

Performance Enhancement of a Domestic Refrigerator With Nanoparticle Enhanced PCM over the Condenser Side

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The present work investigates the thermal performance of a domestic refrigerator integrated with the phase change material (PCM) and Nanoparticle Enhanced phase change material (NEPCM) based thermal energy storage system (TES). The materials such as Paraffin wax and Multi Walled Carbon Nano Tube (MWCNT) Dispersed Paraffin Wax are used as TES on condenser side. The experiments are conducted to analyze the performance of the refrigerator by placing the PCM and NEPCM based TES system on the condenser side, and to predict the possible energy saving potential. The integration of PCM and NEPCM based TES system over the condenser results in lowering the ratio of on cycle time to the total cycle time of the refrigerator by 8.26% and 17.95% respectively. The Subcooling of refrigerant takes place due to effective absorption of heat on the condenser side using TES in an isothermal manner. The decrease in the ratio of on cycle time to the total cycle time of the refrigerator and sub cooling of refrigerant lead to an energy saving potential. This potential is estimated as 13.06% with PCM and 18% with NEPCM based TES systems.

Keywords: Domestic refrigerator, Phase change material, Nanoparticle enhanced phase change material, Thermal energy storage.

1. INTRODUCTION

Refrigerators are the domestic appliances which consume more power because of its continuous usage. The increase in energy generation and usage requires a system to store the energy temporarily and balance the energy requirement whenever needed [1,2]. Thermal Energy storage becomes more important in energy storage as the conversion loss is comparatively less among other storage methods [3]. The improvement in the performance of the domestic refrigerator by any means will significantly reduce the power consumption [4]. It makes a huge impact on easing the power crisis and also reduces the overall utilization of fossil fuels and other non-renewable sources. The energy efficiency of the domestic refrigerator can be improved by the following ways (i) Enhancing the heat transfer capabilities of the two heat exchangers either evaporator or condenser [5] (ii) Insulation thickness optimization [6] (iii) Compressor speed optimization using Variable drive technologies [7]. The PCM to store the thermal energy efficiently increased the application in various areas such as (i) Passive cooling and heating in buildings [8] (ii) electronics cooling [9, 10], (iii) solar power generation [11,12], (iv) waste heat utilization [13, 14], (v) aerospace applications [15,16], etc. Esen et al. worked in proving the various geometrical and thermal parameters of PCM and its effects in domestic heating

system [17-19]. The researchers have been working on improving the performance of the domestic refrigerator on recent years. Azzouz et al. [20] performed his research by adding the latent heat storage on an evaporator side using water and eutectic mixture as PCM. The results showed 10% to 30% enhancement in the Coefficient of Performance (COP). Oró et al. [21] used PCM over the evaporator tubes and found performance improvement in the commercial freezer. Cheng et al. [4] analysed the novel refrigerator by placing PCM over the condenser and thus overall performance was significantly improved. Gin et al. [22] analysed the defrost cycle and door openings in the refrigerator, and also the improvement in performance of storing the frozen foods using PCM panels. The TES system Using PCM Integration in the refrigerator and air conditioning applications, enhances their performance significantly due to their high energy storing capability [23, 29]. But the PCM in a liquid state possesses very low thermal conductivity, which can be improved by adding nanoparticles which can enhance the conducting properties. From the literature, it is inferred that the performance of the refrigerator using NEPCM on condenser side has not been analysed. Considering the energy crisis and demand in power production, the need of this project is to analyze and improve performance of the domestic refrigerator through integration of TES using PCM and NEPCM on the condenser side and comparing the energy consumption of these refrigerators.

2. MATERIALS SELECTION

Paraffin wax (Fisher Scientific, Hempton, N. H., USA) was selected as PCM because of its phase change

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temperature (57°C to 60°C) matching the condenser temperature (55°C to 60°C) and also it has a high latent heat capacity and non-corrosive action on the copper tubes. The Thermophysical properties of paraffin wax provided by manufacturers are shown in Table 1. Multi walled carbon nano tube (MWCNT) procured from Cheap tubes, U.S.A. MWCNT was selected as nano material as it has good thermal conductivity and high mechanical strength. MWCNT is a carbon based nano material which provides modification in structure that has more advantages in improving the applications such as energy conservation and management, materials and its properties and some of the chemical processing systems [24]. The specifications of MWCNT provided by the manufacturer are shown in Table 2.

Table 1. Thermophysical properties of paraffin wax

Properties	Values
Melting/Freezing temperature	57-60 °C
Latent heat	140-145 kJ/kg
Thermal conductivity (solid at 30 °C)	0.245 W/mK
Thermal conductivity (liquid at 60 °C)	0.161 W/mK

Table 2. Specification of MWCNT

Parameters	Values
Outside tube diameter	30 – 50 nm
Inside tube diameter	5 – 10 nm
length	10 – 20 nm
Specific surface area	60 m ² / g
True density	2.1 g / cm ³

3. PREPARATION OF NEPCM

The NEPCM is prepared by adding MWCNT nano material with Paraffin wax base material. The initial process is to do the ball milling of the MWCNT which is carried out for 90 minutes using tungsten carbide balls and the nano material is taken for Ultrasonication under dry condition using ultrasonicator for the next 30 minutes. The Paraffin wax is melted initially and brought to liquid state and then the nano material is added to it. For perfect dispersion, the solution is kept higher than its phase change temperature and stirred for 30 minutes using magnetic stirrer. After the above process the solution was taken into the ultrasonicator which is at 65°C and the Ultrasonication is done for more than 90 minutes, so that the uniform dispersion of nano-material over the base material takes place. The above procedure is repeated for three different mass concentrations 0.3 wt %, 0.6 wt % and 0.9 wt %. The steps to be followed in preparing the NEPCM are shown in figure 1 as follows.

1. Melting of paraffin wax.
2. Dispersion of nanoparticle (MWCNT) in the paraffin wax.
3. Stirring the sample and sonification.
4. Prepared sample.

From the DSC(Differential Scanning Calorimetry) analysis of the samples, it is found that 0.6 wt % has high latent heat compared to other samples. Thus 0.6 wt % of NEPCM was used for the further analysis. The influence of MWCNT on the major phase change

properties and thermal energy storage behaviour of the NEPCM were analysed using DSC (TI instruments Q-200) with a cooling attachment using liquid nitrogen. The DSC analysis was performed with a sample size of 5 to 10 mg at a scanning range of 30 °C – 70 °C. The DSC analyses for the different weight percentage of paraffin wax and NEPCM is shown in the Figure 2 and Figure 3 respectively. The Figure 4 shows the comparison of DSC analysis and there are two peaks, one is during melting (heating) and the other one is during solidification (cooling). The small peak represents solid to solid transition and the large peak represents the solid to liquid and liquid to solid during melting and solidification respectively. The NEPCM of 0.6 weight percentage has highest latent heat compared to paraffin wax. The DSC analysis was helpful to infer the following results shown in Table 3. The thermal conductivity of base material is improved by adding MWCNT as nanomaterial. The experimental results of PCM and NEPCM were published by Lokesh et al [25], from which it is evident that thermal conductivity of PCM is improved when 0.6wt% of MWCNT was added to the base material. It is inferred that there is an increase in thermal conductivity of NEPCM over base PCM by 10% - 15% in solid state (i.e. upto 57°C) and 6% - 18% in liquid state (i.e. from 58 °C – 80 °C). The thermal conductivity gets reduced for both PCM and NEPCM when it changes its phase from solid to liquid state due to molecular disorder during phase change. The paraffin wax has negligible degradation of latent heat up to 200 thermal cycles [26], so it can be used as a thermal energy storage system for medium temperature applications.

Table 3. Phase change properties

Process	MELTING		SOLIDIFICATION	
	Paraffin wax	0.6 wt. %	Paraffin wax	0.6 wt. %
Onset temperature (°C)	47.28	48.20	57.85	58.55
Peak temperature (°C)	57.55	57.82	56.61	56.93
Latent heat (kJ/kg)	131.8	147.6	139.2	140.6

4. EXPERIMENTAL SETUP AND PROCEDURE

The schematic arrangement of experimental facility and the experimental procedure are presented in this section along with the necessary measuring instruments. The domestic refrigerator (R290 and R600a equal proportion) used is 165 litre capacity, single door and plate type evaporator. The evaporator is of natural convection type and condenser is also a free convection type exposed to ambient. The experiments were carried out in a test room where the ambient temperature and humidity were almost maintained constant and it is recorded (31°C ± 2 °C, and 50 – 60% RH). A compressor ON/OFF indicator is connected to the refrigerator, the power supply to this indicator is taken by making a junction between power supply line of thermostat and compressor. Therefore it glows when the system is running and turns off when the system is off. The Resistance Temperature Detectors (RTD) are located at various positions as shown in figure, totally eight sensors are fixed in the

refrigerator at specific distance between each other. Similarly three RTDs are connected at inlet, outlet and in between the in and out positions of the condenser side. The figure 5 demonstrates the RTD locations in the refrigerator. Each RTD location is indicated by a small symbol. RTDs are kept inside the refrigerator cabin according to the partitions at an interval of 20 cm between each RTD.

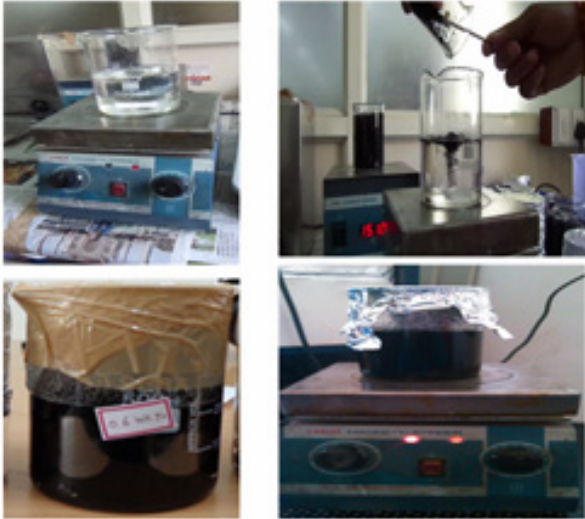


Figure 1. Steps of NEPCM preparation

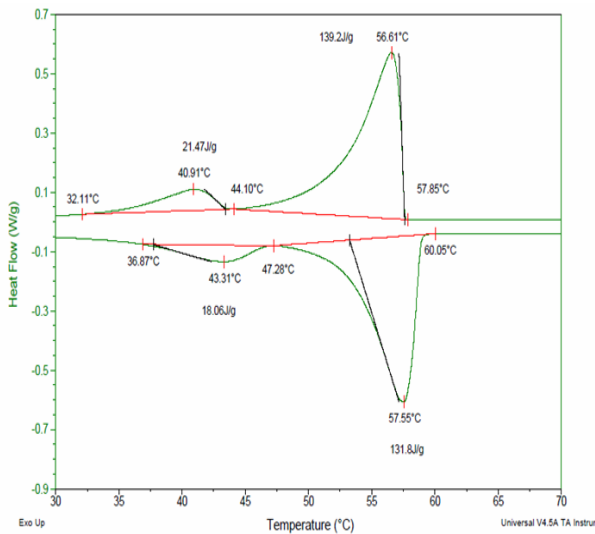


Figure 2. DSC analysis of the paraffin wax

In the above shown experimental set up, a pair of RTDs was provided at the evaporator: one at the plate of the evaporator (RTD 1) and other at the space of evaporator (RTD 2). In the refrigerator cabin at the top compartment three RTDs (RTD 3, RTD 4, RTD 5) were kept at an interval of 20 cm between each other, in the middle compartment i.e. 20 cm from top compartment a RTD (RTD 6) was kept and two other RTDs (RTD 7, RTD 8) were kept one each in the vegetable compartment and in the bottle cooling cabin respectively. The RTDs were connected to the data logger to display the temperature measured by the RTD. To find the cut in and cut off timing the refrigerator was provided with an indicator bulb (green) which glows for the duration of cut in cycle. Figure 6 shows kJ the arrangement of RTDs along the condenser side to measure the

temperature. Three RTDs were provided along the condenser, one RTDs at the ambient of the refrigerator so that we could relate the temperature variation along condenser and ambient conditions. In addition to this setup, eight RTDs were also connected inside the refrigerator cabinet, so that all the values can be related and studied. The RTD readings were measured using data logger. It should be noted that the temperature was measured at a minimum time gap of 10 seconds. Therefore the variation in performance of the refrigerator at different conditions could be studied.

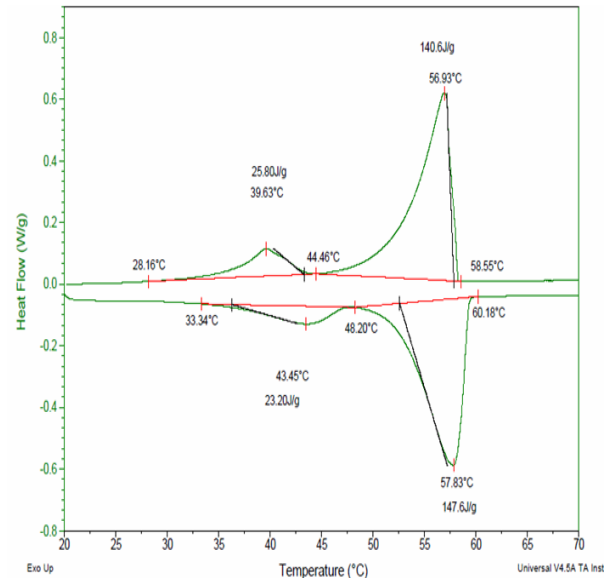


Figure 3. DSC analysis of the 0.6 weight percentage NEPCM

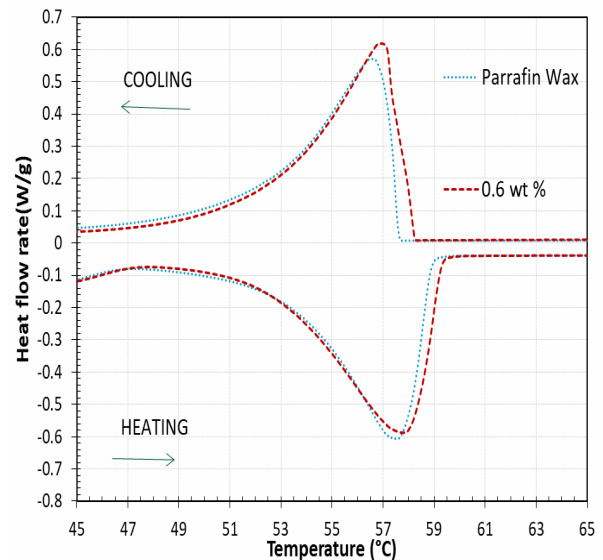


Figure 4. DSC analysis Comparison of paraffin wax and NEPCM

During the experimental study the refrigerator and the temperature indicator were switched on. The thermostat knob was set to minimum condition and the refrigerator was made to run continuously for at least 6 hours. The temperature inside the refrigerator cabin drops and attains a saturation point where the compressor cut-off takes place and once the temperature starts increasing the compressor cut-in takes place. The refrigerator working was continuously monitored and

measured for a time interval of 10 seconds using data logger which was connected to a Personal Computer for storing the data continuously. The refrigerator on and off timing and the corresponding temperature could be noted with the help of indicator light. The indicator light glows (green) during cut-in cycle and switched off during cut-off cycle.

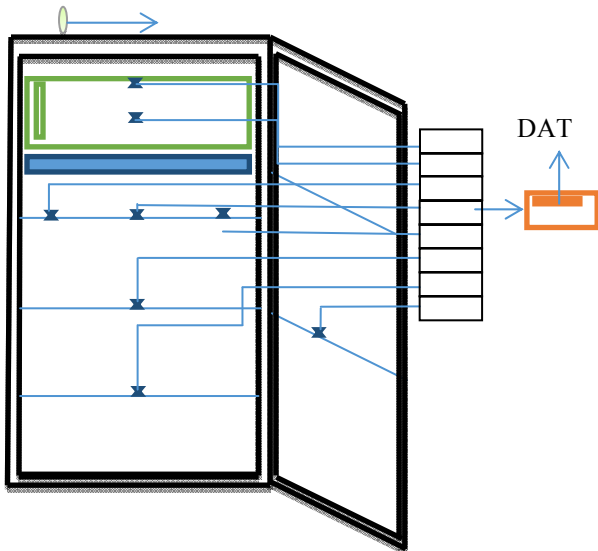


Figure 5. Schematic diagram of Experimental setup

5. FABRICATION OF TES SYSTEM

The TES was fabricated along the condenser tubes by fastening the PCM using aluminium foil tape. Initially the fins of the condenser were removed till the half way to roll the PCM over it. The PCM was heated using a hot water bath which has a temperature of above 75 °C, then the aluminium foil tape is cut into number of pieces according to the dimensions of the tube.

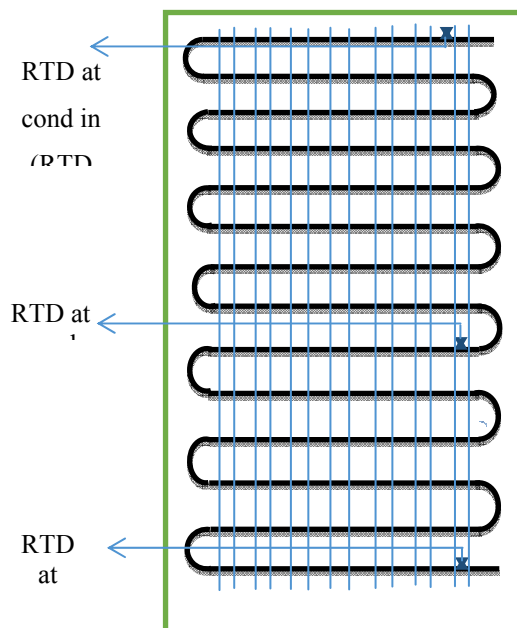


Figure 6. Schematic diagrams of the RTD locations across condenser side

The PCM in a liquid state was applied to a thickness of 5 mm on the aluminium foil tape which was rolled

over the condenser tube and the procedure was repeated for every tube of the condenser. The PCM was packed over the condenser tubes and RTDs were kept at the different location of the PCM and its temperature variations were continuously monitored and recorded during ON/OFF cycle. The view of the PCM encapsulated condenser was exhibited in Figure 7 and 8.



Figure 7. Photographic view of PCM rolled condenser tubes

6. DISCUSSION OF RESULTS

The experiments were conducted at no load conditions. The Figure 9 shows the variation of evaporator plate temperature measured using RTD 1 for the refrigerator without TES, with TES (PCM) and with NEPCM based TES. It has been observed from the figure that for the cases without TES, with TES (PCM) and NEPCM based TES the pull down time taken by the refrigerator to drop from ambient (29°C) to the cut-off temperature (-12°C) of the refrigerator are 5410 s, 4220 s and 3040 s respectively. From the observation it is evident that the refrigerator without TES took larger time to attain the cut off temperature, due to the fact that the heat dissipation rate of the condenser is lower when compared to system with TES. The cut in and cut off time are observed for the refrigerator without TES are 1750 s and 510 s respectively. With TES (PCM) refrigerator shows the cut in and cut off time duration reduced by 30% and 4% respectively.

The NEPCM based TES refrigerator shows the cut in and cut off time duration was reduced by 52% and 10% respectively. From the measured values above it is noted that with NEPCM based TES refrigerator shows significant improvement in the heat transfer on condenser side due to the high latent heat value of NEPCM compared to the PCM. The ratio of on cycle to the total cycle time of NEPCM based TES refrigerator system is lower than that of other systems. For the cases, considering the initial pull down cycle and operating time the compressor of the refrigerator without TES, with TES (PCM) and with TES (NEPCM) are in operation for a duration of 85.6%, 72.7% and 66.7% of the total time respectively. Figure 10, illustrates the variation in the temperature of refrigerant at the condenser midpoint measured using RTDs in the case of condenser without

TES, with TES using PCM and NEPCM. It is observed from the figure that the refrigerant temperature increases rapidly from ambient of 31°C to a maximum temperature of 55°C during on cycle period. During off cycle period, the midpoint temperature dropped to the minimum temperature of 34.1°C. It is noticed that the refrigerant temperature doesn't attain the ambient temperature due to the presence of thermal inertia even during the off cycle period. The refrigerant temperature increases slowly from ambient of 31°C to a maximum temperature of 52°C during on cycle period. During off cycle period the midpoint temperature dropped to a minimum temperature of 32°C in the case of refrigerator with PCM based TES. It is inferred from the graph that the refrigerant temperature is lower by 3°C and 2.1°C in the case of refrigerator integrated with PCM based TES system during on and off cycle period respectively. It could be due to heat rejected from the refrigerant during condensation is conducted at a faster rate by the solid PCM than the refrigerator without TES system.

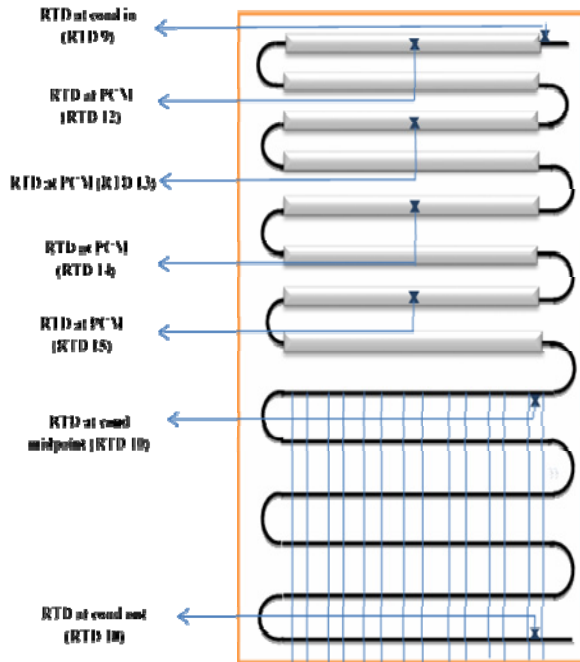


Figure 8. Schematic diagram of PCM integrated condenser

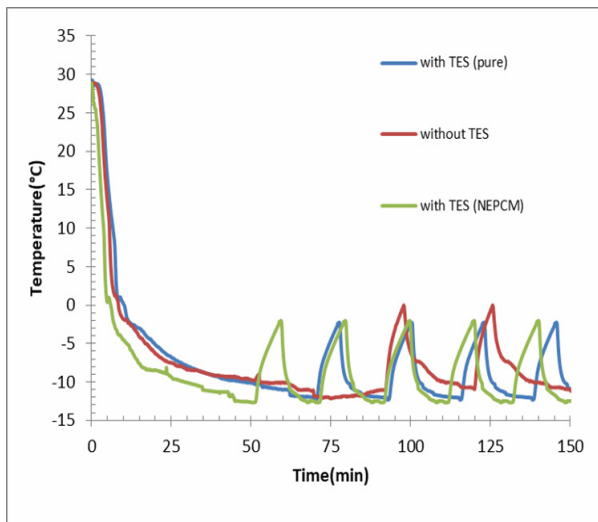


Figure 9. Cut in and Cut off cycle for different conditions

In case of refrigerator with NEPCM based TES, the refrigerant temperature increases slowly from ambient of 31°C to a maximum temperature of 48°C during on cycle and during off cycle it dropped to a minimum temperature of 31°C. It is noted that the refrigerant temperature is lower by 4°C and 2.1°C during on and off cycle compared to the refrigerator with PCM based TES system. It has also been noticed that the temperature of the refrigerant is further lowered using NEPCM based TES on the condenser side, due to its enhanced heat transfer properties with the presence of high conductive MWCNT. The mechanism for the increased thermal conductivity was examined and stated by Kumaresan et al. [27]. According to the result published by Cheng et al. [4], using an improved HCE-SSPCM with a thermal conductivity of $1.35 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$ and a latent heat of 103.3 kJ kg^{-1} , the condenser outlet temperature in a novel refrigerator decreased by 6.5°C compared to the ordinary refrigerator.

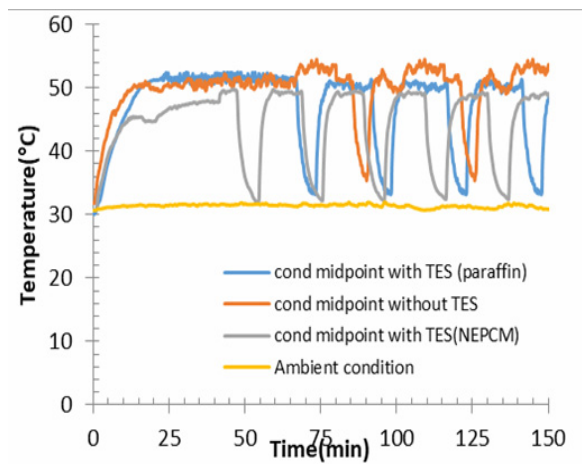


Figure 10. Comparisons of Condenser Midpoint temperatures

The difference in the result in the present investigation and results of Cheng et al. is owing to the difference in the type of a refrigerator, the refrigerant used and the type of PCM. It is construed from the above result that the integration of TES of the TES results in lower operating temperature that will be very useful to improve the thermal performance of the refrigerator. Figures 11 and 12 shows the fleeting temperature variations of the PCM and NEPCM at various locations along the length of the condenser. It is noticed from the figures that the heat rejected by the refrigerant during condensation is conducted by the encapsulated PCM during on cycle. The temperature of the base PCM decreases during the off cycle to 44°C as the PCM dissipates the heat to the surrounding and to the refrigerant in the stagnant condition. Once the next cycle started the temperature of the PCM increases until it attain its phase change temperature of 52°C. However in the case of NEPCM the phase change temperature is found to be lower than the base PCM both during on and off cycle by 2°C - 3°C. The difference in temperature results in enhanced heat conduction/dissipation characteristics of NEPCM with the presence of MWCNT [28]. This enhanced heat transfer, characteristics which is very useful to maintain the temperature of a refrigerant at a relatively lower temperature inside the condenser which

in turn very helpful to attain a higher degree of subcooling, and the same trend of transient temperature variation was absorbed along the condenser length, and the corresponding temperature variation is displayed in Figure 11. Figure 12 shows the comparison of energy consumption between the common domestic refrigerator and the customized TES refrigerator proposed in this study for the period of 4 hours without considering the initial pull down cycle.

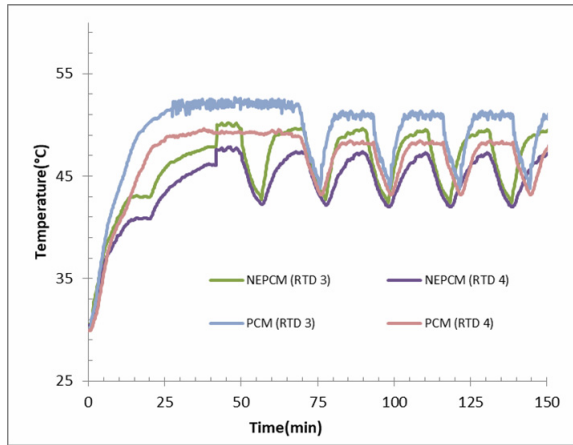


Figure 11. Fleeting temperature variation of PCM and NEPCM

The energy consumed is obtained by using the expression shown below in equation. The power consumed P is measured using a Wattmeter.

$$E=P \times t$$

It is perceived from the figure 13 that there is a possible energy saving potential of 13.06% and 18% in the case of refrigerator, with TES using PCM and NEPCM respectively. It is due to the enhanced heat transfer rate in the condenser. This energy saving potential through the integration of the TES system in the refrigerator will influence more in reducing the electricity consumption and also lead to considerable reduction carbon footprint.

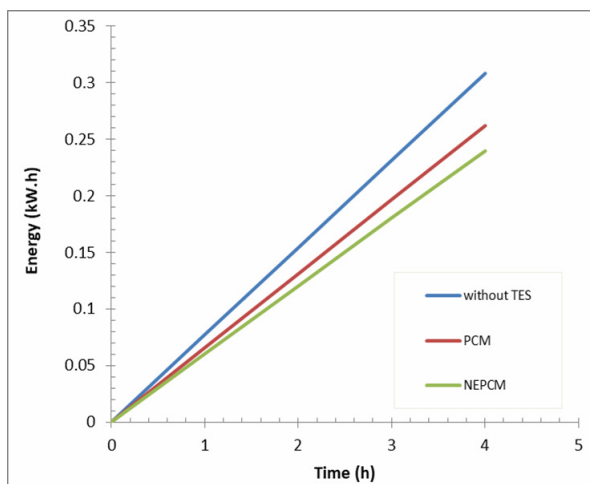


Figure 12. Comparison of refrigerator energy consumption

7. CONCLUSION

The following conclusions are observed over a refrigerator integrated with the PCM and NEPCM based TES system on the condenser side at no load conditions.

- i. The integration of the PCM based TES system on the condenser side results in lowering the condensation temperature by 3 °C and 2.1 °C during on and off cycle period respectively and the integration of the NEPCM based TES system on the condenser side results in lowering the condensation temperature lower by 4°C and 2.1°C during on and off cycle compared to the refrigerator with PCM based TES system that is very useful to enhance the COP of the refrigerator.
 - ii. The temperature of the refrigerant is further lowered using NEPCM based TES on the condenser side, due to the enhancement in thermal conductivity of the material using MWCNT.
 - iii. The ratio of on cycle time to the total cycle time gets reduced by 8.26 % and 17.95 % when the refrigerator is integrated with PCM and NEPCM based TES system respectively.
- It is anticipated that the energy can be saved upto 13.06 % and 18 % in the case of refrigerator, with TES using PCM and NEPCM respectively.

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NOMENCLATURE

t	Time (s)
E	Energy (kJ)
P	Power consumption (kW)
T	Temperature (K)
COP	Coefficient of Performance
NEPCM	Nanoparticle Enhanced Phase Change Material
TES	Thermal Energy Storage
PCM	Phase change material
RTD	Resistance Temperature Detector
DSC	Differential Scanning Calorimetry
MWCNT	Multi Walled Carbon Nano Tube

УНАПРЕЂЕЊЕ ПЕРФОРМАНСИ ФРИЖИДЕРА ЗА ДОМАЋИНСТВО КОРИШЋЕЊЕМ РСМ ПОБОЉШАНОГ НАНОЧЕСТИЦАМА НА СТРАНИ КОНДЕНЗАТОРА

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Рад истражује топлотне перформансе фрижидера за домаћинство са интегрисаним РСМ и НЕРСМ у ТЕС систем. Материјали као што су парафински восак и МWCNT са диспергованим парафинским воском су употребљени као ТЕС систем на страни где је смештен кондензатор. Циљ експеримената је био да се утврде перформансе фрижидера интегрисањем РСМ и НЕРСМ у ТЕС систем на страни кондензатора и да се предвиди могућност уштеде енергије. Интегрисањем РСМ и НЕРСМ постигнута је редукција

односа времена укључивања и укупног времена циклуса фрижидера за 8,26% односно 17,95%. Потхлађење расхладног средства се врши услед ефикасне апсорпције топлоте на страни кондензатора коришћењем ТЕС на изотермални начин. Опадање процента односа времена укључивања и укупног времена циклуса и потхлађења расхладног средства доводе до могућности уштеде енергије. Израчунато је да ова могућност износи 13,06% са РСМ и 18% са НЕРСМ.