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A novel household refrigerator with a phase change material (PCM) heat exchanger:An experimental investigation

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Abstract:*In this study, a phase change material (PCM) was adopted for constructing heat storage-PCM heat exchanger with a setup based on an ordinary single-door refrigerator.The experimental investigation of the characteristics of the novel refrigerator and an ordinary refrigerator was carried out. For the novel refrigerator, the PCM heat exchangerat the evaporator,has replaced the heat transfer mechanismwith the higher rate heat transfer mechanism of a combination of conduction and convection process during on-time. And the heat gain to the system was absorbed by PCM during the off-time.Thus, the overall heat-transfer performance of the evaporator with PCM heat storage exchanger could be significantly improved. This has resulted in a lower condensation temperature, a greater stability of temperature inside cabinet. Compared to the ordinary refrigerator, the ratio of on-time to the total cycle timeof novel refrigerator was much smaller, which led to lower energy consumption. Experiments demonstrated that the novel refrigerator could increase the COP of system by 21.5% and energy efficiency by about 15% withthe least cost addition.*

Keywords: *Energy consumption, heat exchanger, household refrigerator, latent heat storage, phase change material (PCM).*

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I. Introduction

Domestic refrigerators and freezers are among the most energy demanding appliances in a household due to their continuous operation [1]. Worldwide the no. of consumers is constantly increasing [2]. The study shows that refrigerator consumes about 1/4th of the total energy consumption in a house. It also accounts to about 1/6th of greenhouse gas emission. Although, the recent technologies use hydrocarbon as a refrigerant to reduce the greenhouse gas emission; the overall performance enhancement of domestic refrigerator is mandatory to reduce the indirect emissions and the amount of energy consumption.

So far, the techniques used to reduce the energy consumption of household refrigerators are as follows: 1) Usage of high efficiency compressor;2) Improvement of the thermal insulation;3) The enhancement of the performance of the evaporator and condenser [3]. Another approach is to use of a latent heat storage by integrating PCM in VCC system. Many research works have been devoted to the numerical and experimental studies on the household refrigerators which integrates a latent heat storage system. K. Azzouz et al. have designed refrigerator using 5mm thick PCM slab at the back of the evaporator. The study has shown 10-30% increase in COP [4] and 5-9 h of continuous operation without electric supply [5]. The similar results found by A. Marques et al. [6].

C. Tulapurkar et al., and B. Gin et al. have found the improved food quality of stored food material, with PCM application [7, 8].Furthermore, they found that, the PCM inclusion in the system has decreased the energy consumption during defrost cycle by 8% and by 7 % during frequent door opening condition [9]. E. Oro et al. have found that, PCM has maintained the freezer temperature 4-6°Clowest during the 3h of power failure [10]. Md. I. Khan et al. have designed the PCM box and studied the effect of increasing the PCM volume on the COP enhancement potential of the PCM integrated system and found that, with a 42% increase in PCM volume only additional 6% COP has increased [11]. Y. Yusufoglu et al. have performed the economic analysis to present the economic benefit of PCM[12]. R. Elarem et al. have experimentally investigated the effect of integration of specially designed U-tube type heat exchanger and found that, 12% reduction in power consumption and 8% increase in COP [1].

On the other hand, few researchers have worked on the PCM integration at the condenser. W. Cheng et al. have experimentally investigated and numerically validated the effect of shape-stabilized PCM (SSPCM) as a heat storage condenser and found that 12% energy saving but with the frequent compressor on-off cycling [3]. G. Sonnenrein have experimentally tested the three different PCMs (water, paraffin, copolymer compound) integration with wire-and-tube condenser. They found, by integrating a copolymer compound heat storage, power consumption has reduced up to 10% [13]. Furthermore, X. Yuan et al. have optimized the refrigerator with novel heat storage condensers by genetic algorithm and the optimized novel system has shownbetter performance than the non-optimized system [14].

Another approach used to integrate PCM in the system was the application of PCM in between components. F. Wang et al. have studied experimentally and numerically the effect of adding a PCM in between components of the VCC system. They found that 6-8% increase in COP by integrating the PCM in between condenser and thermal expansion valve[15, 16, and 17].Furthermore, S. Bakshipour et al. have numerically simulated the refrigeration cycle incorporated with PCM heat exchanger to analyze the parameters those affects the performance of the system [18]. M. Joybari et al. have reviewed all the studies performed and suggested another approach of simultaneous integration of PCM at evaporator and condenser [19].

In summary, the all studies performed till the date have been paid their extensive efforts to reduce the energy consumption of household refrigeration by integrating PCMs. Most of the studies have focused mainly on simple configurations of the PCM heat exchanger (plate type, U-tube type) or construction of shape-stabilized PCM or PCMbox or slab.To the best of the author's knowledge, there are no major studies in the open literature that investigate the effects of PCMand its placements inside the refrigerator to improve the thermal stability and the efficiency.This study presents a household refrigerator equipped with a novel PCM heatexchanger. The effects of this novel heat exchanger on power consumption of thehousehold refrigerator has been investigated experimentally. The integration of the PCM heat exchanger at evaporator has potential to improve the performance of the household refrigerator. This approach can be further explained as follows: 1) the integration of PCM at evaporator replaces the heat transfer mechanism by combination of conduction and convection; which enhances the heat transfer performance of evaporator; 2) PCM acts as thermal inertia which absorbs the heat gain to the cabinet during frequent door opening condition and during off-time also; 3) This ultimately maintains lower condensation temperature, less temperature fluctuations inside the cabinet and lower energy consumption.

II. Experimental Study

2.1. Experimental test rig

In this paper, an ordinary single-door household refrigerator was used for comparison. The maximumtemperature of the freezer during operation was required to be nothigher than (-10℃). The characteristics of the ordinary household refrigerator are as follows:

1) Cabinet: the total storage volume is 250 L, and the storage volumes of fresh food storage compartments and frozen-food storage compartments are 231 L and 19 L, respectively;
2) Evaporator: free convection, external diameter10 mm;
3) Condenser: free convection, wire-and-tube condenser, external diameter 5 mm;
4) Hermetic reciprocating compressor: 220V, 50Hz;
5) Expansion device: Capillary tube;
6) Refrigerant: 45 g of propane (R290) / isobutene (R600a) blend (50/50 Weight).

2.2. Refrigerator with heat storagePCM heat exchanger

Based on the same type of the ordinary refrigerator, a novel refrigerator was built by constructing a tube-type heat exchanger. This novel heat exchanger was an array of six tubes of commercial copper material fixed on a GI sheet frame. The linear length of the each tube, internal and external diameter of the each tubeis 0.415m, 0.008m and 0.009m respectively.The Fig.1shows the design of the heat storage PCM heat exchanger and the placement of the PCM heat exchanger can be seen in Fig.2.

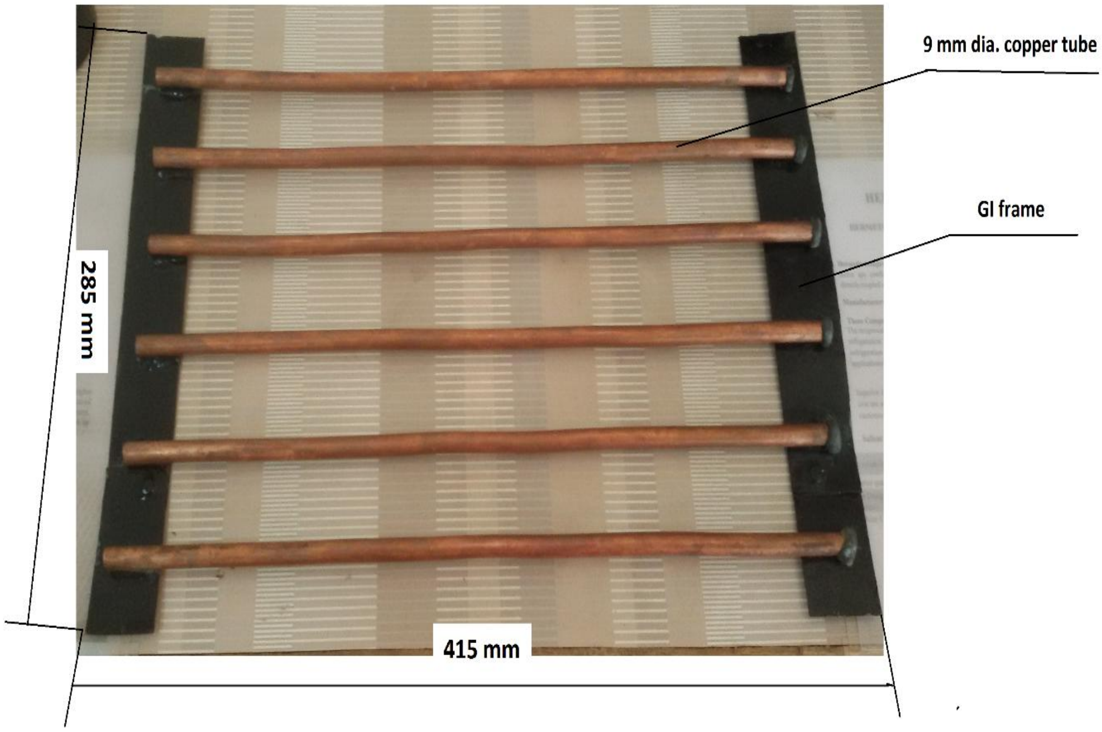

Fig. 1. The design of the tube type heat storage PCM heat exchanger.

The phase change material which was filled inside a tube of the heat exchanger; the thermo-physical properties of PCM are presented in Table 1. The total mass of the PCM used in the novel refrigerator was about 0.25 kg. The selected PCM is helpful to maintain the lower temperature fluctuations duringa variable thermal load condition; as it has the highest capacity ofheat storage[5].

Table 1: Thermo-physical properties of PCM.

PCM type	Melting Point (°C)	Latent heat of fusion (kJ/kg)	Density (kg/m^3)	Thermal Conductivity (W/mK)	Sp. Heat C_p (kJ/kgK)
Distilled water	0	333	1000	0.58	4.184

The experimental set up includes an ordinary refrigerator, the novel PCM heat exchanger, flow meter, two pressure gauges, eight thermocouples and energy meter. Fig. 2 shows the detailed circuit of the setup and the location of the pressure gauges which was used to measure the evaporation and condensation pressure at the inlet and outlet of the compressor. Temperature at various locations (as indicated in Fig. 2), was measured using K-type thermocouples and history of the energy consumption was recorded using an energy meter.

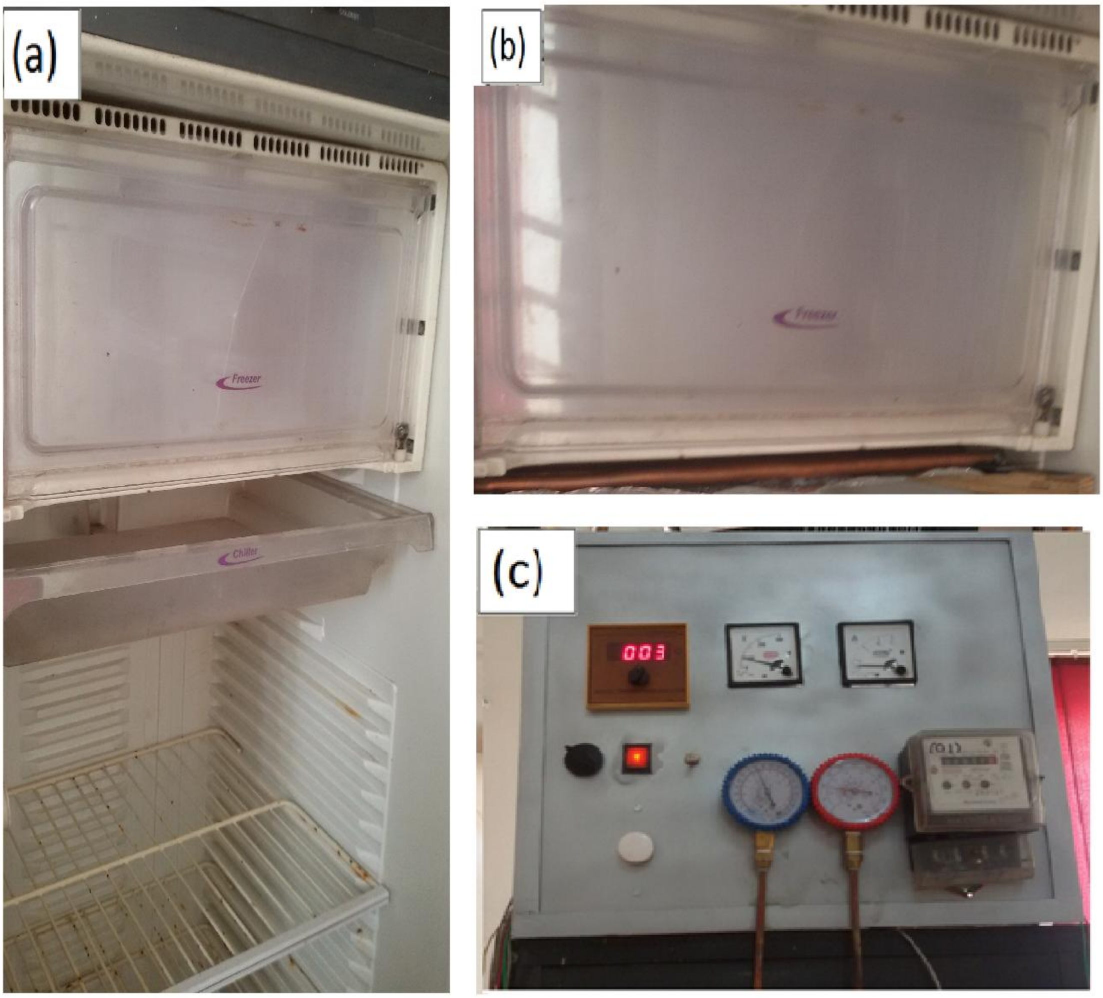

Fig. 2. Pictures of the (a) Experimental setup (b) Fabricated PCM heat exchanger placed at the evaporator section (c) Measuring instrument panel.

III. Experimental Procedure and Analysis

Both the ordinary and the novel refrigerator with PCM was tested under the same operating conditions. The experiments were carried out in a room where the temperature and humidity were maintained constant.The operating pressure, the energy consumption, the compressor outlet temperature, condenser outlet temperature, freezer temperature and evaporator outlet temperaturewere measured. In addition to that, the operating properties of three cases (refer Fig. 3) such as: 1) Case 1: Ordinary system 2) Case 2: PCM heat exchanger integrationwith VCC system 3) Case 3: PCM coverage at the evaporator (i.e. PCM heat exchanger) and at the racks of the VCC system (i.e. novel refrigerator),were recorded and compared to identify the novel system which has the best overall performance.

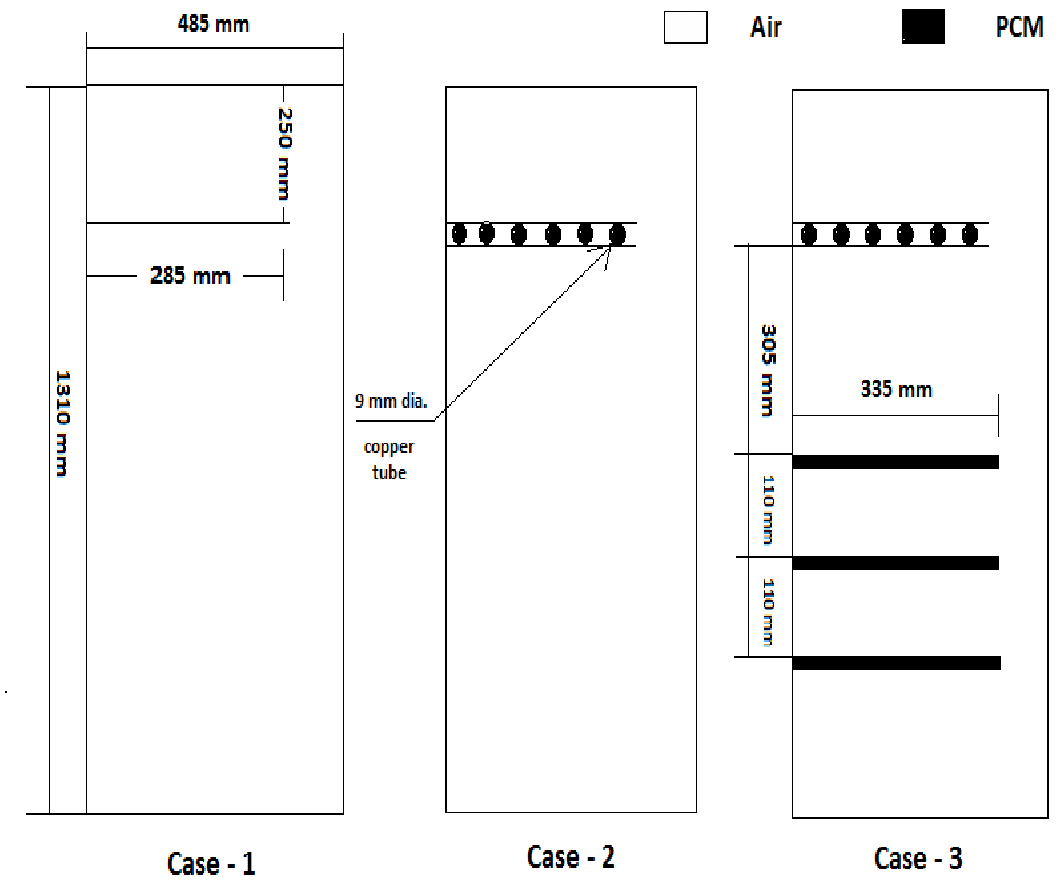

Fig. 3. Various cases of the refrigerator compartment for experimental study.

3.1. Experimental results

For both refrigerators, the operating parameters and the operating cycle properties are listed in Table 2 and 3 respectively. It can be seen from that,

(1) The pressure drop in a lower pressure side due to integration of the PCM heat exchanger in a VCC system was 0.3 bar which was under the allowable pressure drop value of 0.7 bar whereas, the pressure drop in the high pressure side was higher than the allowable pressure drop in value.Whereas, the pressure drop in the high pressure line was not very crucial and it has shown much less effect on cooling capacity and COP. The reason is, liquid is incompressible and its properties are not affected by reduction in pressure; the identified effect of pressure loss was the reduction in the pressure of refrigerant upstream of expansion device;

(2) Novel refrigerator has operated under the lower condensation temperature as compared to ordinary refrigerator;

(3) For novel refrigerator, the evaporator outlet temperature was higher than the ordinary refrigerator. This result was helpful for improving the COP of the cooling system. However, the higher temperature, low pressure refrigerant at the inlet of compressor resulted in a slight decrease in volumetric efficiency of the compressor due to reduction in mass flow rate of refrigerant and the refrigerating effect per unit mass flow rate increases due to an increasing enthalpy difference across the evaporator;

(4) The novel refrigerator has retained lower temperature inside cabinet and achieved the greater temperature stability of the system;

(5) The on-time of the novel refrigerator was higher than that of the ordinary system, whereas the ratio of on-time to the total cycle time of the novel setup was lower;

(6) Under the stable operating conditions, the energy consumptions of the ordinary and the novel refrigerators were 4.46 kWh and 3.79 kWh respectively, which implied that the novel refrigerator could save energy by about 15%.

Table 2: The operating parameters of both the refrigerators.

	Ordinary refrigerator			Novel refrigerator		
	On-time	Off-time	Complete cycle	On-time	Off-time	Complete cycle
Evaporation pressure (bar)	1.30	0.5	1.17	1.0	0.6	0.96
Condensation pressure (bar)	21.64	0.55	18.13	18.72	0.5	16.9
Evaporator outlet temperature (℃)	-0.6	11	0.5	- 1.67	20	3.75
Compressor outlet temperature (℃)	61.2	35	59	53.33	35	48.75
Condenser outlet temperature (℃)	33.4	31	33.2	31	30	30.75
Freezer temperature (℃)	-2	5	-0.25	-3.67	2.5	-2.125

Table 3: Operating cycle properties and energy consumption of both the refrigerators.

	Ordinary Refrigerator	Novel Refrigerator
On time (min.)	25	45
Off time (min.)	5	12
Total cycle time (min.)	30	57
Ratio of on-time to the total cycle time	0.833	0.789
Energy consumption per cycle (kWh)	0.10	0.15
Energy consumption per24 h (kWh)	4.46	3.79

The test results of the three cases under stable operating conditions are illustrated in Fig. 4 (a), (b) and (c)respectively. The maximum freezer temperatures of both the refrigerators were under -7℃, which were consistent with the temperature requirements of single compartment refrigerators. Comparing these three cases, it can be seen that, the Case – 2 has maintained temperature stability inside the cabinet, but the lowest temperature maintained inside the cabinet was higher than the novel refrigerator. And the condenser outlet temperature for Case – 2 and Case -3 was equal and lower than Case – 1. Hence Case – 3 has benefited the system in two ways; by means offunctioning under low condensation temperature and byconserving the lowest temperature and lower temperature fluctuations inside the cabinet. Thus, novel system has the best overall performance as compared to other cases.

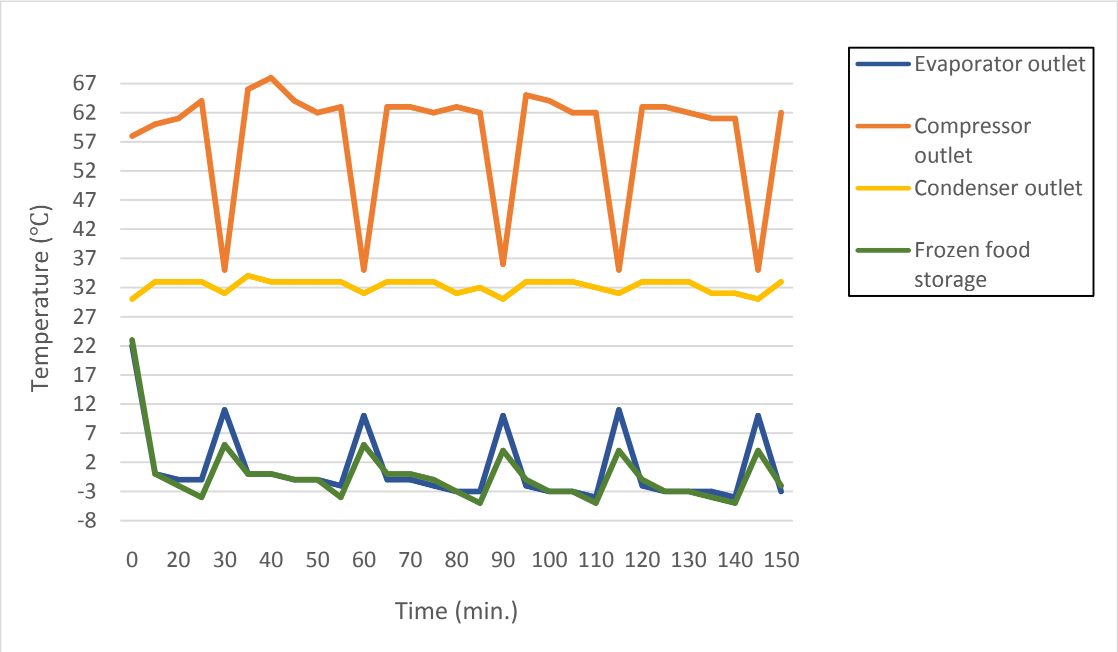

Fig. 4 (a). Case – 1: Testing curves of the ordinary refrigerator.

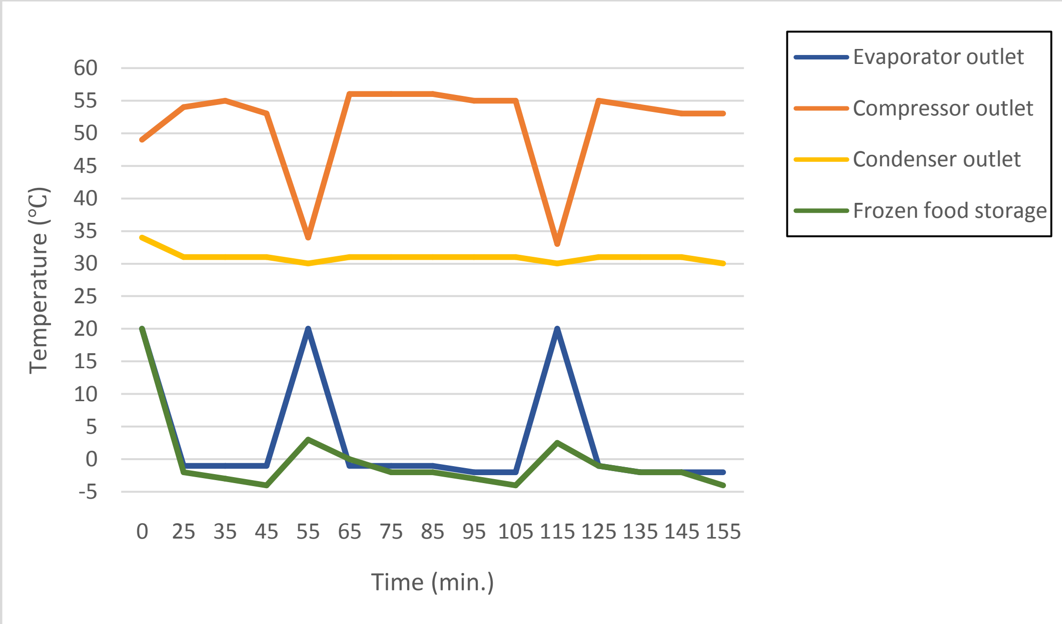

Fig. 4 (b). Case – 2: Testing curves of the PCM heat exchanger integrated with VCC system.

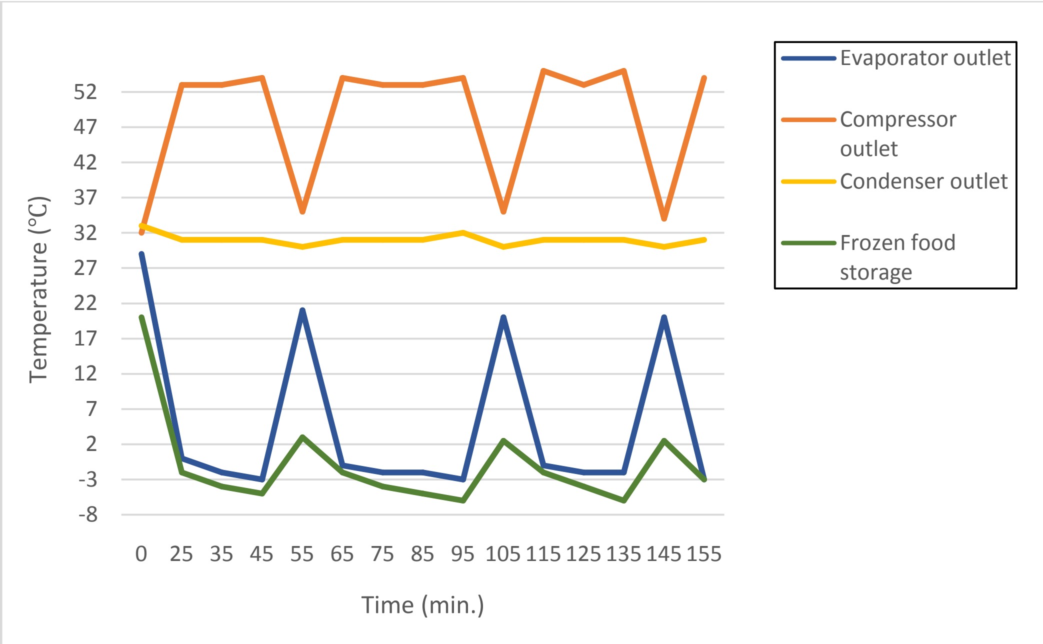

Fig. 4 (c). Case – 3: Testing curves of the novel refrigerator.

To further investigate the operating characteristics of both the refrigerators, the condenser temperature, the frozen food storage temperature, the power input and the energy consumption will be specifically discussed in the following parts.

3.2. Condenser temperature

The comparison between the condenser outlet temperatures for both refrigerators is shown in Fig. 5. For the ordinary refrigerator, the condenser outlet temperatureincreased gradually while the compressor was in operation to a higher outlet temperature (about 33℃) until the compressor was stopped. In the novel refrigerator, the condenser outlet temperature was higher than the ambient temperature by 1℃; whichindicated thata maximum of condensation heat was released into the environment during the on-time. Therefore, the heat dissipation load of the condensers during the operating cycle could be greatly reduced, indicating that the novel refrigerator could work under a lower condensation temperature and pressure.

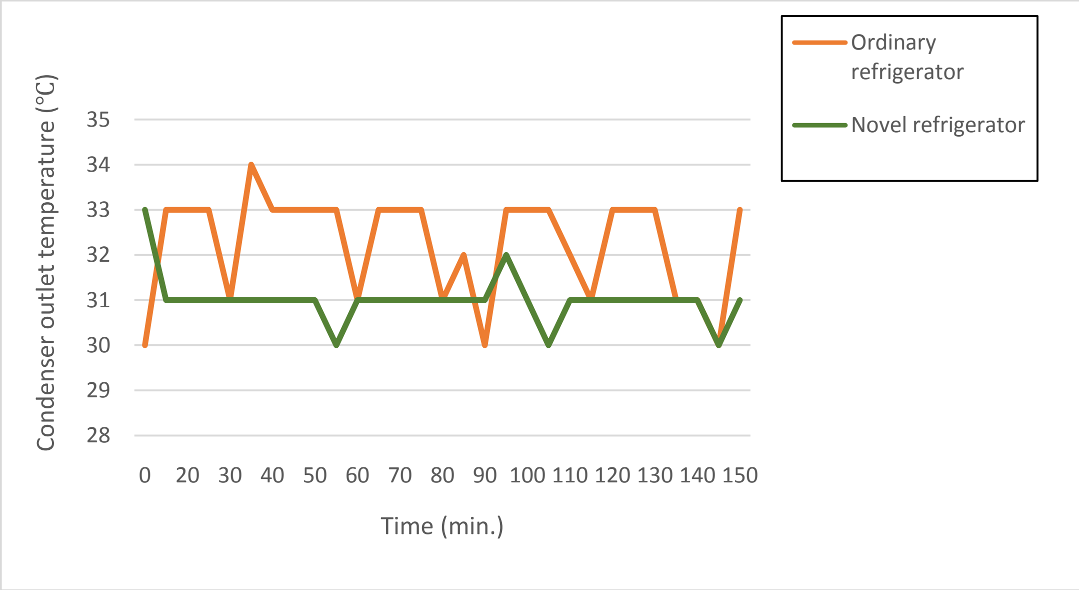

Fig. 5. Comparison of condenser outlet temperature.

3.3. Frozen food storage temperature

The comparison between the frozen food storagetemperatures for both refrigerators is shown in Fig. 6. For the ordinary refrigerator, the frozen food storage temperature was fluctuating in a wide range of 5 to -5°Cand in case of frequent door opening condition the compartment temperature was increased rapidly. On the other hand, for the novel refrigerator, the frozen food storage temperature was fluctuating in the smaller range of 2 to -6 ℃ and in case of frequent door opening condition the compartment temperature was increased slowly. This indicates that, the application of PCM at evaporator and at the wall of racks can maintain the temperature stability inside the cabinet and hence good food quality of stored material also achieved. While, by inclusion of PCM in an ordinary system, in case of the power loss condition, it is observed that, the temperature inside the cabinet was kept lower for a longer period than ordinary system.

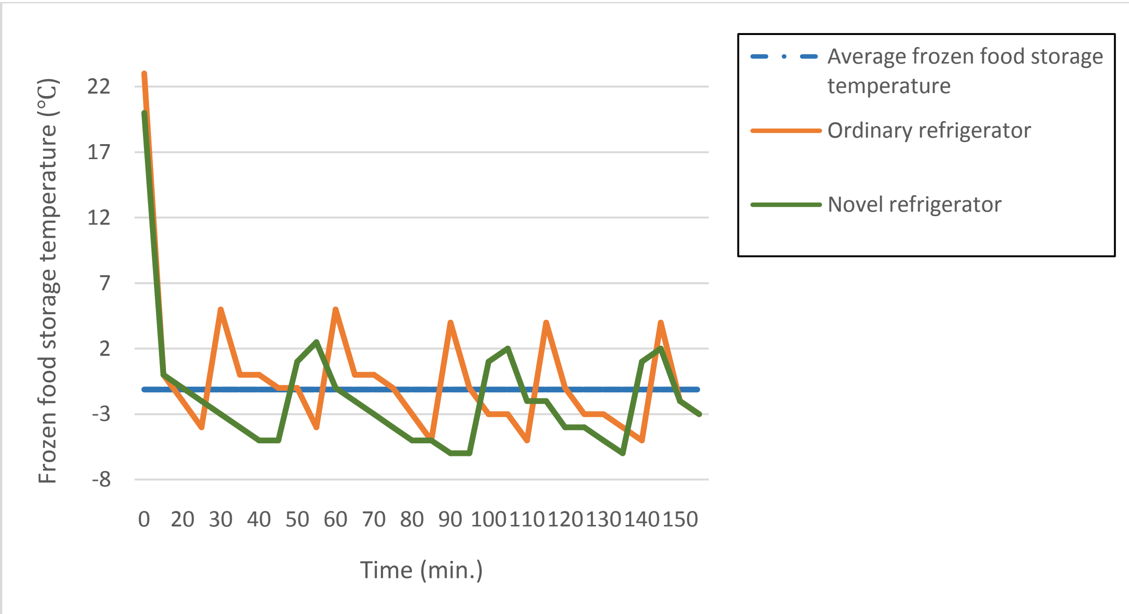

Fig. 6. Comparison of frozen food storage temperature.

3.4. Energy consumption of the refrigerator

The comparison of the energy consumption between the two cases is shown in Fig. 7. It can be seen that, the maximum power consumption of the novel refrigerator was lesser than that of the refrigerator without PCM. This fact can be explained as follows: (i) The refrigerator with PCM was working undera lower condensation temperature, and a higher sub-cooling degree, contributing to anincreased cooling effect; (ii) The temperature stability was achieved within a long period in the novel refrigerator, which has increased the compressor on-time, but reduced the ratio of on-time to the total cycle time. This has ultimately reduced the energy consumption of the system by 15%.

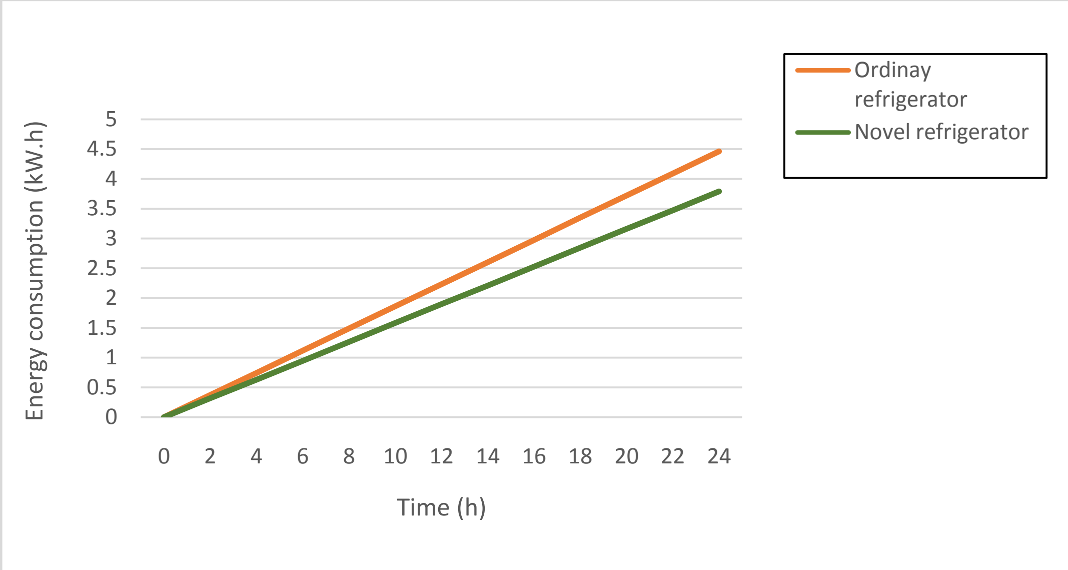

Fig. 7. Comparison of energy consumption between the ordinary and the novel refrigerators.

Furthermore, to present the overall performance of the system, the effect of PCM inclusion in the VCC system on the coefficient of performance was calculated using the cycle plotted in the P-h diagram of refrigerant R290 / R600a refrigerant (also called as care 30). This is presented as follows:

$$COP_{Ordinarysystem} = \frac{h_1 - h_4}{h_2 - h_1} = 2.65 \quad (1)$$

$$COP_{Novelsystem} = \frac{h_1 - h_4}{h_2 - h_1} = 3.22 \quad (2)$$

Hence, the percentage of COP improved by using the PCM heat storage is 21.5% under the operating conditions presented in this study.

3.5. Power input of refrigerator

The comparison of power supplies between the refrigerators is shown in Fig. 8. The maximum power supply of the novel refrigerator was smaller than that of the ordinary refrigerator and the total cycle time of the novel refrigerator was higher, and the ratio of on-time to the total cycle time of the novel refrigerator was smaller.

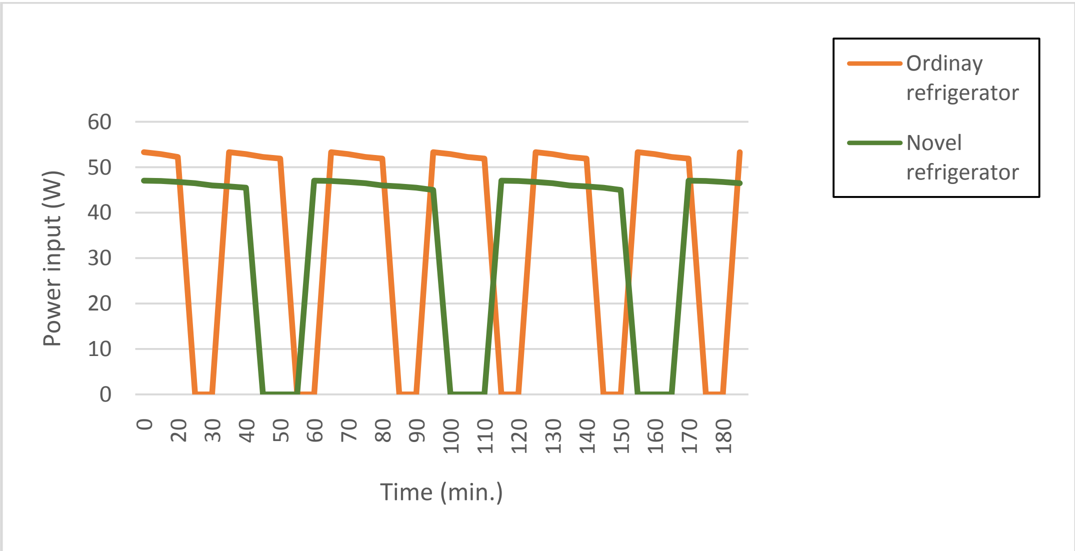

Fig. 8. Power input of the refrigerators.

The above phenomena can be explained as follows:
(1) For the novel refrigerator, the condensation temperature was higher before the compressor started, however, the condensation temperature was lower when the refrigerator worked in the stable status. Therefore, it needed smaller starting power and shorter time to achieve the stable status;
(2) The novel refrigerator was working under a lower condensation temperature, and a higher sub-cooling degree. Consequently, the novel refrigerator had a greater COP;
(3) The higher cooling degree has achieved the lowest freezer temperature and maintained the temperature stability inside the cabinet.

IV. Conclusion

The experimental study of a novel household refrigerator equipped with PCM heat storage was conducted. The operating characteristics of the novel refrigerator were obtained and compared to that of an ordinary household refrigerator.
The results can be concluded as follows:
(1) The overall heat-transfer performances of the novel refrigerator could be significantly improved by adding of the PCM as heat storage material, which has lowered the condenser outlet temperature and increased the inlet temperature of compressor. Both the results have shown the positive effect on VCC system.
(2) In the novel refrigerator, the variation range of the freezer temperature was smaller, which implied a more stable freezer temperature. This would not only help to enhance the efficiency of the refrigerator, but also helped to improve the quality of food preservation.
(3) For the novel refrigerator, it needed smaller starting power.
(4) Under the test conditions, the energy consumptions of thenovel and the ordinary refrigerators were 3.79 kWh and4.46 kWh respectively, which indicated that the novel refrigerator could save energy by 15% approximately.
(5) The novel refrigerator has shown the increased COP from 2.65 to 3.22; i.e. 21.5 % increase in the COP.
(6) The processing and installation of the PCM heat storage was simple, cheap and convenient.
(7) The proposed design of the heat exchanger can be further optimized in terms of size and can be tested with different type ofPCMs, to investigate its effect on cooling capacityof the system with other type of PCMs.

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