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# Industrial Energy Efficiency and Sustainability Using Phase Change Materials

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## Abstract

Phase change materials (PCMs) are substances that can store and release large amounts of energy at constant temperature during phase transition. They are broadly classified into three groups: organics, inorganics, and eutectics. Phase change materials have been utilized in all aspects of engineering, such as chemical, mechanical, material, civil, biomedical, industrial, and electrical engineering. The applications have been extended to the thermal management of solar panels, vehicles, building materials, lithium-ion batteries, electrical appliances, electronics, textiles, and biomedical applications. In this study, a series of experimental runs has been performed under different conditions to evaluate a household refrigerator's performance utilizing Phase Change Materials (PCMs). The PCMs have been placed on the backside of the wire and tube condenser with a cascade arrangement to absorb excessive heat from the condenser to reduce the surface temperature and enhance efficiency. All experimental runs have been conducted in a standard room in Philver Company in Tehran, Iran. The objective of the research was to increase the off-time of the compressor for the reduction of electrical energy consumption. The results indicated that for the novel refrigerator, the condenser surface temperature was reduced significantly, which led to coefficient of performance. The experimental results for the household refrigerator also prove that integration of PCMs on the condenser surface decreases the work time percentage from 32.7% to 27.6% and the energy consumption was reduced by 13%. This application may be considered as one of the most important engineering applications of phase change materials in the industrial sector.

## Keywords
Phase Change Materials, Refrigerator, Cascade, Eutectic, Energy management

## 1. Introduction
Household refrigerators are one of the most essential home appliances that almost energy house has one and is going to increase throughout the world. Therefore, improving refrigerator performance and reducing its energy consumption constitute a worldwide matter (Nandanwar et al. 2023). Different techniques have been studied to enhance the heat transfer in the heat exchangers such as condenser and evaporator and reduce energy consumption of these appliances (Nandanwar et al. 2023). One of the passive cooling techniques for the condenser is utilizing PCMs that demonstrated significant impact on heat transfer enhancement due to their high energy storage capacity and negligible volume change during phase transition period. They can absorb the excessive heat from the system and release it to the environment during phase change period to maintain the application temperature within an acceptable range [Ben Taher et al.2022, Raveendran et al. 2020].

### 1.1 Objectives

Based on the reports published on the literature, the application of eutectic PCMs in cascade arrangement for the performance enhancement of electrical refrigerators and freezers have not been studied yet. Therefore, the objective of this research is to increase the heat transfer rate on the back side of the condenser section of a household refrigerator using two eutectic PCMs with different melting points in cascade configuration. The study has been performed for four cases namely, without measurement packs (M-packs)/without PCM, with M-pack/without PCM, with M-pack/single PCM and with M-pack/cascaded PCMs on the condenser. Compressor performance, energy consumption and condenser and interior temperature distributions have been reported as results of this study.

## 2. Literature Review

PCMs can be applied to the condensers, evaporators, and the compartment section as an energy storage system (Nandanwar et al. 2023). Application of PCM panels with melting point of -15 ºC as a latent heat storage element on the internal walls of the freezer during door openings and defrosting of a household refrigerator has been studied by Gin et al. 2012. They indicated that lower energy consumption can be obtained in the refrigeration system. Similar research has been performed by Oro et al., 2010 and showed that the integration of a commercial PCM with melting point of -18 ºC at different sites inside the freezer can keep the freezer's temperature at 4-6 ºC lower and preserve the quality of the products. Application of a mixture of water and a eutectic mixture for PCMs on the back side of the evaporator as a cold storage system has been studied by Azzouz et al. 2005. 5-15% improvement on the COP has been achieved by their simulation techniques. The system can also maintain 5-9 h of continuous operation during the outage [Azzouz et al. 2008]. A novel multi-objective optimization technique has been conducted by Yuang, et al. 2014 to reduce energy consumption and total cost of a conventional refrigerator. One of the drawbacks of using PCMs on the evaporator section is an increase on the compressor on time which results in a higher condensing temperature (Cerri et al.2003 and Azzouz et al. 2006).

## 3. Materials and Methods

A double-door household refrigerator, model Philver TDF 320, with energy consumption of 98 and 100 kWh/year including and excluding 10 kg of M-packs inside the frozen food compartment respectively, corresponding to energy class A, has been used for this study. All tests have been conducted inside the hot room of a Philver fridge and freezer manufacturing company in Tehran, Iran under standard conditions. The room conditions have been maintained at temperature between 16 and 43 ºC and a relative humidity of 45% and 75%. The maximum temperatures of the fresh foods and frozen food compartments during the 24-h tests were less than 5 ºC and -18 ºC, respectively based on the standard procedure.

## 4. Data Collection

Eutectic mixture of polyethylene glycol-1000 (PEG-1000) and polyethylene glycol-600 (PEG-600) purchased from Merck, Germany, with different weight percentage has been used in this study. Due to the non-toxic, non-corrosive and bio-compatibility nature of the polymeric materials, they can be considered as an environmental friendly material. Due to the fact that the melting point of the PCMs mixture must be very close to condenser surface temperature during the operation, the eutectic mixture of 36% wt. of PEG-1000 and 64% of PEG-600 with a melting point of 32 ºC was prepared as a PCM1 for the experiments. PCM2 was made of mixing 32% wt. of PEG-1000 and 68% of PEG-600 with melting point of 29 ºC. The pysical properties of two polymer-based PCMs are shown in Table 1.

Table 1. Physical properties of PCMs [Pirvaram et al. 2019]

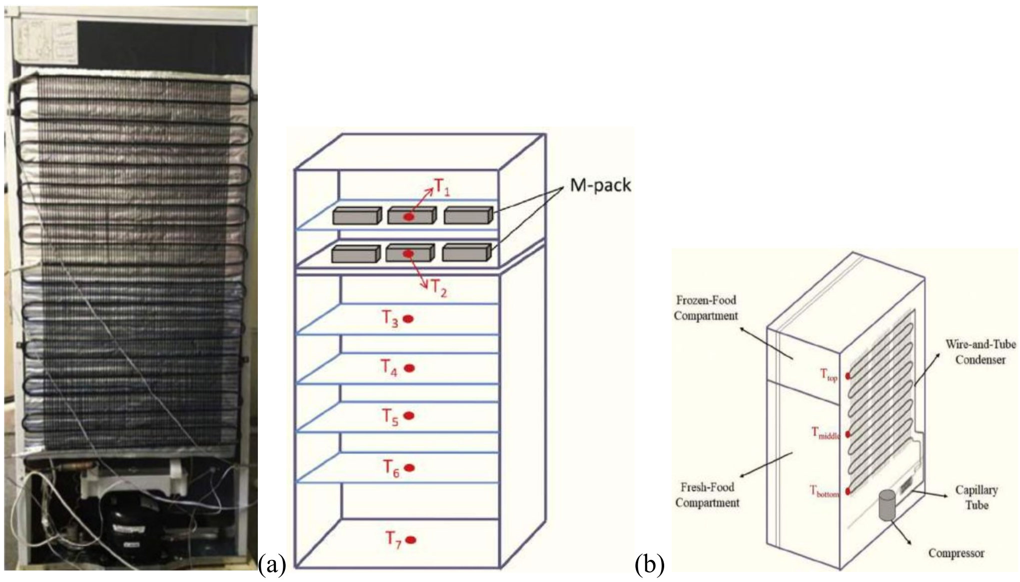
| Characteristics | PEG-1000 | PEG-600 |
|---|---|---|
| Phase change temperature (°C) | 34–40 | 15–25 |
| Latent heat of fusion (Cal $g^{-1}$) | 38 | 35 |
| Density (g $ml^{-1}$ at 20 °C) | 1.09 | 1.12 |
| Thermal conductivity (W $m^{-1}$ °$C^{-1}$) | 0.2–0.3 | 0.2–0.3 |
| Liquid specific heat (Cal $g^{-1}$ °$C^{-1}$) | 0.51 | 0.51 |

Each PCM pack with a mass of 250 g has been stored in three-layer aluminium packages using eutectic PCMs and 500 g pack of single PCM with melting temperature of 32 ºC has been fixed on the backside of the condenser as illustrated in Figure. 1. The dimensions of single PCM pack are 104 Cm × 55 Cm and the PCM1 and PCM2 packs in the case of cascade arrangement have dimensions of 52 Cm × 55 Cm. Measurement packages (M-packs) are used for the substitution of the frozen food in the top compartment of the fridge. Each M-pack contains 232 g of a mixture of chemicals mixed with water with dimensions of 5 Cm × 10 Cm × 10 Cm with freezing point of -5 ºC and with similar meat properties.

The experimental runs have been conducted in four different load conditions of PCM and M-packs and under the same standard operating environment as:

- Case 1: Without M-packs and no PCM on condenser
- Case 2: With M-packs inside the frozen-food compartment and with no PCM on condenser
- Case 3: With M-Packs inside the frozen-food compartment and with a single PCM on condenser
- Case 4: With M-Packs inside the frozen-food compartment and with a cascaded PCMs on condenser

More information regarding the application of PCMs in thermal management of refrigerators and freezers by experimental analysis can be obtained from Pirvaram et al. 2021.

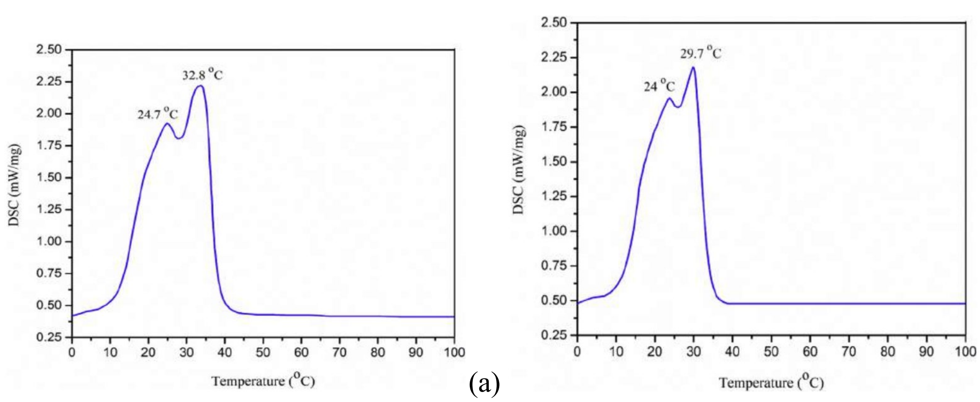



(a) (b) (c)

Figure 1. Schematic of the condenser with PCMs (a), M-Packs on the trays (b), and an ordinary fridge (c)

## 5. Results and Discussion

Differential Scanning Calorimetry (DSC) has been used for the enthalpies of the single and eutectic PCM consisting of PEG-600 and PEG-100 with different weight percentage and the results are illustrated in Fig. 2.a and Fig.2.b for 32 ºC and 29 ºC respectively. The measurements were taken while increasing the temperature at a rate of 10.0 ºC/min in a dynamic atmosphere of Argon.




(a) (b)

Figure 2. DSC curves of eutectic PCMs at 32 ºC (a) and 29 ºC (b)

Both DSC curves indicate a minor exo-effect at 24 ºC which is due to the solid-solid phase change of eutectic mixtures whereas second peaks corresponds to the solid-liquid phase transition process of materials. Codenser surface temperatures have been measured at three different locations on the condenser tubes (Fig. 1.c) and temperature distributions of the top and bottom sections for four different cases are illustrated in Fig. 3. which clearly indicates that the condenser temperature for cascaded arrangement (Case 4) was reduced substantially in all condenser sections.
As can be seen from Fig. 3.a in the ordinary fridge with M-packs inside the frozen compartment the top condenser temperature reaches to the maximum at 41 ºC but the average maximum temperatures of this section for cases of single PCM and eutectic PCM integrated on the condenser reduces to 39 ºC and 37 ºC respectively.

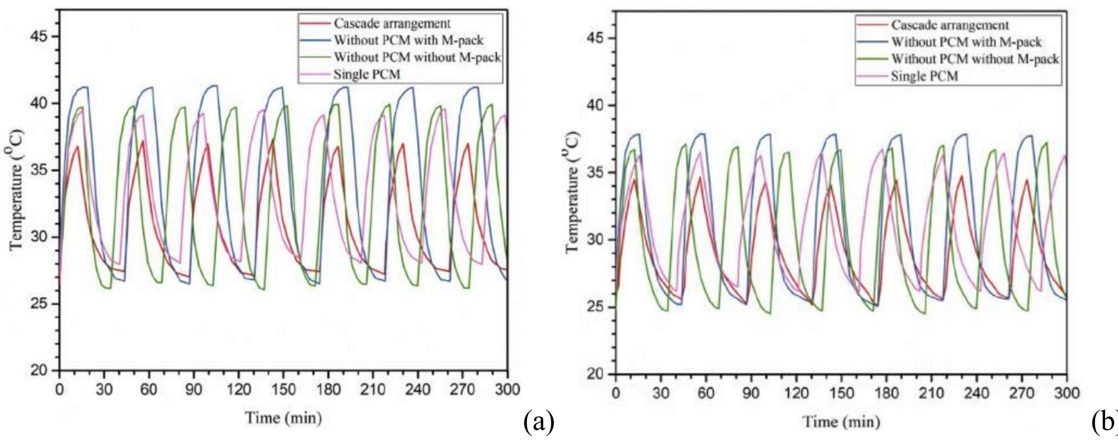



Figure 3. Temperature discributions of top (a) and bottom (b) sections of condenser for four cases

The maximum temperature of the ordinary fridge containing M-packs was 37.5 ºC for the bottom part as illustrated in Fig. 3.b. This has been reduced to 36.5 ºC and 34.5 ºC for condenser equiped with single PCM and with cascaded PCM respectively. It can be concluded from the results that reduction of the condenser temperatrue and as a result of this, lower refrigerant pressure lead to an improved COP in the novel refrigerator utilizing cascaded energy storage system.The average temperature of the fresh-food compartment changes from 3.9 ºC to 4.8 ºC for the fridge with M-packs and without PCMs whereas this temperature for the case of single PCM varies from 4.0 to 4.7 ºC and for the cascade arrangement case changes from 4.1 to 4.6 ºC respectively which proves that more food preservation quality can be achieved by utilizing cascaded PCM on the condenser.

Summary of the experimental results for this study are listed in Table 2. As can be observed from the energy consumption results, utilizing energy storage system on the condenser can decrease the condenser surface temperature which results in COP enhancement and energy consumption reduction. Therefore, energy consumption in the case of two PCMs in cascade configuration is reduced from 0.7578 kWh/24h to 0.6564 kWh/24h. Maximum electrical energy saving of 13.38% can also be achieved using a eutectic PCM in cascade arrangement.

Table 2. Experimental results of four refrigerators under different conditions

| | Case1 | Case2 | | Case3 | Case4 |
|---|---|---|---|---|---|
| Phase change temperature (°C) | 32 | PCM1<br>29 | PCM2<br>32 | No | No |
| Mass of PCM (gr) | 500 | PCM1<br>250 | PCM2<br>250 | No | No |
| Maximum condenser temperature at bottom (°C) | 36.5 | 34.5 | | 37.5 | 37 |
| Energy consumption (kWh/24h) | 0.6917 | 0.6564 | | 0.7578 | 0.7562 |
| Energy saving | 8.72 | 13.38 | | No | No |

Case1: Refrigerator with a single PCM.
Case2: Novel refrigerator with two PCMs arranged in a cascade configuration.
Case3: Ordinary refrigerator with M-packs.
Case4: Ordinary refrigerator without M-packs.

## 6. Conclusion

Efficiency enhancement of using latent heat thermal energy storage units containing two PCMs in cascade arrangement on the back side of the condenser surface in a household refrigerator has been studied. The experimental data have been obtained for the novel refrigerator with single PCM and two PCMs in cascade configuration under standard conditions and compared with two ordinary refrigerators with and without M-packs. The ratio of compressor on-time to the total operating time during 24 h test decreased from 32.7 to 27.6% while this for the refrigerator equipped with a eutectic PCMs reduced to 29.6% indicating that compressor running time was considerably reduced by arrangement of latent heat storage in cascade configuration. Finally, the energy consumption of the ordinary refrigerator containing M-packs and refrigerator equipped with a single PCM were measured as 0.7578 kWh and 0.9617 kWh per day respectively. Under the same conditions the electrical energy consumption of the novel refrigerator with eutectic PCMs in cascade configuration has been added to the condenser was measured to be 0.6564 kWh/24h which indicates that the novel refrigerator consumed 13.8% less energy in comparison to other systems.

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## Biography
Seyed Mojtaba Sadrameli is a Professor of Chemical (Process) Engineering at the German University of Technology in Oman. He earned his B.Sc. degree in Chemical Engineering from Sharif University of Technology (SUT), Tehran, in 1980, followed by M.Sc. and Ph.D. degrees from Leeds University, UK, in 1984 and 1988, respectively. In 1989, he joined the Chemical Engineering Department at TMU, Tehran, Iran where he served for 30 years in teaching, research, and administrative roles before retiring in 2020. During his sabbatical leave in the USA (2003–2008), Ali contributed to hydrogen production from biomass gasification at the University of Florida and the production of biojet fuel (JP8) through thermal cracking of triglycerides at the University of North Dakota. His research interests span a wide range of topics in chemical engineering, including industrial heat recovery, simulation of chemical and petrochemical processes, thermal energy storage systems using phase change materials (PCMs), and thermochemical production of biofuels from biomass feedstocks. His current research focuses on the encapsulation and application of

phase change or smart materials for thermal energy storage in solar cells, building materials, electrical appliances, lithium-ion batteries, and more. Additionally, he is working on the production of biofuels through the thermal and catalytic cracking of biomass and plastic waste.