INVESTIGATION AND NUMERICAL ANALYSIS OF A HOUSEHOLD REFRIGERATOR INCORPORATED WITH A PCM BASED CONDENSER

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ABSTRACT

In this study, a phase transition material (PCM) was adopted for constructing heat storage-PCM device with a setup supported a standard single-door refrigerator. The experimental investigation of the characteristics of the novel refrigerator and a standard refrigerator was administered. For the novel refrigerator, the PCM device at the evaporator ,has replaced the warmth transfer mechanism with the upper rate heat transfer mechanism of a mixture of conduction and convection process during on-time. and therefore the heat gain to the system was absorbed by PCM during the off-time. Thus, the general heat-transfer performance of the evaporator with PCM heat storage exchanger might be significantly improved. This has resulted during a lower condensation temperature, a greater stability of temperature inside cabinet. Compared to the standard refrigerator, the ratio of on-time to the entire cycle time of novel refrigerator was much smaller, which led to lower energy consumption. Experiments demonstrated that the novel refrigerator

Keywords: *Energy consumption, heat exchanger, household refrigerator, latent heat storage, phase change material*

INTRODUCTION

According to world's 6% of the produced energy is used by household refrigerators and freezers. In U.S.A., the energy consumption share of the refrigerators is 7.2% One of the reports about energy consumption in Brazil showed that refrigerators and freezers consumed about 23% of total residential electricity (EPE, 2014). In Europe, refrigerator and freezer consumed about 20% of total electricity in household appliances reported that in France, refrigerators consume about 26% of the residential electricity demand and they are responsible for 17% of the overall greenhouse gas emission. One of the studies, shows that there are about 200 millions of refrigerators in China and they consume about 30-40% of the residential electricity demand

In recent years, refrigerator became an integral part of the household in India also. Nearly, 46% of the urban and 8% of the rural population utilizes refrigerators

In this regard, a number of countries have introduced labeling programs and minimum energy efficiency standards. Accordingly, a standard (A to G) is assigned to the appliance based on the energy consumption. In India, the Bureau of Energy Efficiency (BEE) is running standard and labelling program for different appliances. Herein, it is noted that considerable amount of energy can be conserved when more energy efficient appliances are used. The International Institute of Refrigeration (IIR) 5th Informatory Note on Refrigeration and Food, 2009 estimated that with improving the refrigerators to higher efficiency standard would help to preserve over 200 million metric tons of perishable foods.

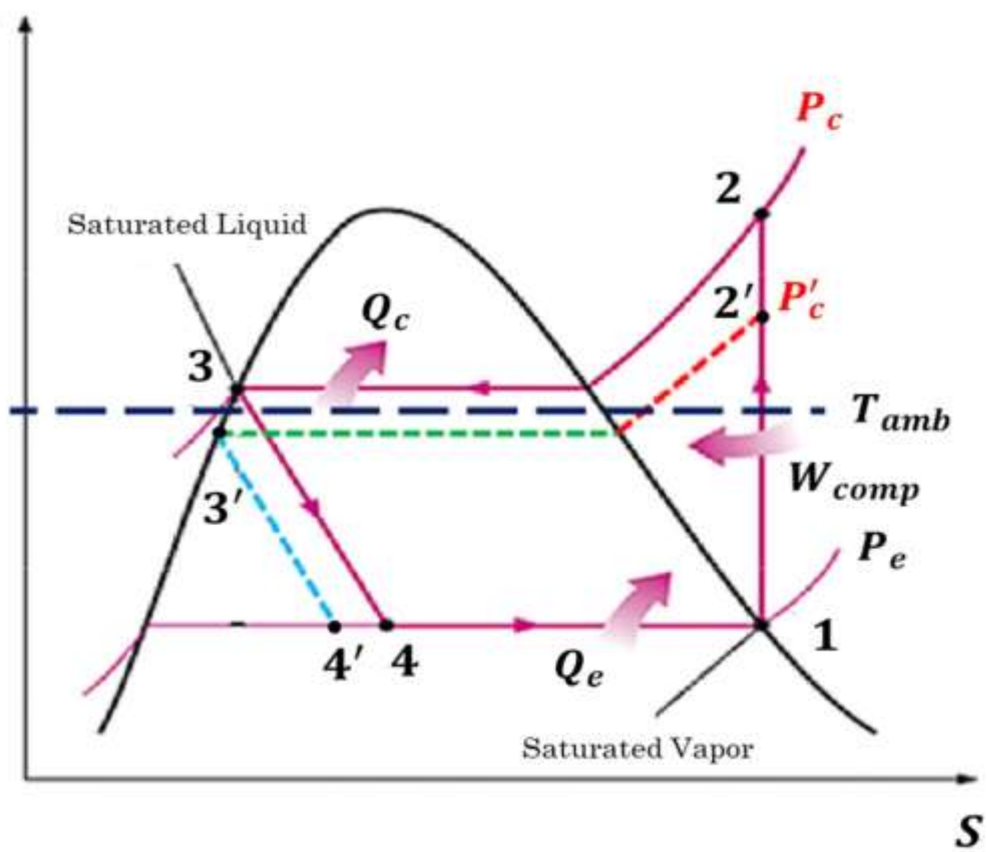
This scenario motivated to look for the options to reduce the energy consumption for the refrigerator. Consequently, the improvement in the performance of household refrigerators is taken up for the present research work.

Vapor compression refrigeration cycle

The domestic refrigerator works on vapor compression refrigeration cycle (VCRC) as shown in Figure 1.1. At point 1, a refrigerant enters a compressor and compression takes place (1-2). During the isobaric process 2-3 in condenser, heat rejection occurs from refrigerant to the ambient. Here the refrigerant phase changes at higher pressure (condenser pressure) from super-heated vapor to the saturated liquid form. In process 3-4, the refrigerant expands in the expansion device, capillary tube, which is an isenthalpic process. In the last process of the cycle (3-4), refrigerant absorbs heat from the space to be cooled and converts from two-phase region (liquid-vapor) to the superheated vapor state in the evaporator.

The performance of the refrigerator is measured using a coefficient of performance (COP), defined as the ratio of heat absorbed in the evaporator to the work provided to the compressor. It is explicable from the Figure 1.1 that by decreasing the condensing temperature, the work of

compression can be reduced and the heat absorption amount can be increased, in turn, the COP would enhance. In this presented work, a novel method of decreasing condensing temperature is implemented to the household refrigerator and tested through experiments.



Vapor compression refrigeration system

Objectives

1. To design and develop an experimental model of a PCM based heat exchanger and its integration to the household refrigerator

2. To conduct experiments on the refrigerator with and without a PCM based heat exchanger and their performance comparison

3. To develop three-dimensional numerical model of a PCM based heat exchanger and its validation with the experimental results

Literature Survey

Nethaji and Mohideen (2017) increased the heat removal rate from the compressor shell by employing the drip cooling. It reduced the compressor shell temperature by 4.2°C. Reduction in compressor shell temperature improved the COP of refrigerator by 10.3%. The average energy consumption per month observed to be 45.33 kWhr without drip cooling system, while that of 40.9 kWhr using drip cooling of compressor shell.

Hermes et al. (2009) developed a mathematical model to access the energy performance of vapor compression system by analyzing the sensitivity of the compressor stroke. They have reported that by decreasing the compressor piston displacement from 5.96 to 3.77 cm^3, the energy consumption drops by 13%.

Waltrich et al. (2011) analyzed the impact of the components (compressor, condenser and evaporator) on both overall system cost and COP using a genetic optimization algorithm and showed an optimized model having a COP/cost ratio approximately 50% higher than the conventional model.

Afonso and Matos (2006) reported that the ambient air near the compressor has slightly higher temperature due to the heat rejection of the compressor, which is generated during the compression process. This higher temperature air has negative effect on refrigerator performance as there are chances of air infiltration to the refrigeration compartment while having the door opening and heat transfer through the wall of refrigerator to the cabinet air. To address this issue, Afonso (2013) proposed a plenum with a fan near to the compressor and conducted experiments. This modification leads to decrease in air temperature by 11°C near the compressor and reduced the overall energy consumption up to 9% per year.

Chang et al. (2008) performed experiments with variable speed reciprocating compressor with a brushless DC motor inside. Based on their experimental analysis, they observed energy saving of 35% for the 560 liters capacity refrigerator as compared to the same capacity refrigerator having a fixed speed compressor.

Kumara (2011) modified condenser of domestic refrigerator by adopting proper design procedures. The optimum combination was achieved for different values of copper tube pitch, number of copper tubes and the number of steel wires. The selection of the optimum combination was done based on total heat transfer, mass flux and the material cost. In modified condenser, the heat transfer increased by 32.9% while the material cost reduced by 19% from base model. This modification improved the COP by 17%.

Bassiouny (2009) analyzed the effect of space surrounding the condenser numerically and experimentally. By changing the space between wall and refrigerator from 30 to 300 mm, the temperature around the condenser reduces by 70%. It enhanced the driving force of heat transfer, which improves the heat transfer from 20 W to 60 W. Blocking the space around the condenser will resist the up flow of buoyant air.

Kılıçaslan (2002) performed experimental study on a commercial refrigerator by implementing different sized chimneys fitted on the condenser and achieved performance improvement of 54%. Similar concept was tested by

Gedik et al. (2016) on a household refrigerator, with which they have attained increase in COP by 5% and 10% with loaded and unloaded conditions of the refrigerator, respectively

Zhang et al. (2017) improved the performance of refrigerator by installing outer foam ring and central foam in spiral wire and tube condenser. They found increase in compressor off time by 4.1% with no change in the compressor on time and reduction of power input by 2.37%. Another type of condenser used in vapor compression refrigeration system is plate heat exchangers (PHE) because it has higher heat transfer co-efficient and it can provide the most compact design in terms of surface area with low initial cost.

Raveendran and Sekhar (2017) improved the performance of 190-liter capacity domestic refrigerator by installing water cooled brazed plate heat exchanger. It requires 84% less heat transfer area than conventional wire and tube condenser. The COP or refrigerator increased by 57-75% and energy consumption per day was also reduced by 21-27% as compared to wire and tube condenser. However, the management of cooling water is a challenging task in the domestic refrigeration system.

Ablanque et al. (2010) had carried out parametric study on capillary tubes used in household refrigerators having isobutene as refrigerant. They studied the influence of double tube heat exchanger length, tube total length, tube diameter and tube roughness on the COP of refrigerator and concluded that the COP increases as the heat exchanger length increases, whereas other parametric variation does not affect the COP of the system.

One of the methods used to improve the performance of small refrigerator is to increase heat transfer between the refrigerant in capillary tube and suction line. Jeong et al. (2012) carried out a theoretical study on the suction line heat exchanger and showed that both the location and the length of heat transfer section influence the COP as well as the cooling capacity. The COP and cooling capacity were increased by more than 2.7% and 12.6%, respectively, by increasing the heat transfer sections to a simple refrigeration cycle.

Pisano et al. (2015) provided a practical tool for deciding the best combination of refrigerant charge and capillary tube diameter for a commercial refrigerator. They reported that the decision should be based not only on maximization of COP, but also on the limitations imposed by other parameters such as the evaporator superheat, condenser sub cooling, run time ratio, suction line temperature.

Rasti et al. (2012) had performed experimental investigation substituting R134a with R436A in a domestic refrigerator of 238 liters. They found that the ON time ratio and the energy consumption per day reduce by 13% and 5.3%, respectively with R436A as compared to the R134a and the optimum refrigerant charge also reduced by 48% with R436A. R436A raised the energy efficiency index of the refrigerator from label ‘‘E’’ to label ‘‘D’’ according to Iranian National Standard No. 4853-2.

Ghadiri and Rasti (2014) carried out experiments for a domestic refrigerator of 318 liters capacity with R134a as a refrigerant. The experiments were conducted at 32°C ambient temperature and 50% relative humidity. They have achieved 23.6% reduction in energy consumption by removing hot-wall condenser, increasing condenser air-cooling and reducing compressor-cooling capacity.

Jia et al. (2014) had investigated the performance of refrigerator using different kind of nano-oils in compressor for two different refrigerants, R134a and R600a. It was concluded that the performance did not improve for R134a, while it improved by 5% for R600a.

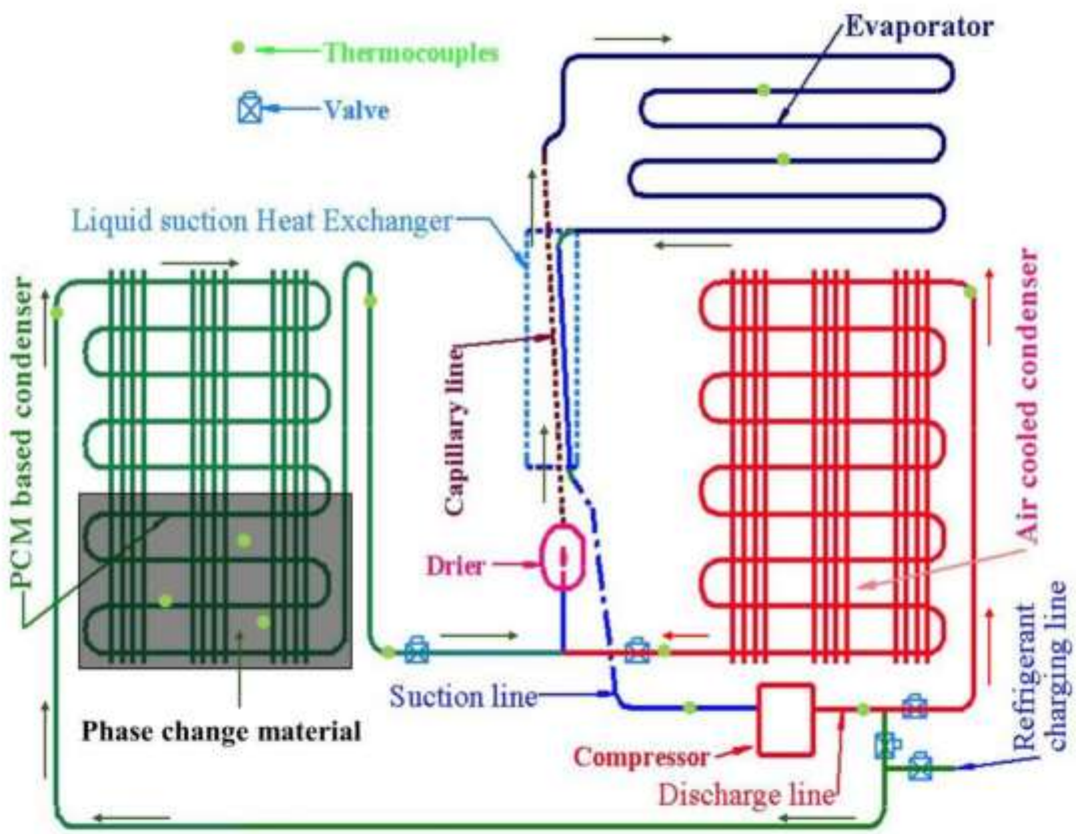
Thiessen et al. (2016) conducted experimental analysis on a household refrigerator by varying the VIP coverage area and positioning of it around the cabinet. They observed that the energy consumption is dependent upon the positioning and coverage area of insulation panel. The installation of VIP near the doors and the rear wall reduces the energy consumption by 6% and 11%, respectively and by covering the insulation area of about 56%; the VIP reduces the energy consumption by 21%.

EXPERIMENTAL SETUP

Working principle

Conventionally, an air-cooled wire and tube type condenser is attached to the backside of household refrigerator. The refrigerant flowing inside tubes rejects heat to the ambient via the natural convection heat transfer. It is a known fact at the higher ambient temperature, the condenser temperature and consequently condenser pressure settles on higher side, due to which the power consumption of refrigerator would be the highest at noontime.

In order to minimize the energy consumption at the peak ambient duration, a PCM based condenser (heat exchanger) parallel to the wire and tube condenser is incorporated to the household refrigerator. Figure 3.1 shows a schematic diagram of the proposed modified refrigerator. At the noontime, the refrigerant is made to flow through the PCM condenser instead of a conventional condenser. The selection of the PCM would be such that the melting temperature would be lower than the ambient temperature at noontime. This makes refrigerant heat rejection at a lower temperature, which reflects reduction in the compressor energy consumption. Once the PCM is converted into a liquid, it requires the lower ambient temperature to reject its own heat and convert back into solid. Such scenario would be possible in the nighttime when the ambient temperature

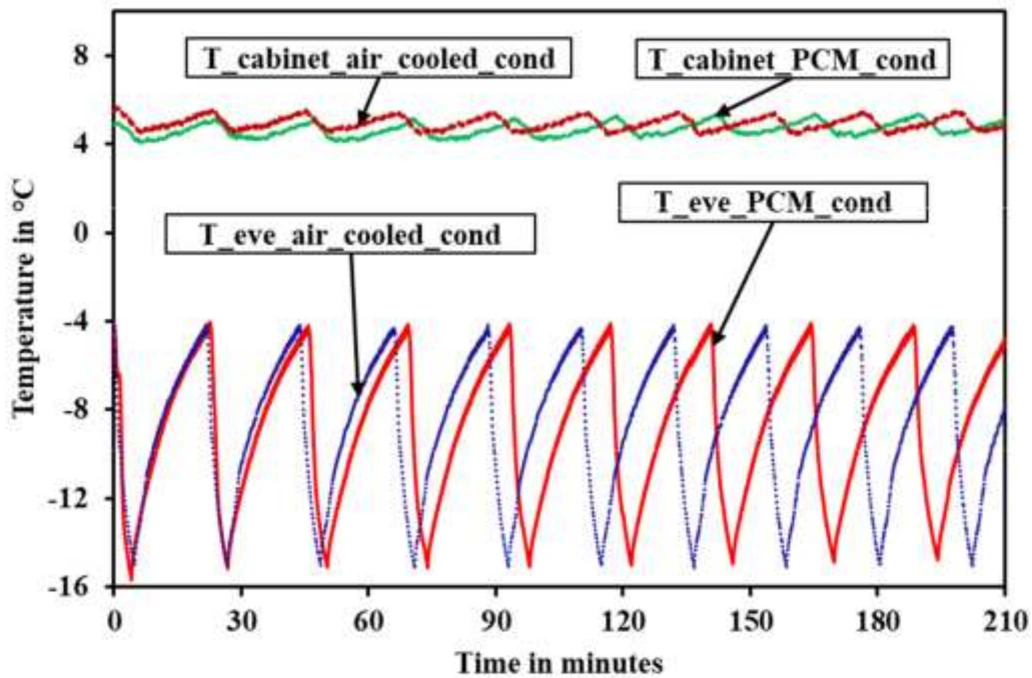


compares change in the condenser exit temperature for the air-cooled condenser and PCM based condenser having a PCM initial temperature of 17.5°C. The plot indicates that the exit temperature of condenser varies in the range of 26-48°C for an air-cooled condenser, while 18-27°C in case of PCM based condenser for the first 60 min. It is clearly visible that the PCM based condenser shows a lower temperature range. This is due to the utilization of latent heat of PCM in the temperature range of 18-23°C.

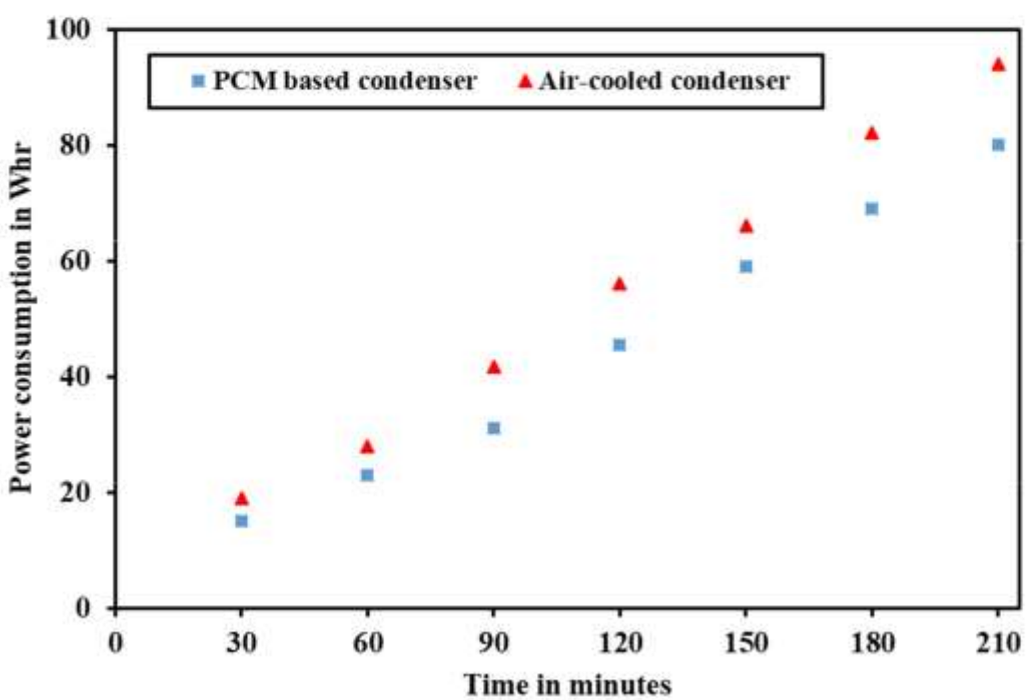
Evaporator and cabinet temperature

The things, which need to be refrigerated, are placed in the cabinet section of the refrigerator. Therefore, it is essential to look the changes of the cabinet air and the evaporator temperatures because of the proposed modification. Figure 4.5 displays variation of cabinet air and evaporator temperatures with respect to time for both the condensers. It is observed from the figure that, with the proposed condenser, both the cabinet air and evaporator temperatures are varying in the same range as that of with the conventional condenser refrigerator. The average temperature of refrigerator cabinet air during the 3½ hrs of experiment observed to be 4.7°C with PCM based condenser, while it was 4.9°C with conventional condenser. The average temperature of evaporator in 3½ hrs of experiment for both PCM based and air-cooled condenser remain the same as -8.9°C.

This indicates that the proposed modification does not have any effect on the cabinet air and evaporator temperatures.



Evaporator and cabinet air temperature variation with time



Variation of power consumption by refrigerator with time

Energy consumption by the refrigerator

Ultimately, energy consumption by the refrigerator is the key parameter, which should be looked upon in order to get check worthiness of the PCM based condenser. It has been plotted with time for air-cooled and PCM based condensers as shown in Figure 4.6. It is noticed that for the first hr of experiments, PCM condenser based refrigerator consumes ~18% less energy compared to air-cooled condenser refrigerator. Later, these energy consumptions are ~19% and ~15% for 2 and 3½ hrs of refrigerator operation, respectively.

During the initial period, the energy consumption found to be lowest due to the utilization of latent heat of PCM. However as the time progresses, because of the sensible heating of PCM, it resulted into the drop of percentage energy saving.

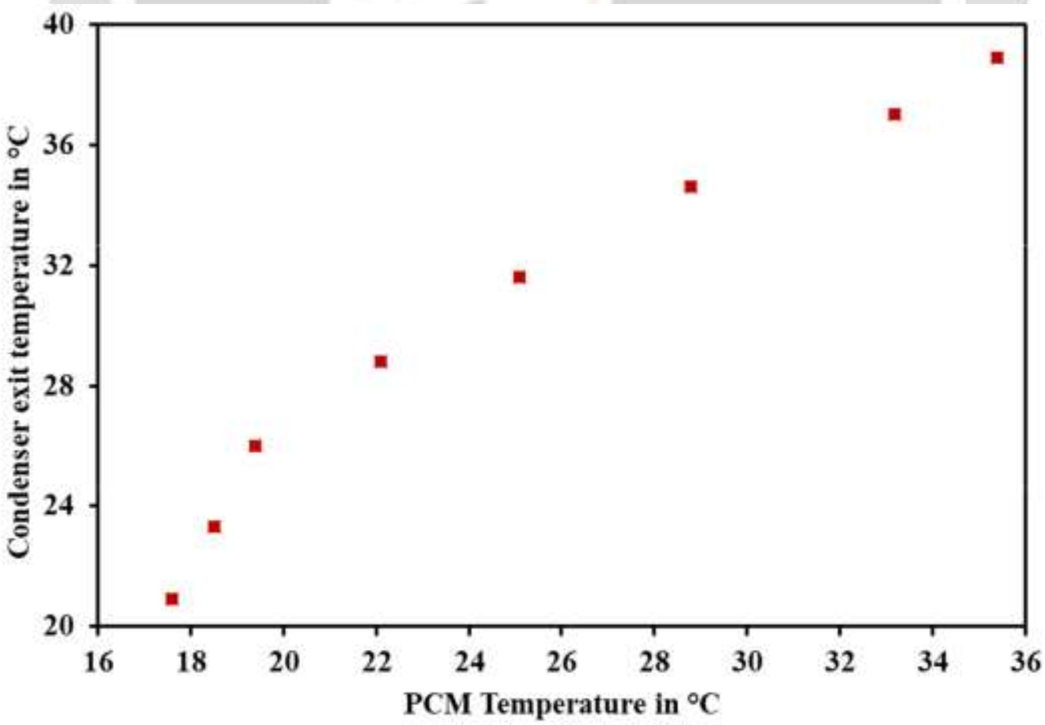
Effect of PCM temperature on the performance of refrigerator

In the modified refrigerator, the PCM temperature drives the performance of the refrigerator. Because of the PCM temperature, the condenser exit temperature, eventually compressor exit temperature and in turn energy consumption of the compressor changes. Therefore, the effect of PCM temperature on the performance parameters such as condenser exit temperature, ratio of compressor on time to total cycle time and COP have been analyzed in this section.

Condenser exit temperature

Figure 4.7 shows the condenser exit temperature variation with the PCM temperature. As the temperature of PCM rises after every next cycle due to the heat absorption from the refrigerant, the condenser exit temperature also moves up. With changing the PCM temperature from 17.5°C to 35.5°C, the condenser exit temperature also varies from 21°C to 39°C.

It is noted from the slope of the curve is higher at the lower value of PCM temperature as compared to higher temperatures. It is due to the large heat storage capacity of PCM at the lower temperature.



Variation of condenser exit temperature with PCM temperature

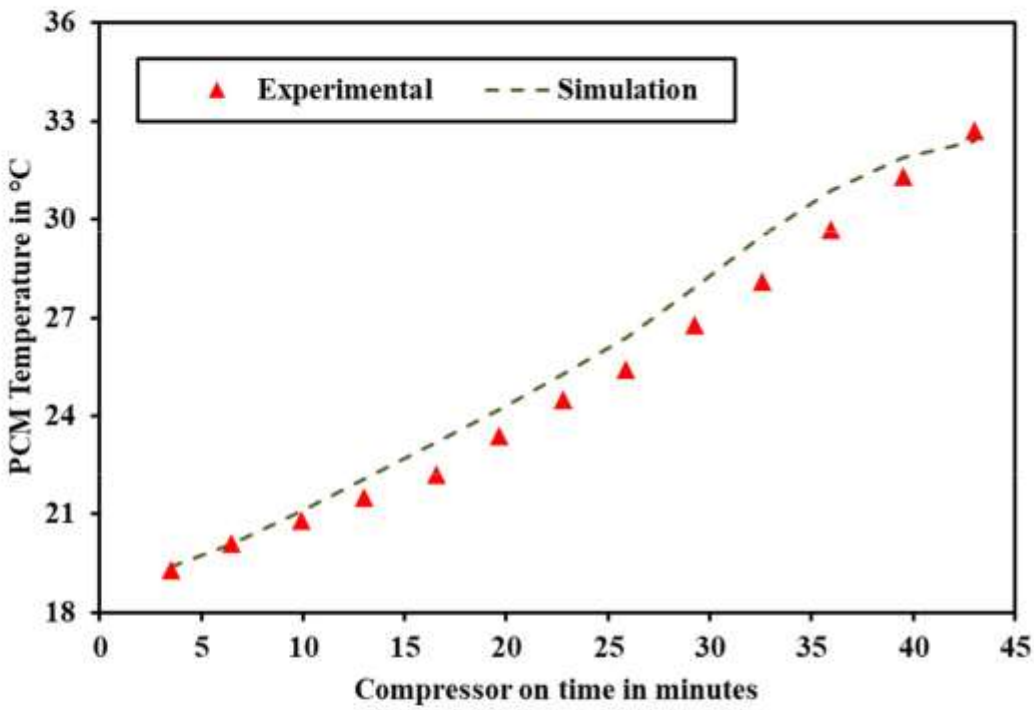
Compressor on time to total cycle time ratio

Figure 4.8 describes the variation in refrigerator on time to total cycle time ratio with PCM temperature. With increase in the PCM temperature, from 17.5°C to 35.5°C the ratio also increased from 0.18 to 0.23.

The plot indicates that the increase in ratio is just 9% with the change in PCM temperature from 18 to 22°C, due to the utilization of latent heat of PCM at this range of temperatures. However, for the PCM temperature of 18 to 35°C, the ratio increases by 27%, which uses the sensible heat of the PCM. This elucidates that for the lower PCM temperatures the compressor on time would be lower.

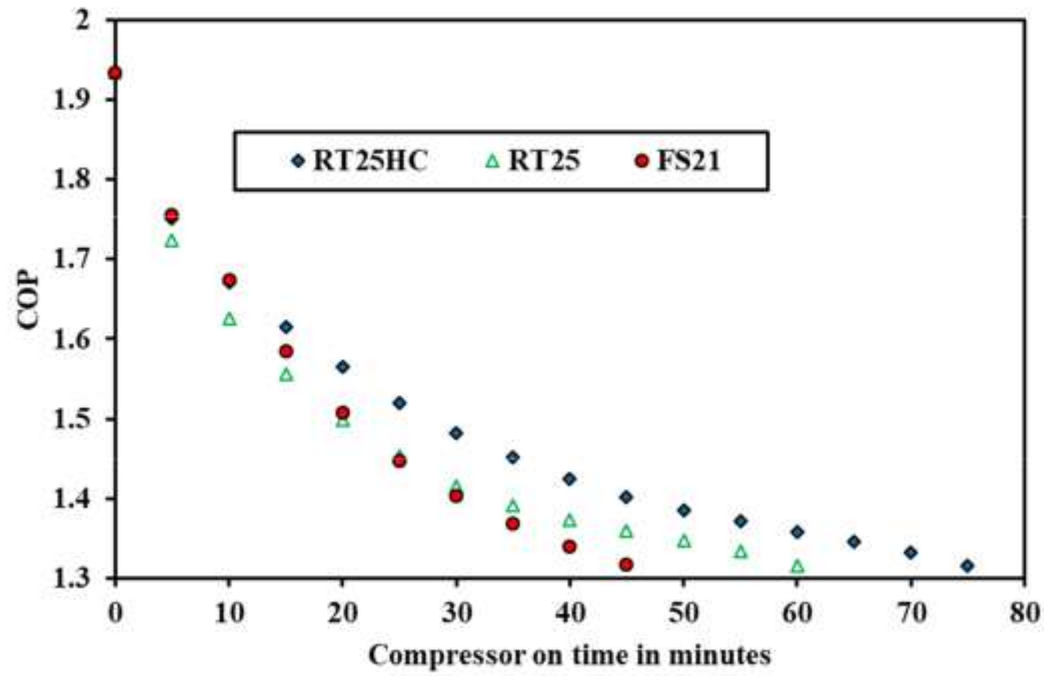
Validation of 3D numerical model

To validate 3D numerical model the PCM temperatures calculated from the simulation are compared with the experimental test temperatures as shown in Figure 5.4. The plot depicts that the PCM temperatures obtained from the simulation are closely matching with the experimental test data with an error up to 5%.



Comparison of numerical and experimental PCM temperatures

The COP plot is shown in Figure 5.10 also follows the same trend as the PCM temperature plot. It exhibits that initially all the PCMs have the same COP of about 1.9, but with the time, it decreases. Having the highest heat storage capacity of RT25HC, it reaches to COP of 1.3 in 75 min, whereas RT 25 in 60 min and FS21 in 45 min. This demonstrates RT25HC as the best performing PCM for the refrigerator.



Variation of COP with time for various PCMs

It is clearly visible from the plot that among all the PCMs, FS21 achieved the temperature of 31°C from 17°C in 45 minutes, while RT25 and RT25HC achieved the same temperature in 60 and 75 minutes, respectively. It means RT25HC takes longer time to melt and consequently the condenser exit temperature would be lower for the larger time duration. This variation is directly proportional to the heat storage capacity of the PCMs, which are 143 kJ kg^{-1}, 165 kJ kg^{-1} and 213 kJ kg^{-1} for FS21, RT25, and RT25HC, respectively.

Summary

This chapter presented development of a 3D numerical model for a PCM based wire and tube heat exchanger and its validation with the experimental results. It covered the insight of heat transfer process occurring in the PCM heat exchanger. It also discussed performance comparison of household refrigerator with three different PCMs, FS21, RT25 and RT25HC based on the numerical analysis.

Conclusion:

The research work presented in this thesis is an experimental and numerical investigation of a household refrigerator integrated with a PCM based condenser in parallel to the conventional air-cooled condenser aiming to reduce the energy consumption of the refrigerator. The work contains majorly two sections. The first one is development of experimental set up incorporating the proposed concept and its performance analysis and the second one is development of the numerical model for the PCM based heat exchanger and performance prediction of refrigerator with different PCMs.

Based on experimental analysis of the modified refrigerator, following conclusions are derived,

REFERENCES:

1. Lade AV, Paropate RV, Choube AM and Wakulkar RE, "Analysis of mono suspension spring with different materials", International Journal of Research in Science & Engineering e-ISSN 2394-8299, Volume: 1 Issue: 2, 60-64

2. Kumhar Vikky, “Structure Analysis Of Shock Absorber Spring Using Finite Element Analysis”, VSRD International Journal of Mechanical, Civil, Automobile and Production Engineering, Volume: 6, Issue: 1 January 2016, e-ISSN: 2249-8303, p-ISSN: 2319-2208, 1-10
3. Choube AM, Finite Element Analysis of Helical Spring in Mono suspension System, International Journal of Engineering Science and Computing volume 6, Issue 5, May 2016, 4947-4951
4. Lavanya N and Rao P Sampath and Reddy Pramod M, “Design and Analysis of A Suspension Coil Spring For Automotive Vehicle”, International Journal of Engineering Research and Applications, ISSN: 2248-9622, Vol. 4, Issue 9, Version 5, September 2014, pp.151-157
5. Manjunatha, TS and Budan, D Abdul, “Manufacturing and experimentation of composite helical springs for Automotive suspension”, International Journal of Mechanical Engineering \& Robotics Research, volume 1, issue 2, July 2012
6. Singh Niranjan, GENERAL Review Of Mechanical Springs Used In Automobiles Suspension System, “International Journal of Advanced Engineering Research and Studies”, International Jornal of Advanced Engineering Resarch Studies, Volume 3, Issue 1, Oct.-Dec 2013, 115-122
7. Setty Thriveni, G and Gowd, G Harinath, Design Evaluation & Optimization of a Two-Wheeler Suspension System, International Journal of Emerging Technology and Advanced Engineering, ISSN 2250-2459, Volume 4, Issue 8, August 2014
8. Vijayeshwar BV, Preetham B M, Bhaskar U, Design and Static Analysis of Helical Suspension Spring with Different Materials, International Advanced Research Journal in Science, Engineering and Technology, Vol. 4, Special Issue 7, May 2017, pp 94-98
9. H. Douville, P. Masson, A. Berry, On-resonance transmissibility methodology for quantifying the structure-borne road noise of an automotive suspension assembly, Applied Acoustics 67 (2006) 358–382.
10. P.Kindt, D.Berckmans, F.DeConinck, P.Sas, W.Desmet, Experimental analysis of the structure-borne tire/road noise due to road discontinuities, Mechanical Systems and Signal Processing, 23 (2009) 2557–2574
11. Julia Winroth, Wolfgang Kropp, Carsten Hoever, Thomas Beckenbauer, Manuel Männel, Investigating generation mechanisms of tire/road noise by speed exponent analysis, Applied Acoustics 115 (2017) 101–108
12. Cristobal Gonzalez Diaz, Peter Kindt, Jason Middelberg, Stijn Vercamme, Christophe Thiry, Roland Close, Jan Leyssens, Journal ofSoundandVibration364(2016)147–164
13. Sakthivel Palanivelu, Narasimha Rao K.V, Krishna Kumar Ramarathnam, Determination of rolling tyre modal parameters using Finite Element techniques and Operational Modal Analysis , Mechanical SystemsandSignalProcessing64-65(2015)385–402,
14. Pawel Baranowski a, Jerzy Malachowski a,⁎, Jacek Janiszewski b, Jerry Wekezer, Detailed tyre FE modelling with multistage validation for dynamic analysis, Materials and Design 96 (2016) 68–79
15. Carrella, Nonlinear identifications using transmissibility: Dynamic characterisation of Anti Vibration Mounts (AVMs) with standard approach and nonlinear analysis, International Journal of Mechanical Sciences 63 (2012) 74–85
16. MikeKolich, Steven D. Essenmacher, James T. McEvoy, Automotive seating: the effect of foam physical properties on occupied vertical vibration transmissibility, Journal of Sound and Vibration 281 (2005) 409–416
17. Mike Kolich, Using Failure Mode and Effects Analysis to design a comfortable automotive driver seat, Applied Ergonomics 45 (2014) 1087-1096
18. Anriette van der Westhuizen, Johannes L. van Niekerk, Verification of seat effective amplitude transmissibility (SEAT) value as a reliable metric to predict dynamic seat comfort , Journal of Sound and Vibration 295 (2006) 1060–1075
19. Y . Du, R.A. Burdisso, E. Nikolaidis, D. Tiwari, Effects of isolators internal resonances on force transmissibility and radiated noise, Journal of Sound and Vibration 268 (2003) 751–778
20. J.L. van Niekerka,*, W.J. Pielemeierb, J.A. Greenberg, The use of seat effective amplitude transmissibility(SEAT) values to predict dynamic seat comfort, Journal of Sound and Vibration 260 (2003) 867–888