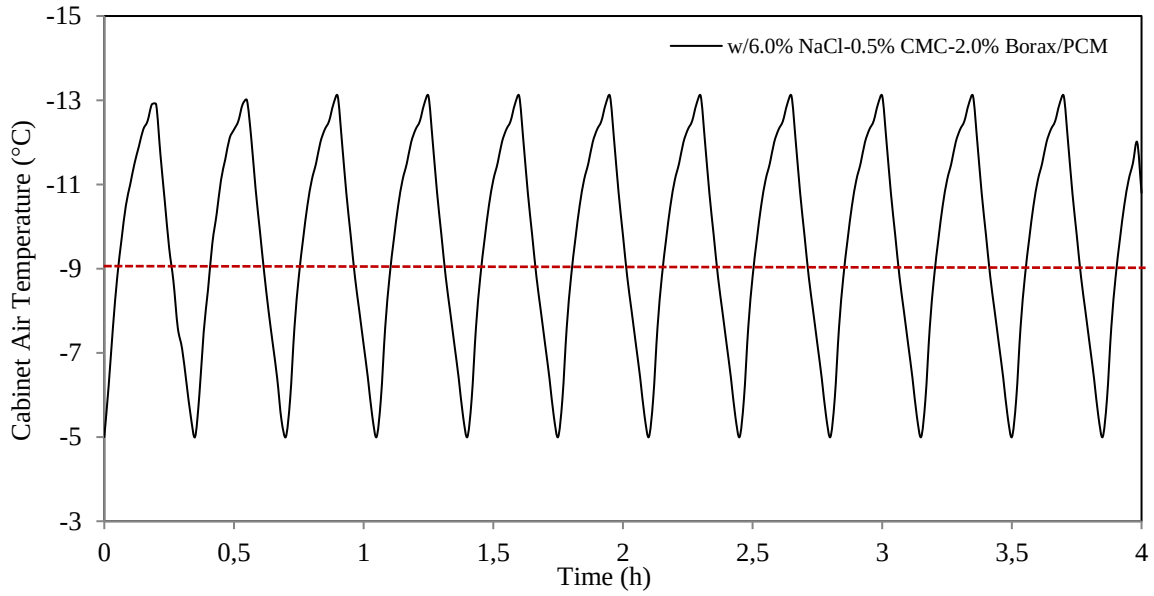

Figure 3.43 The profile of cabin air temperature in the case of with 6.0% NaCl - 0.5% CMC - 2.0% borax solution.

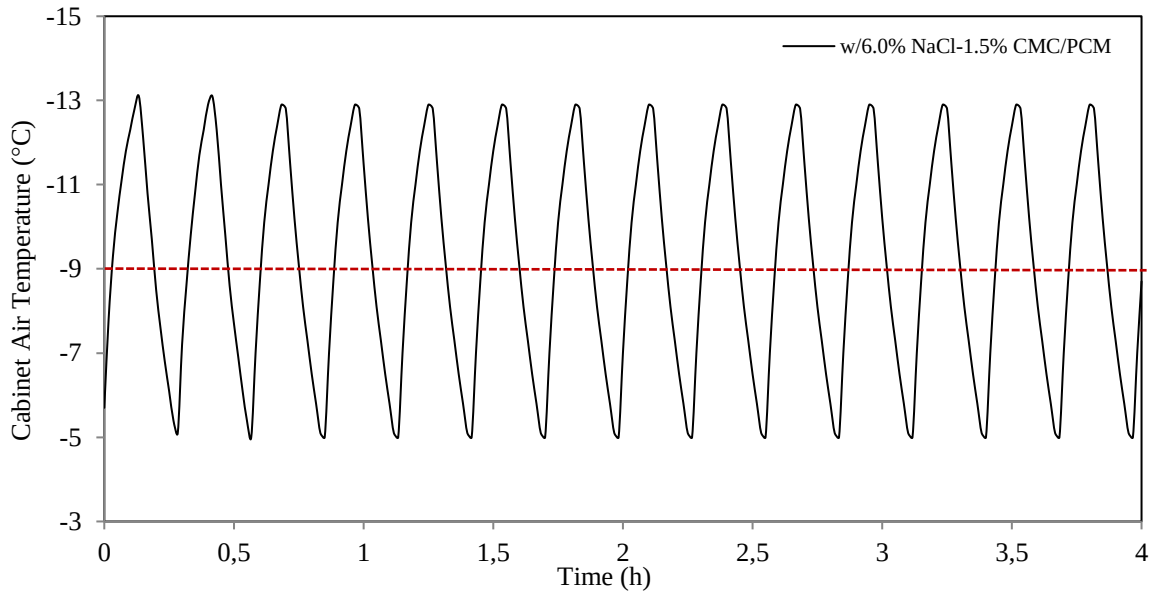

Figure 3.44 The profile of cabin air temperature in the case of with 6.0% NaCl - 1.5% CMC solution.

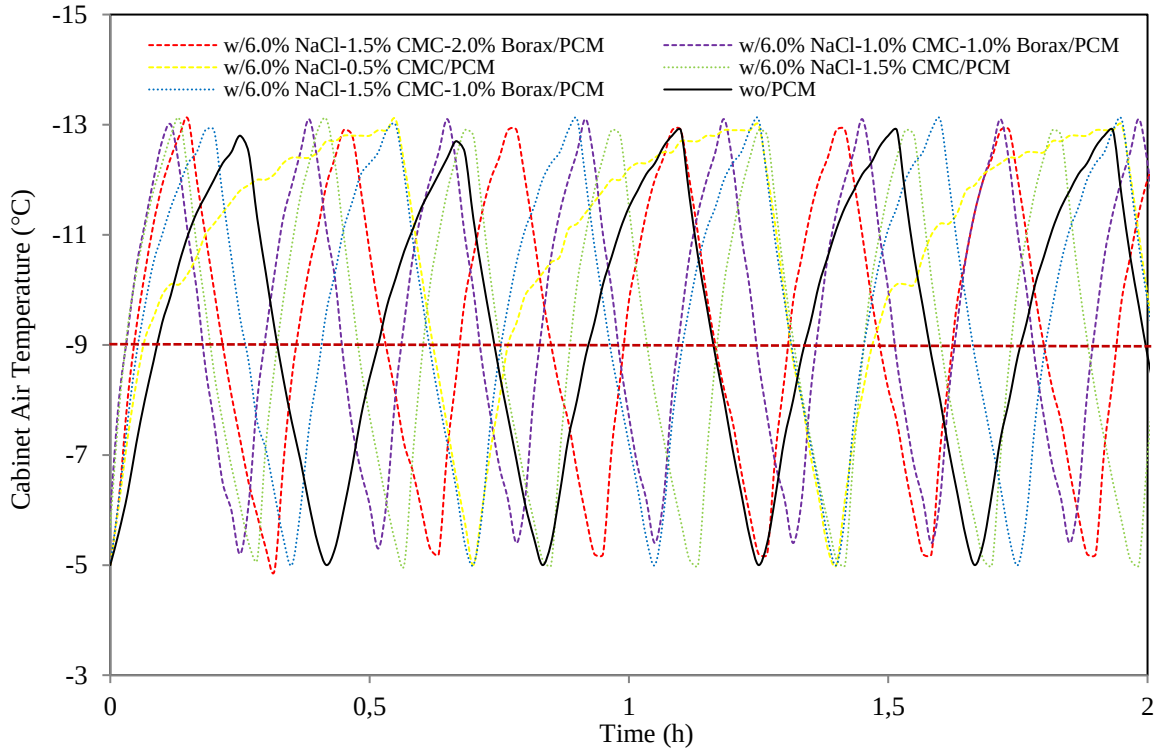

Figure 3.45 The profile of cabin air temperature in the case of without PCM and with different PCMs.

As seen in Figure 3.45, the cabin air temperature fluctuated within the range of -5°C to -13°C. The running time (%) was calculated with the Equation 2.1, using the data of the compressor on-time (t_{on}) and off-time (t_{off}) for 4 hours of a running period and the results can be seen in the Table 3.6.

Table 3.6 The compressor on-time (t_{on}) and off-time (t_{off}) values for running periods of 4 hours in the case of without and with NaCl (6.0 wt.%)- CMC-borax solutions as PCMs.

PCM	**Cycle Time $t_{on}+t_{off}$ (min)**	**Compressor on time, t_{on}(min)**	**Compressor off-time, t_{off} (min)**	**Running Time (%)**
without PCM	25	16	9	64.00
6.0% NaCl – 1.0% CMC – 1.0% borax	16	7	9	43.75
6.0% NaCl – 1.5% CMC – 2.0% borax	19	9	10	47.37
6.0% NaCl – 0.5% CMC	42	33	9	78.57
6.0% NaCl – 0.5% CMC – 2.0% borax	21	12	9	57.14
6.0% NaCl – 1.5% CMC	17	8	9	47.06

The running time (%) was calculated to be 64.00% without PCM, 43.75% with 6.0% NaCl – 1.0% CMC – 1.0% borax solution, 47.37% with 6.0% NaCl – 1.5% CMC – 2.0% borax solution, 78.57% with 6.0% NaCl – 0.5% CMC solution, 57.14% with 6.0% NaCl – 0.5% CMC – 2.0% borax solution, 47.06% with 6.0% NaCl – 1.5% CMC solution as PCM by using Equation 2.1.

Effect of PCM on the compressor power consumption

The power consumption variation over time in the case of without and with PCMs are presented in Figures 3.46-3.50. All results are shown in Figure 3.51.

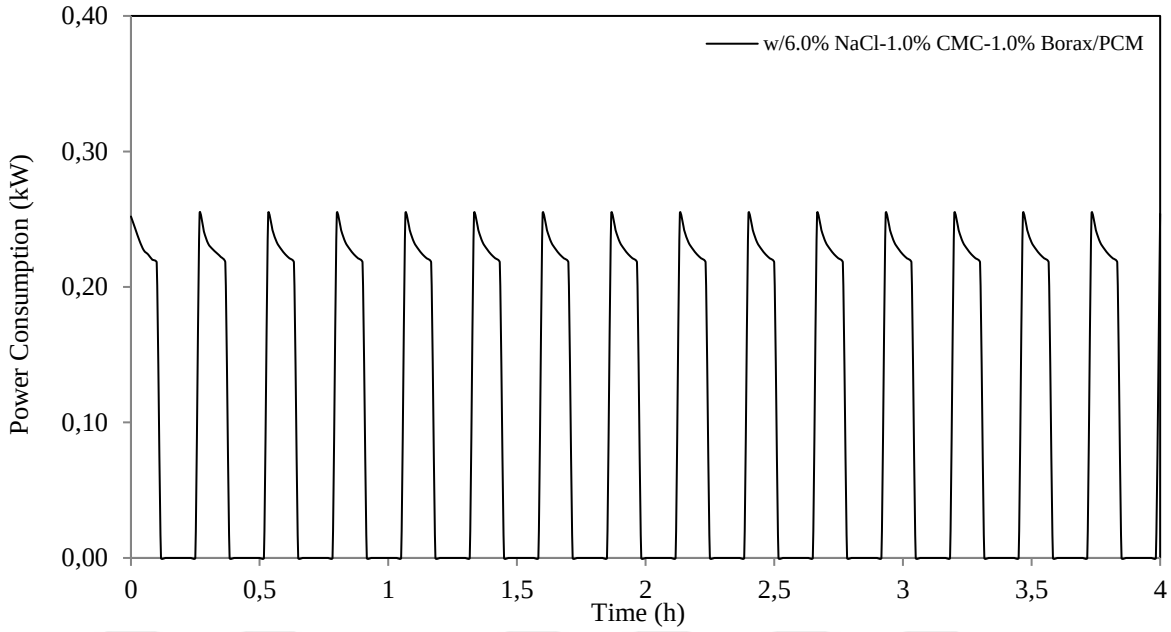

Figure 3.46 Compressor power consumption versus time in the case of with 6.0% NaCl - 1.0% CMC - 1.0% borax solution.

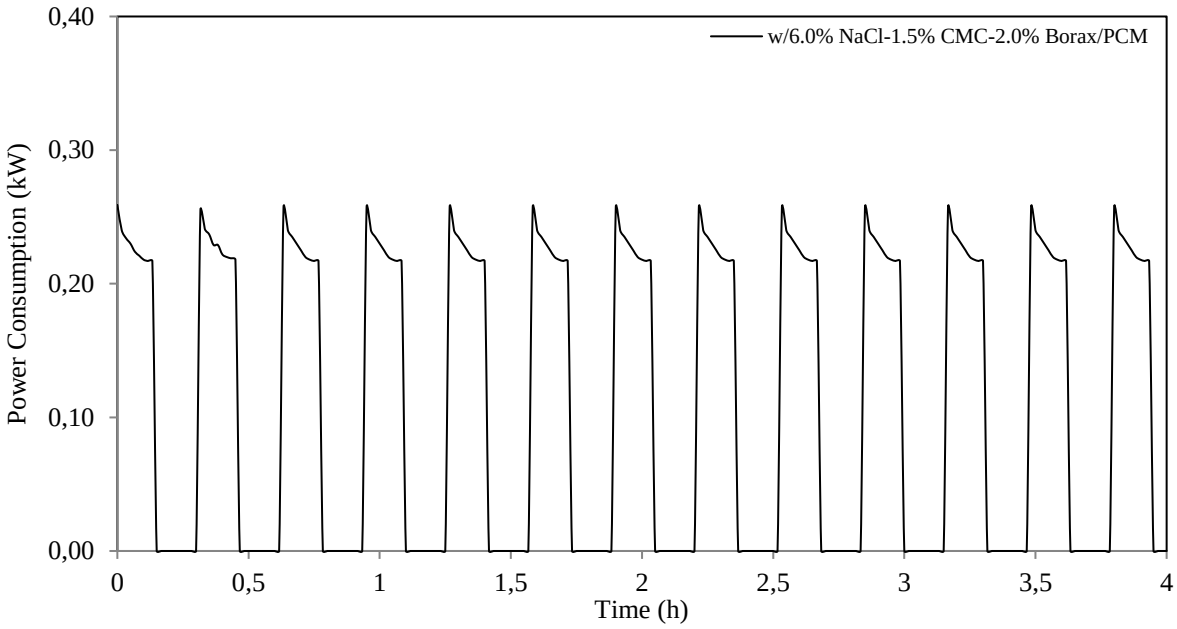

Figure 3.47 Compressor power consumption versus time in the case of with 6.0% NaCl - 1.5% CMC - 2.0% borax solution.

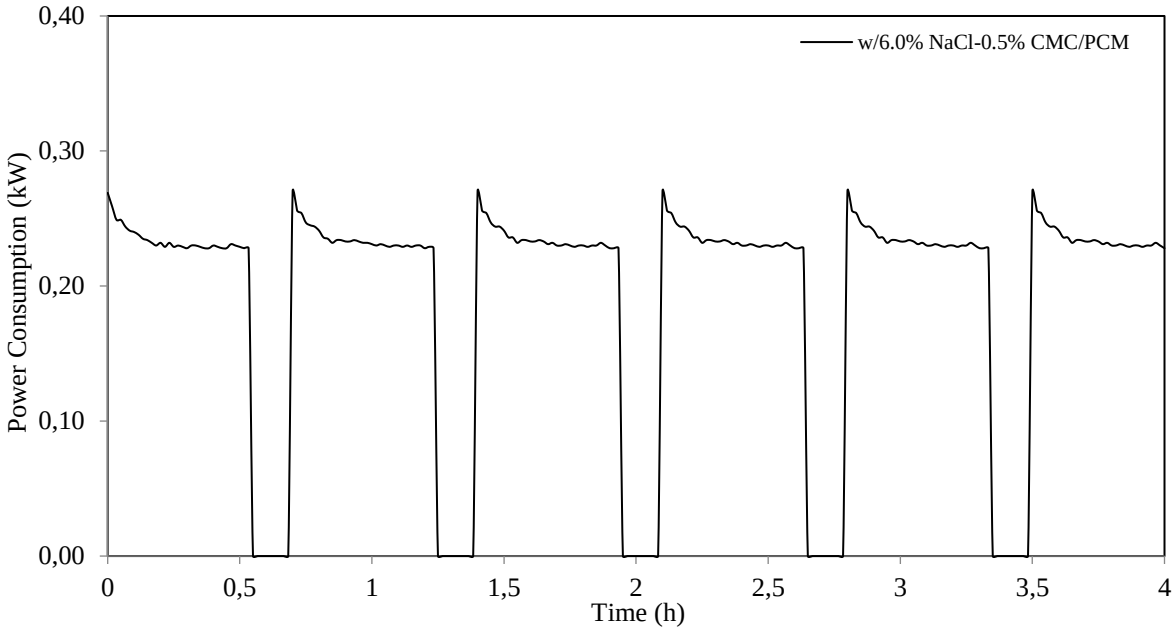

Figure 3.48 Compressor power consumption versus time in the case of with 6.0% NaCl – 0.5% CMC solution.

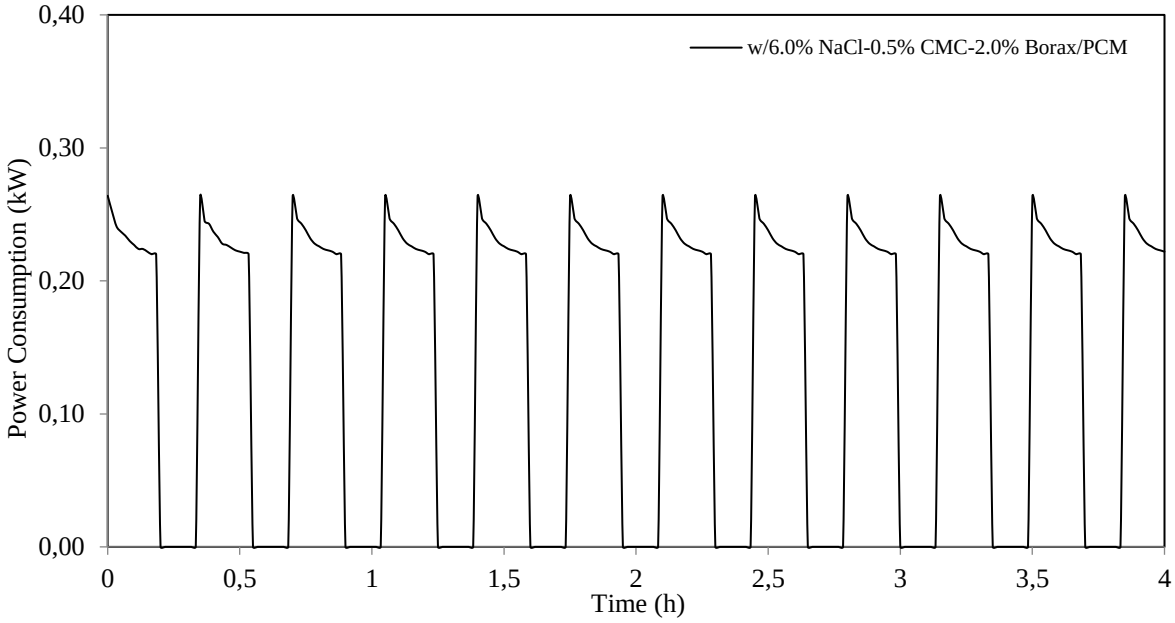

Figure 3.49 Compressor power consumption versus time in the case of with 6.0% NaCl - 0.5% CMC - 2.0% borax solution.

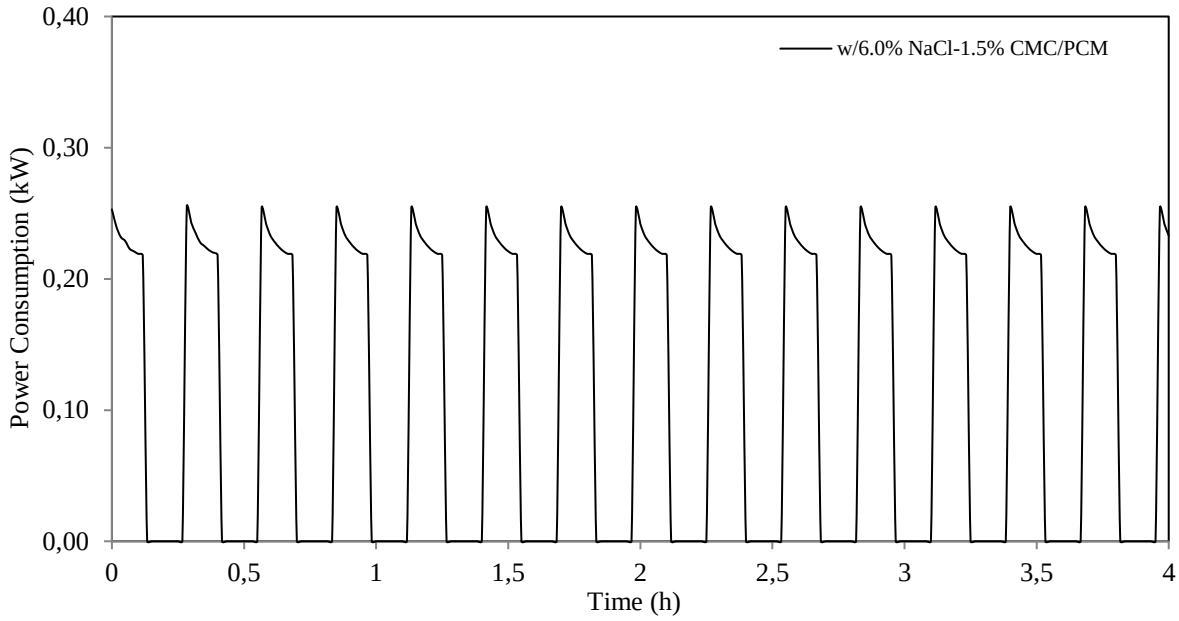

Figure 3.50 Compressor power consumption versus time in the case of with 6.0% NaCl - 1.5% CMC solution.

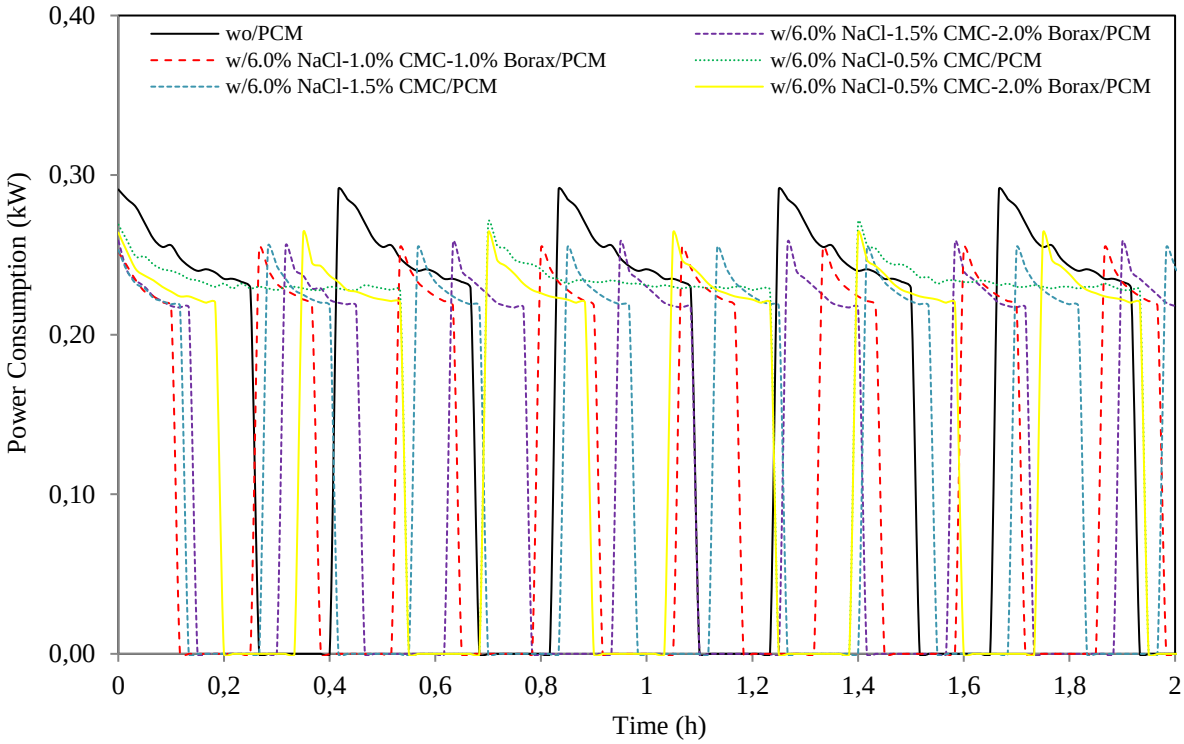

Figure 3.51 Compressor power consumption versus time in the case of without PCM and with different PCMs.

The total energy consumptions during the compressor running periods of 4 hours were calculated to be 40.22 kJ without PCM, 24.55 kJ with 6.0% NaCl - 1.0% CMC - 1.0% borax solution, 26.78 kJ with 6.0% NaCl - 1.5% CMC - 2.0% borax solution, 46.12 kJ with 6.0% NaCl - 0.5% CMC solution, 32.78 kJ with 6.0% NaCl - 0.5% CMC - 2.0% borax solution, 26.48 kJ with 6.0% NaCl – 1.5% CMC solution by using Equation 2.2.

The minimum and maximum power consumption values were measured as 0.229 kW and 0.292 kW without PCM, 0.218 kW and 0.254 kW with 6.0% NaCl - 1.0% CMC - 1.0% borax solution, 0.217 kW and 0.259 kW with 6.0% NaCl - 1.5% CMC - 2.0% borax solution, 0.228 kW and 0.270 kW with 6.0% NaCl - 0.5% CMC solution, 0.220 kW and 0.264 kW with 6.0% NaCl - 0.5% CMC - 2.0% borax solution, 0.218 kW and 0.255 kW with 6.0% NaCl – 1.5% CMC solution, respectively.

Effect of PCM on cabin air temperature during power failure period

The system was also tested during a power failure with these PCMs. The time required for reaching the cabin air temperature to the ambient temperature of 18°C was determined during a power failure. The cabin air temperature fluctuation with time in the cases of with different PCMs during a power failure period are represented in Figures 3.52-3.55. All results are shown in Figure 3.56.

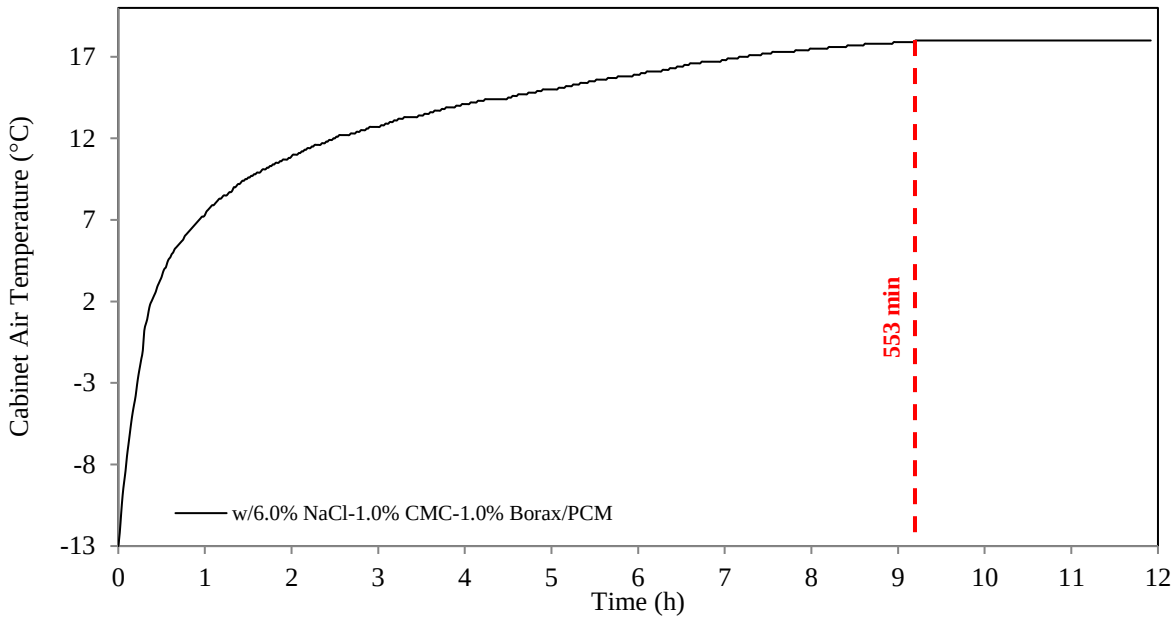

Figure 3.52 Temperature of cabinet air– time in the power failure period with 6.0% NaCl - 1.0% CMC - 1.0% borax solution.

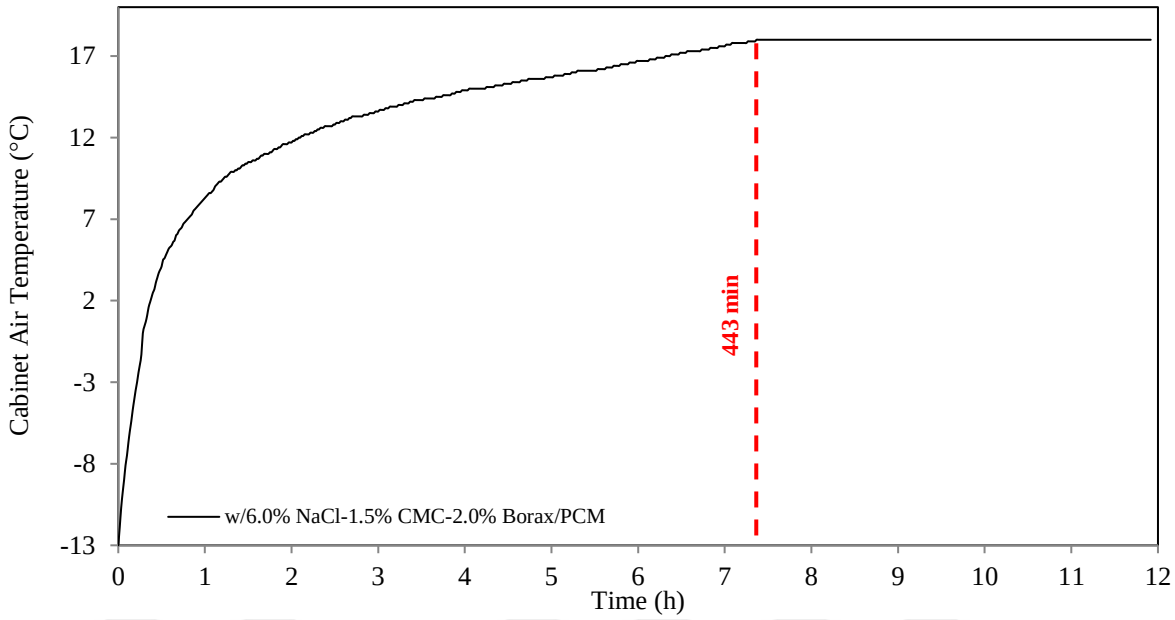

Figure 3.53 Temperature of cabinet air– time in the power failure period with 6.0% NaCl – 1.5% CMC – 2.0% borax solution.

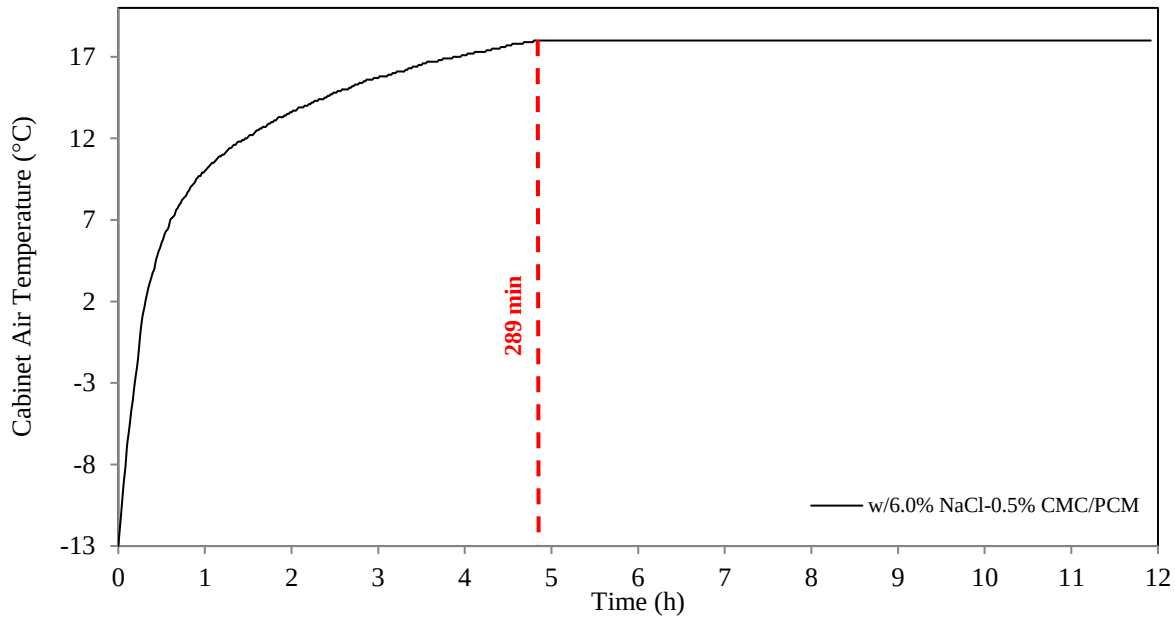

Figure 3.54 Temperature of cabinet air– time in the power failure period with 6.0% NaCl – 0.5% CMC solution.

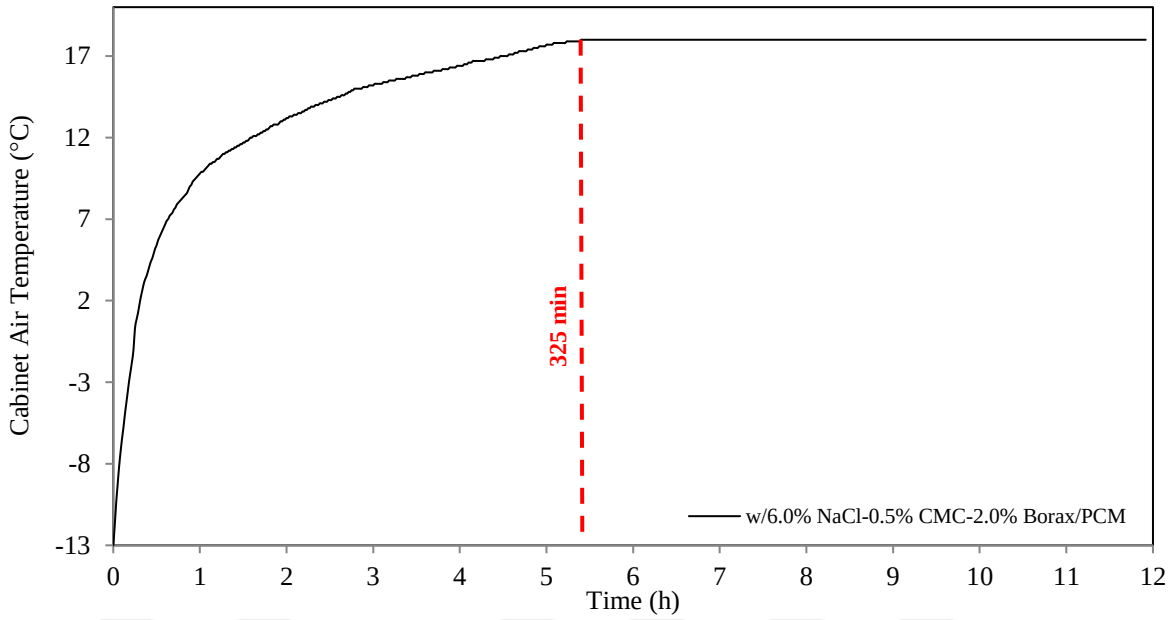

Figure 3.55 Temperature of cabinet air– time in the power failure period with 6.0% NaCl - 0.5 % CMC - 2.0% borax solution.

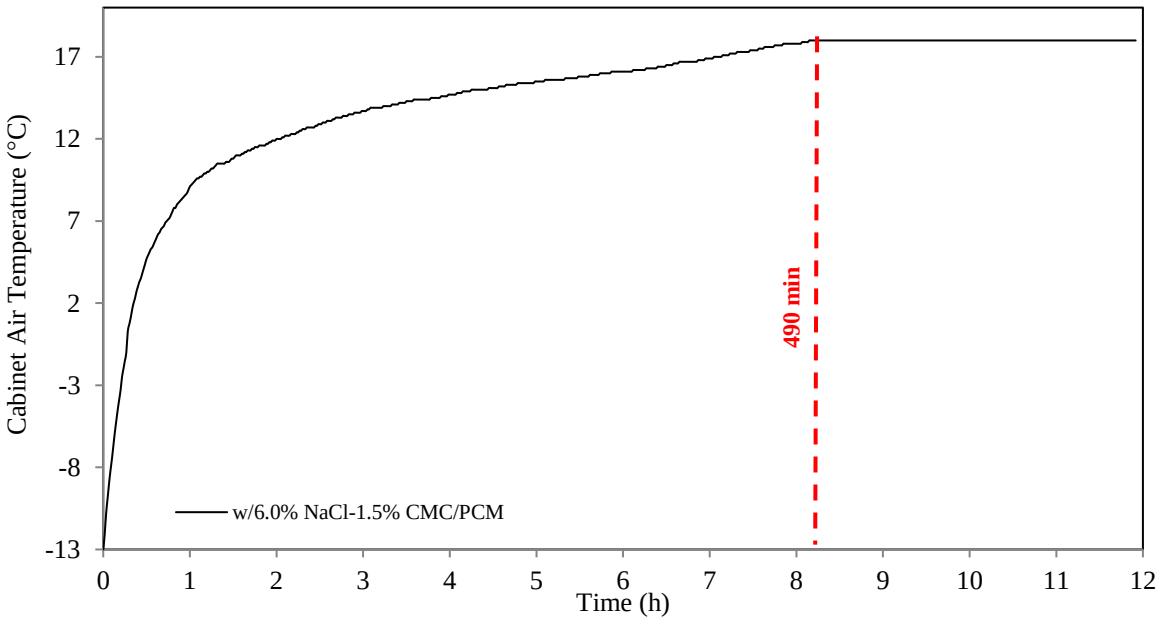

Figure 3.56 Temperature of cabinet air– time in the power failure period with 6.0% NaCl – 1.5% CMC solution.

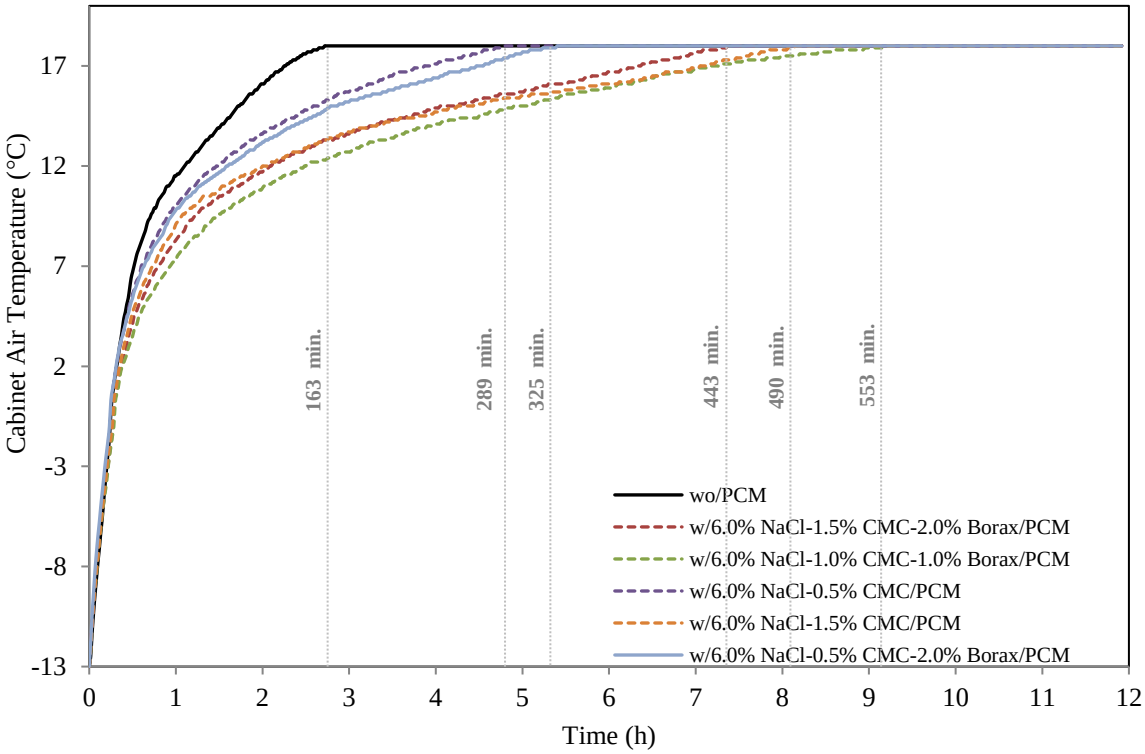

Figure 3.57 Temperature of cabinet air– time in the power failure period without PCM and with different PCMs.

The cabin air temperature reached 18.0°C in 163 min. without PCM, in 553 min. with 6.0% NaCl - 1.0% CMC - 1.0% borax solution, in 443 min. with 6.0% NaCl – 1.5% CMC – 2.0% borax solution, in 289 min. with 6.0% NaCl - 0.5% CMC solution, in 325 min. with 6.0% NaCl - 0.5% CMC - 2.0% borax solution, in 490 min. with 6.0% NaCl – 1.5% CMC solution.

The evaluation of energy consumption for running periods of 4 hours and power failure values as in the case of without and with NaCl (6.0 wt.%)- CMC-borax solutions as PCMs can be seen in the Table 3.7.

Table 3.7. Energy consumption for running periods of 4 hours and power failure values in the case of without and with NaCl (6.0 wt.%)- CMC-borax solutions as PCMs.

PCM	Total Power Consumption (4h), (kJ)	Energy Saving (%)	Power Failure (min)
without PCM	40.22	-	163
6.0% NaCl – 1.0% CMC – 1.0% borax	24.55	-38.96	553
6.0% NaCl – 1.5% CMC – 2.0% borax	26.78	-33.41	443
6.0% NaCl – 0.5% CMC	46.12	14.66	289
6.0% NaCl – 0.5% CMC – 2.0% borax	32.78	-18.49	325
6.0% NaCl – 1.5% CMC	26.48	-34.16	490

3.2.3 Effect of integrating 8.0 wt.% NaCl solution as PCM on the system performance

The experiments were carried out for 4 hours by integrating different PCMs; 8.0% NaCl - 0.5% CMC - 1.0% borax solution, 8.0% NaCl - 1.0% CMC solution, 8.0% NaCl – 1.5% CMC - 1.0% borax solution, 8.0% NaCl - 1.0% CMC - 2.0% borax solution.

Effect of PCM on the cabin air temperature

The cabin air temperature fluctuation with time in the cases of with different PCM solutions containing 8.0% NaCl are presented in Figures 3.58-3.61. All results are shown in Figure 3.62.

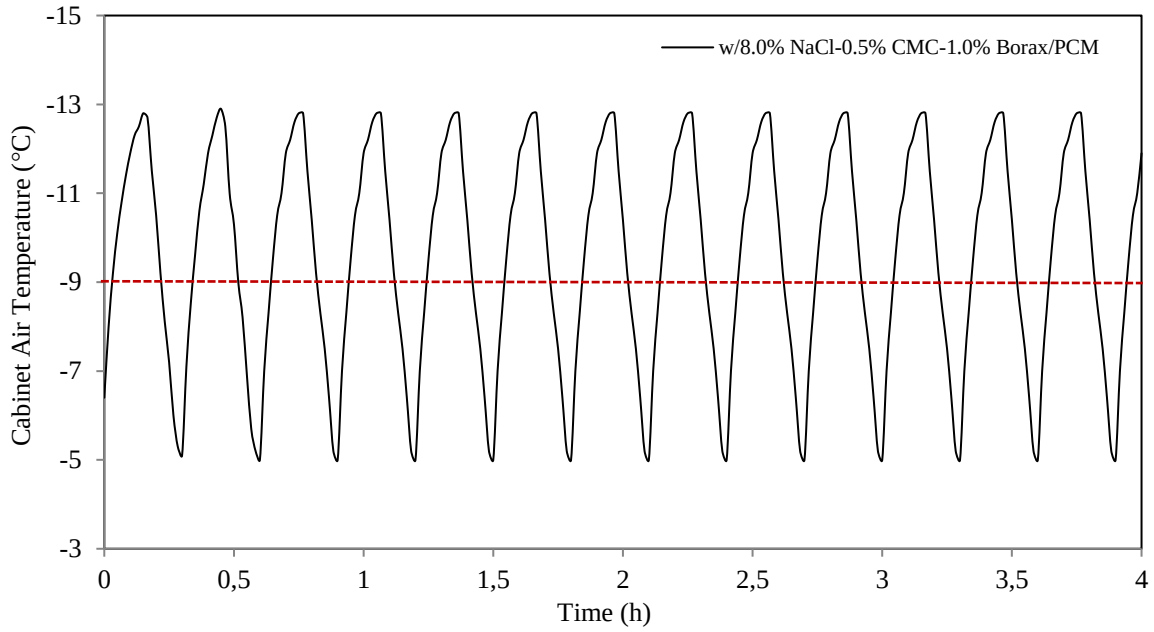

Figure 3.58 The profile of cabin air temperature in the case of with 8.0% NaCl - 0.5% CMC - 1.0% borax solution.

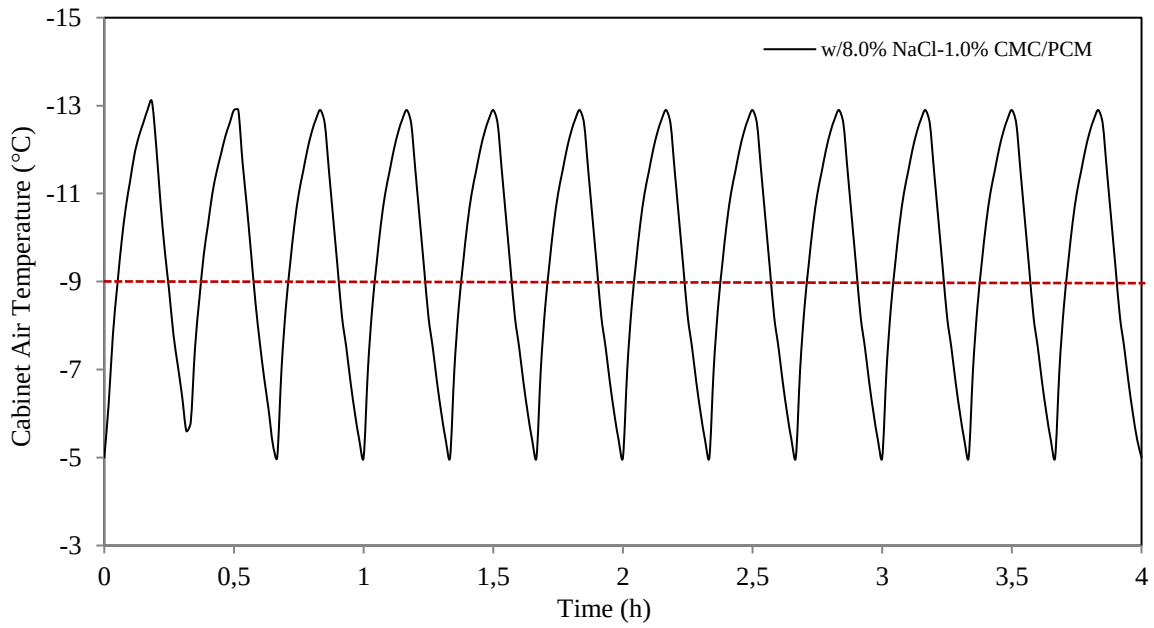

Figure 3.59 The profile of cabin air temperature in the case of with 8.0% NaCl - 1.0% CMC solution.

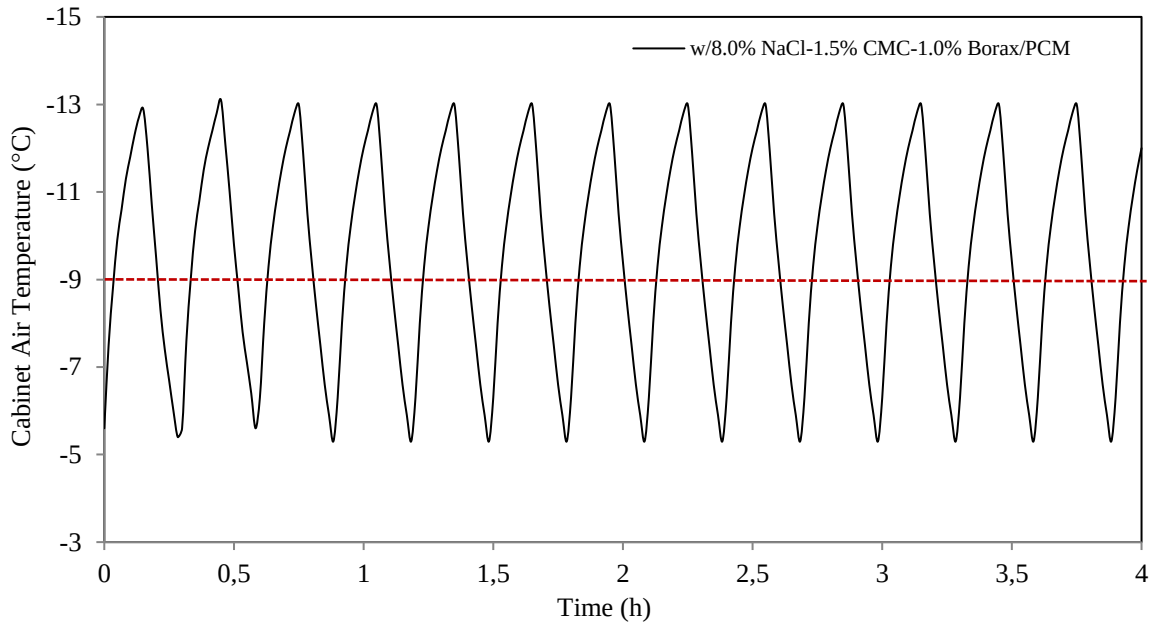

Figure 3.60 The profile of cabin air temperature in the case of with 8.0% NaCl - 1.5% CMC - 1.0% borax solution.

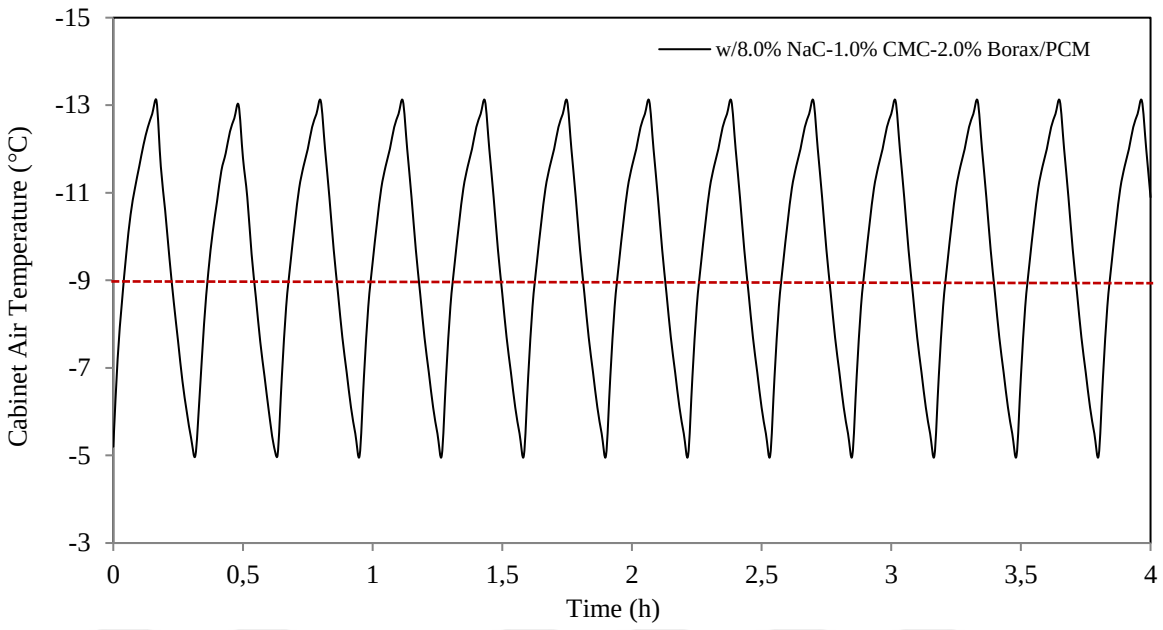

Figure 3.61 The profile of cabin air temperature in the case of with 8.0% NaCl – 1.0% CMC – 2.0% borax solution.

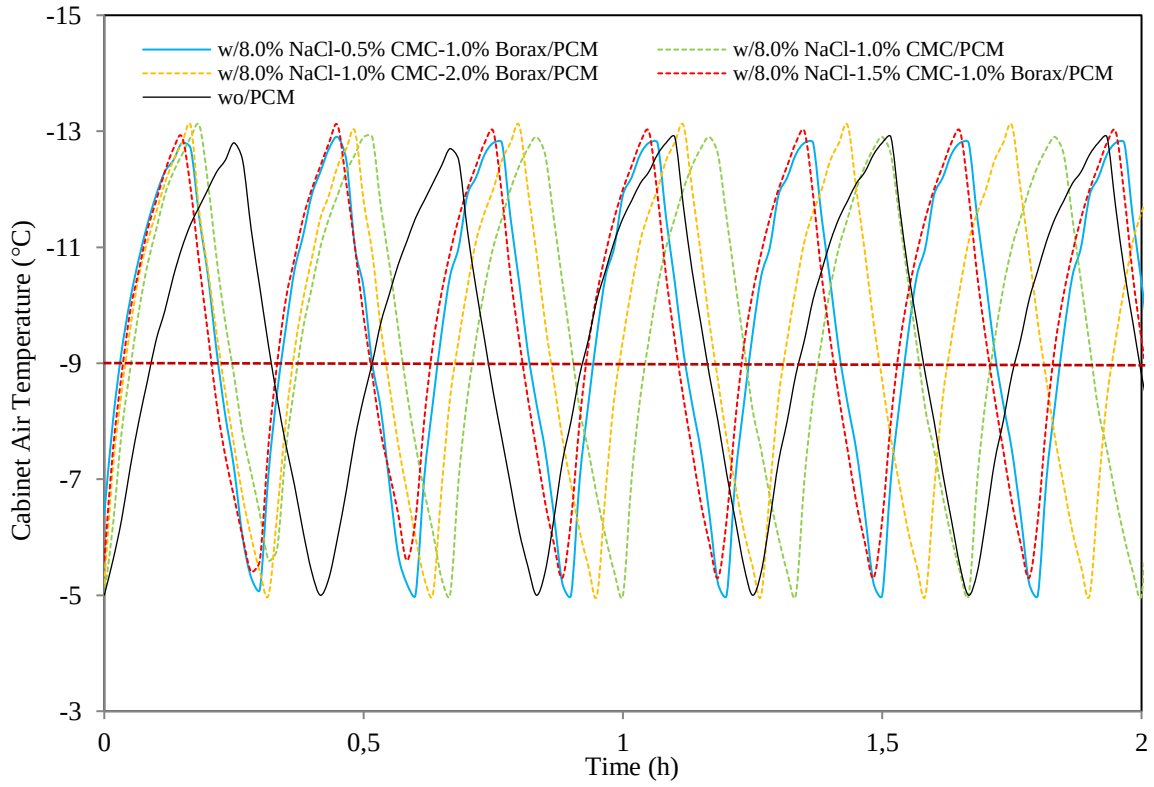

Figure 3.62 The profile of cabin air temperature in the case of without PCM and with different PCMs.

As seen in Figure 3.62, the cabin air temperature fluctuated within the range of -5°C to -13°C. The running time (%) was calculated with the Equation 2.1, using the data of the compressor on-time (t_{on}) and off-time (t_{off}) for 4 hours of a running period and the results can be seen in the Table 3.8.

Table 3.8 The compressor on-time (t_{on}) and off-time (t_{off}) values for running periods of 4 hours in the case of without and with NaCl (8.0 wt.%)- CMC-borax solutions as PCMs.

PCM	**Cycle Time $t_{on}+t_{off}$ (min)**	**Compressor on time, t_{on}(min)**	**Compressor off-time, t_{off} (min)**	**Running Time (%)**
without PCM	25	16	9	64.00
8.0% NaCl – 0.5% CMC – 1.0% borax	18	10	8	55.56
8.0% NaCl – 1.0% CMC	20	11	9	55.00
8.0% NaCl – 1.5% CMC – 1.0% borax	18	9	9	50.00
8.0% NaCl – 1.0% CMC – 2.0% borax	19	10	9	52.63

The running time (%) was calculated to be 64.00% without PCM, 55.56% with 8.0% NaCl – 0.5% CMC – 1.0% borax solution, 55.00% with 8.0% NaCl – 1.0% CMC solution, 50.00% with 8.0% NaCl – 1.5% CMC – 1.0% borax solution, 52.63% with 8.0% NaCl – 1.0% CMC – 2.0% borax solution as PCM by using Equation 2.1.

Effect of PCM on the compressor power consumption

The power consumption variation over time in the cases of with different PCMs are presented in Figures 3.63-3.66. All results are shown in Figure 3.67.

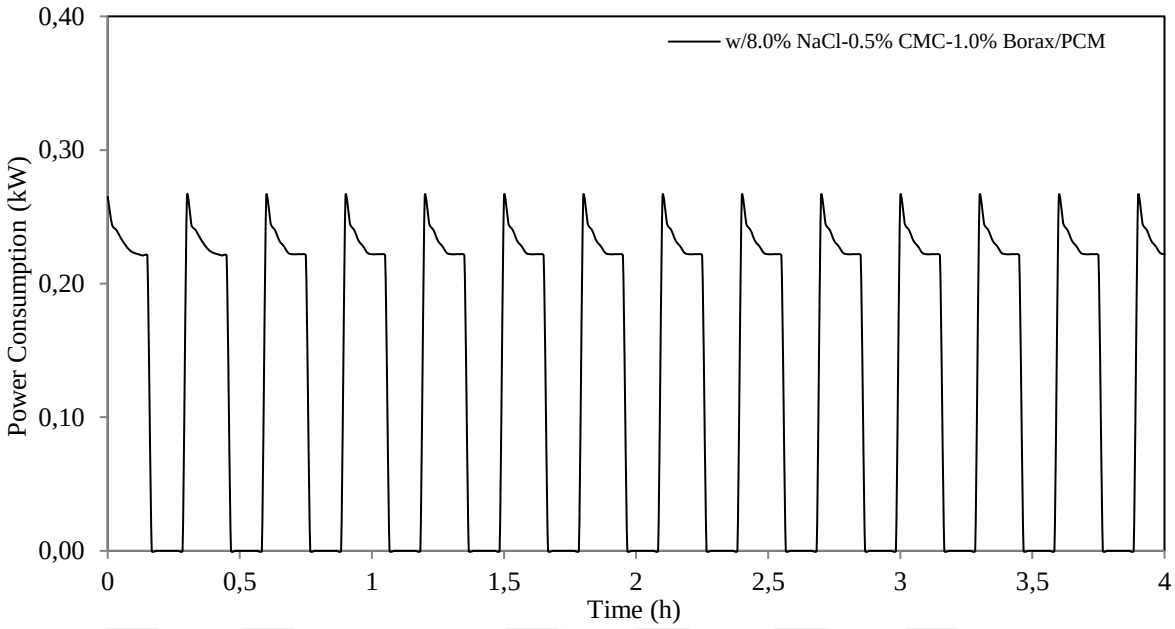

Figure 3.63 Compressor power consumption versus time in the case of with 8.0% NaCl - 0.5% CMC - 1.0% borax solution.

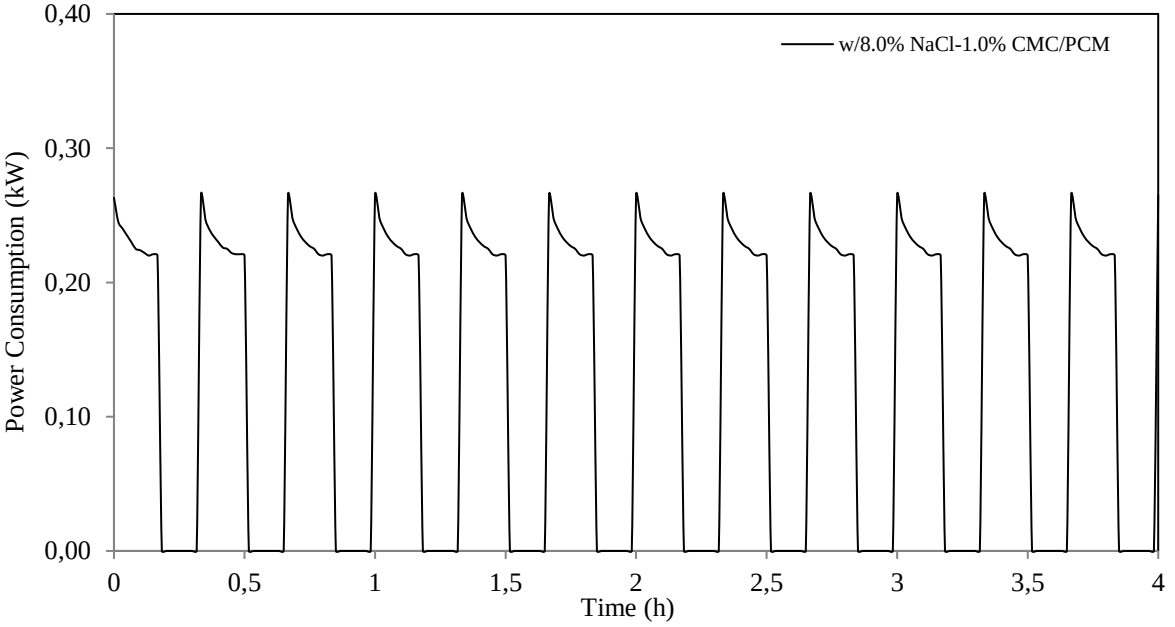

Figure 3.64 Compressor power consumption versus time in the case of with 8.0% NaCl - 1.0% CMC solution.

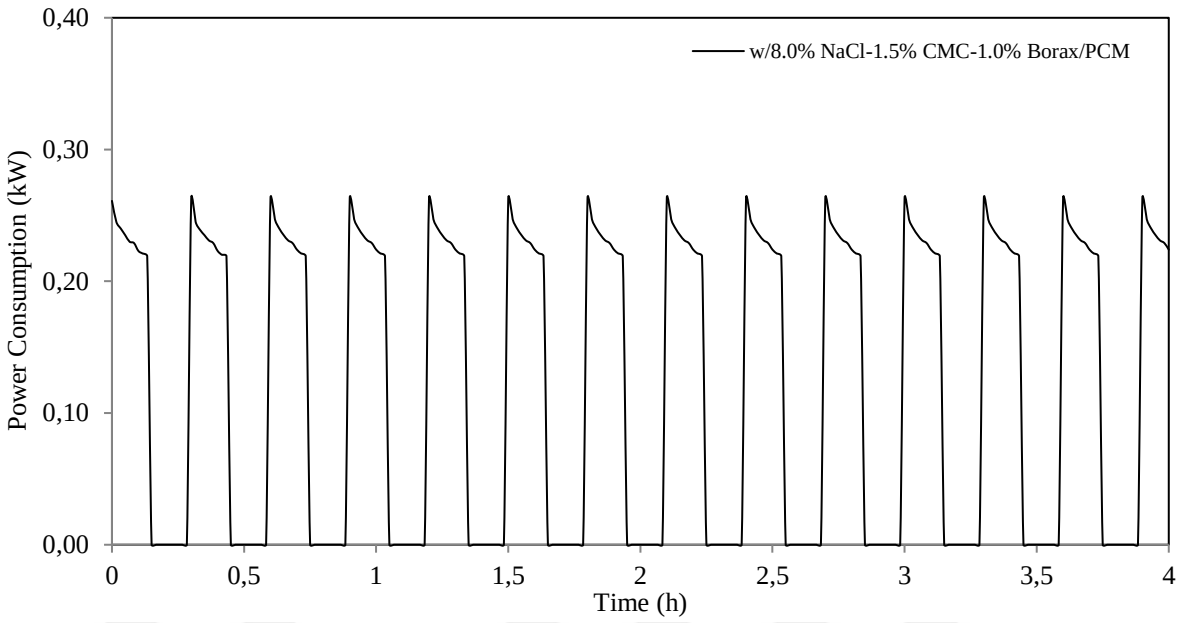

Figure 3.65 Compressor power consumption versus time in the case of with 8.0% NaCl - 1.5% CMC - 1.0% borax solution.

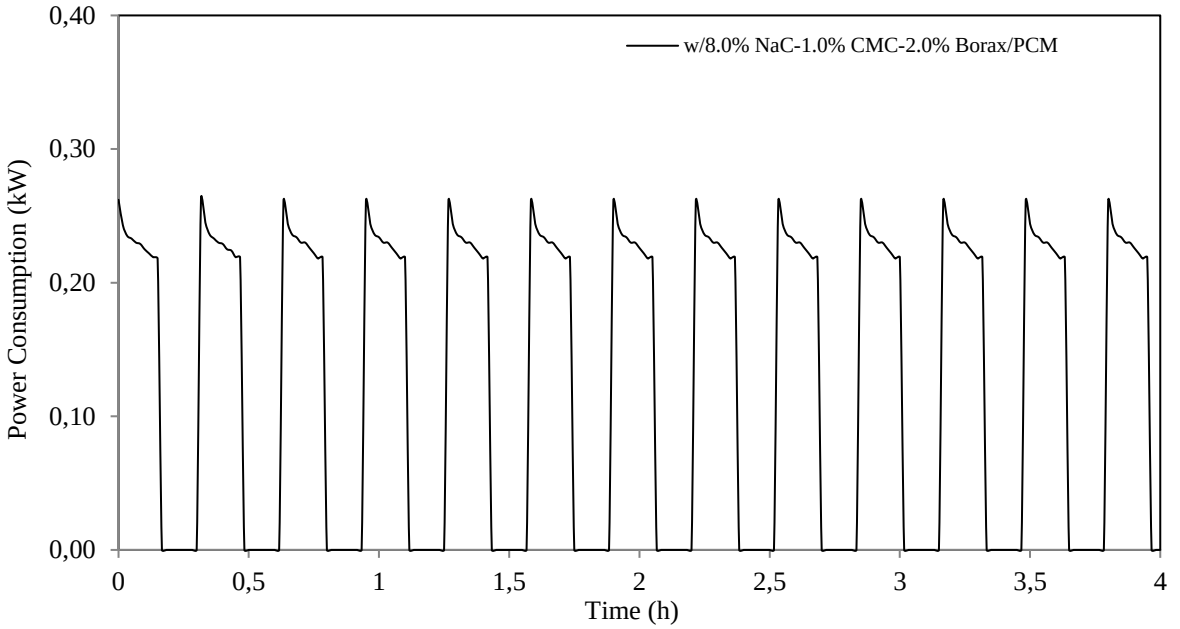

Figure 3.66 Compressor power consumption versus time in the case of with 8.0% NaCl – 1.0% CMC – 2.0% borax solution.

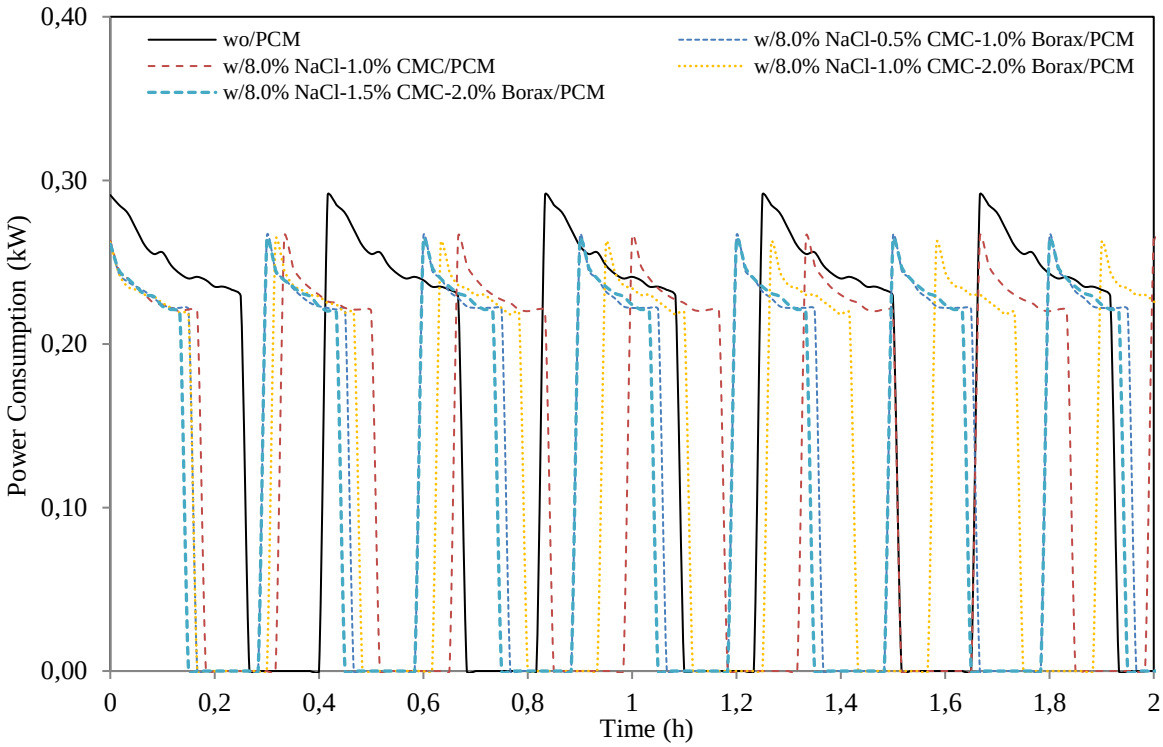

Figure 3.67 Compressor power consumption versus time in the case of without PCM and with different PCMs.

The total energy consumptions during the compressor running periods of 4 hours were calculated to be 40.22 kJ without PCM, 31.60 kJ with 8.0% NaCl - 0.5% CMC - 1.0% borax solution, 30.87 kJ with 8.0% NaCl - 1.0% CMC solution, 29.08 kJ with 8.0% NaCl - 1.5% CMC - 1.0% borax solution, 30.16 kJ with 8.0% NaCl – 1.0% CMC – 2.0% borax solution by using Equation 2.2.

The minimum and maximum power consumption values were measured as 0.229 kW and 0.292 kW without PCM, 0.221 kW and 0.265 kW with 8.0% NaCl - 0.5% CMC - 1.0% borax solution, 0.220 kW and 0.265 kW with 8.0% NaCl - 1.0% CMC solution, 0.219 kW and 0.263 kW with 8.0% NaCl - 1.5% CMC - 1.0% borax solution, 0.218 kW and 0.263 kW with 8.0% NaCl – 1.0% CMC – 2.0% borax solution.

Effect of PCM on cabin air temperature during power failure period

The system was also tested during a power failure with different PCM solutions containing 8.0% NaCl. The time required for reaching the cabin air temperature to the ambient temperature of 18°C was determined during a power failure. The cabin air temperature fluctuation with time

in the cases of with different PCMs during a power failure period are represented in Figures 3.68-3.71. All results are shown in Figure 3.72.

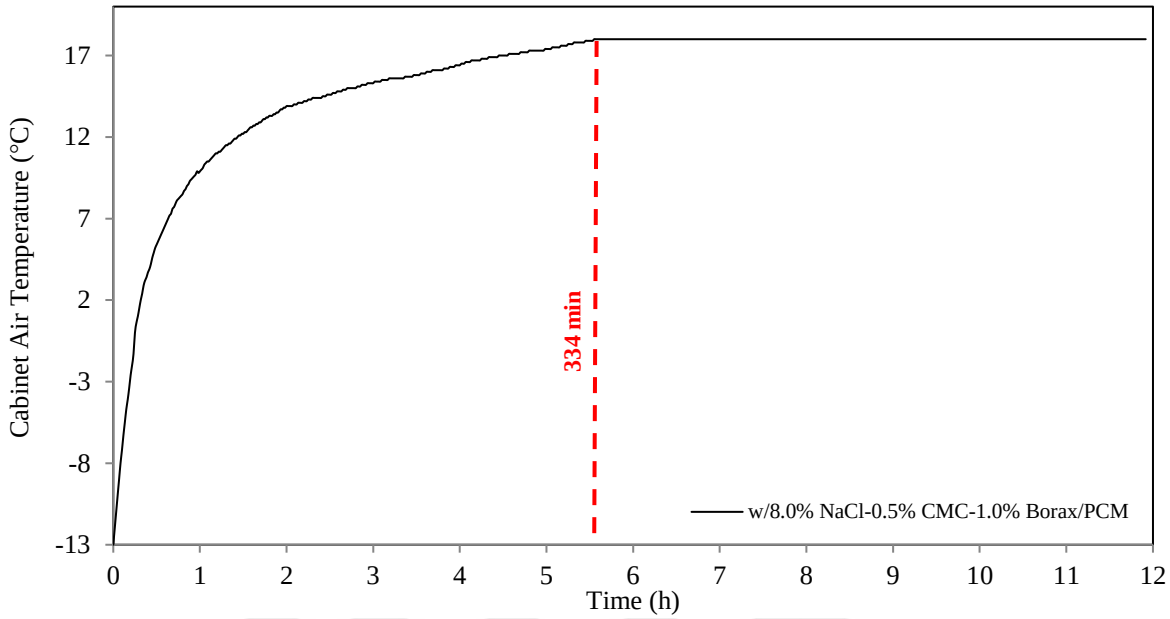

Figure 3.68 Temperature of cabinet air– time in the power failure period with 8.0% NaCl - 0.5% CMC - 1.0% borax solution.

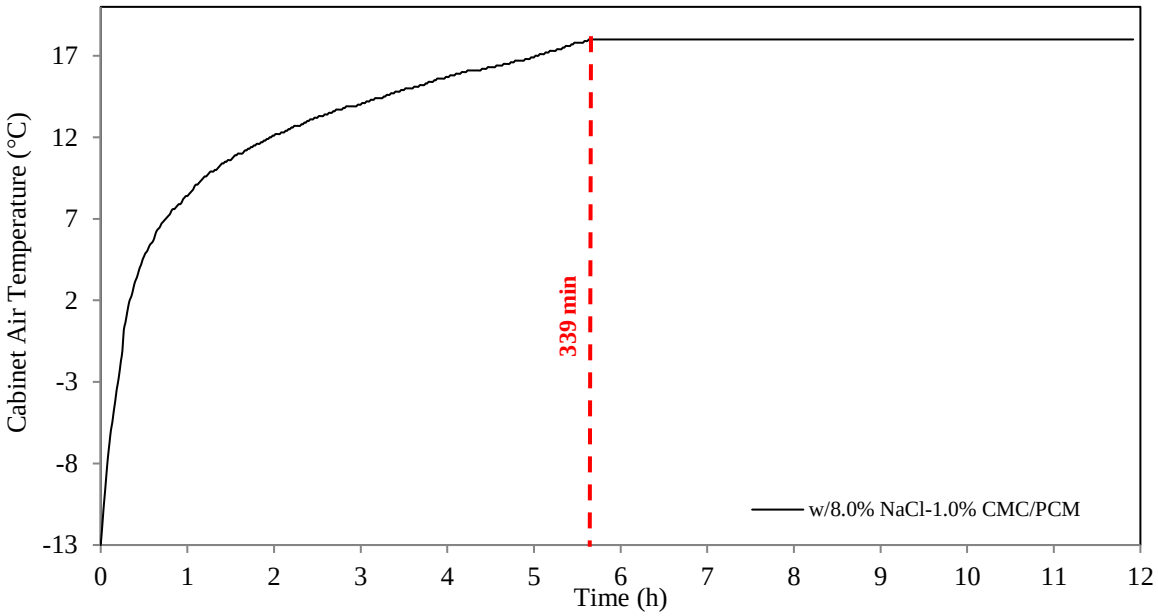

Figure 3.69 Temperature of cabinet air– time in the power failure period with 8.0% NaCl - 1.0% CMC solution.

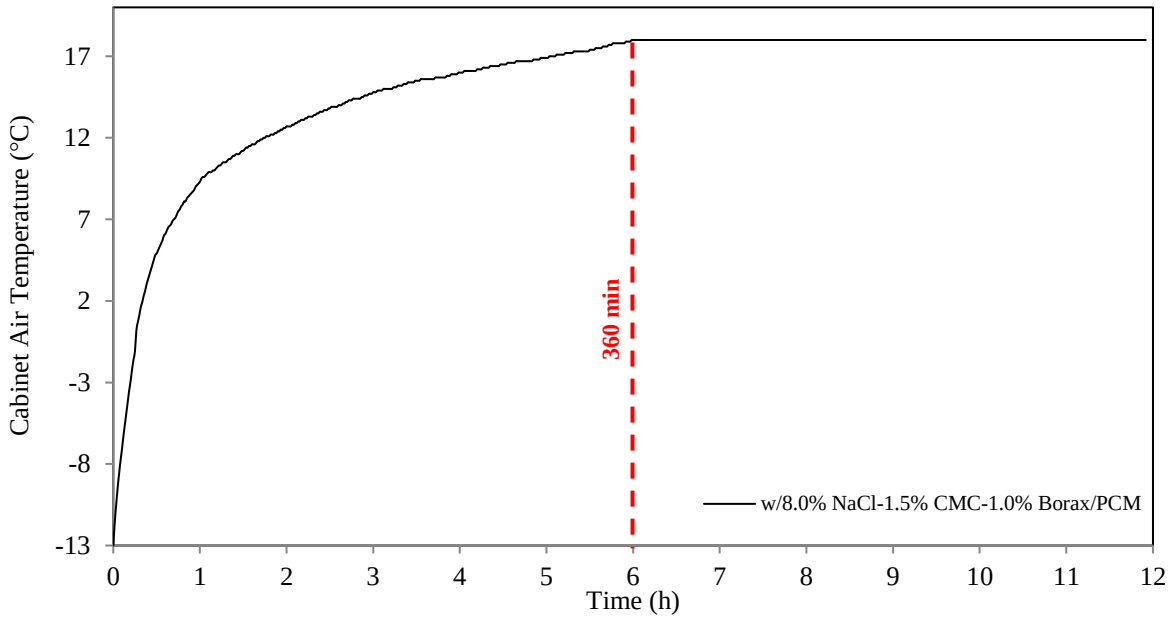

Figure 3.70 Temperature of cabinet air– time in the power failure period with 8.0% NaCl - 1.5% CMC - 1.0% borax solution.

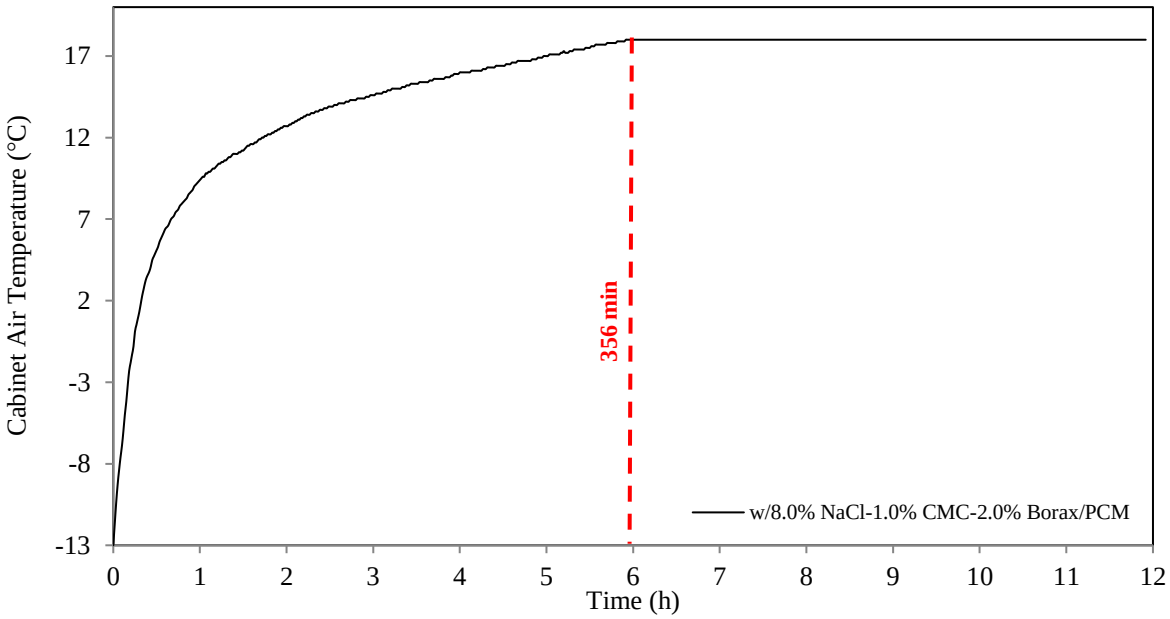

Figure 3.71 Temperature of cabinet air – time in the power failure period with 8.0% NaCl - 1.0% CMC - 2 wt.% borax solution.

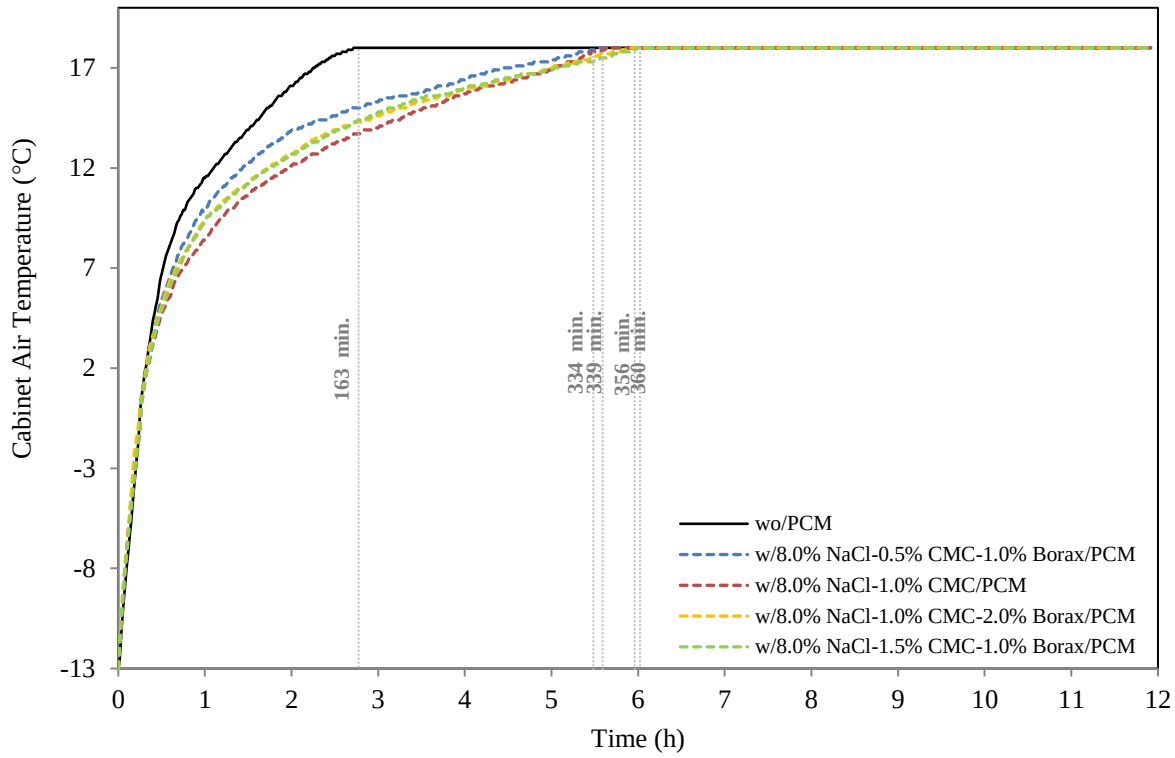

Figure 3.72 Temperature of cabinet air – time in the power failure period with and without PCMs.

The cabin air temperature reached 18.0°C in 163 min. without PCM, in 334 min. with 8.0% NaCl - 0.5% CMC - 1.0% borax solution, in 339 min. with 8.0% NaCl - 1.0% CMC solution, in 360 min. with 8.0% NaCl - 1.5% CMC - 1.0% borax solution, in 356 min. with 8.0% NaCl – 1.0% CMC – 2.0% borax solution.

The evaluation of energy consumption for running periods of 4 hours and power failure values as in the case of without and with NaCl (8.0 wt.%)- CMC-borax solutions as PCMs can be seen in the Table 3.9.

Table 3.9. Energy consumption for running periods of 4 hours and power failure values in the case of without and with NaCl (8.0 wt.%)- CMC-borax solutions as PCMs.

PCM	Total Power Consumption (4h), (kJ)	Energy Saving (%)	Power Failure (min)
without PCM	40.22	-	163
8.0% NaCl – 0.5% CMC – 1.0% borax	31.60	-21.43	334
8.0% NaCl – 1.0% CMC	30.87	-23.24	339
8.0% NaCl – 1.5% CMC – 1.0% borax	29.08	-27.69	360
8.0% NaCl – 1.0% CMC – 2.0% borax	30.16	-25.01	356

3.3 Statistical analysis

The models were tested statistically by ANOVA. The results are given in Table 3.10. As seen in **Table 3.10**, the probability value was determined to be lower than 0.05 (p value < 0.05). This result implements that the model is statistically significant.

Table 3.10 ANOVA results of quadratic model for compressor running time (%).

Source	Sum of Squares	df	Mean square	F-value	p-value
Model	1593.69	9	177.08	15.46	0.0008
A-NaCl Concentration	36.04	1	36.04	3.15	0.1194
B-CMC Concentration	698.07	1	698.07	60.95	0.0001
C- Borax Concentration	42.64	1	42.64	3.72	0.0950
AB	124.66	1	124.66	10.88	0.0131
AC	13.65	1	13.65	1.19	0.3111
BC	118.16	1	118.16	10.32	0.0148
A^2	96.10	1	96.10	8.39	0.0231
B^2	146.07	1	146.07	12.75	0.0091
C^2	262.45	1	262.45	22.91	0.0020
Residual	80.17	7	11.45		
Lack of Fit	80.17	3	26.72		
R^2	0.9521				

The models fitted to the experimental data with a coefficient of determination R^2 of 0.9521. The sample variation of more than 95.21 % is attributed to the independent variables, while the model is unable to define for approximately 4.79% of the total variance.

The model equation was developed to establish the relationship between the running time (%) and three parameters (concentrations of NaCl, CMC and Borax) (see Equation 3.1).

$$Y_{running\ time} = 184.38 - 20.05A - 110.17B - 23.43C - 5.58AB - 0.92AC - 10.87BC - 1.19A^2 - 23.56B^2 - 7.90C^2 \quad (3.1)$$

The increase in **negative values** results in decrease in the running time percentage. ANOVA results of the quadratic model for running time were listed in Table 3.6.

3.3.1 Mutual interactions between the significant factors

The correlations of the running time (%) with the interaction effect of two variables while the third variable is at a constant level are represented in **Figure 3.73 (**the variables are the concentrations of NaCl (weight %), CMC (weight %), and borax (weight %)). In **Figure 3.73**, a circular contour plot shows a negligible effect while an elliptical contour plot shows a prominent interaction (Fu et al., 2007).

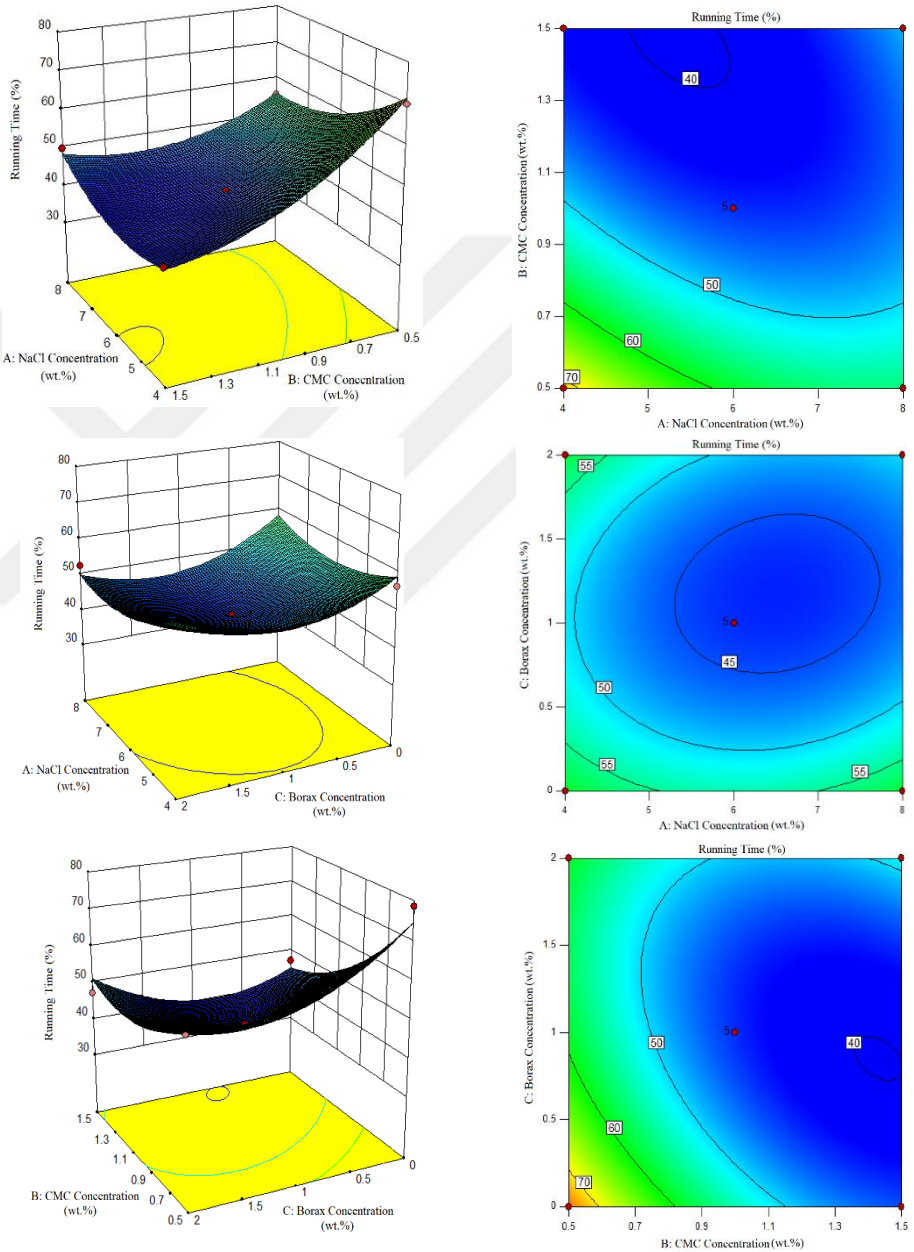

Figure 3.73 Surface and contour plots showing the effect of (a) NaCl concentration and CMC concentration, (b) NaCl concentration and borax concentration, (c) CMC concentration and borax concentration on the running time (%).

4.CONCLUSIONS

Performance of a cooling system, simulating a freezer operating between -13°C and -5°C, was examined without PCM and with different PCMs. NaCl solutions with borax and carboxymethyl cellulose (CMC) as nucleating and thickening agents, respectively were prepared as PCMs. RSM was applied to reveal the optimal PCM. The important results were listed as follows:

- The effect of different concentrations of NaCl (16.0 and 4.0 wt.%), borax (0.0-2.0 wt.%) and CMC (1.0 and 1.5 wt.%) was examined for a colling system operating between -5 to -13°C. All results reveal that the performance of the freezer highly depends on the concentrations of both NaCl and the agents. **4.0 wt.% NaCl - 1.0 wt.% CMC - 1.0 wt.% borax solution** was revealed as **the more suitable** PCM due to a 26% reduction in the running time percentage and being approximately 33.57% lower of the energy consumption compared to the scenario without PCM. Moreover, the cabin air temperature reached the ambient temperature of 18ºC after 482 min with 4.0 wt.% NaCl - 1.0 wt.% CMC - 1.0 wt.% borax solution as PCM, while it took 163 min without PCM during power failure period.
- **The optimal PCM formulation** was revealed by Response Surface Methodology (RSM) based on the Box-Behnken design. A set of PCM formulations based on sodium chloride (4.0-8.0 wt.%)- carboxymethyl cellulose (0.5-1.5 wt.%) and water binary system including borax (0.0-2.0 wt.%) were tested for the cooling system simulating a freezer operating between -5°C and -13°C. **The minimum running time (42.11%)** was determined with **4.0 wt.% NaCl – 1.5 wt.% CMC – 1.0 wt.% borax solution.** Therefore, this PCM are concluded to be that one provided the more advantage for operating of the system than that of the other PCMs. The model equations were established to reveal the relationship between the running time and three parameters (concentrations of NaCl, CMC and borax in PCM). The probability value was determined to be lower than 0.05 (**p value < 0.05**). This result establishes the **statistical significance** of the model. The models fitted to the experimental data with a coefficient of determination R^2 of 0.9521. The sample variation of more than 95.21 % is attributed to the independent variables, while the model is unable to define for approximately 4.79% of the total variance.

- The experimental results of this study may allow the selection of optimum PCM formulation for this system. The eutectic solution of 4.9% NaCl - 1.5% CMC- 0.8% borax solution was determined as the **optimum PCM candidate** with 39.45% of running time.

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