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# EXPERIMENTAL STUDY ON THERMAL ENERGY STORAGE PRODUCED BY SOLAR ENERGY FOR DRIVING DOMESTIC FREEZER

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## Abstract

A prototype of photovoltaic based domestic chest type freezer was constructed, the prototype incorporates Phase Change Materials (PCM), as a thermal storage medium. Thereby, the units can work without the aid of the conventional batteries. A eutectic potassium chloride (KCl) aqueous solution was prepared to serve as phase change material. The PCM was stored in an integrated tank within the freezer box. Using PCM enables the freezer to preserve its cool storage at a temperature level below (-8 °C) for a holdover period not less than 30 hours without the need for power supply. The effect of PCM mass and PCM integrated storage tank thickness on the thermal performance of the freezer were studied experimentally. The experimental results showed that for 7 mm integrated storage thickness; the freezer box reaches steady state condition in two days with net compressor period operating time of 16 hours in which, the PCM changes from liquid to solid phase. The minimum temperature obtained was (-10 °C). In 18 mm integrated storage tank thickness three days of net compressor period operating time of 24 hours was required to reach steady state condition. In which, the minimum PCM temperature was (-8 °C). The study was extended to find the effect of frequently freezer door opening on the thermal performance of freezer.

Keywords: Battery-free refrigerator, Domestic refrigerator, PCM, Solar refrigeration.

## 1. Introduction

Photovoltaic refrigeration is a promising technology for the sake of minimization of Greenhouse Gas Emissions (GHG). The developed power from PV panels can be stored into thermal energy. The stored energy can be in the form of sensible and/or latent thermal energy. Sensible energy storage is based on the temperature rise of the material. While the latent thermal energy storage is based on the store and release of the required energy to change the substance phase.

The phase change can be from solid-liquid, liquid-gas, solid-gas and vice versa [1]. Also, it can be in the sensible form such as changing the temperature of solid materials. Latent heat stored is an attractive solution for practice, due to the higher energy density of storage within an isothermal process. The thermal energy storage system, that utilizes the solid-liquid phase change, requires an easier containment design, due to its small volume expansion. Solid-liquid phase change experiences of less than 10% of volume change upon melt/freezing. Usually, the phase change process occurs in an isothermal manner where the material begins to crystallize while the temperature remains constant until the phase transition ends and all the latent heat of fusion is released.

As shown in Fig. 1, there are four significant parts, the first one is the liquid sensible cooling curve in which, it has a steep slope followed by a dip of a less level of melting temperature in which, the latter has a flat plateau over the period of the freezing process. Finally, the curve continues to go down for the process of solid sensible cooling, the dip in the curve represents the amount of supercooling in which, it is known as the process of temperature reduction, that liquid experience below the freezing temperature without phase change in solid. At that point, the liquid start to nucleate and the crystal begin to grow until full freezing is done [2].

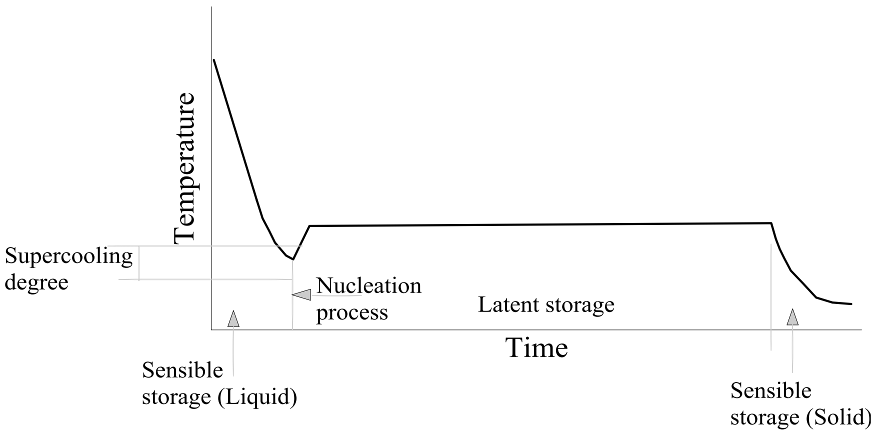



**Fig. 1. Freezing behaviour of an inorganic salt-water solution with a supercooling tendency [2].**

Onyejekwe [3] done some earlier work in the late eighties when he developed a parametric study to optimize the PCM container shape, its thermal characterization, volume, PCM stratification and cyclic stability. The study used a conventional refrigerator that is powered by AC power. El Tom et al. [4] made the earlier steps into using PV for refrigeration without PCM backup. Toure and Fassinou [5] studied the experimental and thermodynamic aspect of cold storage autonomy in a three compartments photovoltaic refrigerator. The cold storage was water being employed as PCM to increase the system's autonomy. Ewert et al. [6] published reported results on a number of PV panel battery-free refrigerators, in eight locations around the world. Most of the eight locations were lie in the USA and the others were in Mexico, Guatemala and South Africa.

Further, Pedersen et al. [7] developed a battery-free PV refrigerator that is backed-up with thermal energy storage instead of battery backup power. This refrigerator was designed to be vaccine cooler with box temperature falling in the range of (0 to -8ºC). Tulapurkar et al. [8] developed a novel dual evaporator with PCM for a domestic refrigerator. Cheng et al. [9] studied the effect of replacing the traditional condenser of a household refrigerator by kind of shape-stabilized phase change material (SS-PCM) on the refrigerator performance. The authors mentioned that adding SS-PCM to the condenser reduced the condensing temperature, as well as increased the degree of sub-cooling of the refrigerant. As a result, the cycle COP enhanced and the ratio of working-time to the total cycle time of the novel refrigerator was much smaller, as compared with that for the traditional refrigerator.

Liu et al. [10] have made a comparative experimental study on the performance of solar photovoltaic (SPV) refrigerator with cold storage PCM, SPV refrigeration without PCM and a conventional refrigerator. Oro et al. [11] studied by the effect of using low freezing point of PCM in a thin plate. The aim of their work was to investigate the effect of using PCM to improve the thermal performance of a commercial freezer. The importance of PCM selection was demonstrated. Khan and Afroz [12] employed an immersed evaporator coil inside a PCM tank in a household refrigerator. They have investigated the effect of PCM presence on refrigerator performance with and without PCM. Marques et al. [13] yet made a novel design and performance study on enhancing the performance of domestic refrigerators with thermal storage.

El-Bahloul et al. [14] have studied experimentally the performance of solar driven with DC motor vapour compression refrigerator in order to investigate the design and operation of thermal storage refrigeration. The study extended to find the system performance with/without thermal storage and with/without loading. Li et al. [15] investigated the effect of thermophysical parameters of PCM on the thermal performance of a PCM-introduced in a double-glazing system. The authors showed that the thermal performance of the PCM filled double glazed unit was improved by increasing the density, specific heat capacity, latent heat, thermal conductivity and melting temperature of the PCM materials. Sze et al. [16] studied the performance of thermal storage of a non-eutectic phase change materials at a wide range of storage temperatures. The PCM used in the study was a solution of ethanol and aqueous ethylene glycol. The PCM that use high-grade cold thermal energy storage showed no issue of phase separation, as well as the low degree of supercooling, was achieved.

Suttaphakdee et al. [17] studied numerically the performance of the PCM that produced by the combination of incorporating paraffin and recycle block concrete. They found that the best adsorption ratio of paraffin in recycling block concrete was 25% by weight. The latent heat and transition temperature of fusion for the proposed PCM were about 31 J/g and 52.85 °C respectively. Cheng and Zhai [18] studied the performance of a three-stage cascaded cold storage unit (CCSU) experimentally, the packed bed of the cold storage unit (CSU) was filled with three types of PCM of different phase change temperatures. A one-dimensional mathematical model was used to validate the experimental data. Many key variables were studied, namely; exergy efficiency, charging time and accumulated cold stored ability. This work gives an evolution for the solar-powered freezer by shifting the need for inverter and batteries. The DC compressor is driven by direct connection with the solar panels. A PCM is introduced through the refrigerator walls to store latent heat at daytime, while at night the phase change materials tend to absorb the heat from refrigerator cabinet. The variables studied in this work are the mass of PCM. Two masses of PCM are used namely, 4.7 kg and 12.5 kg. Two PCM containers type are used, in this work.

## 2. Experimental Work

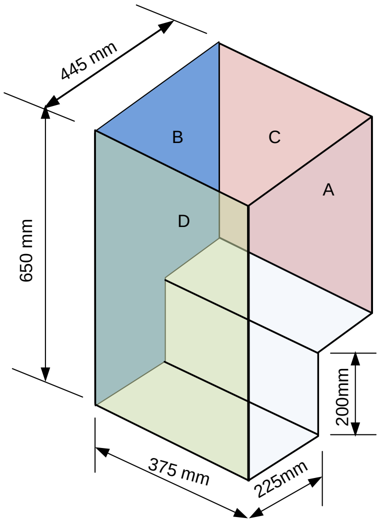
A 100-litre chest type freezer is used in this work. Refrigerant R134a is the working fluid. The freezer has a cooling capacity of 86 W at inside temperature of (-26 ºC) as specified by the manufacturer datasheet of the freezer compressor (HUAYI B38H). Technical data of the freezer are listed in Table 1. Figure 1 shows freezer internal dimensions and indicates the faces that are adjacent to the PCM storage tank. The PCM storage unit is made from rectangular aluminium tubing of two cross-sections. The first one rectangular with dimensions of 40 × 20 mm and the second tubing is a semi-rectangular one with special geometry that allows the consecutive tubing to be male-female connected. This tubing has bulk dimensions of 90 × 9 mm. Two separate PCM tanks were constructed using those tubing, being cut to the appropriate length just to cover all around the freezer interior walls and making a layer to contain the PCM. In order to prevent liquid PCM from leakage, both tubings are sealed from below by 2 cm of expandable polystyrene, followed by 3 cm of polyurethane. Figure 2(a) shows a photograph of the PCM tank that is constructed for the experimental test rig.

**Table 1. Technical specification of the chest freezer.**

| Specification | Value |
|---|---|
| **Power supply (voltage/frequency)** | 220~240/50 Hz |
| **Displacement (cm³)** | 3.8 |
| **Cooling capacity (W)** | 86 |
| **Power consumption (W)** | 86 |
| **COP** | 0.95 |
| **Motor type** | RSIR |
| **Refrigerant/amount (gram)** | R-134a/55 |
| **Internal volume (L)** | 100 |
| **Insulation material/thickness (cm)** | Polyurethane 6.3 mm |

Eutectic potassium chloride aqueous solution (KCl + $H_2O$) is selected as a PCM in the experimental work. KCl is one of the ingredients of some foodstuffs such as table salt substitute. KCl aqueous solution shows corrosiveness against some common metallic objects. It was found that at specific concentrations the solution has the lowest aggressiveness against aluminium. That was the reason for choosing aluminium as a containing material for the PCM. The thermo-physical properties are shown in Table 2. The chemical composition of KCl are 99.5% assay, 0.01% bromide, 0.002% iodide and 0.0005% phosphate.

Twelve thermocouples of type-*K* are implanted in a vapour compression cycle, PCM containers and the refrigerated cell. Eight of these thermocouples are implanted in the PCM container as shown in Fig. 2(b). Rest of thermocouples are one the midway of freezer condenser tube, one adjacent to freezer interior wall concealed behind PCM container and the last one is hanged inside freezer interiors. All thermocouples are calibrated to an accuracy of 0.5 °C. An external extension is developed to connect the thermocouples to 12 channels data logger.




**(a) Internal dimensions chest freezer.**


**(b) Top view of PCM containers configuration.**

**Fig. 2 The internal chest freezer specifications.**

**Table 2. Thermo-physical properties of the KCl [14].**

| Property | Value |
|---|---|
| **Melting/freezing point** | - 10 °C |
| **Latent heat of fusion** | 253 kJ/kg |
| **Specific heat (liquid/solid)** | 3.25/2.108 kJ/kg K |
| **Density liquid/ solid** | 1126/1105 kg/ $m^3$ |
| **Thermal conductivity (liquid/solid)** | 0.6/2.22 W/m K |
| **Molar mass** | 74.55513 kg/kmol |

A commercial digital DC power meter with the model number (MS6170) is used to measure the current, voltage, watt and register the maximum and minimum voltage and current, watt hour, ampere-hour and total run time. All these data are logged in the meter and can be retrieved to a PC via an optional data adapter and software.

A (TES 1333) solar radiation meter was used to measure the total solar radiation incident on the PV panel tilted surface, being placed vertically upward off the PV array tilted plane; data measurement was taken at an interval of one hour on a daily basis through each test run. The experimental accuracy is shown in Table 3.

A 300 W solar panel is connected in parallel with a 200 W panel to act as a power source to the DC powered refrigerator. The PV array has a maximum efficiency of 15% with a maximum power production of 500 W at standard test condition, which is 1000 W/m$^2$ of Global solar radiation and PV cell temperature of 25º C. Table 4 lists the technical data related to the PV panel. A 20 Amp DC-DC power converter is used to lower the voltage of PV array from 36 to 12 V. The generated power is used to feed an 1100 W power inverter that converts the 12V DC into 220 V/50 Hz to provide alternating current to power the freezer. The test rig block diagram is shown in Fig. 3.

**Table 3. Experimental accuracy.**

| Variables | Accuracy error |
|---|---|
| **Thermocouple** | ± 0.5 ºC |
| **Power data logger** | ± 0.1 W |
| **Solar power meter** | ± 10 W/m$^2$ |

**Table 4. Manufacturer technical data of PV panels.**

| Specification | Value | |
|---|---|---|
| | **PV (300 W)** | **PV (200 W)** |
| **Peak power voltage (Vm)** | 35.8 V | 36 V |
| **Maximum power current (Im)** | 8.37 A | 5.56 A |
| **Open circuit voltage (Voc)** | 44.8 V | 45.8 V |
| **Short-circuit current (Isc)** | 8.93 A | 6 A |

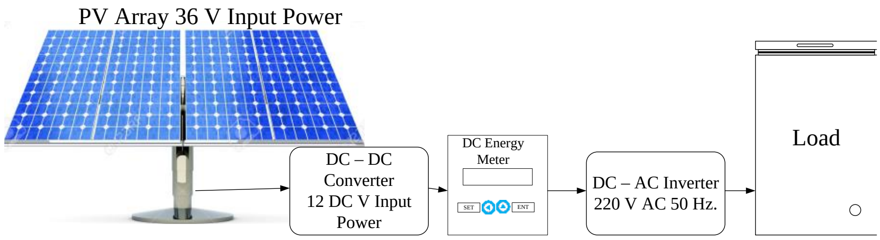



**Fig. 3. Test rig electrical wiring block diagram.**

In order to supply power from PV array to the freezer through the inverter, it was found that PV array is never able to start freezer compressor due to high torque of compressor during the moment of starting, but PV array is able to furnish the steady current to the compressor. Two solutions were at hand; the first was to employ a soft starting electronic module, it is designed so that it reduces the torque requirement of 10-50% by extending the starting time from millisecond to 6-10 seconds.

This module has a drawback of constraining the operational time on solar mode to only three hours rendering the system inefficient. So, this solution was not suitable for a PV operated freezer that we hope to operate efficiently for longer possible periods. Another solution is to employ the grid electricity to help the compressor to start for only 10 seconds. While the freezer is working, a switching mechanism is interfaced to bring the inverter electricity output to the freezer isolating the grid electricity in on time. This approach helped the compressor to be able to work on an early morning from 8 a.m. until 4 p.m. Two contractors were used; to prevent the overlapping troubles that will lead to damage the power inverter when grid electricity flows back to inverters 220 V outlet.

## 3. Results and Discussion

In order to investigate the stability of PCM solution upon multiple freezing/melting cycles a sample of 200 gram of (KCl + $H_2O$) of eutectic concentration was placed in a freezer. Performance of PCM temperature sample was monitored manually to control the freezer on and off, by turning the freezer on when the PCM temperature is between 0 and -15 ºC. The freezer was off when exceeding these temperatures limits. The reason for these temperature cycling is to make a maximum possible number of cycling test within a period of four days. Temperature observation from data logger showed an average PCM temperature of (-10 ± 4.6 °C) and that of internal air of (-16.3 ± 7.9 °C) through the freezer working period.

### 3.1. Behaviour of freezing and melting curves

The behaviour of freezing and melting curves at each cycle is shown in Fig. 4. It is clearly noticeable from the figure, that the PCM has a freezing temperature of about (-11 ºC) and the melting temperature of (-8 ºC). This is one of the characteristics of salt solutions that have different melting and freezing points. Besides, there is a deviation of (1 °C) in the general trend line of freezing and melting processes between the first cycle and tenth cycle. This deviation is due to salt precipitation accumulatively upon each melting cycle. Thereby, precipitation of KCl causing the PCM to have its thermal properties changed and then reducing its energy storage capacity. In the first freezing cycle PCM, it was noticed that there was a subcooling of (1.2 ºC), two subcooling points were detected in this test this was due to the start of the crystallizing of ice and salt. The starting solution has a salt concentration, which is lower than the eutectic concentration. Therefore, it is safe to say that the first jump indicates the start of ice crystallization because the ice line is reached first and then followed to the eutectic point. This means the second jump indicates the starting point of the salt crystallization. This is also where the eutectic temperature is reached. According to the temperature graph, the eutectic temperature is -10.8 °C. Pronk [19] given close value, which is -10.6 °C.

### 3.2. Compressor operation periods

Many tests were carried out to find the best operation period for compressor, these test can be useful in selecting the PV area, and the first test was achieved under the following conditions; 4.7 kg of PCM that represents the full mass capacity of 7 mm thickness PCM container, 2.25 kg of water as internal load for the freezer. The operating time for this test was 118 hours (nearly 5 days). The result of this test is shown in Fig. 5. It can be seen from this figure, that the first compressor operating period was about 7 hours. During this period, the PCM temperature fell from 18 to about -11 °C, as the compressor stopped the PCM temperature, which increased rapidly. This indicates that the PCM is still in the liquid phase.

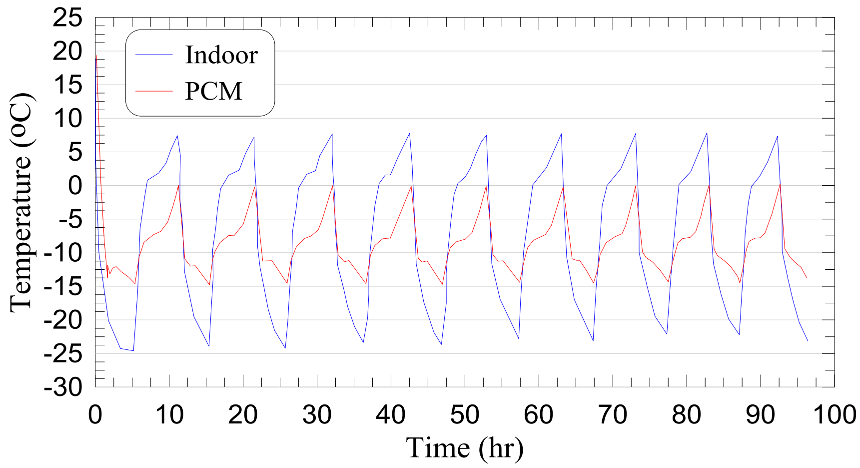



**Fig. 4. Cycling test on eutectic KCl aqueous solution (10 cycles).**

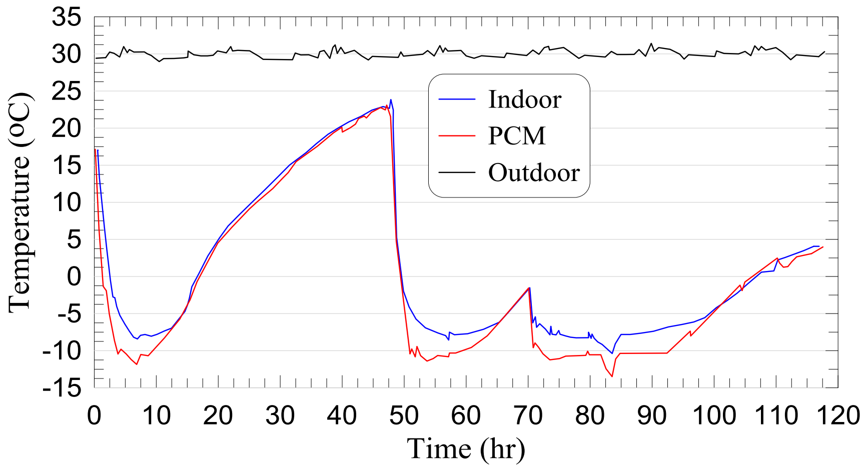



**Fig. 5. Temperature evolution of internal air, PCM and ambient temperature.**

The second operating period was selected to be 10 hours. It can be seen from the figure, that as the compressor turns off, the PCM temperature increases. But, there is a time delay when the temperature increases. This means, that the PCM has been partially solidified. In the third trial, the compressor operating period was 14 hours and the PCM temperature dropped to (-13.5 ºC). The freezer was turned off for the rest of the test time, i.e., from 82$^{nd}$ to 117$^{th}$ hours the data showed a constant PCM, internal air temperature plateau of (-10.5 ºC) for PCM and (-8 ºC) for air in eight hours. After that, PCM was completely melted and started to absorb the sensible heat for 15 hours until the PCM and air reached 0ºC. Through this test run, it was not purely solar powered one (assisted with grid electricity) for the excess hours (above 8 solar hours), but it showed the behaviour of thermal storage with a small thermal load of 2.25 kg of water.

In order to find the effect of cloudy day on the operation of the freezer, the second test was achieved; the compressor operating time was 14 hours and miscellaneous foodstuffs in freezer box filled with 60% of box volume. After continuous 14 hours of operation, PCM temperature was reduced to (-13.6 °C). The freezer was left off for the next 34 hours to simulate the effect of low availability of solar energy. PCM temperature showed a plateau for about 8 hours as shown in Fig. 6. After the PCM was fully melted, it began to absorb sensible heat and its temperature along with freezer internal air increased in the same manner for 8 hours until the PCM and internal air temperature reached 0 ºC. As a result of receiving solar radiation, compressor motor starts and PCM temperature falls to about (-10 °C) at the end of 8 hours compressor operation period.

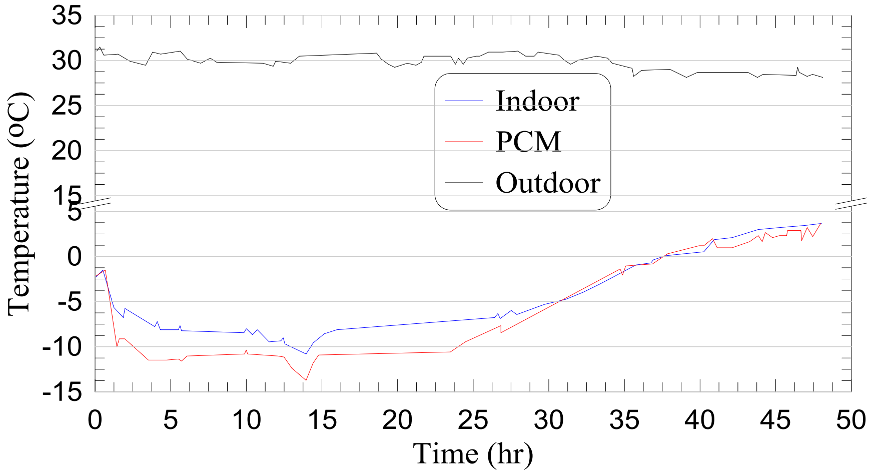



**Fig. 6. Temperature evolution of internal air, PCM and ambient temperature.**

Another test was conducted in five consecutive days from 1st to 5th May, 2014, using 7 mm thickness aluminium container fully filled with 4.7 kg of PCM, besides adding a thermal load of 10 kg of apricot jam. The freezer was operated on solar energy for eight hours a day. Figure 7 shows the temperature evolution of PCM, internal air, ambient temperatures and global solar radiation. It can be seen from the figures, that the PCM, indoor and ambient temperatures are the same as the initial starting time. As the current PV panels produced as a result of receiving solar radiation, freezer motor starts and PCM temperature falls to about (-10 °C) at the end of 8 hours compressor operation period.

The compressor stops for about 16 hours during sunset time and this tends to increase PCM temperature to (8 °C). With another 8 hours operating period, the PCM temperature falls again to about (-11 °C). The second period of compressor shutdown makes the PCM temperature increase to about (-4 °C). After two days, the motor shutdown period has an insignificant effect on PCM temperature. From the figure, it can be seen that the PCM and inside air temperatures are stabilized at about (-10 °C). This means that the PCM has been solidified and the shutdown period makes the PCM melt partially without increasing in temperature. The reduction in PCM temperature at sunset time for days 4 and 5 means that there is a sensible cooling in PCM. From the above mentioned, it can be concluded that the PCM solidification temperature is about (-10 °C).

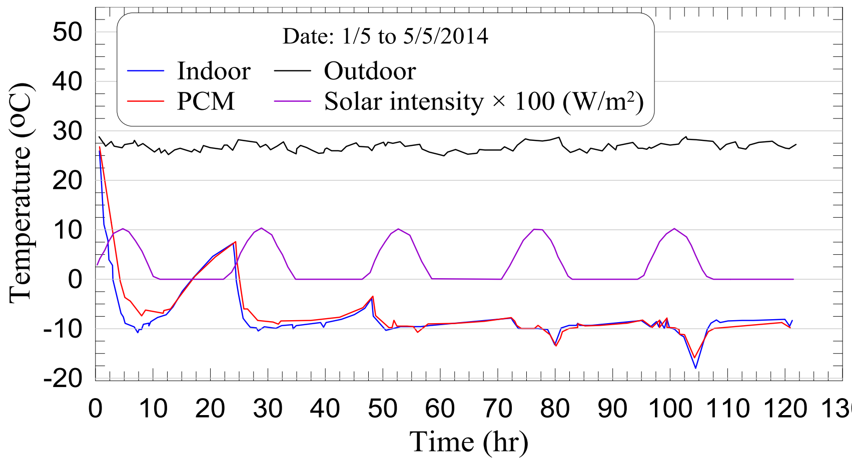



**Fig. 7. Temperature evolution and solar radiation variation.**

The data derived from Fig. 6 shows that the average ambient temperature through the five days is 26.8 ºC and the minimum temperature recorded for the PCM was (-18.2 ºC). Clearly, this minimum temperature was noticed at the end of solar day five because a large portion of heat was removed from the PCM through the previous days. Similarly, the minimum temperature recorded for the internal air was (-17 ºC) and it was conjugated with that of PCM mentioned earlier.

By taking a closer view to the variation of internal and PCM temperatures through day one (unsteady period). It can be seen that the first eight hours of operation in Fig. 6, are just not enough to remove all of the liquid sensible heat of PCM. That is not surprising since the presence of thermal load inside the freezer is slowing the process, and the PCM temperature is reduced rapidly from 28 °C to about (-10 °C) in about 8 hours. While the time required for increasing PCM temperature to about 8 °C was about 16 hours. Internal air temperature evolution on day three, of the mentioned figure, where a steady state began to reach due to solidification of PCM. It is clearly noticeable that internal air temperature was very stable and was never 0.5 ºC higher than PCM during freezing and partially melting after the steady state reached. Minimum unstable PCM temperature recorded is (-13 ºC), while the PCM was stable at (-10 °C).

Another mass of PCM was selected as shown in Fig. 8. The mass of PCM used was 12.5 kg to fill 18 mm thickness aluminium containers; freezer was operated for five days, eight hours a day. Also, a thermal load was added inside the freezer (10 kg of apricot jam); it can be seen from the figure that for all five days operating time, the PCM temperature does not follow evaporate temperature exactly, and the time required to reach steady state is three consecutive operational days. This is due to the high mass of PCM. Also, the figure shows that the steady-state temperature of PCM was (-10 °C) as in 7 mm container thickness.

## 3.3. Effect of door opening on the cabinet temperature

A door opening test was carried out in 7 mm container thickness, right after its operational on the fifth day (on day six), ensuring a stable condition within its PCM and internal temperature sustained at low overshooting throughout the operation on and off periods. The pattern of the door opening was proposed as a two minutes opening every one hour under the same thermal load of the preceding five days (10 kg of apricots jam) as a thermal load.

Figure 9 shows the variation in internal, PCM and evaporator temperatures inside the freezer. The pattern of the door opening was extended even to the off period; a total number of door openings was 15 times. It can be seen from the figure. that even the inside temperature fluctuates over the day due to the door opening, but the PCM temperature shows more stability than inside air temperature. This is because the heat lost from PCM is latent heat, which does not affect PCM temperature. The result of the frequent door opening gradually increases in PCM and indoor to reach an end of the day to (-6 °C) for PCM and (-8 °C) for inside air temperature. The inside air temperature shows fewer increases than the PCM temperature at end of the day, this is due to the high thermal mass of food contents.

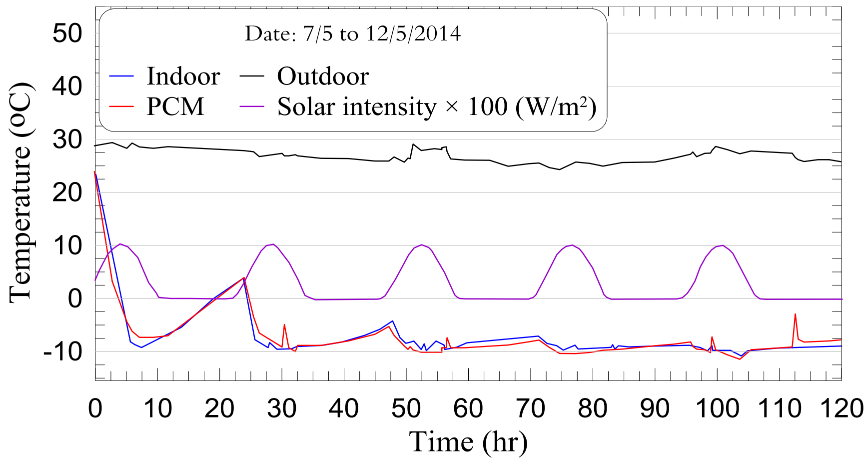



**Fig. 8. Temperature evolution and solar radiation variation.**

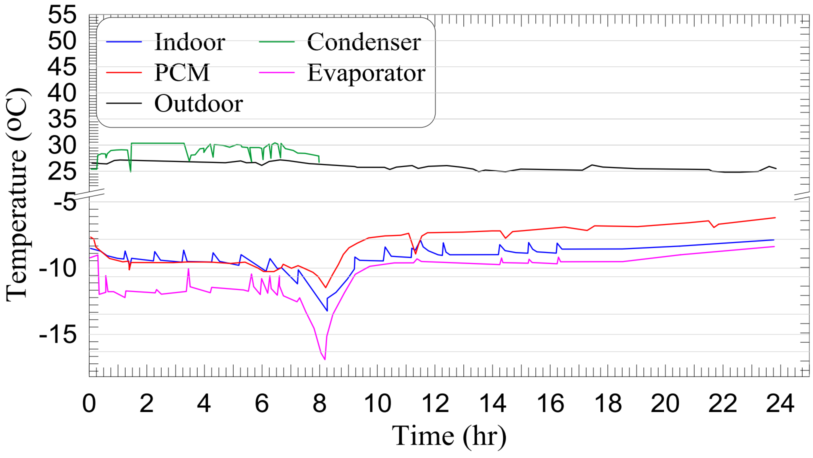



**Fig. 9. Overview on temperature evolution for door opening test.**

### 3.4. Effect of PCM thickness on the cabinet temperature

As it was mentioned before, to get the same height of PCM in the freezer, two types of containers were used in this work. The first was 7 mm thickness and filled with 4.7 kg of PCM and the second was 18 mm thickness filled with 12.5 kg of PCM. Figure 10 shows the internal air temperature evolution. It can be seen, increasing of PCM affects both inside air and PCM temperatures weakly, and this is due to the fact that the mass of PCM for both cases was less than the compressor capacity, it means that more PCM mass can be used with overloaded of the compressor. Noting that, the use of more mass of PCM reduces the freezer cabinet volume.

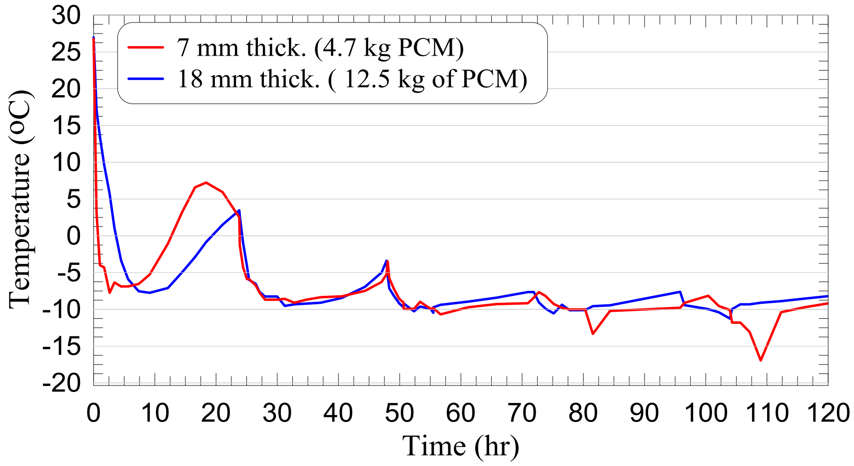



**Fig. 10. Internal air temperature evolution for 4.7 and 12.5 kg PCM.**

## 4. Conclusion

From the given results, the following conclusions can be derived:

- Potassium chloride aqueous solution (consecration 19.5% KCl by weight) was used successfully as PCM for storage surplus current produced by PV panel in the thermal form in PCM instead of DC electricity of batteries.
- For most experimental tests, freezer internal air temperature was kept below (-8 ºC) for more than (70%) of holdover periods without power supply.
- For the 7 mm and 18 mm PCM container thickness, test rig reached its steady state of storage condition in two and three days respectively, by powering the freezer on solar power for eight hours a day in summer season.
- A tank of 18 mm can hold inside freezer temperature at (-8ºC) for a long time as compared with that of 7 mm thickness. So, it can be said that the best tank thickness, for this work, is 18 mm.

It is recommended to replace the high torque compressor that used in this work by a low starting torque compressor since the PV array was unable to start compressor due to high torque of compressor during the moment of starting.

## References


1. Mehling, H.; and Cabeza, L.F. (2008). *Heat and cold storage with PCM. An up to date introduction into basics and applications*. Berlin: Springer-Verlag Berlin Heidelberg.
2. Li, G.; Hwang, Y.; Radermacher, R.; and Chun, H.-H. (2013). Review of cold storage materials for subzero applications. *Energy*, 51(C), 1-17.
3. Onyejekwe, D.C. (1989). Cold storage using eutectic mixture of NaCl/H2O: An application to photovoltaic compressor vapour freezers. *Solar and Wind Technology*, 6(1), 11-18.
4. El Tom, O.M.M.; Omer, S.A.; Taha, A.Z.; and Sayigh, A.A.M. (1991). Performance of a photovoltaic solar refrigerator in tropical climate conditions. *Renewable Energy*, 1(2), 199-205.
5. Toure, S.; and Fassinou, W.F. (1999). Technical note Cold storage and autonomy in a three compartments photovoltaic solar refrigerator: Experimental and thermodynamic study. *Renewable Energy*, 17(4), 587-602.
6. Ewert, M.K.; Bergeron, D.J.; Foster, R.E.; Estrada, L; and LaFleur, O. (2002). Photovoltaic direct drive, battery-free solar refrigerator field test results. *Proceedings of the ASME International Solar Energy Conference*. Reno, Nevada, 7 pages.
7. Pedersen, P.H.; Poulsen, S.; and Katic, I. (2004). Solar chill-a solar PV refrigerator without battery. *Proceedings of the 7$^{th}$ WSEAS International Conference on the on Power Systems.* Freiburg, Germany, 4 pages.
8. Tulapurkar, C.; Subramaniam, P.R.; Thagamani, G.; and Thiyagarajan, R. (2010). Phase change materials for domestic refrigerators to improve food quality and prolong compressor off time. *Proceedings of the International Refrigeration and Air Conditioning Conference.* Purdue, 8 pages.
9. Cheng, W.L.; Mei, B.J.; Liu, Y.N.; Huang, Y.H.; and Yuan, X.D. (2011). A novel household refrigerator with shape-stabilized PCM (phase change material) heat storage condensers: An experimental investigation. *Energy*, 36(10), 5797-5804.
10. Liu, Z.B.; Wang, B.H.; and Yang, S. (2012). Experimental investigation of a solar photovoltaic DC refrigerator with cold storage. *Advanced Materials Research*, 550-553, 3103-3107.
11. Oro, E.; Miro, L.; Farid, M.M.; and Cabeza, L.F. (2012). Improving thermal performance of freezers using phase change materials. *International Journal of Refrigeration*, 35(4), 984-991.
12. Khan, M.I.H.; and Afroz, H.M.M. (2013). Effect of phase change material on performance of a household refrigerator. *Asian Journal of Applied Sci*ences, 6(2), 56-67.
13. Marques, A.C.; Davies, G.F.; Maidment, G.G.; Evans, J.A.; and Wood, I.D. (2014). Novel design and performance enhancement of domestic refrigerators with thermal storage. *Applied Thermal Energy*, 63(2), 511-519.
14. El-Bahloul, A.A.M.; Ali , A.H.H.; and Ookawara, S. (2015). Performance and sizing of solar driven DC motor vapor compression refrigerator with thermal storage in hot arid remote areas. *Energy Procedia*, 70, 634-643.

15. Li, D.; Li, Z.; Zheng, Y.; Liu, C.; Hussein, A.K.; and Liu, S. (2016). Thermal performance of a PCM-filled double-glazing unit with different thermophysical parameters of PCM. *Solar Energy*, 133, 207-220.
16. Sze, J.Y.; Mu, C.; Romagnoli, A.; and Li, Y. (2017). Non-eutectic phase change materials for cold thermal energy storage. *Energy Procedia*, 143, 656-661.
17. Suttaphakdee, P.; Pongsa, U.; Kasemsiri, P.; Posi, P.; Lorwanishpaisarn, N.; Tasai, A.; Dulsang, N.; and Chindaprasirt, P. (2017). Thermal energy storage properties of form-stable paraffin/recycle block concrete composite phase change material. *Journal of Engineering Science and Technology* (*JESTEC*), 12(1), 256-264.
18. Cheng, X.; and Zhai, X. (2018). Thermal performance analysis of a cascaded cold storage unit using multiple PCMs. *Energy*, 143(C), 448-457.
19. Pronk, P. (2006). *Fluidized bed heat exchangers to prevent fouling in ice slurry systems and industrial crystallizers.* Ph.D. Thesis, Delft University of Technology, Delft, Netherlands.