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Experimental Investigation of the Performance of a Household Refrigerator Using Phase Change Material

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Abstract

A household refrigerator represents an essential device for all houses nowadays. The electric energy consumed by the refrigerator and the fluctuation of the temperature inside the fresh food cabin is the main two problems affecting its performance. Incorporating phase change material (PCM) inside the refrigerator is one of the solutions for the previous mentioned problems. In the present study, a water PCM is added to the cabinet of 220-litters double door refrigerator. The PCM (0.5 ml of water) is added at three different locations, touch the front of the evaporator part inside the cabin, touch the rear of the evaporator part in the cabin, and far away from the evaporator part inside the cabin. The location of the PCM determines how much energy is released and stored from the evaporator. The use of phase change material (PCM) touch to the evaporator increases the rate of heat transfer due to the conduction method being used throughout the whole heat transfer process from the evaporator to the phase change material (PCM), which raises the refrigeration system's COP (coefficient of performance). The experimental test period is 24 hours for each day. Firstly, the refrigerator is tested without using PCM, and the power consumption, the temperatures at different points for the refrigerator, suction pressure, discharge pressure, the ambient temperature, and the time on period and time off period of the compressor are measured. Secondly, for same testing period all previous parameters are measured with using PCM at different locations inside the refrigerator. The results show that, adding the PCM (water) behind the evaporator led to increase the COP by 21.97%, increase the compressor off time by 73 minutes, reduction in power consumption of 14.4%, decrease of exergy losses of the system by 8% and temperature fluctuation reduced inside the fresh food cabin, that enhance the quality of stored food. Adding the PCM front the evaporator improve the previous parameters but less than that of the first case. The third location, adding the PCM far away from the evaporator has no improvement on the refrigerator's performance.

Keywords: Refrigerator, Exergy analysis, Vapor compression cycle, Exergy destruction, Cold thermal energy storage, Phase change material, Latent cold thermal energy.

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1. Introduction

A refrigerator (colloquially, a fridge) is a common household appliance that consists of a thermally insulated compartment and a heat pump (mechanical) that transfer heat from the inside of the fridge to its external environment, allowing the inside of the fridge to be cooled to a temperature lower than the room's ambient temperature. PCM is a substance that can store or release large amounts of latent heat by transforming from solid and liquid phases. It has been shown that introducing phase change material into refrigeration systems.

Even simple enhancements to refrigerator performance can lead to significant energy savings. Turning off the compressor has serious consequences, such as working outside of peak hours and keeping the cabin cool during a power outage. The usage of PCM in the evaporator for cold storage was used to discuss several techniques for increasing the refrigerator's thermal performance [1]. An experimental investigation of house hold refrigerator used a three-finned aluminum container with pure water as PCM that showed a 45-minute increase in the duration of compressor off time during each cycle and a 17.4% decrease in daily energy consumption [2]. Explained the benefit of using PCMs (OM03 organic material) in the evaporator component, which reduces compressor temperature fluctuations and offers stable conditions against changes in thermal load; also showed important impacts on the system's performance as COP increased by 6.7%, cooling effect by 0.69%, and compressor work decreased by 1.8%; also, temperature in the compressor was reduced to 3.91% in comparison to without PCM in the evaporator [3].

The analysis of a freezer with PCMs eutectic mixture of polyethylene glycol) for 24 hours in the test room under the required conditions, both with and without the PCMS at typically state, discovered that the best point is at -20 C and 1.61 kg PCM, which results in a reduction in temperature variations of 37.67% and energy consumption of 8.14% because PCM prolong compressor off time by providing a source of cooling while the compressor is off [4]. Temperature and pressure are two important parameters considered for the analysis, so by using a U-shaped box with three different types of PCMs located behind the evaporator in order to evaluate the performance enhancement of the household refrigerator, where PCMs affect based on the difference in their melting point and latent heat capacity, integration of 400 ml phase change materials inside the evaporator cabin maintains the desired temperature of 5°C for 40 minutes, 70 minutes, and 90 minutes, respectively without power supply, also, according to the results, the eutectic solution shown high COP under no-load conditions [5]. presents a method for optimizing the functioning of a cabinet refrigerator with a PCM such that energy use can be distributed across the day to lessen peak energy demand. As time-of-use (TOU) tariffs have been adopted by many nations, the cost of power under this tariff is influenced by the hour of the day, the type of day (weekend or working day), the season, and 2-TOU (peak and off-peak) pricing. economic advantages 3-TOU (peak, off-peak, off-peak) has more economic advantages than the better alternative without PCM [6]. PCM was used as a cold thermal storage device in a refrigerator for two different types of evaporators during the energy analysis:

1st flat plate evaporator: the PCM phase change temperature should be set to be near to the cooling phase change temperature where the PCM comes into contact with air and the evaporator's surface. The evaporator's performance is improved and compressor downtime is decreased because to PCM's improved evaporator heat transfer.

2end vented fin evaporators, where the PCM only makes contact with ambient air. The PCM should be set at a temperature that falls between the refrigerator's maximum and minimum air temperatures. The PCM doesn't directly affect how the refrigerator works, but it does make it possible to control the compressor downtime with better accuracy [7]. The performance of the refrigerator is improved by 28% COP and 15% less energy use when PCMs are added to the condenser compared to the standard condenser. However, a number of operational factors, including the ambient temperature, the PCM type, the PCM quantity, and others, may alter the performance of the refrigerator [8]. A new PCM heat exchanger design is proposed, consisting of twelve U-type tubes occupying the entire evaporator covered with A Plus-ICE PCM of phase change temperature 4 C, and the results are simulated by CFD, indicating that the energy consumption is reduced by 12% and the COP is increased by 8% when compared to the refrigerator without PCM [9]. Thermal performance of a refrigerator with a PCM-charged functional duct unit (FDU) (shown in fig.1). Because the FDU's performance is determined by the thermal properties of the PCM, the eutectic water-salt PCM was created by diluting eutectic chemicals with distilled water and testing the thermal properties

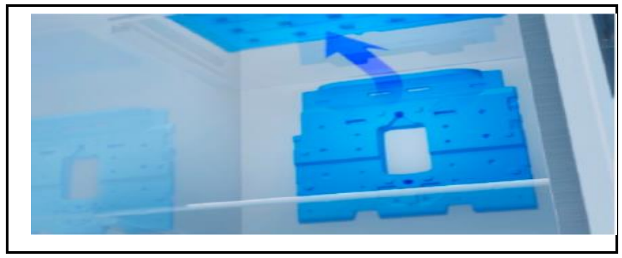

Figure 1: A FDU installed in the refrigerating compartment [10]

choosing a PCM containing 1% eutectic salt compounds can reduce total energy consumption by lowering the supercooling temperature and thus increasing energy efficiency. In the event of a power outage, the PCM in the FDU released latent heat, effectively preventing a drastic temperature rise inside the refrigerating compartment [10]. The application of PCM was encapsulated between the coil of the evaporator and the insulation to improve the energy efficiency of the refrigeration system. The results showed significant effects on system performance such as cop increased by 7.1%, per energy consumption decreased by 6.7%, and temperature variations were also relatively lower inside the freezer cabinet [11]. ANSYS-FLUENT software is used to numerically investigate the effects of the integration of a PCM slab with varying thicknesses placed on the rear surface of the evaporator inside a vertical cooler using forced convection the results of a parametric set of analyses: The volumetric flow rate decreases dramatically as the thickness of the PCM slab grows, volumetric flow rate reduced, the air temperature remains constant for a long time, and the PCM slab lower the run-time ratio [12]. According to the international standard IEC 62552:2015, polymer-bound PCM with a phase change temperature of around 9 °C was developed, integrated, and studied for its impact on daily energy consumption, cooling capacity, and temperature rise time results show a considerable positive influence on the performance indicators cooling capacity and temperature rise, without any significant negative effects [13]. The melting of the PCM slab during the compressor's off-cycle and the addition of heat from the evaporator during the compressor's on-cycle are the two key factors that determine how much heat is removed from the PCM slab to the refrigerator cell during the off-cycle [14]. Researchers have employed phase change materials (PCMs) as potential thermal energy storage rather than sensible thermal energy storage over the past two decades. The solid-liquid PCM absorbs, stores, and releases latent heat after phase transition for charge/discharge periods under an essentially isothermal regime. As materials melt, thermal energy is stored and released when they solidify, or the other way around [15]. The evaporator performance factor is used as criteria for estimating the refrigeration system, which is used to calculate COP with the power consumption by the compressor [16]. Based on previous research, it was concluded that COP is the major criterion that shows improvement in the refrigerator's performance however, various types of phase-changing materials were used, in either the refrigerator or freezer and their benefits and drawbacks have been discussed; however, attention has not been given enough to changing where the phase-changing materials are placed inside the refrigerator and determining the best location for them to achieve the greatest improvement in the performance of the refrigerator and reduce energy consumption.

2. Experimental set-up

•A 220 liters double-door refrigerator **Fig.2.1** is used for the present experimental study with the following characteristics:

1) Cabinet: the total storage volume is 220 L, and the storage volumes of fresh food storage compartments 168 liters (84x46x43.5) cm^3 and frozen-food storage compartments 52 liters (32x39x41) cm^3 .
2) Compressor: Hermetic reciprocating compressor (1/6 HP), QD52H 220-240V/50Hz.
3) Evaporator: mode of heat transfer - Free convection (32x32x1) cm^3 placed in front of an insulation wall vertically.
4) Condenser: free convection, steel and wire tube at back side of refrigerator.
5) Capillary tube: inner diameter: 0.3 mm, external diameter: 1.7 mm, length: 3000 mm.
6) Refrigerant: 120g of 1,1,1,2-Tetrafluoroethane (R-134a).

Figure 2.1 experimental refrigerator

•The measuring instruments **Fig2.2** used: K-type thermocouples were used to measure temperatures at various locations, including compressor, condenser, evaporator, capillary tube, compartment, PCM, all thermocouples are calibrated using ice/boiling points method. At the input and exit of the compressor, two pressure gauges are employed to monitor the evaporation and condensation pressures, and a digital wattmeter is also clamped to record the amount of electricity consumed. Avometer to gauge the voltages and amps needed for a compressor.

Figure 2.2 measuring instruments

2.1. Experimental Methodology

The experimental test period is 24 hours for each day. Firstly, the refrigerator is tested without using PCM and the power consumption, the temperatures at different point for the refrigerator **Fig2.3**, suction pressure, discharge pressure, the ambient temperature, and the time on period and time off period of the compressor are measured. Secondly, for same testing period all previous parameters are measured with using PCM at different locations inside the refrigerator.

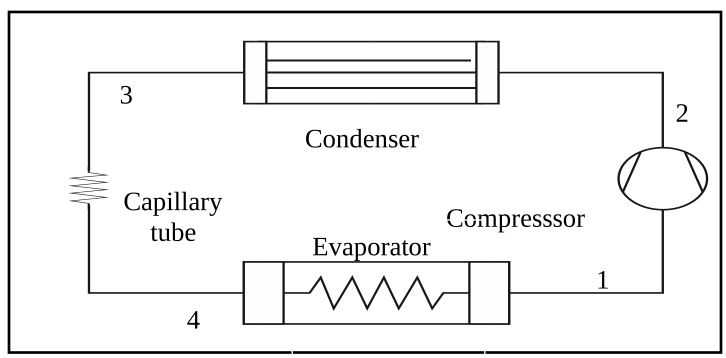

Figure 2.3 Schematic diagram of vapor compression cycle

Where the pressure, temperature and power consumed are recorded for every (10-15) minutes during the period of operation of the refrigerator and note the changes that occur on all the points, as well as the change in temperature inside the refrigerator compartment is observed during its operation as well as during the shutdown period.

2.2. Selection of PCM

The selected PCM was water because water presents many advantages: high latent heat, good time stability and perfectly known thermophysical properties **[**17] shown at **Table 1.**

Table 1. Properties of PCM (pure water)

Property	**Value**
Melting Temp (°C)	0
Freezing Temp (°C)	0
Latent Heat (kJ/kg)	330
Density of water (kg/m3)	1000
Liquid Specific Heat	4.2
Solid Specific Heat (kJ/kgK)	2.108

2.3. PCM thickness

The amount of PCM to be required is the next step after choosing a proper PCM with appropriate thermophysical properties. Based on a very simple determines the minimum volume of PCM[1] . If a compartment only contains PCM, the amount of energy (E) stored in PCM neglecting its sensible heat variations is:

$$E = \rho V \lambda \qquad (1)$$

ρ: density (kg/m3)
V: volume (m3)
λ: the latent heat of fusion of PCM (kj/kg)

The compartment has heat gain from the ambient:

$$Q_{gain} = (UA)(T_{amb} - T_{cold}) \qquad (2)$$

where the indices *amb* and *cold* represent the ambient and cold compartment, respectively and *UA* is the overall thermal conductance
In order to marginally meet the required load, The energy stored in the PCM should be equal to the energy passing through compartment walls during compressor OFF time(t_{OFF})as results, minimum volume for PCM:

$$V_{min} = \frac{t_{OFF}[(UA)(T_{amp} - T_{cold})]}{\rho\lambda} \qquad (3)$$

Therefore, the amount of PCM should be greater than what was determined using Equation (3) to account for heat gain through the walls during compressor off time [1].

2.3. PCM location

Place PCM (pure water) in three different location the refrigerator and investigating each case by understanding the differences in COP, power consumption, temperature of air at cabinet, pressure and temperature inlet and out let of each component and energy and exergy analysis of each case.

- Case (1) :500 mL of (H_2O) at cabinet of fresh food storage placed in two aluminums as M-pack (20x20x5) cm^3 shown in **Fig 2.4.**

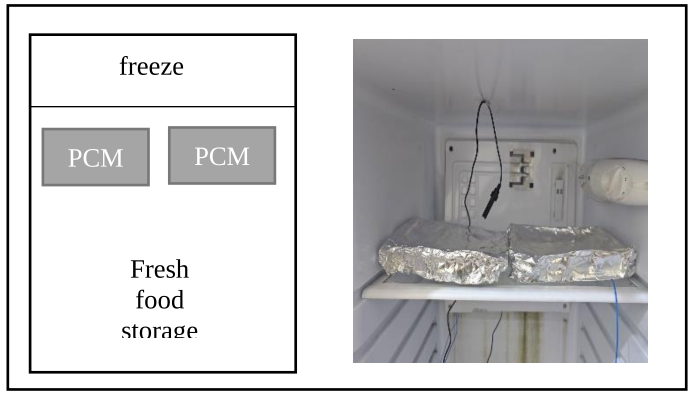

Figure 2.4 M-pack of PCM in cabinet

- Case (2): 500 mL PCM slap behind the evaporator wall

between insulated wall & evaporator wall shown in **Fig2.5**

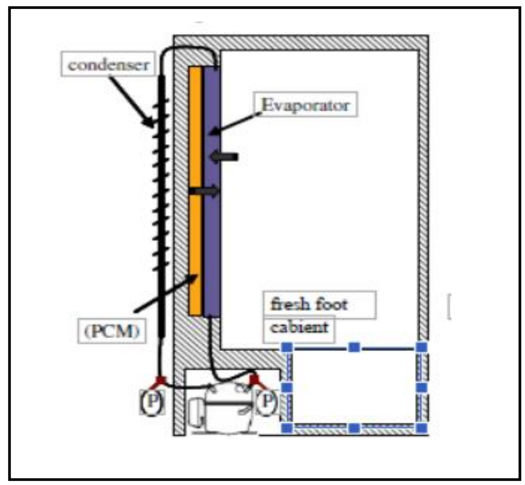

Figure 2.5 PCM behind the evaporator [17]

- Case (3): 500 mL PCM slap in front of the evaporator wall
  between evaporator and air of fresh food storage.

3. Performance Analysis model

A theoretical model based on energy, exergy and entropy balance of the refrigeration system was used to calculate the performance criteria for the refrigerator with and without PCM. The model was used to built a code by using EES program to calculate the refrigerator COP and heat load, compressor time on and time off and the exergy destruction at each component and also the whole system. The input data for the performance analyses code are the experimental measurements pressure, temperature and power.

3.1. Energy, Entropy and Exergy analysis

3.1.1. Energy analysis

The work required for the compressor by is given by:

$$W_c = I \times V \times PF \qquad (4)$$

Where:
W_c: work done by compressor (w)
I: current of compressor (amp)
V: voltage of compressor (volt)
PF: power factor

$$W_c = \dot{m}(h_2 - h_1) \qquad (5)$$

Assumed: $\dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}_4 = \dot{m}$
$\dot{m}$: mass flow rate of refrigerant (kg/s)

The heat Absorbed in the evaporator (Q_e):

$$Q_e = \dot{m}(h_1 - h_4) \qquad (6)$$

The heat rejected by the condenser (Q_c):

$$Q_c = \dot{m}(h_2 - h_3) \qquad (7)$$

Coefficient of performance (COP):

$$cop = \frac{Q_e}{W_c} = \frac{h_1 - h_4}{h_2 - h_1} \qquad (8)$$

Where:
h_o : Is enthalpy at dead state (kj/kg)
h_1 : Is enthalpy at outlet of evaporator (kj/kg)
h_2 : Is enthalpy at inlet of condenser (kj/kg)
h_3 : Is enthalpy at out of condenser (kj/kg)
h_4 : Is enthalpy at outlet of evaporator (kj/kg)

3.1.2. Entropy analysis

Entropy is typically estimated for refrigeration systems when they are in a steady state, since the system is actual and all real processes are irreversible, maybe we just would assume that the system reaches a quasi-steady state.
The general formulas for the entropy balances of VCRs are shown in **tables 3.1.**

Table 3.1. entropy analysis of each component of VRCs

Component	Entropy generation (kj/s. k)	Eqa.N
compressor	$S_g = \dot{m}(S_2 - S_1)$	9
evaporator	$S_g = \dot{m}(S_1 - S_4) + \frac{Q_e}{T_e}$	10
condenser	$S_g = \dot{m}(S_3 - S_2) + \frac{Q_c}{T_c}$	11
Capillary tube	$S_g = \dot{m}(S_4 - S_3)$	12

Where:
S : Is entropy at dead state (kj/kg. k)
S_1 : Is entropy at outlet of evaporator (kj/kg. k)
S_2 : Is entropy at inlet of condenser (kj/kg. k)
S_3 : Is entropy at out of condenser (kj/kg. k)
S_4 : Is entropy at outlet of evaporator (kj/kg. k)
T_e: temperature at boundary of evaporator (k)
T_c: temperature at boundary of condenser (k)

3.1.3. Exergy analysis

The concept of exergy is determined by the second law of thermodynamics, which is a useful tool for analyzing both the amount and quality of power consumption. It is defined as the largest amount of work that can be accomplished when a stream of matter is transported from its starting state to its dead state by processes in which the stream can only interact with the environment. The exergy balance is similar to an energy balance, but the key distinction is that, whereas the energy balance is a statement of a rule of energy conservation, the exergy balance may be viewed as a statement of a law of energy degradation (18).
The exergy at any point of system calculated:

$$\mathrm{Ex} = (\mathrm{h} - \mathrm{h}_{\circ}) - \mathrm{T}_{\circ}(\mathrm{s} - \mathrm{s}_{\circ}) \qquad (13)$$

Reference enthalpy (ho) and entropy (so) of the refrigerant have been calculated corresponding to the dead-state temperature (T0) of (20°C-23°C)

Table 3.2. exergy analysis of each component of VRCs [18]

Component	Exergy destruction (w)	Eqa.N
compressor	$E_d = \dot{m}T_o(S_2 - S_1)$	14
evaporator	$E_d = \dot{m}(h_4 - T_oS_4) - \dot{m}(h_1 - T_oS_1) \quad + Q_e(1 - \frac{T_o}{T_e})$	15
condenser	$E_d = \dot{m}(h_2 - T_oS_2) - \dot{m}(h_3 - T_oS_3) \quad + Q_c(1 - \frac{T_o}{T_c})$	16
Capillary tube	$E_d = \dot{m}T_o(S_4 - S_3)$	17

So, the total exergy losses in the system($E_{d_{total}}$):

$$E_{d_{total}} = E_{d_{comp.}} + E_{d_{evap.}} + E_{d_{cond}} + E_{d_{cap.}} \quad (18)$$

Where:
$E_{d_{total}}$: total exergy destruction of all component (w)

3.2. Refrigerator heat load

The refrigerator heat load is consisting from the heat gain through the walls, the material storage heat load, light load and the load due to refrigerator opening and closing. The present experiment was performed for empty and closed refrigerator during the period of the test. So, the heat load of the refrigerator only the heat gain through the walls as follow:
The heat load into domestic refrigerator 168 Liter volume was calculated by consider the heat gain from ambient through the walls of refrigerator. The ambient temperature is 22°C and the heat gain is given by:

$$Q_{gain} = UA\Delta T \quad (19)$$

Q_{gain}: average heat leakage rate from ambient to fresh food storage (w)
U: global heat transfer coefficient (w/$m^2.k$)
A: area of each wall insulation of refrigerator (m^2)

$\Delta T = \left(T_{amp} - T_{cold}\right)$ (K)

$$\frac{1}{UA} = \frac{1}{h_o A_o} + \frac{x}{kA} + \frac{1}{h_i A_i} \qquad (20)$$

h_i: internal convection heat transfer coefficient (w/$m^2.k$)
A_i: $inernal\ area\ (m^2)$
h_o: external convection heat transfer coefficient (w/$m^2.k$)
A_o: $external\ area\ (m^2)$
x: thickness of wall (m)
k: thermal conductivity of insulator (w/$m.k$)
assume [19]
k=0.03 (w/$m.k$)
$h_i = 10$ (w/$m^2.k$) : $h_o = 30$ (w/$m^2.k$)
found out that $Q_{gain} = 24.61\ w$

3.3. PCM heat storage and release

Phase Change Material (PCM) is used in systems as a liquid or solid medium to release heat from the evaporator. As the compressor is operating, the refrigerant will extract the heat energy from the PCM through conduction. Heat transmission by conduction is quicker than through natural convection. The refrigerant in a traditional refrigerator uses natural convection to extract heat from the cabinet. Hence, the PCM will enhance the evaporator's capacity to transfer heat.
The energy that PCM absorbed classification into sensible heat and latent heat and the percentage rate of melting and solidification of PCM was influence the amount of energy released by PCM.
To calculate energy absorbed and released by PCM (H2O):

$$Q_{pcm} = Q_S + Q_L \qquad (21)$$

Q_{pcm}: $energy\ storge\ by\ pcm\ (kj)$
Q_S: $sesible\ heat$; Q_L :latent heat

$$Q_s = \dot{m}_{pcm}[(\phi_{liq} cp_{liq}(T_i - T_f)) + \phi_{sol} cp_{sol}(T_i - T_f))] \qquad (22)$$

$\dot{m}_{pcm}$: $mass\ of\ pcm\ (kg)$
ϕ_{liq}: $percentage\ of\ liquid$
ϕ_{sol}: $percentage\ of\ solid$
cp_{liq}: $spesifice\ heat\ of\ water$, $cp_{liq} = 4.2 \frac{kg}{kg.k}$
cp_{sol}: $spesifice\ heat\ of\ ice$, $cp_{sol} = 2.108 \frac{kg}{kg.k}$
T_i: high temperature (k)
T_f: low temperature (k)

$$Q_L = \dot{m}_{pcm} \phi_{sol} \lambda \qquad (23)$$

λ: $latent\ heat\ of\ pcm, \lambda = 330\ kj/kg,$
ϕ_{sol}: $percentage\ of\ solid$

Now, from eq. (19),(21),(3) the time off period of compressor provides by using the PCM can be determined theoretically. knowing the volume or mass of PCM added to the system, the percentage of water freezing and melting, and whether it completely or partially melts and freezes. The time off period is given by:

$$t_{off_{pcm}} = \frac{\dot{m}_{pcm}\left[\left(\phi_{liq} cp_{liq}(T_i - T_f)\right) + \phi_{sol} cp_{sol}(T_i - T_f)\right) + (\phi_{sol}\lambda\ ]}{UA\Delta T} \qquad (24)$$

$t_{off_{pcm}}$: PCM increase in off duration

Based on equation (24), we could calculate the off time provided by PCM if it is totally or partially frozen and melting, and compare it to the experimental determined time when knows the mass or weight of the phase-changing substance.

5. **Results and discussion**

The experimental test results for adding PCM at three different locations inside the refrigerator will be explained. Also, its effect on compressor time on and off period, cop and exergy destruction will be discussed.
The global effect of adding the PCM for the three locations are given below:

Case (1): in this case the PCM is added at the cabin far away from the evaporator part inside the cabin. This addition has no significant influence on the refrigeration system performance because the water doesn't reach freezing temperature. So, only the sensible heat is available, and its quantity small compared to latent heat.
Cases (2,3): in these cases, the PCM is touch the rear and front of the evaporator part in the cabin. For the two cases, there is improvement in the performance criteria of refrigerator. These additions, reducing the number of cycles, reducing the on-time ratio, increasing COP, reducing energy consumption and reducing the average temperature fluctuation inside the refrigerator cabinet. The improvement in all these parameters for the case of PCM touch the rear of the evaporator is greater than that for the case of PCM touch the front of the evaporator.
The variation in the performance criteria for all cases will be explained below.

5.1. compressor on-time ratio

Represents the percentage of the compressor on time to the total time of the experiment period as given by the following relation:

$$ontime\ rartio\% = \frac{comp.on\ time}{(comp.on\ time + comp.offtime)} \times 100\% \quad (\frac{hr}{day}) \quad (25)$$

Table 5.1 shows the compressor on time, compressor off time and compressor on time ratio for all cases for a test period of (24) hours. Case number two has the minimum compressor on time ratio of (27.27%) which means that, best location for the PCM is touch the rear of the evaporator part inside the cabin. This reduction due to that, the heat transfer to or from the PCM is by conduction. Also, the number of cycles for compressor on time plus compressor off time for cases number two and three is less than other cases.

Table 5.1. Operating cycle properties with and without PCM.

	Without PCM	Case (1)	Case (2)	Case (3)
Number of cycles	16	16	8	8
On-time (min)	451	447	390	417
Off-time (min)	927	959	1040	955
Ratio of on-time to the total cycle time	32.7%	31.79%	27.27 %	30.39%
Energy consumption (kWh/year)	434.5	433.5	371.6	396.3

Fig 5.1 Shows the variation of compressor work with time for all cases with and without using PCM. The figure clarify that, adding PCM touch to the rear and front of the evaporator led to less compressor work consumption compared to other cases. The reduction in the compressor work is due to increasing the cut off period of compressor and the reduction in the number of on-off cycles of compressor.

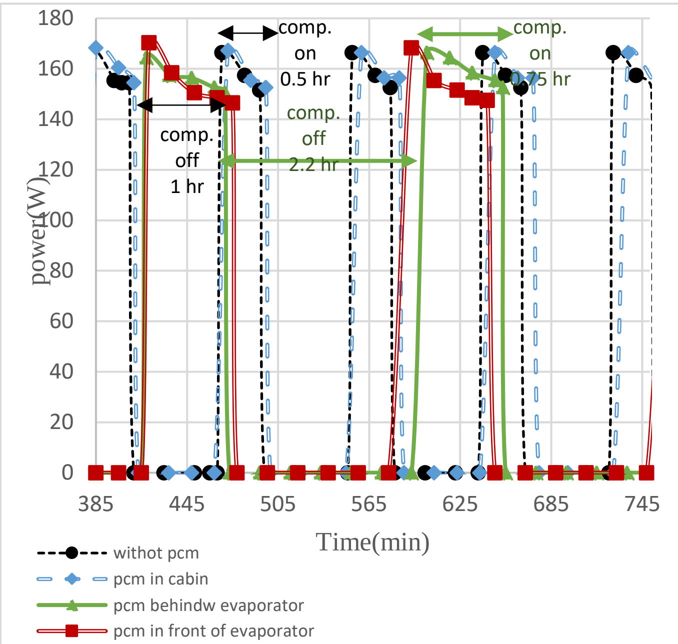

Figure 5.1 experimental power supply of VCRs

Figure 5.2 also shows that a sample was taken from one of the tests as a comparison model between practical and theoretical cases of increasing the time when the PCM was placed behind the evaporator, where a significant convergence was found between practical and theoretical calculations

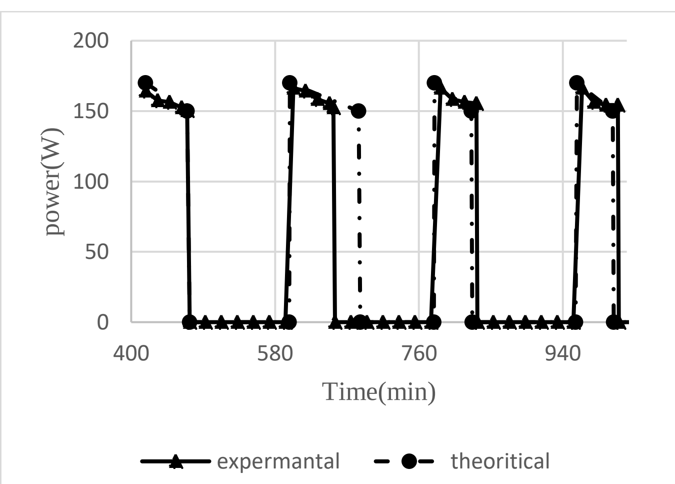

Figure 5.2 experiential on-time% vs theoretical; on-time%

5.2. Energy consumption

Both refrigerators with and without PCM were tested under the similar conditions at **Fig.5.1&Table5.1** the refrigerator's energy consumptions after 24 hours were 1.19 kWh/day, 1.187 kWh/day, 1.018 kWh/day, and 1.1085 kWh/day for the system without PCM and the system with PCM, respectively. This indicates that the system equipped with PCM could save energy more when put PCM behind evaporator because PCM prolongs compressor off time and provides the major source of power.

5.3. Effect on COP

Fig. 5.3 shows the compression between the performance co-efficient (COP) of a refrigerator without PCM to three different situations with PCM.

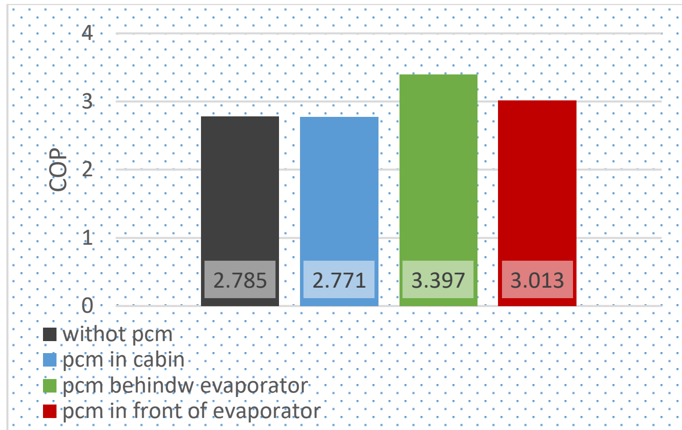

Figure 5.3: PCM Effect on COP

The coefficient of performance of refrigerator with PCM is higher than that without PCM. The COP for the second and third cases when the PCM is in direct contact with the evaporator is higher than that for the PCM indirect contact to the evaporator. This is due to an increase in temperature and pressure of evaporation as shown in **Fig.5.4**. This increase in evaporator temperature due to absorbing the heat from the PCM by direct conduction. The COP is increased by 21.9% as PCM contact the rear of the evaporator, while the COP increased by 8.2% for the PCM contact the front of the evaporator.

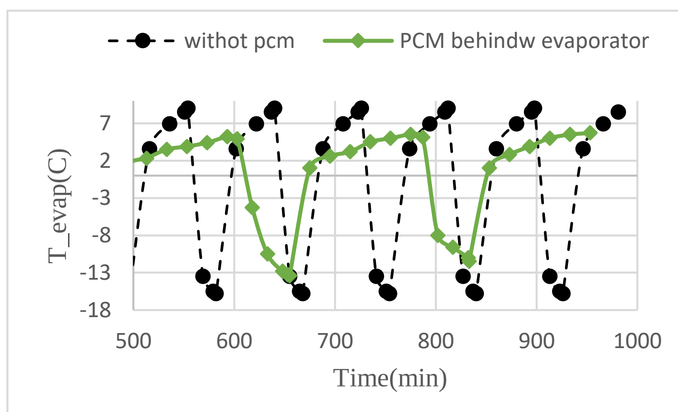

Figure 5.4: Effect of PCM on evaporation temperature

5.4. Effect on temperature fluctuations

Fluctuations temperature inside the cabin of the refrigerator during fresh food storage is an important issue because its adverse effects on food quality therefore must be minimized. **Fig.5.5** shows that temperature fluctuations in the presence of PCM significantly decreased compared to that without PCM. The period for on-off cycle for compressor with PCM is (3hr/cycle) while for the case without PCM is (1.5hr/cycle).

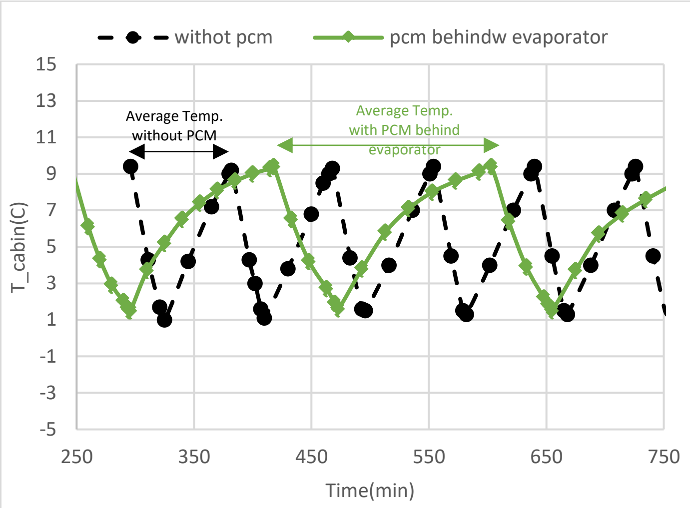

Figure 5.5: Effect of PCM on reduction of temperature fluctuations

5.5. Effect on exergy destruction

The exergetic approach of analysis is helpful for describing the energy flows in different processes of each component of system and helpful to reduces system losses. The exergy analysis results **Table 5.2** show that, the percentages of exergy losses take place in the compressor and capillary is greater than that for evaporator and condenser. The addition of PCM into the system cause the compressor work decreased and consequently its exergy destruction reduced. while the heat transfer in the evaporator increased as a result of adding the PCM and so decreasing exergy loss in the evaporator may be explained by the fact that the average temperature differential between the evaporator and the cool room reduces with rising evaporating temperature.

Table 5.2. the percentage of exergy destroyed of each component.

Case study	Ed_comp %	Ed_evap %	Ed_cond %	Ed_cap %
Without PCM	28%	20%	19%	33%
PCM-at cabin	27%	20%	20%	33%
PCM-behind evap.	30%	22.5%	19.5%	29%
PCM-front of evap.	37%	12%	20%	31%

Fig.5.6 shows the total exergy for the whole system with and without using PCM. The total exergy destruction for cases of adding the PCM touch to the rear and front the evaporator is the best, which means more energy saving. The exergy destruction is greater than that without PCM due to bad location of the PCM which led to increasing the heat load of the refrigerator only.

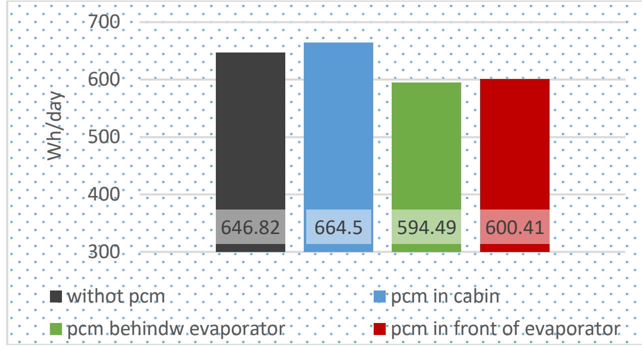

Figure 5.6: Effect of PCM on exergy destruction

6. Conclusion

The effect of adding a PCM (water) on the performance of household refrigerator is studied experimentally. From the results the conclusion is that the performance criteria improved when the PCM is contact to the evaporator. The improvement in the performance criteria for the case of adding the PCM touch to the rear of the evaporator is greater that the PCM touch the front of the evaporator.
Adding the PCM contact the rear of the evaporator led to energy consumption reduced by 14.4%, exergy losses decreased by 8% and increased off-time of the compressor by 72 minutes, and COP improvement achieved around 21.9% through the application of phase change material between evaporation and insulation.

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