TEMPERATURE BEHAVIOR /CHARACTERISTICS OF STORED WATER AND PHASE CHANGE MATERIAL IN THE HOUSEHOLD REFRIGERATOR

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In rural areas, electrical power failure leads to the rise in temperature of the stored items in a household refrigerator. The use of phase change material (PCM) inside the refrigerator keeps the change in storage temperature to a minimum. This paper presents an experimental study of the temperature behavior of stored water inside the household refrigerator with and without PCMs: potassium chloride, sodium chloride, and sodium fluoride. The percentage reduction in drop of stored water temperature varies between 11.4% and 27.2%. The temperature drop of stored water during compressor on time helps to limit its temperature rise during power off time.

Keywords: Temperature behavior, phase change material, temperature drop/rise.

1. Introduction

Low temperatures are necessary for many perishables. Controlled temperature settings help to protect products from environmental damage, prevent losses, and ensure their quality and safety in each case. Temperature rise of storage stuff should be minimized because it may negatively impact the quality. Refrigeration plays a vital role in food preservation. By lowering the temperature, refrigeration inhibits the growth of microorganisms in perishable goods such as meats, dairy products, fruits, and vegetables. This preserves food quality, prolongs shelf life, and lowers food waste [1]. Electricity load shedding is the most common in India. During a power failure, a refrigeration system is unable to maintain the temperature of the cabin because of the heat gain through its walls and door opening. A technique to reduce temperature rise brought on by these heat loads is necessary because many of them are unavoidable. The use of cold thermal energy storage by the addition of phase change material (PCM) inside the refrigerator or freezer helps to minimize the change in storage temperature. [2]

When B. Gin et al. [2] placed anodized aluminum panels filled with PCM (a eutectic solution of ammonium chloride and water with a freezing point of

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-15.4 ºC) against the freezer walls, they discovered a little increase in the freezer's temperature during an electrical power outage. When the product and freezer air temperatures were compared, the freezer with PCM panels had fewer temperature fluctuations than the one without. He carried out research to determine how well PCM panels mounted on the inside walls of freezers maintained a constant temperature. After a 3-hour power outage, the product temperature stayed about 8 ºC lower when PCM was employed. Oro et al. [3] have determined that the use of PCM in a commercial freezer has resulted in a decrease in both the freezer's and its contents' temperature. The product temperature remained about 2 °C lower during the 3 hours of power outage when PCM was placed, keeping the freezing temperature between 4 and 6 °C lower. As a result, PCM use has improved food quality during frequent power outages. V. Raj et al. [4] created cold storage and used the phase change material Polyethylene Glycol 400 to improve performance and achieve an interior temperature that was 1-4 ºC lower than without PCM. In the event of an electrical power outage, the current study was conducted to ascertain how much the temperature of the air inside the cold room would rise. The primary objective of this experiment was to observe the decrease in temperature rise when PCM was employed inside the cold storage room. In the event of an electrical power outage, the experimental results demonstrated that the temperature maintained within the cold chamber was 1-4.5 °C lower when PCM was applied than when this was not. A. Omara et al. [5] review and assess several studies on the application of phase change materials (PCMs) for better performance and temperature control in household freezers and refrigerators. In addition to improving the COP and energy efficiency of refrigeration systems, the previous research covered in this review indicates that PCMs can reduce energy consumption, CO_2 emissions, and temperature changes in compartments. By installing commercial PCMs (OM32, OM29, OM03, and HS3N) at the freezer, refrigerator, and condenser, Karthikeyan et al. [6] investigated the effectiveness of vapour compression refrigeration systems. The findings of the trial showed that the vapour compression refrigeration system was more efficient. Compared to the situations of no PCM, PCM in the freezer, refrigerator, and condenser section, the PCM configuration at all locations has shown decreased temperature fluctuation: 3.9 ºC to 4.4 ºC in the refrigerator section. It has been discovered that the use of PCM arrangements at the freezer, refrigerator, and condenser can effectively reduce the temperature swings of the refrigerator. Rahimi et al. [7] affix a PCM box made of various materials to the evaporator's bottom surface. A phase change material is water with a melting point of 0 ºC. The effect of improving heat conduction across the PCM domain is further examined by inserting fins with various geometrical designs into the PCM slab. The results show that keeping a PCM slab below the surface of the evaporator keeps the cabin temperature within the acceptable range.

An extensive review revealed a unique opportunity to explore the effects of phase transition materials like potassium chloride, sodium chloride, and sodium fluoride on the storage temperature of household refrigerators.

In rural areas load shedding is major challenge. During power failure the cabin storage temperature rise occurs due to heat gain to refrigerators cabin. Use of PCM inside the cabin, limits the rise of temperature and provide the backup time. Few evidences found on investigations of effect of PCMs: KCl, NaCl and NaF on storage temperature of domestic refrigerator according to IS 1476 standard in literature undertaken by the authors.

Charging of phase change material during power on of domestic refrigerator store the cold thermal energy which is utilized during power failure time to absorb the heat gain to the refrigerator cabin thus the rise of storage temperature is reduced.

The specific objective of the research work is to study the impact of applying the above-mentioned phase change materials inside a household refrigerator on the temperature of the stored water. That is to study the temperature behavior /characteristics of stored water and phase change material in the household refrigerator.

2. Test facility and methodology

The test chamber, household refrigerator, PCM modules, temperature data logger, and temperature sensors make up the test facility, as seen in Fig. 1 [8]. The household refrigerator is evaluated inside the test chamber, which has a width, depth, and height of 1120 × 1104 × 1930 mm, respectively, to make sure heat reaches the refrigerator and to replicate the chamber environment in domestic use. The test chamber's inner wall is fully insulated to prevent heat from being added or leaking, which helps to keep the chamber's temperature at the ideal level. A variable-speed fan and a heater controlled by a temperature controller are positioned at the top of the test chamber. In accordance with IS 1476 [9], this heater provides heat to the test chamber in order to keep the temperature there at 32 ± 0.5 ºC. The test chamber's air circulation allowed for the achievement of the desired ambient temperatures within the given tolerance ranges. To keep the temperature consistent, the fan is utilized to move air around the chamber. According to IS 1476, the air velocity inside the test chamber is kept at about 0.6 m/s. The test chamber's air has a relative humidity of 45–50%. The impact of using phase change material on the temperature of stored water is examined using a household refrigerator with an internal volume of 165 liters. The freezer compartment was dried prior to the test in order to mitigate the impact of relative humidity, and the cooling coil was kept free of frost buildup throughout the test. To avoid direct radiation from the space heating or ventilation equipment in the test chamber, a refrigerator is positioned there. According to P. Bansal et al. [10], the thermostat is set to the refrigerator cabin's lowest internal temperature of 5 ± 0.5 °C. The lowest temperature in the freezer is maintained at −15 °C ± 0.5 °C [10]. Experimental tests are conducted, and measurements are taken as per the guidelines stated by the standard IS 1476.

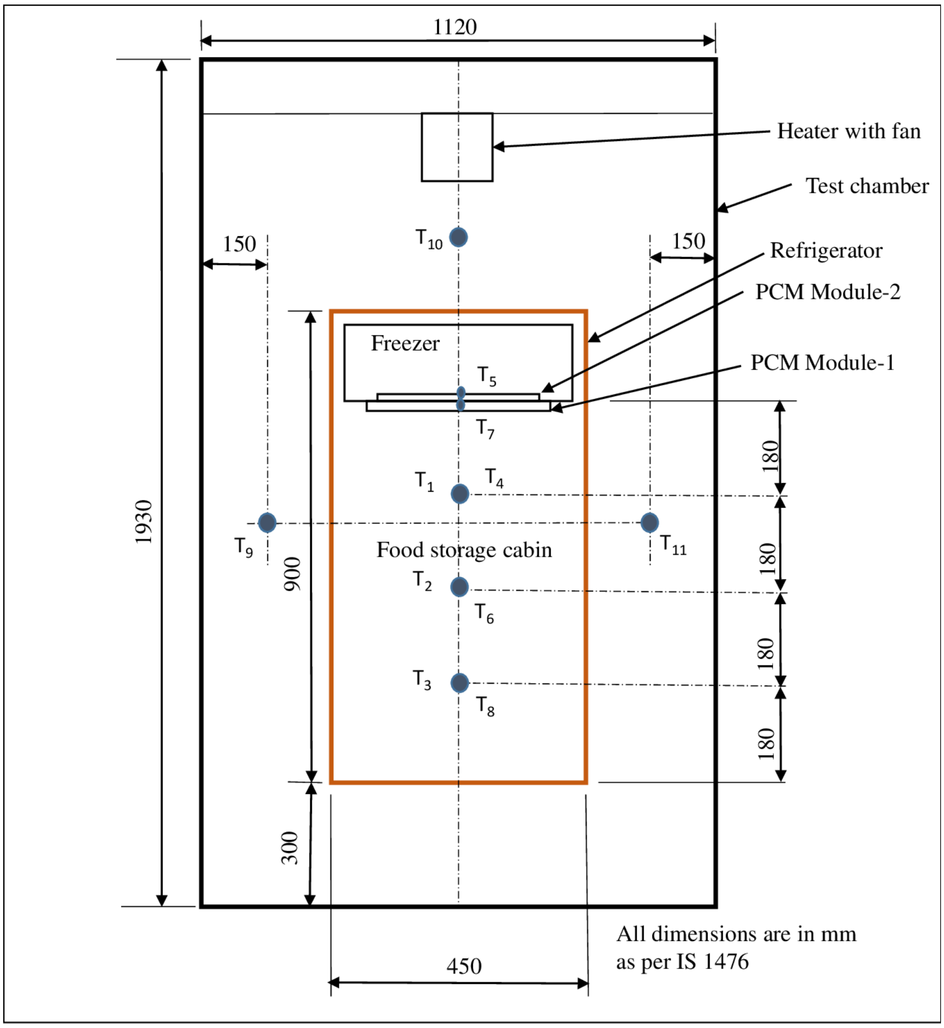


Fig. 1. Test facility [8]

2.1 Phase change material

A phase change material (PCM) is a material that, at a specific temperature, releases its stored cold thermal energy during melting and stores it while freezing. In low-temperature applications, such as refrigerators and freezers, it helps to lower the temperature increase that results from heat entering the chilled compartment. In order to keep the system's temperature stable, phase change material (PCM) alters its phase by absorbing latent heat from the system. These materials often have a low melting point. Three eutectic-type phase change materials named potassium chloride, sodium chloride, and sodium fluoride are used for testing. The physical properties of them (i.e., freezing temperature, specific heat, and latent heat) are identified based on literature data elaborated in Table 1.

Table 1

Thermo physical properties of PCMs

Material	Concentration (%wt) + H_2O	Freezing Temperature (ºC)	Specific Heat (kJ/kg °C)	Latent Heat (kJ/kg)	References
KCl	10	-6.6	3.84	283	[11], [12]
NaCl	10	-5.0	3.85	289	[13]
NaF	3.9	-3.5	4.06	314	[14]

2.2 PCM module

In this investigation, the PCM to be tested is filled into a container known as a module. The module material is stainless steel S304 because the PCMs employed in this research work are corrosive in nature [15]. PCM modules of 0.5 kg, 0.75 kg, and 1 kg storage capacities are employed in the testing process. The existing freezer section of a household refrigerator can only hold a maximum practical PCM mass of 1.75 kg.

2.3 Thermal mass

The total quantity of heat energy that must be extracted from the refrigerator's interior in order to maintain the required low temperature inside the refrigerator cabin is referred to as the thermal mass or thermal load. An efficient method of simulating the thermal mass of a household refrigerator is to uniformly distribute bottles with a total of 15 kg of water inside a refrigerator storage compartment.

2.4 Temperature data logger

For better capturing of temperatures, the best possible positions of the 12 Pt-100 temperature sensors with an accuracy of 0.1 ºC in the test chamber, as shown in Fig. 1, are identified according to the standard IS 1476. A 16-channel data logger with an accuracy of 5 volts is used for the continuous recording of all temperatures of the test. The accuracy of the temperature controller is 0.1 ºC.

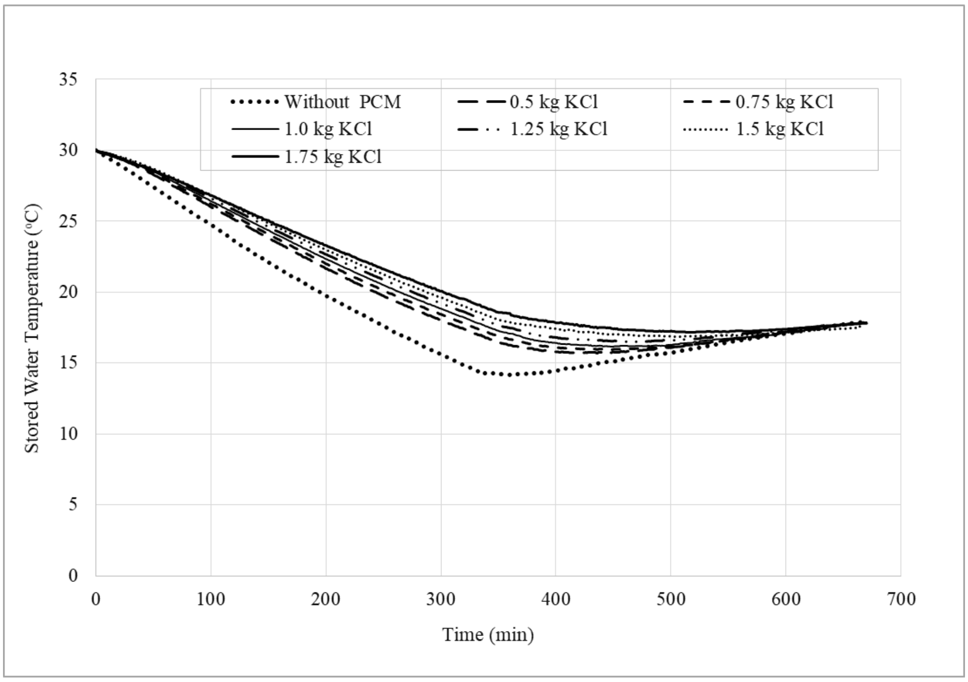
2.5 Test Methodology

Each test consists of two components: a 6-hour compressor on time and a 310-minute temperature rise during compressor power off. PCMs: KCl, NaCl, and NaF of masses 0, 0.5, 0.75, 1, 1.25, 1.5, and 1.75 kg each are tested both with and without PCM. Before the experimental test begins, the PCM temperature, average stored water temperature, and average cabin air temperature are all maintained at 30 °C. In the first part of the test, the refrigeration system removes the heat content of the cabin air, stored water, and PCM, lowering the temperature of the cabin, stored water, and PCM. In the temperature rise test, power of the compressor is shut down, thus cabin, stored water, and PCM temperatures are increased due to heat leakage to the refrigerator space. To study the behavior of the stored water temperature, these are continuously recorded for a time interval of every 1 minute during the tests carried out at an ambient temperature of 32 ± 0.5 °C and relative humidity 45-50% inside the test room according to the standard IS 1476. For all masses

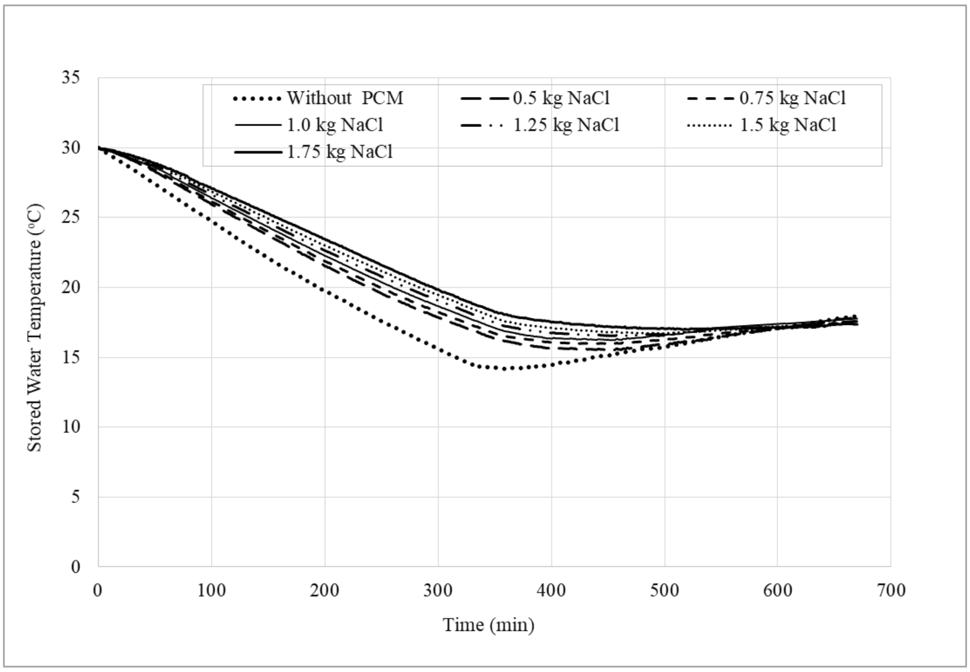
3. Experimental Results

3.1 Effect of PCM mass on stored water temperature

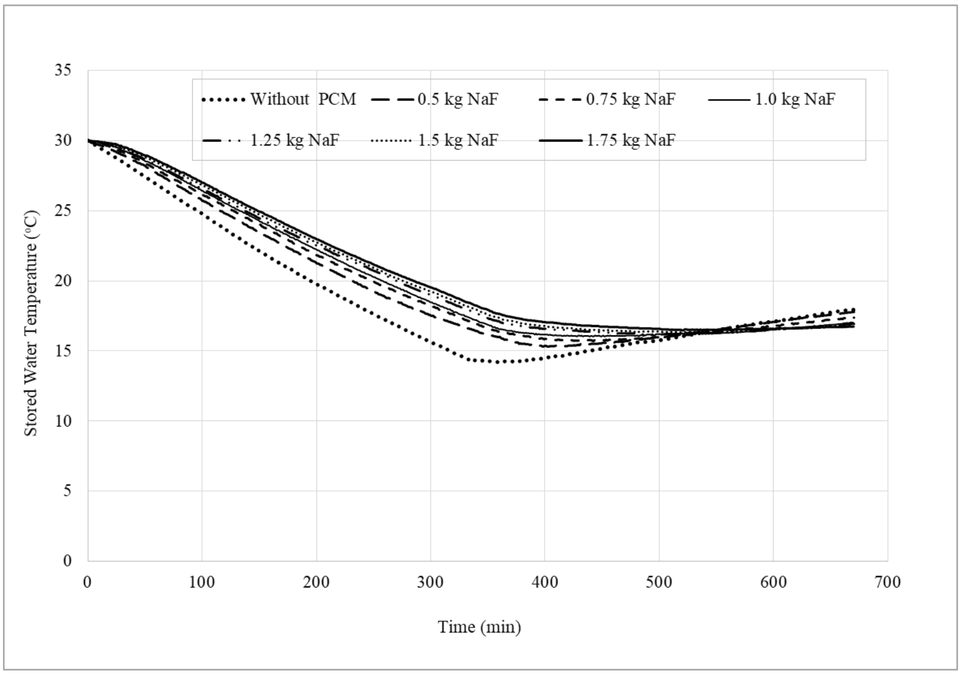
The variations in the temperatures of the stored water throughout the 6-hour compressor on time and the 310-minute compressor power off for PCMs are depicted in Fig. 2. (a)–(c). PCMs: KCl, NaCl, and NaF of masses 0, 0.5, 0.75, 1, 1.25, 1.5, and 1.75 kg each are tested with and without PCM. The PCM was charged with a cooling coil while the compressor was on, and the frozen PCM drew heat from the water that was stored after the compressor power off. Due to the PCM module's interaction with the cooling coil, the PCM's temperature dropped quickly while the compressor was on. This is when PCM gets charged. As the PCM's mass increases, the pace at which the temperature of the stored water changes slows. Therefore, the temperature curve of the stored water rises as the mass of PCM grows from 0 to 1.75 kg. Every PCM test shows this phenomenon. Due to PCM NaF's higher specific heat than that of PCM KCl and NaCl, the cooling rate of the stored water was quicker for PCM NaF. Compared to NaF and NaCl, PCM KCl's stored water cooled more slowly.


Without PCM
0.5 kg KCl
0.75 kg KCl
1.0 kg KCl
1.25 kg KCl
1.5 kg KCl
1.75 kg KCl
Stored Water Temperature (°C)
Time (min)
0
5
10
15
20
25
30
35
0
100
200
300
400
500
600
700

(a)


Without PCM
0.5 kg NaCl
0.75 kg NaCl
1.0 kg NaCl
1.25 kg NaCl
1.5 kg NaCl
1.75 kg NaCl
Stored Water Temperature (°C)
Time (min)
0
5
10
15
20
25
30
35
0
100
200
300
400
500
600
700

(b)



(c)

Fig. 2. Variation in stored water temperature during compressor on and power off time (a) KCl, (b) NaCl, (c) NaF.

During compressor on time for all masses load temperature varies from 30 ºC to 14.2 ºC for without PCM, it dropdown to 18.5 ºC for KCl, 18.07 ºC for NaCl and 17.65 ºC for NaF test respectively. The rate of change in load temperature becomes slower with the increase in mass of the PCM. Thus, as the mass of PCM increases from 0 to 1.75 kg, the load temperature curve moves upward. After power off, load temperature rises for tests without PCM, but temperature falls for tests with PCM masses because heat entering the cabin due to leakage is absorbed by PCM, and PCM also absorbs heat from the cabin load after power off.

3.2 Stored water temperature drop during compressor on time

Cold thermal energy stored by PCM is utilized to limit the change of stored water temperature during compressor on time. Fig. 3 shows stored water temperature drop for PCMs: KCl, NaCl, and NaF of masses 0, 0.5, 0.75, 1, 1.25, 1.5, and 1.75 kg each. The drop in stored water temperature decreases with an increase in PCM mass. It varies from 15.8 ºC to 11.5 ºC for 0 to 1.75 kg mass of all tested PCMs. PCM NaF shows the maximum drop in stored water temperature because of its good thermal properties (specific heat and latent heat).

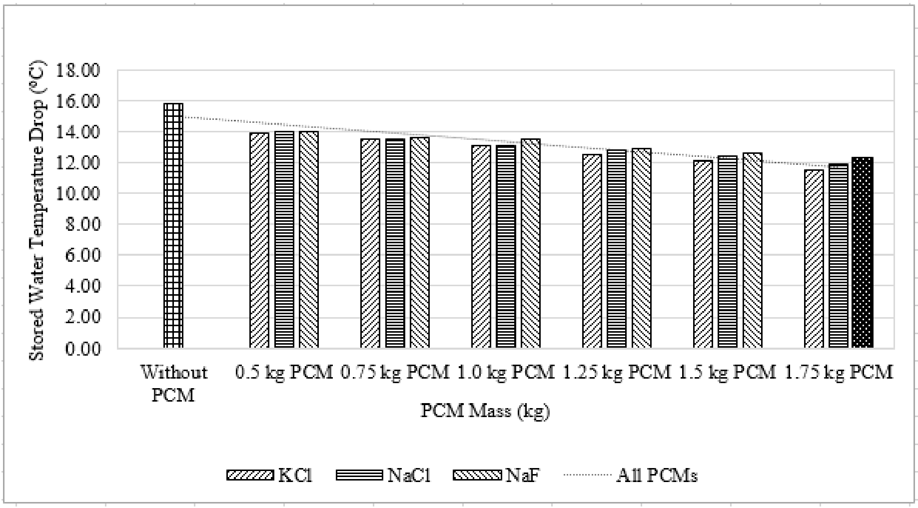


Fig. 3. Stored water temperature drop during compressor on time

Percentage reduction in drop of stored water temperature varies between 11.4% and 27.2%, shown in Fig. 4. Percentage reduction in drop of stored water temperature increases with mass of PCM. Percentage reduction in drop of stored water temperature is more for all masses of PCM KCl as compared for masses of NaCl and NaF because its higher thermal conductivity than PCMs NaCl and NaF. Thermal diffusivity of KCl is higher, thus thermal storage capacity of KCl is good.

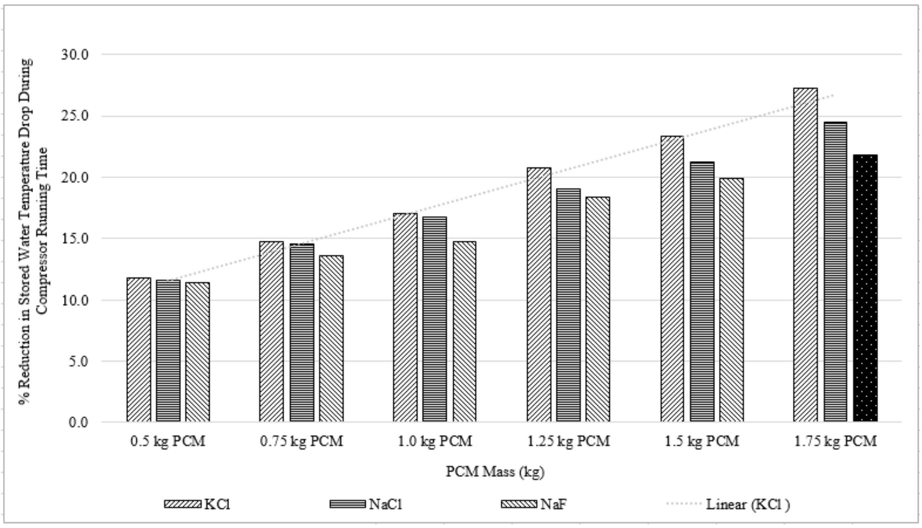


Fig. 4. % Reduction in stored water temperature drop during compressor on time

3.3 Stored water temperature rise or drop during compressor power off time

The second component of the test is followed by a compressor on time of 6 hours. The compressor was shut down for a period of 310 minutes. Rise or drop of stored water temperature during compressor power off for all masses of PCM is shown in Fig. 5. The stored water temperature began to increase owing to the leakage of heat from the surroundings into the compartment of the refrigerator.

The temperature rise was high for the test without PCM. The temperature rise was limited in all PCM mass tests because of the absorption of heat by PCM (cold thermal energy storage) leaked from surrounding to the compartment. The rise of stored water temperature is lessened as the mass of the PCM increases. For a higher mass of PCM, the rise in stored water temperature is less. Hence the stored water temperature curve of PCM Naf 1.75 kg mass shows the least temperature rise than the others because of two reasons: first, a higher mass and second, higher specific heat and latent heat values than the other masses of KCl and NaCl PCM.

The change in stored water temperature during compressor off time is almost minimized by the use of PCMs. Hence, compressor off time can be termed as backup time provided by PCM. During the backup period of 310 minutes, the maximum rise of stored water temperature is found to be 3.73 ºC for a test without PCM and 1.8 ºC for 0.5 kg of PCM; however, for 1.75 kg of PCM NaF, the temperature drop is -0.92 ºC. After a 310-minute power off, the stored water temperature stayed about 1.2 °C lower when PCM NaF was used. The drop in the stored water temperature continued during power off time because of heat transfer from stored water to the frozen PCM. It continues till cold thermal energy stored in PCM is utilized to absorb the heat of stored water. This is a benefit of PCM. Thus, PCM limits the rise of stored water temperature. The drop in the stored water temperature is more for PCM NaF of 1.75 kg during compressor power off because of its thermal properties (specific and latent heat) being higher than those of PCM KCl and NaCl. These properties help the PCMs to store the cold thermal energy during charging time i.e compressor on time and is released during the compressor shut down time which absorbs the heat gain to the refrigerator cabin and thus limit the rise of cabin storage temperature.

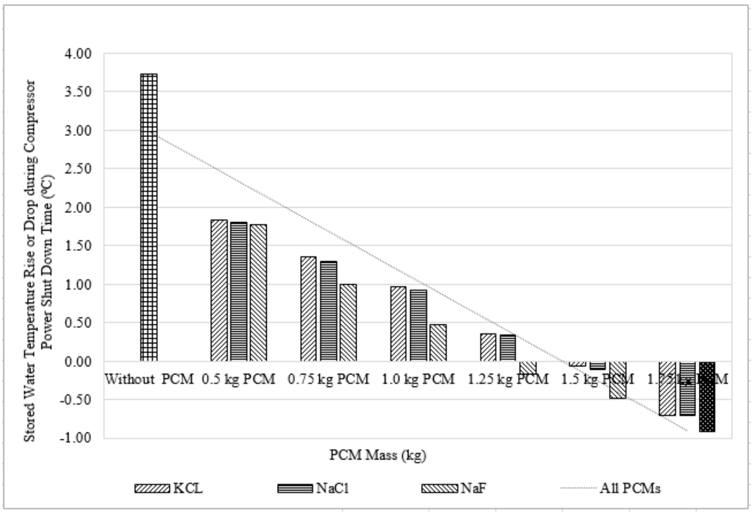


Fig. 5. Stored water temperature rise or drop during compressor power off time of 310 minutes

4. Conclusions

The research work illustrates the temperature behavior of stored water inside the household refrigerator equipped with different masses of PCMs: potassium chloride, sodium chloride, and sodium fluoride of masses 0 kg, 0.5 kg, 0.75 kg, 1.0 kg, 1.25 kg, 1.5 kg, and 1.75 kg. Temperature of stored water is dropped during compressor on time of 6 hours and is increased during compressor power off time. Temperature drop of stored water during compressor on time (period of running) varies from 15.8 ºC to 11.5 ºC for all masses. The percentage reduction in drop of stored water temperature is more for all masses of PCM KCl as compared for masses of NaCl and NaF because of its higher thermal conductivity than PCMs NaCl and NaF. Thermal diffusivity of KCl is higher, thus thermal storage capacity of KCl is good. The temperature drop of stored water during compressor on time assists to limit the rise of temperature of stored water during compressor power off time; accordingly, it keeps the rise in storage temperature of the household refrigerator minimum. As PCM mass increases, the temperature drop of stored water decreases during compressor on time. During the backup period of 310 minutes, the maximum rise of stored water temperature is found to be 3.73 ºC without the PCM test and 1.8 ºC for 0.5 kg of PCM; however, for 1.75 kg of NaF PCM, there is a drop in temperature of -0.92 ºC. The drop in the stored water temperature is more for PCM NaF of 1.75 kg during compressor power off time because of its thermal properties better than PCM KCl and NaCl. After a 310-minute power off, the stored water temperature stayed about 1.2 °C lower when PCM NaF was used. Due to space limitations in the existing refrigerator, the maximum PCM mass tested is 1.75 kg. PCMs can be tested for further increase of mass with the same thickness of PCM module in a household refrigerator with higher storage volume.

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