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RESEARCH ARTICLE

Refrigerator Performance Enhancement with Nanoparticle Infused Phase Change Material

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Abstract

Objectives: This research aims to improve the energy efficiency and performance of traditional refrigerators by integrating Phase Change Material (PCM) and Nano-Enhanced Phase Change Material (NEPCM) on the condenser. **Methods:** This research integrated paraffin wax as phase change material and Titanium dioxide (TiO_2) nanoparticle enhanced phase change material as Nano enhanced phase change material on the condenser side and evaluated their effects on the coefficient of performance (COP), Energy Efficiency, and Temperature regulation through experimental analysis. **Findings:** The results demonstrate that the integration of PCM increases the coefficient of performance (COP) by 21%, while the NEPCM achieves a 36% improvement. PCM integration reduces the condenser mid-temperature by 1°C, and NEPCM further lowers it by 2.5°C due to the enhanced thermal conductivity of TiO_2 nanoparticles. Energy savings are significant, with PCM providing up to 10% savings and NEPCM achieving up to 21%, indicating a clear improvement in energy efficiency. **Novelty:** The research demonstrates significant energy efficiency improvements using NEPCM, providing measurable results to validate the enhanced thermal conductivity of TiO_2 nanoparticles.

Keywords: Domestic refrigerator; Energy Efficiency; Nanoparticle enhanced Phase Change Material; Phase Change Material; Titanium Dioxide Nanoparticles

1 Introduction

Refrigerators are vital household devices, crucial for everyday activities such as food preservation and medical storage. Due to their continuous operation, they consume considerable power, making it essential to explore methods to reduce their energy consumption [(1)]. The refrigeration cycle can be enhanced by using a high-performance compressor that can directly impact the COP of the cooling system or by using other advanced thermal insulation techniques. Many studies have been conducted to reduce the working time of the compressor using various methods. Still, using PCM, few studies have been undertaken by placing PCM at the evaporator section and a few by placing the PCM at the condensing coil [2].

Enhancing the energy transfer function of heat exchangers with Phase Change Material in refrigeration systems can greatly enhance their effectiveness because of the substantial heat absorption of Phase Change Material [3]. Utilizing the latent heat of phase change materials (PCMs) for solar thermal energy storage is considered the most favorable approach. Due to their ability to transfer heat from the molecular level to real-time applications, PCMs are of tremendous interest in TES [4]. PCM-based TES systems are currently being considered for various applications such as building cooling/heating, thermal control of electronic devices, solar thermal storage, and load-following capability enhancement for nuclear power plants [5]. However, Phase Change Materials in their molten state have extremely poor thermal conductivity. This issue is overcome by adding nanoparticles to the base material to increase heat conductivity [6]. In the vision of energy shortage as well as the growing requirement of energy generation, this project aims to analyze and enhance the performance of domestic refrigerators by incorporating Phase Change Material and Nanoparticle Enhanced Phase Change Material on the condenser side. This investigation intends to evaluate refrigerator power usage and provide insights into its energy-saving potential. These results might help in the development of more sustainable and cost-effective refrigeration technologies.

2 Methodology

2.1 Material Selection

2.1.1 Paraffin Wax as PCM

PCM used in this research was Paraffin Wax since it undergoes phase change at the condenser temperature of 55°C - 60°C and possesses high thermal energy storage and is non-reactive on condenser tubes. Paraffin is chosen because it is readily available and melts at different temperatures corresponding to the carbon number and a general formula C_nH_{2n+2} [7]. Paraffins are chemically inert and their volume tends to expand when they are melted. Most chemical agents are unreactive with paraffins. They are inexpensive, with a high melting enthalpy, low volatility, minimal undercooling, and no phase separation [8]. Paraffins are not corrosive when TES is installed in the latent form using PCMs, it has the features of thermal energy storage from various elements, efficient storage density, and heat capture at nearly fixed temperature [9]. However, when PCM is in the molten phase, heat conduction ability is very low and the conductivity of PCM can be altered by using nanoparticles that increase conduction.

2.1.2 Preparation of NEPCM

Nanoparticles range from 1nm to 100nm. The increase of thermal convection and heat transfer ability of fluids was earlier attained by mixing of micro-sized particles in base fluids. In enhancing the heat transfer capabilities of base fluids, a tiny proportion of nanoparticles incorporated in base fluids, if well dispersed and when in stable suspension, produce remarkable enhancements [10]. Nano materials like graphene oxide, CuO, TiO_2, CNT, and Al_2O_3 nanoparticles were commonly used for incorporation with phase change materials, which improves their thermo-physical properties like thermal conductivity, diffusivity, specific heat and latent heat capacity, and heat transfer rate [11]. Titanium Dioxide (TiO_2) nanoparticles are selected for this work due to their ability to possess high thermal conduction properties and stability. Table 1 provides the characteristics of PCM and TiO_2 nanoparticles.

Table 1. Characteristics of PCM and TiO_2 Nanoparticles

PCM		TiO_2 Nanoparticles	
Characteristics	**Values**	**Characteristics**	**Values**
Solidification temperature	59 – 60 (°C)	Specific surface area	150 (m^2/g)
Phase change heat	140-145 (kJ/kg)	Heat conduction rate	8.4 (W/m-K)
Heat transfer rate (solid at 30 °C)	0.245(W/m-K)	Material density	0.35 (g/cm^3)
Heat transfer rate (liquid at 60 °C)	0.161 (W/m-K)	Surface morphology	Spherical

The Nanoparticle Enhanced Phase Change Material is made by mixing titanium dioxide nanoparticles with paraffin wax. First, the Paraffin Wax is heated until it reaches to liquid state, after which the nanoparticles are included in the composition. To achieve complete dispersion the solution is heated above the melting temperature and agitated for half an hour with a magnetic stirrer [12,13]. Following this process, the mixture is placed in an ultrasonicator at 65°C, where ultrasonication is performed over 90 minutes to achieve uniform dispersion of nanoparticles in the base material. This procedure is repeated for other weight

Fig 1. Steps of Nanoparticle Enhanced PCM preparation. a. Melting of Paraffin Wax, b. Dispersion of Nanoparticles in the Paraffin Wax, c. Stirring Process, d. Ultra-sonification Process, e. Prepared Samples

percentages of 0.2, 0.4, 0.6, and 0.8. Figure 1**(a, b, c, d, e)** presents a representation of this process.

Differential scanning calorimetry analyses were performed to determine the thermophysical properties[14]. From the DSC evaluation of various concentrations of NEPCM results, 0.6 wt% attains higher heat storage capacity than all other prepared samples. Consequently, 0.6 wt% was added to the PCM and the resulting NEPCM was utilized for subsequent experiments. The impact of TiO_2 on the phase transition characteristics and heat preservation behavior of Nanoparticle-Enhanced Phase Change Materials is evaluated with a liquid nitrogen cooling setup. The differential scanning calorimetry measurement is conducted on samples weighing between 5mg to 10 mg with a measurement range from 30°C to 150°C. Figure 2 illustrates **(a)** DSC analysis of paraffin wax and **(b)** DSC analysis of 0.6 wt% NEPCM.

In differential scanning, calorimetry evaluation observed two maximum points, one is during the heating process and another one is during the freezing process. The minimum point indicates the conversion of the solid state and the maximum point indicates melting phase change freezing phase change and solidification. Among the samples, the NEPCM with 0.6 wt% exhibits the superior stored temperature as related to Paraffin Wax and the remaining weight percentage of NEPCM samples. The differential scanning calorimetry valuation facilitates understanding the results of Paraffin Wax and 0.6 wt% of NEPCM shown in Table 2.

Table 2. Thermodynamic Change Properties

Method	Liquefaction		Freezing	
Fraction	**Paraffin Wax**	**0.6 wt% NEPCM**	**Paraffin Wax**	**0.6 wt% NEPCM**
Initial temperature (°C)	59.78	65.87	60.95	61.47
Peak temperature (°C)	71.25	70.90	54.08	53.43
Latent heat (kJ/kg)	88.40	116.7	64.46	130.4

The use of titanium dioxide (TiO_2) nanoparticles improves the thermal conduction rate of a phase change material, particularly paraffin wax. According to recent research outcomes, it is clear that the thermal conduction rate for Phase Change Material is improved by mixing nanoparticles with paraffin wax. As a result, it can be concluded that the heat transfer rate of NEPCM is greater than Paraffin Wax[15,16].

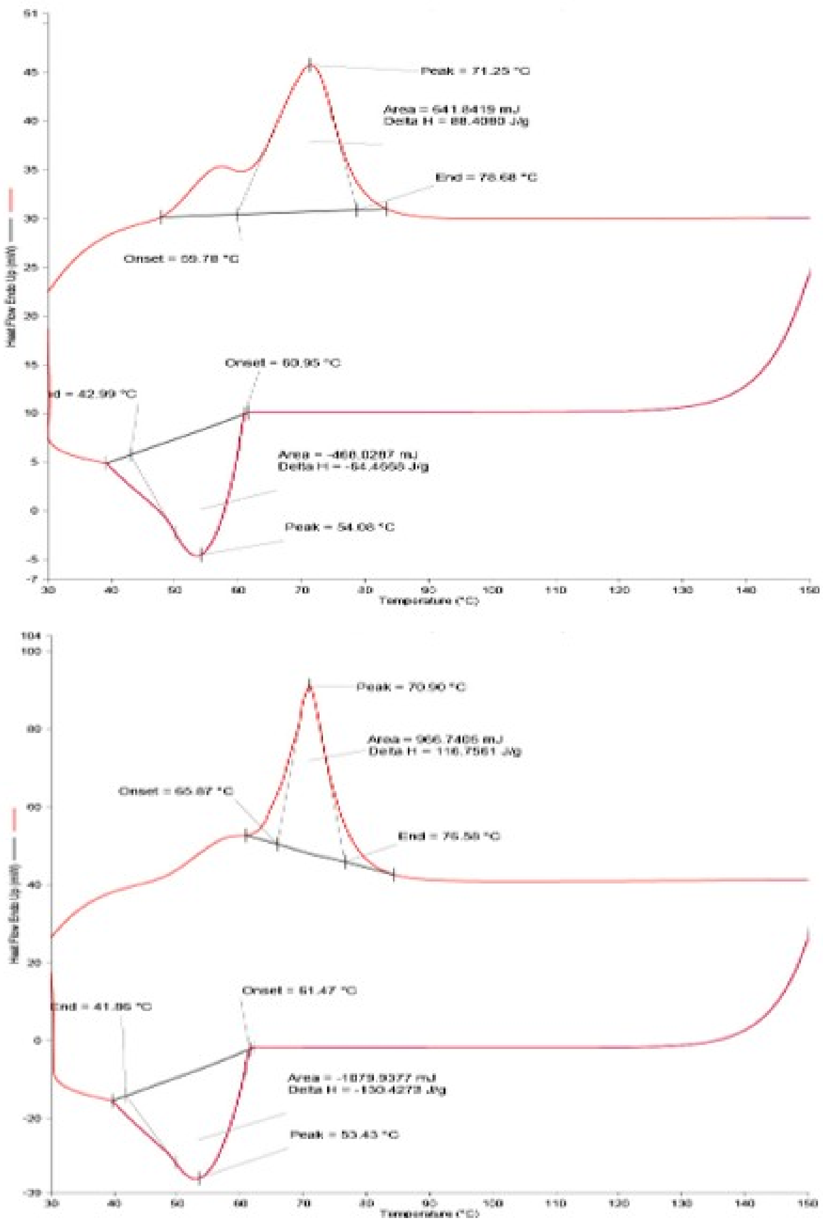

Fig 2. a) DSC analysis of paraffin wax, b) DSC analysis of 0.6 wt% of NEPCM

2.2 Fabrication Of NEPCM-Based Condenser

The fabrication process of the PCM-based and NEPCM-based condenser is similar, with the only difference being the placement of Nanoparticle Enhanced Phase Change Material in place of Phase Change Material. The structure of the Nanoparticle Enhanced Phase Change material-based condenser is shown in Figure 3.

The Nanoparticle Enhanced Phase Change Material-based condenser was built by placing the condenser within a rectangular box and filling it with NEPCM material. The package includes 5 kg of NEPCM. Initially, the NEPCM was heated in a thermal bath at 75°C until it became liquid. Once liquefied, the NEPCM was carefully poured into the box[17]. The same procedure was repeated for the PCM-based condenser. For measuring temperature variations thermocouples were placed at mid of PCM and NEPCM, which were continuously monitored and recorded.

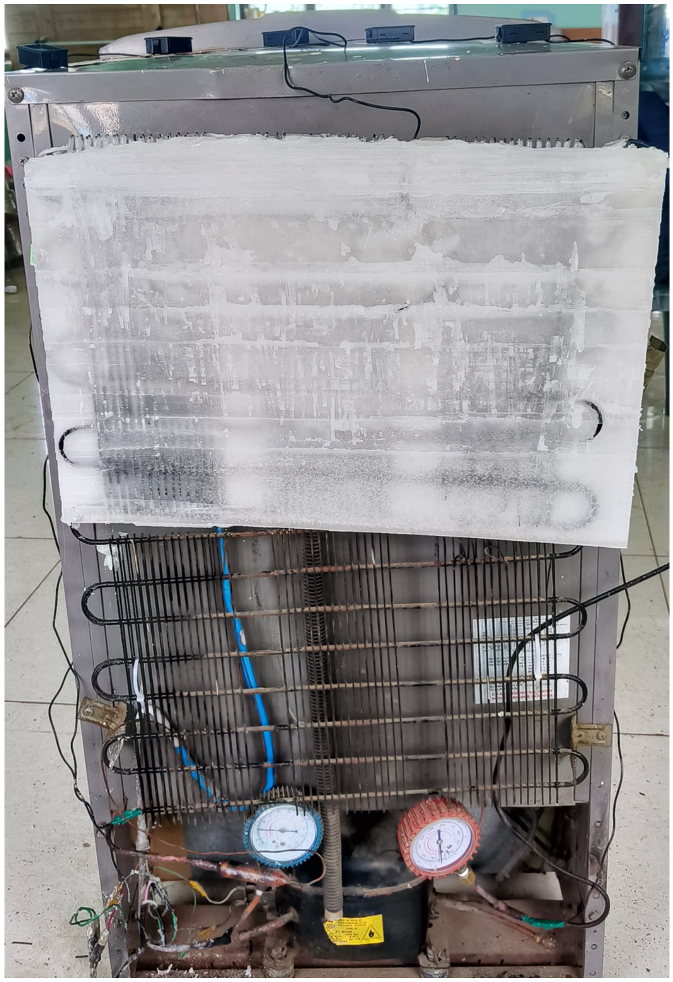

Fig 3. NEPCM based condenser

2.3 Experimental Design And Process

The experimental layout and procedure with essential measuring instruments are mentioned in this section. The experimental refrigerator used in the investigation is a domestic model with a capacity of 150 liters, utilizing R600a refrigerant and featuring a single door [18]. It is equipped with a plate-type evaporator that operates on natural convection, while the condenser employs free convection and is exposed to external environmental conditions. A schematic representation is presented in Figure 4.

The experiments were conducted in a test room for which the external conditions can be regarded as almost constant and It was observed that the conditions were 28 °C ± 2°C and 50 – 60 % RH. An indicator is attached to indicate compressor status either ON/OFF. The supply for the indicator is given from the power supply line of the compressor and thermostat. As a result, the indicator is ON when the system is operating and OFF when the system is not in operation. For measuring the inlet and outlet pressures of the compressor pressure gauges are installed at the inlet and outlet of the compressor. Thermocouples are placed at various locations, including the compressor inlet and outlet, the middle and outlet of the condenser, and inside the evaporator cabin to monitor temperature variations. Furthermore, an energy meter is connected to the refrigerator power cable to measure energy consumption. The working of the refrigerator is monitored continuously and noted readings for a time interval of 2 minutes. Initially, experiments are conducted on a standard refrigerator and the relevant readings necessary for the subsequent calculations are recorded. Next, the experiment is repeated on a PCM-based condenser-installed refrigerator, and corresponding readings are noted. Finally, the experiment is performed using a refrigerator with a NEPCM-based condenser and relevant data is collected. The collected data from the three different cases are used for calculations and comparative analysis is illustrated in the result section.

Fig 4. Experimental setup

3 Result and Discussion

The experiments were conducted at no-load conditions. During the experiment, the pressure and temperature of the various places in the refrigeration cycle were measured with thermocouples and pressure gauges respectively. As a result of these values, the refrigeration cycle was plotted on a pressure–enthalpy (p - h) chart. Enthalpy values were computed from the p-h chart taken at various points of the cycle. The coefficient of performance (COP) was then determined using these enthalpy values and the standard COP formula. From Figure 5, it is evident that the COP improves significantly with NEPCM in the condenser, compared to the other two configurations. It indicates that baseline COP without PCM is 3.3, which improves to 4.0 with PCM, indicating a 21% enhancement in performance. The use of NEPCM further increased COP to 4.5, reflecting a notable 36% improvement over the baseline. This enhanced performance can be attributed to the superior heat transfer properties provided by the nanoparticles in the NEPCM, which leads to more efficient condensation, improved thermal management, and overall system efficiency.

Figure 6 shows the comparison of energy consumption of domestic refrigerators in various cases for 4 hours. It has been observed from the figure that the standard refrigerator without PCM consumed 0.05 kWh of energy per 30 minutes, totaling 0.38 kWh over 4 hours. This serves as the baseline for comparison. When PCM is introduced, energy consumption drops to 0.04 kWh per 30 minutes, amounting to 0.34 kWh for 4 hours, representing a 10 % decrease in energy consumption. The inclusion of NEPCM further enhances the refrigerator's efficiency, with energy consumption reduced to 0.03 kWh per 30 minutes, totaling 0.30 kWh over 4 hours, resulting in a 21% reduction compared to the baseline. This comparison illustrates that incorporating advanced materials like PCM and NEPCM significantly improves energy efficiency in refrigeration systems, with NEPCM offering more energy savings. According to the results published by Elakkiyadasan et al., there is a potential energy savings of 13.06% and 18% in refrigerators when using TES with PCM and NEPCM, respectively [17]. In the present investigation, the results obtained are better than those reported by Elakkiyadasan et al., which is attributed to differences in the type of refrigerator, the refrigerant used, and the type of PCM and NEPCM. From these results, it can be inferred that the integration of PCM and NEPCM leads to lower operating temperatures, which significantly improves the thermal performance and energy savings of the refrigerator.

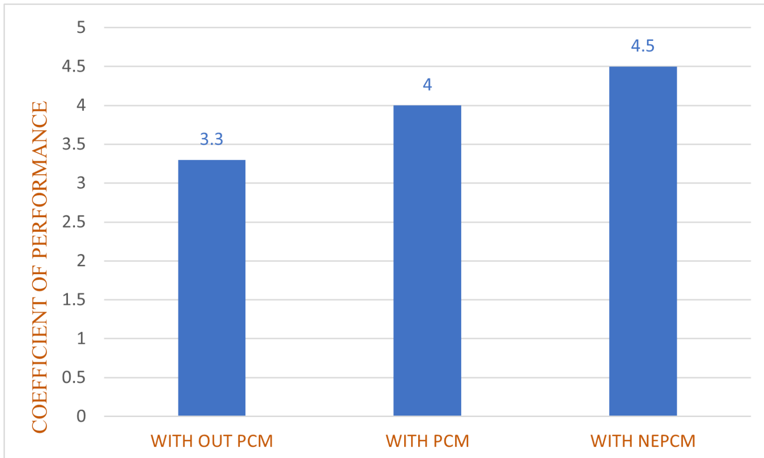

Fig 5. Comparison of Coefficient of Performance

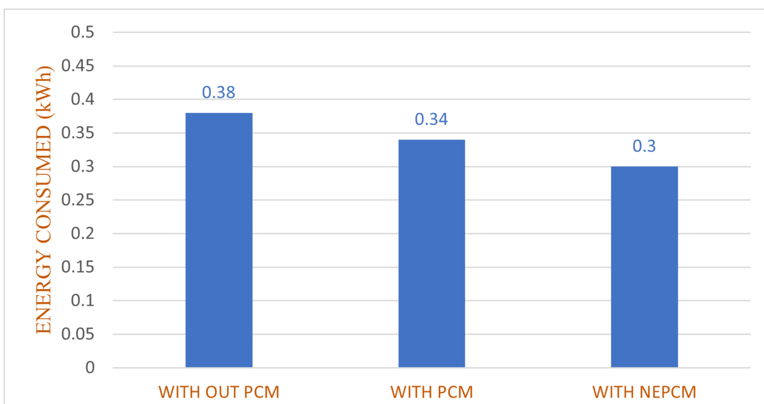

Fig 6. Comparison of Energy Usage

The comparison of the mid-temperature of the condenser in a domestic refrigerator under three different cases: without PCM, with PCM, and with NEPCM is shown in Figure 7. In the first case, where no Phase Change Material is used, the mid-temperature reaches 42.1°C, which is the highest among the three scenarios. When the PCM is introduced into the condenser, the mid-temperature drops to 41.1°C, demonstrating a beneficial effect on temperature control due to the thermal energy-storing capabilities of the PCM. Finally, with the use of NEPCM on the condenser, the temperature is further reduced to 38.6°C. This shows that incorporating Nanoparticles promotes the thermal flow rate of the PCM, resulting in improved temperature regulation.

Figure 8 illustrates the comparison of the refrigeration effect and compressor work for various cases. It shows that the refrigeration effect is 250 kJ/kg where the refrigerator operates without any PCM. This value increases to 260 kJ/kg when PCM is used. The significant refrigeration effect, 270 kJ/kg, is achieved when nanoparticle-enhanced PCM is utilized. This enhancement is due to the improved thermal conductivity provided by the nanoparticles, allowing for more effective heat transfer and greater overall refrigeration efficiency.

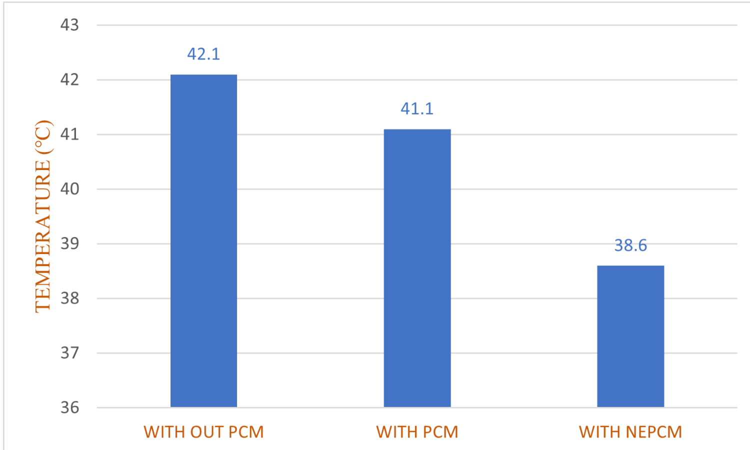

Fig 7. Comparison of Condenser mid-temperature

Fig 8. Comparison of Refrigeration Effect and Compressor Work

Similarly, when no PCM is used, the compressor work is at its highest, measuring 75 kJ/kg. This indicates that the compressor must work harder to maintain the desired cooling effect. Introducing PCM decreases compressor effort to 65 kJ/kg, which indicates that compressor load is lowered by employing PCM. The highest decrease in compressor work occurs while using nanoparticle-infused Phase Change Material is 60kJ/kg, because of the improved thermal conductivity of nanoparticles. The results show that both PCM and NEPCM play a crucial role in increasing the overall efficiency of the refrigerator and reducing the energy consumption required for compression.

4 Conclusion

The majority of research has focused on utilizing phase change materials (PCM) and nano-enhanced phase change materials (NEPCM) in the evaporator section to improve the performance of domestic refrigerators. The present research investigates performance improvements in residential refrigerators by utilizing paraffin wax as PCM and titanium dioxide nanoparticle-infused paraffin wax as NEPCM on the condenser side, yielding significant results under no-load conditions. The coefficient of performance (COP) increased to 4.0 with PCM and 4.5 with NEPCM, reflecting improvements of 21% and 36%, respectively, indicating a marked enhancement in performance with the application of NEPCM. Furthermore, energy consumption decreased from 0.38 kWh to 0.34 kWh with PCM and to 0.30 kWh with NEPCM, signifying reductions of 10% and 21%, respectively, suggesting that NEPCM is particularly effective in minimizing energy usage. Notably, NEPCM reduced the condensation temperature by an additional 2.5°C compared to PCM, thereby enhancing the heat transfer rate, increasing system efficiency, and decreasing the load on the compressor. These results highlight NEPCM's potential to not only improve energy efficiency but also reduce operational costs for consumers. This research is novel in its focus on the application of NEPCM in the condenser side of refrigerators, an area that has received limited attention in existing literature. The implications of these findings suggest that NEPCM can play a pivotal role in future refrigeration technologies, paving the way for innovations that prioritize both efficiency and sustainability.

Further research should look into the cost-effectiveness of NEPCM and address economic challenges to its adoption. Furthermore, studies on the long-term stability and environmental impact of NEPCM are required to establish its feasibility in practical applications. Field testing in real-world situations will help verify these research results and provide insight into the operational dynamics of NEPCM in varied refrigeration contexts. By focusing on these areas, further research can improve the understanding of NEPCM and facilitate its integration into next-generation refrigeration systems, resulting in more sustainable and efficient energy solutions.

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