

Performance evaluation of a laboratory-scale cooling system as a household refrigerator with phase change materials

Bercem Kiran-Yildirim

To cite this article: Bercem Kiran-Yildirim (2022) Performance evaluation of a laboratory-scale cooling system as a household refrigerator with phase change materials, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44:3, 5852-5867, DOI: [10.1080/15567036.2022.2089300](https://doi.org/10.1080/15567036.2022.2089300)

To link to this article: <https://doi.org/10.1080/15567036.2022.2089300>



Published online: 04 Jul 2022.



Submit your article to this journal [↗](#)



Article views: 200



View related articles [↗](#)



View Crossmark data [↗](#)



Citing articles: 1 View citing articles [↗](#)



Performance evaluation of a laboratory-scale cooling system as a household refrigerator with phase change materials

Bercem Kiran-Yildirim 

Chemical Engineering Department, Marmara University, Istanbul, Turkey

ABSTRACT

In this study, a laboratory-scale cooling system, simulating a household refrigerator, was examined experimentally for an average cabinet temperature of 4°C with two different types of phase change materials (PCMs) (water and eutectic solution). The system was tested with various amounts of water and different concentrations of sodium sulfate (Na_2SO_4) in water. The influence of different amounts and types of the PCMs on the cabinet air temperature and compressor power consumption was analyzed during the running period. The cabinet air temperature change over time was also observed during the power failure period. The examinations suggest using 1.0 wt.% Na_2SO_4 solution as the PCM in the cooling systems. This solution provides the lowest energy consumption (19.5 kJ), and the running time percentage (21.7%); while maximizing the energy saving (14.2%). In addition, integrating it as PCM could allow preserving products for long periods without significant quality loss during a power failure; because it prevented the rapid increase of the cabinet air temperature in this scenario. Lastly, when the cycle frequency is considered, it has the best time interval and the number of cycles (5.3). Thus, it has a positive effect on reducing the compressor cycling frequency, which eventually increases the compressor lifespan.

ARTICLE HISTORY

Received 10 March 2022
Revised 6 June 2022
Accepted 8 June 2022

KEYWORDS

Cooling system; energy consumption; household refrigerator; phase change material; power failure

Introduction

Cooling systems are mainly responsible for a huge amount of total global energy consumption due to their widespread applications and continuous operations. They are utilized not only industrially but also in domestic usage. All households have at least one domestic appliance for preserving sensitive food products at proper temperature values. A household refrigerator/freezer is liable for 15–20% of the total domestic electricity consumption (Liu, Chang, and Lin 2004). The energy consumption of refrigerators is related to lots of parameters such as the ambient and the set-point temperatures, the system components' efficiency, the refrigerant type, the number of door openings, *etc.* (Marques et al. 2014). This set of parameters makes the refrigerators' energy consumption minimization a complicated subject. The aim of the relevant studies can be classified into four main groups: the improvement of thermal insulation, the increase of heat transfers from heat exchangers, the circulation improvement, and the enhancement of compressor efficiency (Cheng et al. 2011). Most of the studies have focused on the last category since 80% of the total energy consumption belongs to the compressor of refrigerators (Marques et al. 2013). In domestic refrigerators, hermetically sealed reciprocating on/off compressors are favored due to their low cost and noise generation, besides their efficiency and reliability (American Society of Heating, Refrigerating, and Air Conditioning Engineers American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) 2010). The low energy consumption of these compressor types could be achieved by decreasing the compressor cycle frequency. It is well-known that an important technique

to reduce the compressor cycle frequency is the integration of Phase Change Materials (PCMs) into the system components or the cabinets. PCMs are also called latent heat thermal energy storage (TES), because they can absorb or release latent heat during their phase change. Therefore, the PCM integration results in less energy consumption than the case without PCM.

In the literature, there are comprehensive reviews covering the PCM integration into the cooling systems (Joybari et al. 2015). Azzouz, Leducq, and Gobin (2008) developed a model and evaluated it experimentally in the cases of with and without PCM. The results showed that PCM integration improved the coefficient of performance (COP), the compressor cycling frequency, and the temperature fluctuation. Azzouz, Leducq, and Gobin (2009) also studied the effect of the PCM integration to a household refrigerator prototype; of which, the results were compared with a classical refrigerator. Water and a eutectic mixture, with a freezing point of -3°C , were the preferred PCMs. Without a power supply, the case with PCM ensured longer operation (5–9 h) than the case without PCM (1–3 h). Marques et al. (2014) also preferred the distilled water PCM. The results indicated that the PCM integration into the refrigerator had resulted in continuous operation for 3–5 hours during power failure. Alzuwaid et al. (2015) compared the power consumption, the product, and the cabinet temperatures of a refrigerated display cabinet, in the cases with and without PCM. While the defrost time increased; the power consumption, the product, and the cabinet temperatures decreased due to the PCM integration. In addition, the energy saving of the cabinet with PCM was approximately 5% higher than the energy saving of the cabinet without PCM. The studies have been conducted numerically as well. Pavithran, Sharma, and Shukla (2021) concentrated on the numerical simulation of a PCM integrated refrigerator. The results deduced that the refrigerator temperature could be maintained with PCM integration into the refrigerator. Moreover, they revealed that the various parameters, such as the area coverage and the PCM configurations arrangement, have a remarkable influence on the results. Thus, even though PCM integration into the systems could seem easy, there are different parameters that should be considered; such as the phase change temperature, the amount, the thickness, the position, *etc.* (Khan 2016). The phase change temperature relates to the PCM type, classified into three groups: organic and inorganic compounds, and a mixture of them, eutectics (Sharma et al. 2015). Even though the organic PCMs have various advantages such as a higher enthalpy of fusion, chemical stability, *etc.*, their high cost and low latent heat are undesired properties. On the other hand, inorganic PCMs have high thermal conductivity, high latent heat, and low price; making them attractive. However, their usage could result in corrosion (Pahamli and Valipour 2021). Therefore, the refrigeration systems are generally tested with salt-water solutions, which are the most common PCMs; and, the results are also compared with the water PCM. Pahamli and Valipour (2021) prepared a review on the effect of the PCM integration into the cooling systems through various PCM types, and locations, and their outcomes. This review paper provides insight into the usage frequency of the water PCM. The reasons for preferring the water are its high latent heat, well-known thermo-physical properties, and stability. Besides, it is cheap, easily accessible, and fully eco-friendly (Afsharpanah et al. 2022; Azzouz, Leducq, and Gobin 2009). For instance, Khan and Afroz (2013a, Khan and Afroz 2013b) tested a system representing a household refrigerator with two types of PCMs (water and eutectic solution) and their different amounts. The eutectic solution PCM improved the COP of the system over the water PCM. Moreover, the amounts of PCMs were investigated (0.003 to 0.00425 m³). They revealed that increasing the amount resulted in an increase in COP. Abdolmaleki, Sadrameli, and Pirvaram (2020) tested a novel freezer containing an internal phase change material compartment with eutectic PCMs. The optimum amount and phase change temperature of eutectic mixtures of polyethylene glycol (PEG) 200 and PEG300 with different weight percentages were determined by applying Response Surface Methodology (RSM). The maximum energy saving (8.37%) was allowed with PCM with a phase change temperature of -20°C and weight of 1.5 kg. Pirvaram, Sadrameli, and Abdolmaleki (2019) investigated the effectiveness of a household refrigerator with eutectic PCMs. The two PCMs were the mixtures of polyethylene glycol-600 and polyethylene glycol-1000 with different weight percentages. The results showed that integrating two PCMs in a cascade fashion instead one PCM provided higher energy saving. In addition, some studies focused on the preparation of alternative PCMs with eutectic hydrate salts. Xin et al. (2019) proposed a novel binary eutectic hydrated salt (BEHS) as a phase change material, which was produced from sodium sulfate decahydrate ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$)

O) and disodium hydrogen phosphate dodecahydrate ($\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$). They also modified this PCM with a nucleating agent and thickener. In terms of subcooling degree and phase change enthalpy, the study revealed the appropriate $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ - $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ system composition and the amounts of nucleating agent and thickener. Hence, this study also integrated water and eutectic solution PCMs to improve the performance of a cooling system, simulating a household refrigerator. The selection reason of sodium sulfate (Na_2SO_4) solutions as eutectic solution PCMs is mainly their phase change temperatures presented in the literature. Khan and Afroz (2014) presented a PCM composed of 31 wt.% Na_2SO_4 , 13 wt.% sodium chloride (NaCl), 16 wt.% potassium chloride (KCl), and 40 wt.% water (H_2O). Its melting point and the latent heat of fusion were listed as 4°C and 234 kJ kg^{-1} , respectively. The phase change temperatures of the eutectic water-salt solutions prepared with 12.7 wt.% Na_2SO_4 (Li et al. 2013) and 4.03 wt.% Na_2SO_4 (Oró et al. 2012) were -3.55°C and -1.2°C , respectively. Na_2SO_4 is generally preferred for latent heat storage applications based on its high melting temperature, good thermal stability, and relatively weak corrosion to its container (Wu et al. 2018). It also has a relatively high heat of fusion (Kenisarin 2010), low cost, and accessibility. Liu et al. (2015) suggested a porous mullite/ Na_2SO_4 composite, with improved heat storage properties, for thermal energy storage. Considering not only the phase change temperatures but also the unique required properties of Na_2SO_4 , the Na_2SO_4 -water solutions with different concentrations were also selected as PCMs to investigate the PCM integration effect on the energy consumption experimentally.

In the literature, many studies investigate the phase change temperature of various compounds and their mixtures to propose alternative PCMs. However, few apply them on the cooling systems and determine their advantages in terms of energy saving. Therefore, the purpose of this study is to propose potential PCM candidates for a cooling system, simulating the operating condition ($+4^\circ\text{C}$) of a household refrigerator, through experiments and energy saving evaluations. Thus, various PCM options were investigated experimentally, such as different amounts of water (400, 600, 800 mL) and different concentrations of Na_2SO_4 in water (1.0, 2.0, 4.0 wt.%). During the running period of 2 hours, the cabinet air temperature variations, the compressor power consumption, and cycle frequency were measured and compared. On the other hand, during the running period of 8 hours, the total energy consumption, running time, and energy saving percentages were calculated. Moreover, the cabinet air temperatures were also recorded to simulate the system behavior during a power failure.

The novelty of this work is the application of the Na_2SO_4 solutions as eutectic solution PCMs, for a cooling system simulating the operating condition of a household refrigerator. The reason for selecting Na_2SO_4 solutions is related to not only their proper phase change temperature, but also the unique required properties of Na_2SO_4 ; such as, having good thermal stability and relatively high heat of fusion; and, being nontoxic, cheap, and easily available. According to all the evaluations, an appropriate concentration of Na_2SO_4 solution, which increases the compressor life span by reducing the compressor cycle frequency, is proposed.

Materials and method

Cooling system

The test setup built in a previous study (Kiran-Yildirim et al. 2021) and its schematic diagram are represented in Figure 1. The setup mainly included a compressor, an evaporator, a condenser, an expansion valve, and a cabinet with an inner volume of 72 liters. The cabinet has internal dimensions of $0.435 \times 0.390 \times 0.425 \text{ m}$. A fan was integrated on the cabinet sidewall to provide the homogeneity of the cabinet air temperature. The evaporator was placed in the cabinet backside wall. Free convection heat exchangers were used as an evaporator and a condenser. The compressor was a hermetic reciprocating compressor. A data logger unit recorded the refrigerant temperatures measured by the temperature sensors, with $\pm 0.5\%$ accuracy, at the inlet and outlet of the evaporator, the compressor, and the condenser. The mass flow rate of the refrigerant circulating through the system was recorded.

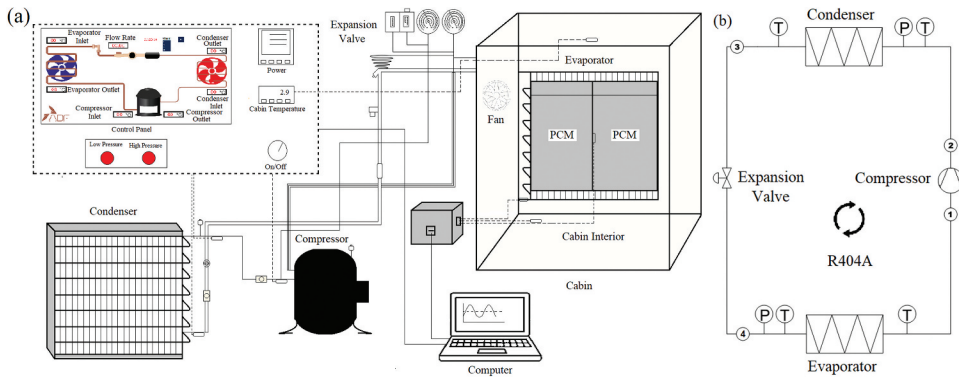


Figure 1. Test setup and main components.

R404A was circulated in the system as a refrigerant. The accuracy of the mass flow meter is ± 0.5 -digit. Simultaneously, the thermostatic controller measured the cabinet air temperature with ± 1.0 -digit accuracy. The network analyzer device recorded the power consumption with ± 1.0 -digit accuracy.

The working principle is that the refrigerant circulates through the system. The refrigerant is firstly compressed from the evaporator to the condenser by the compressor. The superheated vapor at the compressor exit turns into saturated liquid at the exit of the condenser as a result of the heat rejection. The saturated liquid is throttled to the evaporator pressure by passing through the expansion valve. The low-quality mixture completely evaporates in the evaporator by absorbing heat from the cooled space. The operation conditions of this system are listed in Table 1. The temperature and pressure values of evaporation and condensation are chosen to be the conditions of the actual system. The evaporator, condenser, and compressor capacities are calculated from the measured data.

During the experiments, the cabinet air temperature, the input-output temperatures of the evaporator, the compressor, and the condenser; and the system power consumptions were measured during the running period for the cases with and without PCM.

Experimental procedure

The experiments were performed with and without PCM at an ambient temperature of 20.0°C , maintained by an air conditioner. The different amounts of water and different concentrations of eutectic solution were integrated into the system as PCM.

In this study, the behavior of fully charged PCMs, during running and power failure periods was experimentally investigated. The partial melting or solidification processes of the PCM occur during the running period, only the melting process of the PCM occurs during the power failure period.

Table 1. The operation conditions for the experimental cooling system.

Parameters	Value
Evaporation temperature ($^{\circ}\text{C}$)	-7.0
Evaporation pressure (MPa)	0.28
Condenser outlet temperature ($^{\circ}\text{C}$)	32.0
Condenser outlet pressure (MPa)	1.50
Condenser capacity (kW)	1.53
Compressor capacity (kW)	0.46
Evaporator capacity (kW)	1.07
Ambient temperature ($^{\circ}\text{C}$)	20.0

A time interval of 8 h was chosen for the running period in order to observe the effect of PCM on the power failure period. Before starting the experiments, PCMs, which were placed into aluminum zip foil bags to improve the heat transfer, were frozen (charged). They were charged horizontally in a freezer to obtain a uniform ice structure as a thin layer. The charging process, at the beginning of the experiments, was not considered in the calculation of the power consumption for each experiment. After, the experiments started by placing the charged PCMs over to the evaporator inside the cabinet. This application allows the refrigerant to efficiently utilize the stored heat during the compressor on time (Khan 2016). It also prolongs the compressor off time with PCM integration. Yilmaz, Mancuhan, and Yilmaz (2020) revealed the importance of the location of PCM panels in a commercial display cabinet. Panels were located on the backside and the shelves of the cabinet. The results indicated that integrating PCM panels on the shelves of the cabinet is a better option than that of the backside of the cabinet. The integration of PCM over evaporator might provide more advantages for charge and discharge processes. During the compressor off time, heat is released with the phase change of PCM from solid to liquid form, known as discharging (melting) process. After reaching the upper set point of the phase change temperature, the compressor is engaged; and, a phase change occurs in the opposite direction, known as the charging process. Therefore, it should be noted that the phase change temperature should be close to the temperature of the evaporator so that charging and discharging processes are successful. This study focused on the fresh food storage compartment of a household refrigerator. Even though the ideal temperature to preserve food is 0–4°C (Carpentier and Rogues 2006), according to a study conducted in France, 25% of the domestic refrigerators had an average temperature above 8°C, only 11% of refrigerators were at 4°C or below (Derens, Laguerre, and Palagos 2001). International Electrotechnical Commission [IEC] (2007) exhibits the temperature of each compartment related to the type of food. There are three classifications: fresh food storage (unfrozen food), chill (for highly perishable foodstuff), and cellar (particular food) compartments; with temperature ranges: 0–8°C (mean \leq 4°C), (–2)–(+3) °C, and 8–14°C, respectively. Hence, in this study, the cabinet air temperature fluctuated between 0°C and 8°C; to operate the system for an average of around 4°C (\pm 0.5°C) with and without PCM.

Firstly, the experiments were carried out with different amounts (400, 600, and 800 mL) of water PCMs to select the appropriate PCM amount. Secondly, the system was tested with PCMs of Na₂SO₄ solutions (1.0–4.0 wt.%). The melting temperature and the fusion latent heat of distilled water are 0°C and 333 kJ/kg, respectively (Khan and Afroz 2013b). On the other hand, the melting temperature and the fusion latent heat of eutectic solution (4.03 wt.% Na₂SO₄ solution) are –1.2 °C and –1.07 kJ/mol, respectively (Oró et al. 2012). The cases with PCM and without PCM were compared in terms of energy saving.

Energy consumption

The recorded data were evaluated in terms of the running time and the energy saving percentages, calculated according to Eq. (1) and Eq. (2), respectively.

$$\text{Runningtime}(\%) = \frac{t_{on}}{t_{on} + t_{off}} \times 100 \quad (1)$$

where t_{on} and t_{off} stand for compressor on time and compressor off time, respectively.

$$\text{Energysaving}(\%) = \frac{W_{PCM} - W}{W} \times 100 \quad (2)$$

In Eq. 2; W_{PCM} is total energy consumption with PCM, while W is total energy consumption without PCM. The compressor energy consumption over time, $W(t)$ is calculated by integrating the measured power for a duration t , as expressed as Eq. (3).

$$W(t) = \int_{t=0h}^{t=8h} \dot{W}(t) dt \quad (3)$$

Each experiment was repeated at least three times. The data of running time percentage, total energy consumption, and energy saving percentage were analyzed using descriptive statistic. The mean values with standard deviations were presented.

Results and discussion

The influence of PCM on the cabinet air temperature

The system was investigated experimentally without PCM and with different amounts and types of PCMs. Pre-experiments were performed to adjust the suitable operating settings for PCMs' integration. The tests were carried out in a room where the ambient air temperature was kept approximately constant at 20.0°C with an air conditioner. Firstly, the experiments were performed for the average temperature of 4°C without PCM and with water PCM (400, 600, and 800 mL) integrated on the evaporator surface of the cabinet. In addition, the different concentrations (1.0, 2.0, and 4.0 wt.%) of Na₂SO₄ in water were tested as PCMs under the same operating conditions.

Different amounts of water as a PCM

The influence of different amounts of water as PCM on the cabinet air temperature variations is represented in Figure 2 during 2 hours of the operation. While the cabinet air temperature varied between 0°C and 7.9°C without PCM, 400 mL, and 600 mL water PCM, it changed between 0.6°C and 8.0°C with 800 mL water PCM. The average cabinet air temperature was around 4°C ($\pm 0.5^\circ\text{C}$) for all cases.

As illustrated in Figure 2, the numbers of cycles with 400 mL PCM, 600 mL PCM, and 800 mL PCM were measured to be 6.3, 6.8, and 6.9, respectively. On the other hand, the number of cycles without PCM was found to be 7.4. The influence of PCM on the cabinet air temperature was determined more with 400 mL water PCM than that of the other cases. In all cases, the cabinet excess heat is absorbed by the PCM because of its phase change process (solid to liquid) at the time interval of compressor off time; this allows keeping the cabinet air temperature at certain temperature levels for a long time.

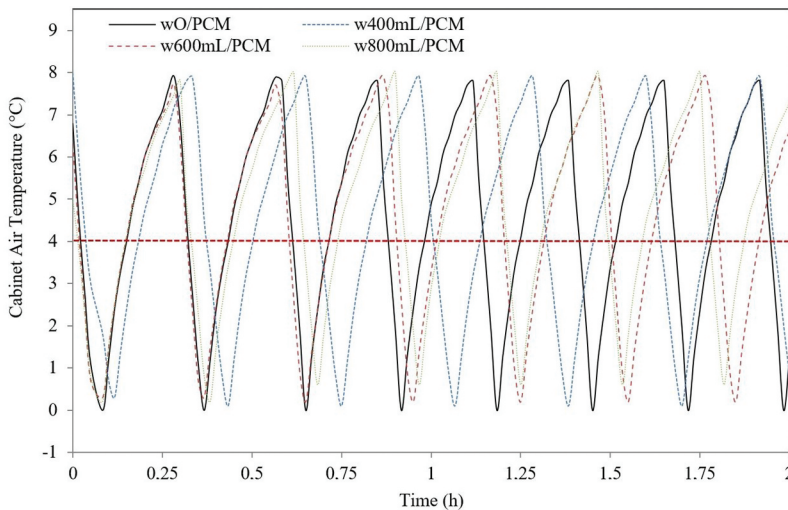


Figure 2. Variations of cabinet air temperatures with different amounts of water as PCM.

These results reveal that the cycle number highly depends on the PCM amount. As specified in the literature, energy saving could be provided by lowering the compressor cycling frequency (Suamir et al. 2019).

When the different cases of water PCM are compared to the case without PCM in terms of the number of cycles, the lowest number of cycles is observed for 400 mL water PCM. Here, the decrease in the number of cycles is 14.9% relative to the case without PCM. However, considering the compressor on and off-times and the running time percentage, 600 mL water PCM is a better choice than 400 mL water PCM. While the on time is 4 minutes for 600 mL water PCM, it is 5 minutes for 400 mL water PCM. On the other hand, the off time is 14 minutes for both 400 mL and 600 mL water PCMs. In order to clearly show the advantage of 600 mL water PCM over 400 mL water PCM, the running time percentage values were calculated by using Eq. (1). For different amounts of water PCM, the compressor on and off-times and the running time percentages are presented in Table 2.

The more PCM amount causes the more compressor off time, because discharging of more PCM requires a longer time. Hence, the running time percentage decreases with increasing PCM amount. The lowest running time percentage is observed for 600 mL water PCM. Its value is 22.2%, much lower than the running time percentage (25.0%) of without water PCM. The running time percentage of 600 mL water PCM is 11.2% less than that of without PCM. Thus, it can be concluded that the appropriate PCM amount is one of the important parameters. The highest value is obtained for 400 mL water PCM, even higher than without PCM. Thus these results reveal that even though the cycle frequency is lower with 400 mL, the on and off-time should be examined in detail. With 400 mL water, the compressor on time is more, which eventually reduces the PCM effectiveness. In summary, 600 mL water was determined to be the appropriate PCM for this system under these operating conditions.

These results were obtained after achieving the steady state condition. Considering the running period data, the running time percentage values, with deviation, were calculated to be $24.6\% \pm 0.4$, $27.1\% \pm 0.8$, $22.6\% \pm 0.4$, and $23.2\% \pm 0.4$ in the cases of without PCM; and, with 400 mL, 600 mL, and 800 mL water PCMs, respectively.

Different concentrations of Na₂SO₄ solutions as PCMs

The system was also tested with different PCM types for selecting the appropriate PCM. In literature, it was emphasized that a temperature interval (from 5 to 10°C) should be considered for thermal energy storage (Lane 1983), and the appropriate PCM could be selected according to its melting temperature; which should be about 10°C below the charge temperature (Kasinathan and Kumaresan 2021). Therefore, the experiments were also carried out with various Na₂SO₄ solutions due to their melting points, as stated in the Introduction Part.

In this study, 600 mL of water was determined as the appropriate amount of PCM, so the water was mixed with 1.0, 2.0, and 4.0 wt.% Na₂SO₄ to prepare 600 mL solutions. The influence of Na₂SO₄ concentrations on the cabinet air temperature variations is presented in Figure 3 during 2 hours of operation. The cabinet air temperature changed between 0°C and 8°C with Na₂SO₄ solutions. Thus, the cabinet air temperature fluctuated between 0°C and 8°C to ensure an average of 4°C, representing the fresh food storage compartment of a household refrigerator.

Table 2. The running time percentages for different amounts of water as PCM.

PCM Amount (mL)	Experimental Results			
	On Time, t_{on} (minute)	Off Time, t_{off} (minute)	One Cycle Time (minute)	Running Time (%)
0	4	12	16	25.0
400	5	14	19	26.3
600	4	14	18	22.2
800	4	13	17	23.5

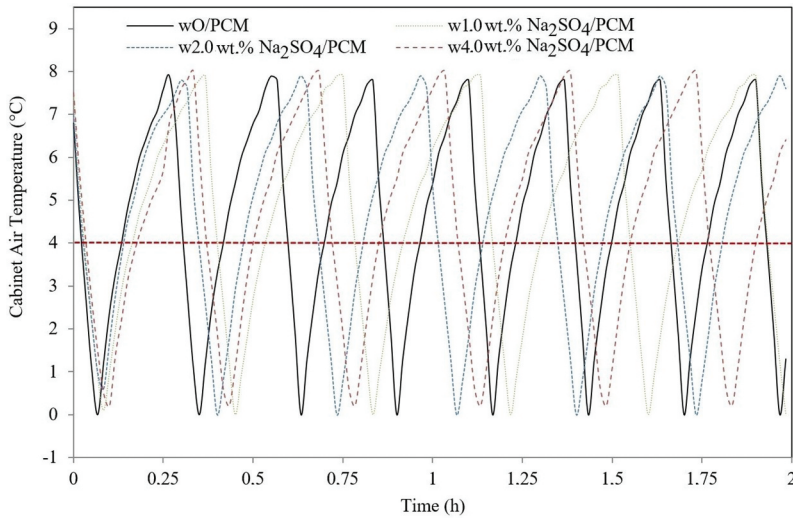


Figure 3. Variations of cabinet air temperatures with different concentrations of Na_2SO_4 solutions as PCM.

Table 3. The running time percentages for different concentrations of Na_2SO_4 solutions of 600 mL.

Na_2SO_4 Concentration (wt.%)	Experimental Results			
	On Time, t_{on} (minute)	Off Time, t_{off} (minute)	One Cycle Time (minute)	Running Time (%)
0	4	12	16	25
1	5	18	23	21.7
2	5	15	20	25
4	6	15	21	28.6

As seen in [Figure 3](#), the number of cycles with PCM decreased from 7.4 to 5.3, 6.1, and 5.8 with 1.0, 2.0, and 4.0 wt.% Na_2SO_4 solutions, respectively. As it is known, the decrease in the cycle frequency results in more energy savings. Therefore, 1.0 wt.% Na_2SO_4 solution should be chosen as the appropriate PCM. Even though the minimum cycle number (5.3) is observed for 1.0 wt.% Na_2SO_4 , the results need to be analyzed in detail in terms of the compressor on and off-times. With the integration of various concentrations of Na_2SO_4 solutions as PCM, the compressor off time was significantly prolonged. However, the compressor on time was prolonged too.

The running time percentages were calculated from the measured on and off-time values and listed in [Table 3](#). While the minimum running time was determined to be 21.7% for 1.0 wt.% Na_2SO_4 solution, the maximum running time was found to be 28.6% for 4.0 wt.% Na_2SO_4 solution. Furthermore, the running time percentage was decreased by 13.2% with 1.0 wt.% Na_2SO_4 solution, relative to without PCM; and even, its running time percentage is 2.3% better than that of the 600 mL water solution. These results revealed that 1.0 wt.% Na_2SO_4 concentration of 600 mL water solution could be an important alternative PCM for this cooling system. This reduction in the number of on/off cycles of the compressor will increase the compressor lifespan and maximize energy saving.

The mean running time percentage values, with deviations, were calculated to be $21.9\% \pm 0.2$, $25.2\% \pm 0.2$, and $28.8\% \pm 0.2$ for the cases with 1.0 wt.%, 2.0 wt.%, and 4.0 wt.% Na_2SO_4 solutions, respectively. The calculated deviations are narrower than the water PCMs', indicating a more stable system.

The influence of PCM on the compressor power consumption

Different amounts of water as PCM

The changes in compressor power consumption over time are compared in Figure 4 for the cases without PCM and with different amounts of water PCMs. The minimum and maximum power consumptions without PCM were 0.187 kW and 0.192 kW, respectively. The maximum power consumption values were 0.198 kW for 400 mL and 800 mL water, while it was determined as 0.195 kW for 600 mL. On the other hand, the minimum power consumption values were 0.185, 0.189, and 0.190 kW for 400 mL, 600 mL, and 800 mL water, respectively. Although the measured maximum power consumptions are close to each other, the lowest consumption (0.195 kW) is for 600 mL of water. Nevertheless, the lowest consumption among the different PCM cases is even greater than the case without PCM. Hence, the cycle frequency during the running period was examined and compared too.

In Figure 4, the highest number of on/off cycles is 7.4 for the case without PCM during 2 hours running period. Meanwhile, the numbers of on/off cycles are 6.3, 6.8, and 6.9 for 400 mL, 600 mL, and 800 mL water, respectively. However, the numbers are too close to each other, especially for 600 mL and 800 mL water. The occurrence of cycles differs for various amounts of water PCM. The time intervals of the 6 cycles were determined to be 1.90 h for 400 mL PCM, 1.77 h for 600 mL PCM, and 1.73 h for 800 mL PCM. Even though these results showed that 400 mL water provided more advantages in terms of energy consumption, the power consumption values during the compressor on time should be evaluated together with these results. When the power consumption values are considered, the appropriate amount of water as PCM for this cooling system might be suggested as 600 mL. These results indicate that the amount of water as PCM significantly affects the power consumption of the compressor.

Different concentrations of Na_2SO_4 solution as PCM

In Figure 5, the power consumption variation over time is illustrated without PCM and with different concentrations of Na_2SO_4 in water as PCMs. As mentioned earlier, the minimum power consumption without PCM was measured to be 0.187 kW; while the maximum was 0.192 kW. The maximum power consumption value was observed to be 0.196 kW for 1.0 wt.% Na_2SO_4 solution, this value was 0.200 kW for 2.0 wt.%, and 4.0 wt.% Na_2SO_4 solutions. On the other hand, the minimum power consumptions were 0.182, 0.187, and 0.190 kW for 1.0 wt.%, 2.0 wt.%, and 4.0 wt.% Na_2SO_4 solutions, respectively. The lowest maximum and minimum power consumption values were determined to be 0.196 kW and 0.182 kW, respectively, for 1.0 wt.% Na_2SO_4 solution.

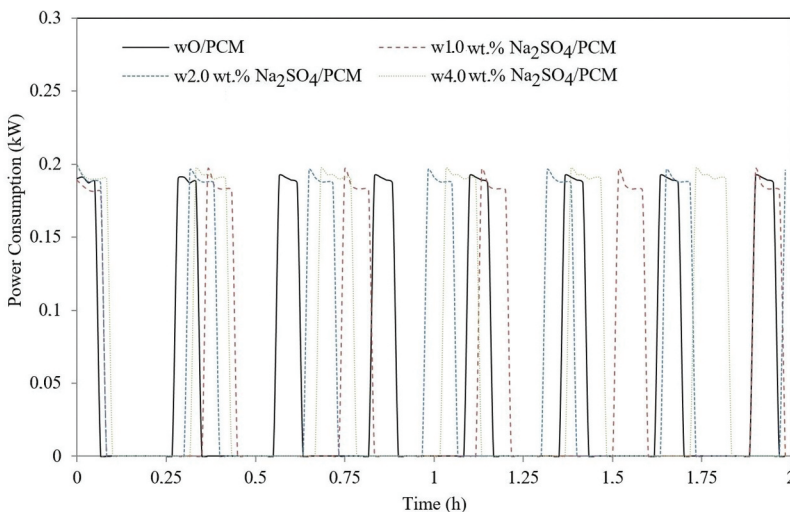


Figure 4. Compressor power consumption versus time without and with different amounts of water.

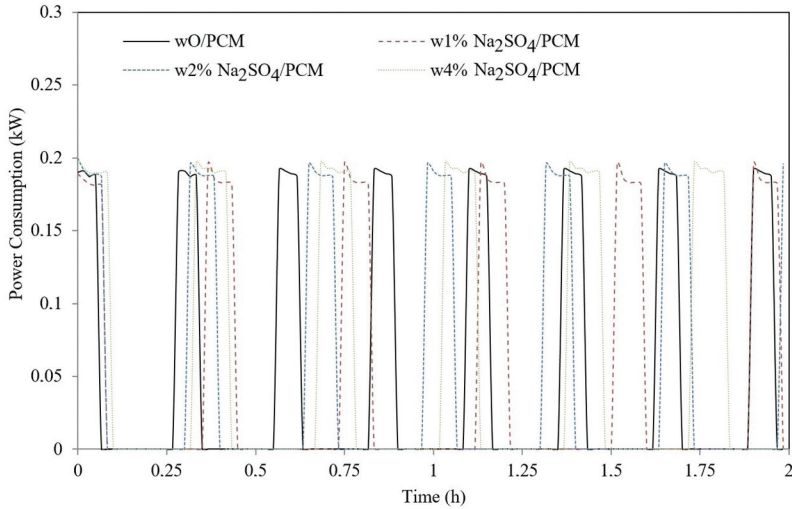


Figure 5. Compressor power consumption versus time without and with various Na_2SO_4 solutions.

In addition, the highest number of cycles was determined to be 7.4 for the case without PCM during 2 hours of operation. During the same operational period, the total number of cycles varied between approximately 5 and 6 for various Na_2SO_4 solutions. However, the time intervals of all for 6 cycles were found to be different. The time intervals of the 6 cycles were measured as 2.28 h, 1.98 h, and 2.08 h for the cases with 1.0 wt.%, 2.0 wt.%, and 4.0 wt.% Na_2SO_4 solutions, respectively.

These results indicated that the system, in which 1.0 wt.% Na_2SO_4 concentration in 600 mL water solution was integrated as PCM, had more advantages than that of the other cases. Therefore, it could be concluded that the parameters such as the PCM type and the PCM amount should be carefully determined to minimize the energy consumption. An inaccurate choice could result in a huge amount of energy consumption, which could be higher than that of the case without PCM.

The influence of PCM on the power failure period

Given the cabinet air temperature, the influence of different amounts (0, 400, 600, and 800 mL) of water and different concentrations (0, 1.0, 2.0, and 4.0 wt.%) of Na_2SO_4 in water is shown in [Figure 6](#), respectively, during the power failure period. The experiments were carried out to monitor how the cabinet air temperature rising to the temperature of 20.0°C for these different cases.

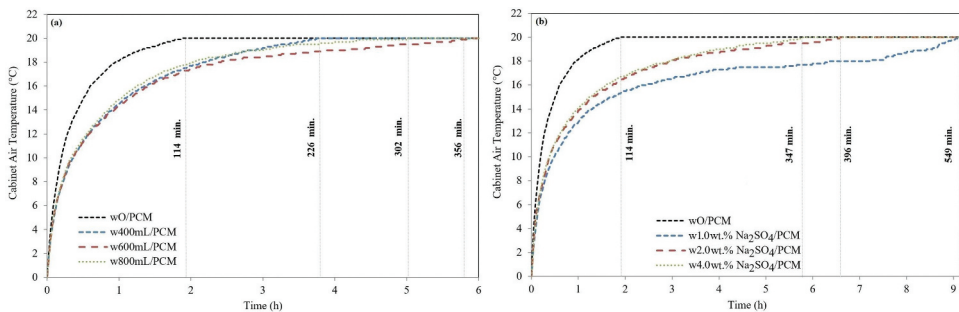


Figure 6. Cabinet air temperature versus time for different (a) amounts of water-(b) concentrations of Na_2SO_4 solutions, as PCMs during the power failure period.

There can be seen in **Figure 6(a)** that the rise in the cabinet air temperature highly depends on the amount of water integrated as PCM during the power failure period. It reached 20.0°C in 114 minutes without PCM, whereas this was 226 minutes, 356 minutes, and 302 minutes for 400 mL PCM, 600 mL PCM, and 800 mL PCM, respectively. When the time duration measurements are compared, it is concluded that the most suitable amount of water is 600 mL.

On the other hand, the different concentrations of Na₂SO₄ solutions as PCMs resulted in the prolongation of reaching the air temperature of 20.0°C too. Considering time duration, it lasted 549 minutes, 396 minutes, and 347 minutes for 1.0 wt.%, 2.0 wt.%, and 4.0 wt.% Na₂SO₄ solutions, respectively (**Figure 6(b)**). In case of power failure, the highest time duration value for reaching 20.0°C was 549 minutes with 1.0 wt.% Na₂SO₄ concentration in 600 mL water solution. As shown in the literature, PCMs begin to melt during the power failure period (Oró et al. 2012); and, this discharging process allows keeping the temperature inside the system at the desired level for a long time, without a power supply. In this study, as it is observed in Oró et al. (2012)'s study, the melting of PCM started; however, 1.0 wt.% Na₂SO₄ solution PCM did not melt completely at the end of the time passed, reaching 20.0°C. Hence, it might be concluded that this PCM could maintain temperature for a much longer time than the other PCMs could have.

All results show that integrating PCMs into the cooling system provides advantages in maintaining the cabinet air temperature at certain temperature levels. For household refrigerator operation, the integration of 1.0 wt.% Na₂SO₄ -water solution of 600 mL as PCM allows keeping the temperature at proper values recommended for the refrigerator with less energy consumption, besides decreasing quality loss of fresh foods during power failure.

Evaluation of the cabinet air temperature and power consumption

Figure 7(a and 7(b)) show the changes in cabinet air temperature versus time with 600 mL water and 1.0 wt.% Na₂SO₄ solution, respectively. The running and power failure periods are denoted with I and II on the figures, respectively.

In both cases, the selected running time was approximately 8 hours. During the running period, the number of cycles (26.78) with 600 mL water is higher than the number of cycles (20.91) with 1.0 wt.% Na₂SO₄ solution. The power failure duration is the time needed to reach the cabinet air temperature to the temperature of 20.0°C. The power failure durations were determined to be approximately 6 h and 9 h for 600 mL water and 1.0 wt.% solution of Na₂SO₄, respectively. In conclusion, the presence of Na₂SO₄ salt in water considerably affects the duration of the power failure.

The power consumption variation versus time graphs were plotted for running and power failure periods of the cases with 600 mL water and 1.0 wt.% Na₂SO₄ solution, and are presented in **Figure 8**, respectively. The compressor cycle frequency with 1.0 wt.% Na₂SO₄ solution was found to be less than that of the case with 600 mL water during the running period. As indicated, the number of cycles was

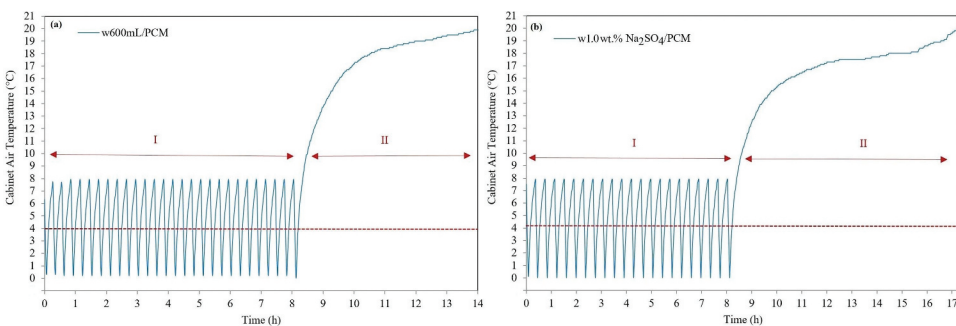


Figure 7. Change in the cabinet air temperature during the running (I) and power failure (II) periods with (a) 600 mL water (b) 1.0 wt.% Na₂SO₄ solution.

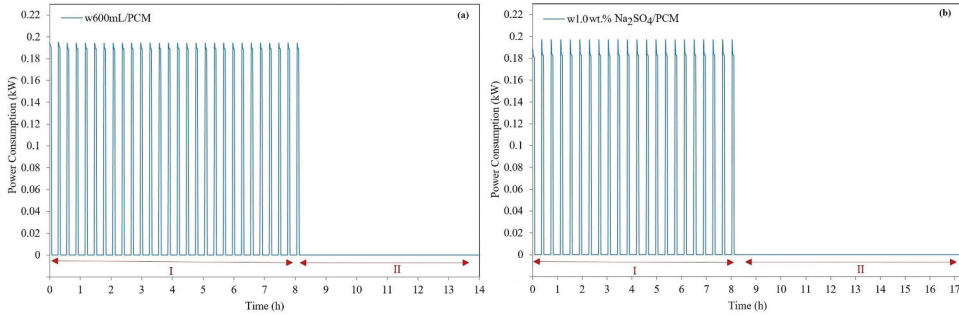


Figure 8. Change in the power consumption during the running (I) and power failure (II) periods-with (a) 600 mL water (b) 1.0 wt.% Na_2SO_4 solution.

determined to be 26.78 for 600 mL water; while it was 20.91 for 1.0 wt.% Na_2SO_4 solution. Therefore, the minimum total compressor power consumption was calculated to be 19.5 kJ for 1.0 wt.% Na_2SO_4 solution during 8 hours running period.

Evaluation of all the cases

The evaluation of energy consumption for all cases is summarized in Table 4. When the compressor running periods were investigated during 8 hours, the total energy consumptions were calculated to be 24.8, 20.6, and 22.1 kJ for 400 mL, 600 mL, and 800 mL water, respectively. This was found to be 19.5, 23.2, and 26.5 kJ for 1.0 wt.%, 2.0 wt.%, and 4.0 wt.% Na_2SO_4 solutions, respectively. Without PCM, the total energy consumption was 22.8 kJ. These results were used to determine the energy saving percentages, as seen in Eq. (2). The mean values with standard deviations of the total energy consumption were $24.9\% \pm 0.1$, $20.6\% \pm 0.1$, and 22.0 ± 0.1 for the cases with 400 mL, 600 mL, and 800 mL water, respectively. It was calculated to be $22.7\% \pm 0.04$ for the case without PCM. In addition, they were 19.4 ± 0.1 , 23.2 ± 0.1 , and 26.5 ± 0.01 for the cases with 1.0 wt.%, 2.0 wt.%, and 4.0 wt.% Na_2SO_4 solutions, respectively. The minimum deviation was determined in the case of with 1.0 wt.% Na_2SO_4 solution.

The appropriate amount of PCM must be selected before integrating the PCM into the systems. The increase of water PCM, from 400 to 600 mL, resulted in reduced energy consumption; furthermore, the increase of water PCM, from 600 to 800 mL, resulted in increased energy consumption. That is why 600 mL water PCM was chosen as the appropriate amount. Similar behavior was also observed in other studies in the literature. Abdolmaleki, Sadrameli, and Pirvaram (2020) focused on the amount and phase change temperature of eutectic phase change materials to improve the efficiency of household freezers. They chose to use three different amounts of PCM (1.0,

Table 4. Energy consumption values of the cooling system for all cases.

	wo/ PCM	w400 mL water/ PCM	w600 mL water/ PCM	w800 mL water/ PCM	w1.0% Na_2 SO_4 / PCM	w2.0% Na_2 SO_4 / PCM	w4.0% Na_2 SO_4 / PCM
Comp-ressor running during 8 h (kJ)	22.8	24.8	20.6	22.1	19.5	23.2	26.5
Total compressor on time in 8 h (h)	2.00	2.18	1.80	1.92	1.75	2.03	2.30
Total compressor off time in 8 h (h)	6.00	5.82	6.20	6.08	6.25	5.97	5.70
Running time (%)	25.0	26.3	22.2	23.5	21.7	25.0	28.6
Energy saving (%)	-	9.04	-9.58	-3.01	-14.3	1.88	16.6

1.5, and 2.0 kg). The appropriate amount was determined as 1.5 kg. Although energy consumption was reduced by increasing the amount from 1 to 1.5 kg, further increases (1.5 to 2.0 kg) resulted in increased energy consumption. For 600 mL water, the energy saving was calculated to be 9.58%, which is better than that of the other cases with water PCM. In addition, the running time is 22.2%, which is the best value among the cases with water PCM. Therefore, this case is observed to be the better option with respect to the other amounts of water PCM for this experimental setup. This amount could also be called as the appropriate water PCM amount. On the other hand, the energy saving and running time percentages were calculated and compared for the cases with 1.0 wt.%, 2.0 wt.%, and 4.0 wt.% Na_2SO_4 solutions. As indicated in the Introduction Part, proper phase change temperature of PCM is one of the key parameters to utilize PCM efficiently with a cooling system. The proper phase change temperature was obtained with 1.0 wt.% Na_2SO_4 solution PCM; because, the operation temperature range was between 0°C and 8°C , with an average of 4°C . Considering the phase change temperature for Na_2SO_4 solutions, presented in the literature (Oró et al. 2012); it is expected that the addition of Na_2SO_4 salt to the water will decrease the phase change temperature of PCM. The lower phase change temperature causes Na_2SO_4 solutions' cabinet air temperature to be lower than the water PCMs' (Azzouz, Leducq, and Gobin 2008). Hence, the Na_2SO_4 -water eutectic solution, which is better than the water PCM's, achieved the minimum running time percentage and the high energy saving. The maximum energy saving (14.3%) and the minimum running time (21.7%) percentages were achieved with the integration of 1.0 wt.% Na_2SO_4 solution. The mean values with standard deviations of the energy saving percentage were 9.40 ± 0.5 , $(-9.34) \pm 0.3$, and $(-3.14) \pm 0.4$ for the cases with 400 mL, 600 mL, and 800 mL water, respectively. They were calculated to be $(-14.5) \pm 0.5$, 2.14 ± 0.3 , and 16.7 ± 0.1 for the cases with 1.0 wt.%, 2.0 wt.%, and 4.0 wt.% Na_2SO_4 solutions, respectively. The minimum deviation was determined in the case of with 1.0 wt.% Na_2SO_4 solution. When the energy saving and running time percentage values are compared, the most suitable type and amount of PCM is determined as 1.0 wt.% Na_2SO_4 -water solution of 600 mL.

In conclusion, given the cooling system simulating the operating condition ($+4^\circ\text{C}$) of a household refrigerator, 1.0 wt.% Na_2SO_4 solution of 600 mL might be recommended as a good alternative PCM. This study is also showed the importance of eutectic solutions, similarly to studies presented in the literature (Azzouz, Leducq, and Gobin 2008, 2009; Khan and Afroz 2013a; Khan and Afroz 2013b).

Conclusion

A laboratory-scale cooling system, simulating a household refrigerator, was tested without PCM and with different amounts and types of PCMs. The cabinet air temperature fluctuated between 0°C and 8°C ; with an average of 4°C , which is the optimal running condition of a household refrigerator. Water and Na_2SO_4 solutions were integrated into the system as PCM to determine the appropriate amount and type of PCM. The main conclusions can be summarized as follows:

- The maximum energy saving (14.3%) and the minimum running time percentage (21.7%) were achieved with the integration of 1.0 wt.% Na_2SO_4 solution.
- The lowest energy consumption (19.5 kJ) during the compressor running periods of 8 hours was calculated for the case with 1.0 wt.% Na_2SO_4 - water solution of 600 mL. The energy saving of 1.0 wt.% Na_2SO_4 solution is 49.3% more than that of the case with 600 mL water, which is the appropriate PCM amount determined between the different amounts of water.
- The best time interval and number of cycles are 2 h and 5.3 for 1.0 wt.% Na_2SO_4 -water solution of 600 mL. This significant reduction in the compressor cycle frequency allows for extending the compressor lifespan.
- The running time percentage of 1.0 wt.% Na_2SO_4 solution is 2.3% less than that of the case with 600 mL water. Na_2SO_4 solution has a lower deviation than water in average running time percentage, which implies a more stable system.

- During the power failure period, the cabinet air temperature was controlled more easily with PCM integration. The Na_2SO_4 solutions are found to be more effective in preventing the rapid increase of the cabinet air temperature than water PCMs. The time needed to reach 20°C ambient temperature was maximized with 1.0 wt.% Na_2SO_4 -water solution of 600 mL (approximately 9 h), ~ 3 h more than that of the case with 600 mL water PCM.

In summary, the results of this study clearly showed that the PCM integration enables more efficient cooling systems. However, the parameters such as the PCM type, the PCM composition, and the PCM amount should be determined to improve the performance of systems. Accordingly, it could be concluded that 1.0 wt.% Na_2SO_4 -water solution of 600 mL is the best option for PCM integration into this cooling system. This solution can ensure that the products are stored for a long time with less energy and without loss of quality during power failure. It also has other advantages, such as being nontoxic, cheap, and easily available. Thus, this solution could be offered as an alternative PCM for a household refrigerator. Future work could focus on exploring the effect of different PCM types and various refrigerants on a cooling system's efficiency. Besides, future research could examine the effects of proper additives.

Nomenclature

PCM	phase change material
TES	thermal energy storage
COP	coefficient of performance
RSM	response surface methodology
BEHS	binary eutectic hydrated salt
w/PCM	with phase change material
wo/PCM	without phase change material

Symbols

M	mass (kg)
$\text{wt.}\%$	weight percentage
t	time [h]
t_{on}	compressor on time [min]
t_{off}	compressor off time [min]
T	temperature [$^\circ\text{C}$]
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]

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributor

Berçem Kiran-Yildirim received her B.Sc., M.Sc., and Ph.D. degrees in Chemical Engineering at Marmara University. She studied at Thermal Process Technology Laboratory, Martin Luther University, for approximately six months. She was a Guest Researcher at the Institute of Process Engineering in Life Sciences, Section I: Food Process Engineering, Karlsruhe Institute of Technology between 07.2018-12.2019. She has been working as a faculty member at Marmara University since 2008. She is currently with the Department of Chemical Engineering as an Assistant Professor. Her research interests are in the fields of crystallization, recrystallization, adsorption, phase change materials, refrigeration systems, and energy consumption.

ORCID

Bercem Kiran-Yildirim  <http://orcid.org/0000-0002-7504-0176>

References

- Abdolmaleki, L., S. M. Sadrameli, and A. Pirvaram. 2020. Application of environmental friendly and eutectic phase change materials for the efficiency enhancement of household freezers. *Renewable Energy* 145:233–41. doi:10.1016/j.renene.2019.06.035.
- Afsharpanah, F., S. S. Mousavi Ajarostaghi, F. Akbarzadeh Hamedani, and M. Saffari Pour. 2022. Compound Heat Transfer Augmentation of a Shell-and-Coil Ice Storage Unit with Metal-Oxide Nano Additives and Connecting Plates. *Nanomaterials* 12 (6):1–17. doi:10.3390/nano12061010.
- Alzuwaid, F., Y. T. Ge, S. A. Tassou, A. Raeesi, and L. Gowreesunker. 2015. The novel use of phase change materials in a refrigerated display cabinet: An experimental investigation. *Applied Thermal Engineering* 75:770–78. doi:10.1016/j.applthermaleng.2014.10.028.
- American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). 2010. *ASHRAE handbook: Refrigeration*. Atlanta, Chapter 17: American Society of Heating, Refrigerating Air-Conditioning Engineers, Inc.
- Azzouz, K., D. Leducq, and D. Gobin. 2008. Performance enhancement of a household refrigerator by addition of latent heat storage. *International Journal of Refrigeration* 31 (5):892–901. doi:10.1016/j.ijrefrig.2007.09.007.
- Azzouz, K., D. Leducq, and D. Gobin. 2009. Enhancing the performance of household refrigerators with latent heat storage: An experimental investigation. *International Journal of Refrigeration* 32 (7):1634–44. doi:10.1016/j.ijrefrig.2009.03.012.
- Carpentier, B., and A. M. Rogues. 2006. AFSSA fact sheet: Household hygiene. Accessed January 18, 2008. <http://www.afssa.fr/Documents/MIC-Fi-Hygienedomestique.pdf>.
- Cheng, W. L., B. J. Mei, Y. N. Liu, Y. H. Huang, and X. D. Yuan. 2011. A novel household refrigerator with shape-stabilized PCM (Phase Change Material) heat storage condensers: An experimental investigation. *Energy* 36 (10):5797–804. doi:10.1016/j.energy.2011.08.050.
- Derens, E., O. Laguerre, and B. Palagos. 2001. Analysis of factors influencing the temperature in household refrigerators. *Bulletin de l'Academie Nationale de Medecine* 185 (2):311–22.
- International Electrotechnical Commission [IEC]. 2007. *IEC 62552:2007, Household refrigerating appliances - characteristics and test methods*. Switzerland: International Electrotechnical Commission.
- Joybari, M. M., F. Haghighat, J. Moffat, and P. Sra. 2015. Heat and cold storage using phase change materials in domestic refrigeration systems: The state-of-the-art review. *Energy and Buildings* 106:111–24. doi:10.1016/j.enbuild.2015.06.016.
- Kasinathan, D., and V. Kumaresan. 2021. Study on the effect of inclusion of thermal energy storage unit in the energy performance of a household refrigerator. *Heat and Mass Transf* 13:1–9. doi:10.1007/s00231-021-03070-5.
- Kenisarin, M. M. 2010. High-temperature phase change materials for thermal energy storage. *Renewable and Sustainable Energy Reviews* 14 (3):955–70. doi:10.1016/j.rser.2009.11.011.
- Khan, M. I. H., and H. M. Afroz. 2013a. Effect of phase change material on performance of a household refrigerator. *Asian Journal of Applied Sciences* 6 (2):56–67. doi:10.3923/ajaps.2013.56.67.
- Khan, M.I.H., and -H.M. Afroz. 2013b. Experimental investigation of performance improvement of household refrigerator using phase change material. *International Journal of Air-Conditioning and Refrigeration* 21 :1350029. doi:10.1142/S2010132513500296.
- Khan, M. I. H., and H. M. Afroz. 2014. Diminution of temperature fluctuation inside the cabin of a household refrigerator using phase change material. *Recent Advances in Mechanical Engineering* 3:43–52.
- Khan, M. I. H. 2016. Conventional Refrigeration Systems Using Phase Change Material: A Review. *International Journal of Air-Conditioning and Refrigeration* 24 (3):1–16. doi:10.1142/S201013251630007X.
- Kiran-Yildirim, B., T. Noya, E. Mancuhan, and S. Titz-Sargut. 2021. Investigation of Energy Consumption for a PCM Integrated Laboratory Scale Cooling System: An Experimental Study. In *23rd Congress on Thermal Science and Technology with International Participation (ULIBTK 2021)*, ed Prof. Yücel, 1002–8. Gaziantep, Turkey: Gaziantep University, Turkish Society of Thermal Sciences and Technology.
- Lane, G. A. 1983. *Solar heat storage: Latent heat material, vol I: Background and Scientific Principles*. Florida: CRC Press.
- Li, G., Y. Hwang, R. Radermacher, and H. H. Chun. 2013. Review of cold storage materials for subzero applications. *Energy* 51:1–17. doi:10.1016/j.energy.2012.12.002.
- Liu, D. Y., W. R. Chang, and J. Y. Lin. 2004. Performance comparison with effect of door opening on variable and fixed frequency refrigerators/freezers. *Applied Thermal Engineering* 24:2281–92. doi:10.1016/j.applthermaleng.2004.01.009.
- Liu, R., F. Zhang, W. Su, H. Zhao, and C.-a. Wang. 2015. Impregnation of porous mullite with Na₂SO₄ phase change material for thermal energy storage. *Solar Energy Materials and Solar Cells* 134:268–74. doi:10.1016/j.solmat.2014.12.012.

- Marques, A. C., G. F. Davies, J. A. Evans, G. G. Maidment, and I. D. Wood. 2013. Theoretical modelling and experimental investigation of a thermal energy storage refrigerator. *Energy* 55:457–65. doi:10.1016/j.energy.2013.03.091.
- Marques, A. C., G. F. Davies, G. G. Maidment, J. A. Evans, and I. D. Wood. 2014. Novel design and performance enhancement of domestic refrigerators with thermal storage. *Applied Thermal Engineering* 63 (2):511–19. doi:10.1016/j.applthermaleng.2013.11.043.
- Oró, E., A. De Gracia, A. Castell, M. M. Farid, and L. F. Cabeza. 2012. Review on phase change materials (PCMs) for cold thermal energy storage applications. *Applied Energy* 99:513–33. doi:10.1016/j.apenergy.2012.03.058.
- Pahamli, Y., and M. S. Valipour. 2021. Application of phase change materials in refrigerator and freezer appliances: A comprehensive review. *International Journal of Heat and Mass Transfer* 8:87–104. doi:10.22075/jhmtr.2021.21860.1316.
- Pavithran, A., M. Sharma, and A. K. Shukla. 2021. An investigation on the effect of PCM incorporation in refrigerator through CFD simulation. *Materials Today: Proceedings* 46:5555–64. doi:10.1016/j.matpr.2020.09.344.
- Pirvaram, A., S. M. Sadrameli, and L. Abdolmaleki. 2019. Energy management of a household refrigerator using eutectic environmental friendly PCMs in a cascaded condition. *Energy* 181:321–30. doi:10.1016/j.energy.2019.05.129.
- Sharma, R. K., P. Ganesan, V. V. Tyagi, H. S. C. Metselaar, and S. C. Sandaran. 2015. Developments in organic solid–liquid phase change materials and their applications in thermal energy storage. *Energy Conversion and Management* 95:193–228. doi:10.1016/j.enconman.2015.01.084.
- Suamir, I. N., I. M. Rasta, S. Sudirman, and K. M. Tsamos. 2019. Development of Corn-Oil Ester and Water Mixture Phase Change Materials for Food Refrigeration Applications. *Energy Procedia* 161:198–206. doi:10.1016/j.egypro.2019.02.082.
- Wu, X., M. Fan, S. Cui, G. Tan, and X. Shen. 2018. Novel Na₂SO₄@SiO₂ phase change material with core-shell structures for high temperature thermal storage. *Solar Energy Materials and Solar Cells* 178:280–88. doi:10.1016/j.solmat.2018.01.030.
- Xin, W., J. Fang, W. Jiang, L. Ping, L. Na, F. Yanhan, and L. Wang. 2019. Preparation and modification of novel phase change material Na₂SO₄·10H₂O–Na₂HPO₄·12H₂O binary eutectic hydrate salt. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 1–12. doi:10.1080/15567036.2019.1646843.
- Yilmaz, D., E. Mancuhan, and B. Yilmaz. 2020. Experimental investigation of PCM location in a commercial display cabinet cooled by a transcritical CO₂ system. *International Journal of Refrigeration* 120:396–405. doi:10.1016/j.ijrefrig.2020.09.006.