Experimental study of cold storage packed domestic refrigerator with solar powered variable speed compressor

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Abstract. A domestic chest type freezer powered by photovoltaic solar panels studied experimentally. Phase change materials (PCM) were incorporated as thermal energy storage instead of traditional batteries for power backup freezer operation under absence/low solar irradiance levels. The test rig consists of three sided freezer divided into two insulated compartments each have its own PCM storage tank. A eutectic potassium chloride (19.4% with -10°C freezing temperature) and sodium chloride (8% with -5°C freezing temperature) aqueous solutions were used as thermal energy storage in each part of cabin. A comparison between different PCMs was made. The results showed a %54 reduction in compressor running time for the PCM packed evaporator. 4Kg of 8% NaCl solution at full load gave higher thermal mass. Also, freezer temperature maintained between -3.5 to -1 °C for 46% of holdover periods without power supply. 8% NaCl solution performance was superior to 14% NaCl. As the mass of PCM increases the freezer performance improves as well. Finally, two compartments freezer showed that 2kg of 19.5% KCl has successfully kept load temperature at (2°C).

Keywords: Refrigeration, PCM, DC compressor, speed control, solar.

1. Introduction
Air conditioners, refrigerators and freezers are common household devices that play main role in keeping the indoor conditions and food at the required temperature. They take about 15-20% of total world power generation[1]. The powering of refrigerators and freezers by solar energy is an old technology. The problem of such technologies is the absence of solar energy during the night, rendering refrigerators un-operational and thus products may deteriorate or at least its quality may deteriorate over time. Solar energy and phase change materials of low melting point can be coupled together to produce a refrigerator powered by solar energy during day time, and using PCM to keep the product at low temperature during night time. The variable speed compressor (VSC) has great advantage in air-conditioning and refrigeration systems since it offers best capacity regulation than conventional on/off compressors[2].

The main parameter studied by Coskun 2014 [3] was the thermal effectiveness of PCMs integrated with a household refrigerators. A numerical model was used to maintain temperature contours at steady-state conditions. The aim of the numerical work was to investigate the best locations of PCMs within the refrigerator space. Then, transient simulations were conducted to understand the transient thermal behavior of the refrigerated space. The results were validated with that of the experimental work.
According to the results, using PCM slabs on the refrigerator was decreased the number of on-off cycle of the compressor in a particular amount of time, for that the COP of the refrigerator was increased. Bagaria M. et al 2015 [4] designed and investigated a solar power refrigerator unit that incorporates a thermal reservoir, compressor and condenser surrounded by acetic acid (CH₃COOH + H₂O) as PCM, the study concluded that the selected volume of PCM material required three days to preserve the vaccines at the storing temperature. The time-temperature graph of organic PCM around the vaccine storage showed a stable temperature of PCM around the reservoir for two days and fourteen hours which serve the purpose in far-flung devoid of electricity. Yusufoglu Y. et al 2015[5] have studied the performance of two refrigerators’ models integrated with different types of PCM. The aim of the work was to optimize the on-off cycle of the refrigerators. The results showed that increasing condenser area by 20% improves the effect of using the PCM. The saving of energy was about 9.4 % when using 9.5 kg of PCM.

El-bahloul et al 2015 [6] investigated the affiance of solar-powered (DC) motor with vapor compression refrigerator with/without (PCM) under hot arid areas condition. Where, methodology model is to set-up a refrigerator working under different environmental conditions to estimate the size and cooling capacity of solar-driven refrigerator. The study showed that the system can work at remote hot arid areas. The refrigerator loses its thermal energy faster than when PCM is installed. The PCM-full load condition and the COP of the refrigerator at indoor conditions is higher than that of an outdoor one. Also, the product stored in refrigerator reached the required storage temperature faster. Sonnenrein et al 2015[7] presented an experimental investigation of the effect of LHS of the heat storage on the temperature distribution and power consumption of house refrigerators. The PCM was integrated with the refrigerator’s two evaporators. The performance was investigated under standard conditions. The work showed that different operation strategies were achieved in the work, a reduction in the power consumption by increasing the evaporator temperature and reducing the condensing temperature. Reducing the fluctuation of the evaporator space temperature from 4 to 0.5 °C, and the time of cooling cycle was tripled without affecting the conditions of the product compartment. Coca-Ortegon 2017 [8] studied the performance of a 350 litter capacity PV-powered refrigerator with 8mm encapsulated PCMs in polyethylene bags for a reliable operation temperature at 11°C. The number of on-off cycles of the compressor and the sizing of the conventional storage system with electrical batteries are investigated. The results indicated that the PCMs do not have high impact on the stratification of product temperature. The PCM is located at the top and middle zone of the refrigerator wall. The saving in power consumption was 1.5%. Dandotiya and Banker 2017 [9] investigated experimentally the integration of savE® FS21as a PCM with the refrigerator condenser, the condenser was a wired and tube air cooled heat exchanger.

The condenser temperature at a tropical environment can be controlled by using the PCM with condenser. The results showed an improvement in the cycle COP by about 28% while the power consumption was reduced by 15% as compared with power consumption without using PCM. A prototype domestic freezer integrated with solar PV panels and KCl PCMs working without using batteries using different mass of PCM were investigated by Khalifa et al 2018[10]. They successfully used KCl as cold storage PCM instead of DC current in traditional batteries. The internal space temperature was kept at less than - 8 °C at night time without any external power supply. Bista et al 2018[11] introduced a review of many types of PCM used in refrigeration units. The review included the effect of PCM on the power consumptions, systems COP and the on-off cycling number. The selection and stability of the PCMs over cycling number was discussed, as well as the PCM thicknesses, the locations of the PCM with the refrigerator space were. Finally the work introduced a review on the reductions in power consumption and the increasing of COP of the cycle for different types of PCM under study. Maiorino et al 2019 [12] used tap water as PCM contained in polyethylene plastic boxes and integrated with evaporator tubes. The variation of cabinet temperature and the utilization of PCM were the main two parameters under study. The results showed that using PCM leaded to reduce the fluctuations and reduced the temperature gradient in the cabinet. As well as there were a significant improvement in the on-off cycle time and the power consumption. The arrangement of the cascade condenser refrigerator
with two types of eutectic PCM was tested by Pirvaram et al 2019[13]. The PCM was installed at the wired and tube refrigerator condenser.

A comparison between the refrigerator performance using two types of PCM, single type PCM, and without PCM was introduced under standard conditions. Using two types of PCM attached at the refrigerator condenser improved the COP. The ratio of ON time to the total time was decreased when using the cascade condenser, as well as decreases the compressor power work from 32.7 to 27.6, while the reduction was 29.6% when using single PCM. The reduction in power consumption was 13% for the cascade condenser and 8% for the single PCM. A comparison between two freezers with internal polyethylene glycol solution as a PCM and without PCM was introduced by Abdolmaleki et al 2020[14]. The study was achieved in a test room at standard conditions.

The full loaded freezers were investigated for 24 hr. The parameters under study were the amount and melting temperature of the PCM. The results showed that using 2 kg of PCM with a melting temperature of -20 °C reduced the fluctuation of the inside cabinet temperature by about 40%. The saving in energy was about 8.37% when using 1.5 kg PCM mass.

In the current work, the performance of a freezer integrated with PCM and variable speed compressor is studied. The DC compressor is powered by PV panels through a speed control system that tracks the intensity of solar radiation. Two types of PCM with different melting temperatures were used to manage compartments setting temperatures. The VSC is implemented to harness the maximum possible solar energy gain by varying compressor speed following solar radiation intensity. Figure 1 presents a solar powered freezer system with DC compressor derived by an appropriate control system to fulfill the above mentioned requirement.

2. Experimental Work

A 25 lit volume house hold freezer was selected to investigate current work objectives. The freezer compressor is a variable speed DC compressor of type BD35F-HD, the specification of the compressor is shown in table 1. The DC compressor speed control depends on solar intensity. The dimensions of the freezer are \(0.5 \times 0.4 \times 15\) cm as shown in figure 2. Two tests are conducted on the freezer; the first one is to keep the space of the freezer as a single compartment in which one type of PCM is used. The second test conducted with the inner space of the freezer is separated into two volumes compartments. The first one is of \(42 \times 20\) cm dimensions, and the second one is \(24 \times 40\) cm as shown in figure 3. Two types of PCM of different melting points are used in these compartments. The freezer walls are insulated by polyurethane of 3 cm thickness.

| Table 1. Compressor specifications |
|-----------------------------------|
| Power supply (Voltage)            | 24  |
| Cooling capacity (W)              | 85.68 |
| Power consumption (W)             | 59.5 |
| COP                               | 1.44 |
| RefrigerantR-134a                 | R-134a |
| Displacement cm³                  | 2.00 |
| Oil quantity (type) cm³           | 150 (polyester) |
| Maximum refrigerant charge g      | 300 |
| Free gas volume in compressor cm³ | 870 |
| Weight – Compressor/Electronic unit kg | 4.3/0.27 |
Figure 1. Solar powered freezer system with DC compressor derived by a control system

The control system that regulates compressor speed consists of Raspberry pi model 4B programmable by Python language and a bh1750 light sensor that perceives light intensity producing a signal manipulated by raspberry pi to regulate compressor speed using PWM signal.

Figure 2. Freezer of $0.5 \times 0.4 \times 15$ cm dimensions.

Figure 3. Freezer separated into two volumes compartments
The Pulse Width Modulated (PWM) is used to control the analog system when the output signal is digital. The PMW fabricates the analog signal feeding the power in pulses form or by controlling the voltage. Instruments that are derived by PMW end up acting like the average of the pulses. Thus the averaging of the voltage can be treated as a steady voltage. When the pulse is driven high as 25% of the time, the cycle is called a 25% duty cycle as shown in figure 4.

The MCU (Micro Controller Unit) consists of Arduino mega 2650 (with 8 waterproof temperature sensors and DC Current – Voltage sensors) coded by C/C++ language. Table 2 presents the accuracy of the sensors. The compressor, control system and data logger powered by solar system with PV panels of 275 W maximum powers. Table 3 presents PV panel specification.

| Variables                  | Accuracy error |
|----------------------------|----------------|
| DS18B20 PCM Temperature    | ±0.27 °C       |
| ACS712 current sensor      | ±1.5%          |
| Voltage sensor             | ±0.00489V      |
| Bh1750 Intensity sensor    | ±20%           |

| Table 3. Presented PV panel specification. |
|--------------------------------------------|
| Maximum Power Voltage (Vpax)               | 31.93 V        |
| Maximum Power Current (Ipmax)              | 8.62 A         |
| Open circuit voltage (voc)                 | 39.42 V        |
| Short circuit current (Isc)                | 9.04 A         |
| Maximum system voltage                    | 1000 V (IEC)   |
| Power tolerance up to                     | +4.9           |
| Measurement tolerance                     | +/- 3%         |
| NOCT                                       | 45 C +0/-2 C   |

Two types of PCM were used in this work, the first is a water solutions of NaCl with mass concentration of 8% and 14%, which gives a melting temperature -5.1 and -10 respectively. The second PCM is KCl (potassium chloride) solution with mass ratio of 19.4% and 8% that gives a melting point of -10 and -5.3.
Table 4 shows the thermo physical properties of the potassium chloride and sodium chloride solutions.

| PCM      | NaCl 8% | NaCl 14% | KCl 8% | KCl 19.4% |
|----------|---------|----------|--------|-----------|
|          | Liquid  | Solid    | liquid | Solid     | liquid    | Solid    | liquid   | Solid    |
| T<sub>solidification</sub> °C | -5.1    | -10.1    | -5.3   | -10       |
| Cp (kJ/kg) | 3.8     | 3.76     | 3.6    | 3.52      | 3.815     | 3.808    | 3.25     | 2.1      |
| ρ(kg/m3) | 1052    | 1062     | 1096   | 1111      | 1024      | 1028     | 1105     | 1126     |
| k (W/m.K) | 0.6     | 0.54     | 0.6    | 0.53      | 0.58      | 5.4      | 0.54     | 4.9      |
| λ (kJ/kg) | 289     | 261      | 258.2  | 247.2     |

The connecting of all instruments, the data logger, and controller is shown in figure 7. Following steps indicated below the test rig with PCM was investigated:
- Examine the freezer operation with speed regulation according to light intensity.
- Examine the freezer capacity performance with variable amount of thermal energy storage media PCMs.
- Upgrading the freezer from one side to three side evaporator.
- Experiment different PCMs types to select the main PCMs for study.
- Approach the steady state operation by running the system for 7 days.
- Find the effect of variable load by changing load for 12 day by (20%, 40%, 60%, and 80%) of cabin full load every 3 days.
- Experiment the performance of two separated types of PCMs at same cabin.

3. Results and Discussion

Figure 5 shows the effect of PCM mass on the PCM and load temperature. Using PCM mass as low as 1.5 kg (figure 5.a), resulted in unstable temperatures changes for both load and PCM. PCM and load temperatures reduce when the compressor turn ON during the period extended from 8 to 16 hr. When the compressor turned off, due to sunset, the PCM and load temperatures increase rapidly to reach the ambient temperature. The time required for the space to reach the ambient temperature is about 16 hours after the compressor turned off. A mass of 2 kg PCM shows the same trends as that for the 1.5 kg as shown in figure 5b. Increasing PCM mass above 2 kg produced more stable conditions in both PCM and load temperatures, as shown in figures 5c and 5.d. After 16 hours of turning off the compressor, the load temperature is maintained at approximately 3 °C when the PCM mass is 3 kg and about 2.7 °C for 4 kg PCM. From above it can be concluded that, increasing the PCM mass defiantly leads to attain the load temperature stability. But, since the freezer space is limited, thus, for this work, the maximum permissible PCM is 4 kg.
c. 3 kg of NaCl of 8% concentration  
d. 4 kg of NaCl of 8% concentration

Figure 5. The solar powered performance for 8% NaCl concentration.

Almost the same behavior is observed for 14% NaCl concentration, as shown in figure 6. The trends of the test are the same as for that of 8% NaCl concentration. Experiments show that the best mass of 14% NaCl is 4 kg also. Hence, the mass of NaCl is set to be 4 kg for all the rest tests.

The second step is to choose the best concentration of NaCl, figures 7 to 10 show a comparison between the load, PCM, internal space and evaporator temperatures for both 8 and 14% NaCl of 4 kg mass. A 24 hrs operation of the solar powered freezer is shown figure 7. The load temperature reduces from ambient temperature of 36 °C to -2.5 °C during the first 4 hrs of operation for both 8 and 14% concentrations. Then, the load temperature keeps the same level during the next 10 hrs, after that the load temperature increases to reach 3 °C for the 8% concentration and about 4 °C for the 14% concentration. When the
PCM temperatures for the both concentration is measured, figure 8, it can be seen that solidification temperature for 8% concentration is -5 °C, while it is -10 °C for 14% concentration. However the 14% concentration shows a lower solidification temperature but the final temperature of the 14% concentration, after 16 hrs of compressor turned off, is more than that of 8% concentration. This is because the latent heat of fusion of the 14% NaCl concentration is lower than that for the 8% concentration, as shown in Table 4. The space and evaporator temperature for the solar powered freezer shows the same trends. The best performance is found for the 4 kg of NaCl of 8% concentration. So, it is reasonable to choose the mass of the NaCl of 4 kg at 8% concentration for the rest of the tests.

The power consumption by the freezer compressor for different mass of NaCl is shown in figure 11. There is a time lag between the solar radiation intensity and the compressor operation. Depending on solar intensity the controller signal may increase or decrease compressor speed. At time from 6 to 7:30 the controller blocked the current even there is solar radiation, because the power produced at the mentioned time is not enough to start the compressor. At 7:30 a low current passes through the circuit, thus the compressor starts at low speed that proportional with the solar intensity. At time 9:00 compressor power increases due to the increase in the intensity of the solar radiation. Thus compressor speed is proportional to the intensity of the solar radiation up to the maximum compressor speed at about 10:00. After 10:00 the
control circuit does not allow the passage of a larger current even if the intensity of radiation increases, to protect compressor from mechanical damage.

To check the performance of the solar powered freezer with another PCM, a second type PCM which is KCl with of 8 and 19.4% concentrations. Depending of the results of the NaCl, the mass of the PCM is 4 kg. The variation of load and PCM temperature with time for both 8 and 19.4% concentration is shown in figure 12. Best performance of the solar powered freezer is when the concentration of KCl is 8%. The solidification period of KCl of 8% concentration is about 1.5 hours while it is equal to 1 hour for the 19.4% concentration. This indicates that the latent heat of solidification for 8% is more than that for 19.4%. The figure shows that the solidification temperature are -5 and -10°C for the concentration 8 and 19.4% respectively.

![Figure 11](image1.png)
**Figure 11.** The variation of compressor power with time for different PCM mass.

![Figure 12](image2.png)
**Figure 12.** The variation of load and PCM temperature with time for KCl at 8 and 19.4% concentration

A comparison between NaCl and KCl both of 4 kg mass and 8% concentration, is shown in figure 13. There is a slight difference between both PCM and load temperature for KCl and for that of NaCl, this is because that the latent heat of fusion of KCl is getater than that of NaCl.

![Figure 13](image3.png)
**Figure 13.** The variation of load and PCM temperature with the time for two types of PCM.

The full performance results for the solar power freezer lined with 4 kg of NaCl of 8% concentration, and loaded with 0.75 kg of Tomato, are shown in figure 14. The day length at June 22, 2020 is about 11 hrs, with actual working time of compressor of about 10 hrs (see figure 11). The load takes about two hrs from the starting compressor time to reach the storage temperature. After 5 hrs of compressor stope time the load temperature tends to increases slightly. A maximum load temperature of 4°C was approached after about 16 hrs of compressor stop time. Thus a 24 hrs operation time is not enough to evaluate unit stability. There is a significant difference between the space and load temperatures as well, which means that the space required another compressor run to reach set temperature. The phase change region
extended from about 10:30 to 14:00 hr. At a temperature of -5 °C, the time of the phase change reflects the amount of the latent heat of fusion.

![Figure 14.](image_url) a 24 hours operating time for the freezer at 4 kg NaCl of 8% concentration.

The solar powered freezer is kept working for seven continues days (3 to 9 July, 2020) as shown in figure 15. The PCM used for this test is 4 kg of NaCl at 8% concentration, and the load is 0.75 kg of tomato. The figure shows the variation of the load temperature during this period. The maximum and minimum load temperature is almost tending to be constant after three days of operation. The time for the rest tests is 3 continues operating days. Also, the evaporator temperature and PCM temperature are the same, but there is a time delay between the two temperatures caused by thermal resistance between PCM container martials and the PCM.

![Figure 15.](image_url) The performance of the solar powered freezer at 4 kg NaCl, 8% concentration.

The effect of the load mass on the freezer performance is shown in the figures 16. In this test a load of 1.5 kg of tomato, which represent 25 of the total capacity of the freezer, is placed in the freezer space. After three days run another 1.5 kg of tomato is placed in the freezer and another three days of run, and so on until the freezer space is completely full with 6 kg of tomato. At the first 1.5 kg of tomato, it can be seen that the load temperature varied from -2.5 °C when the compressor is on, and increases to about 2 °C when the compressor is off. This variation is due to the low
thermal mass of the load. It can be seen from the figure that the load temperature strongly affected by the space and PCM temperatures variation. At the end of the second three days, when the freezer space is 50% loaded, the load temperature changed from -3 to 0°C. This means that as the mass of the load increases the thermal mass improves. But the variation of the space temperature large, that is varied from 0 °C when the compressor on to about 5°C when the compressor off. The load and space temperature show another improvement when the freezer loaded with 75% of its capacity. It can be seen that the difference in space temperature reduces to about 3°C, and the load temperature is varied from -1 to -3°C. The 100% loaded freezer improves only the load temperature that is the variation in load temperature is enclosed in the range of -2 to -3.5°C. The steady state operation of the solar power freezer reached when the freezer space is fully loaded. Also there is an important factor conjugated with the freezer load; this factor is operation continuity of the freezer which gives the best performance of the freezer thermal mass. The effect of thermal mass on the freezer performance can be summarized as follows. The load thermal mass can overcome the lost heat from the freezer, during the long off periods, nearly 14 hours. Since the heat that is extracted from the load is mostly latent heat, then the load temperature shows a slight change. While the temperature of space shows a significant variation since the heat that space loses is sensible.

![Figure 16](image-url)

**Figure 16.** The effect of load mass and operating time on the freezer performance

As mentioned before the freezer space is separated into two compartments, each space is lined by different PCM. Figure 17 shows the two compartments freezer performance. The first compartment is lined by 2 kg NaCl 8% concentration and the second compartment is lined by 2 kg KCl, 19.4% concentration, both PCM masses are 2 kg. The load in each compartment is 2 kg of tomato. Although the solidification temperature of KCl (-10°C) is lower than that for NaCl (-5 °C), but the figure shows that the average temperature of KCl load is greater than that of the NaCl. This is because the latent heat of fusion of 19.5% KCl is lower than that of NaCl. So, the solidification temperature is not the main parameters when designing the two compartments freezer, since the latent heat of fusion (LHF) can affect the load temperature. Also the low latent heat of fusion affected the stability of the load temperature, the low LHF
of KCl shows a large variation in the load temperature through the day, while the relatively high LHF of NaCl shows less variation in the load temperature through the day.

![Figure 17. The variation of NaCl and KCl two compartments freezer](image_url)

4. Conclusions

Pulse Width Modulation speed controlled compressor powered by 275W PV-Cell panels to operate a refrigerator with three sides evaporator packed with sodium chloride aqueous solution (concentration 8% and 14% NaCl by mass) and potassium chloride aqueous solution (concentration 19.4%) as PCM was developed to examine the performance of thermal storage energy and power consumption savings were concluded:

1- Using PV-Cell solar system reduced the compressor power consumption by reducing compressor running time to %54 from actual operation time when the evaporator was packed with 8% NaCl solution.
2- The compressor speed is proportional to the intensity of the solar radiation until the maximum compressor speed reached at about 10:00. After 10:00 the control circuit does not allow the passage of a larger current even if the intensity of radiation increases, to protect compressor from mechanical damage.
3- For 8% NaCl the freezer load temperature was kept between -3.5 to -1 °C for 46% of holdover periods without power supply after 7 day from continual operation.
4- 4kg of 8% NaCl PCMs placed at the evaporator section with full load gives a higher thermal mass to the internal freezer space so, the variation in load temperature is enclosed in the range of (-2 to -3.5°C).
5- As the mass of PCM increases the freezer performance improves, so, using 4kg of NaCl gives the best freezer performance as compared with other masses of 1.5, 2.5 and 3kg PCMs for 24 hr operation time.
6- Using NaCl of 8% concentration gives better freezer performance as compared with that of 14% concentration.
7- For two compartments freezer shows that the 2kg of 19.5% KCl has successfully kept load temperature at (2 °C) where the 2kg of 8% NaCl kept the load temperature at (3.5 °C) for 3 day.

5. References

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