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Low-Cost Potassium Chloride Saltwater Phase Change Material System for a Household Refrigerator

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Abstract: **Thermal energy storage systems (TESS) are receiving attention because there are constant power cuts, major changes in electrical rate structures, increased maximum power demands, and incentive programmes sponsored by utilities. Household refrigerators were one of the main consumers of residential electricity, as they consume up to 26% and have an additional 17% greenhouse gas emissions. By incorporating TESS, this figure can be reduced. This study presents a low-cost potassium chloride saltwater phase change material (PCM) system to maintain a household refrigerator compartment below 5 ° C to preserve food and pharmaceutical products. After determining the 5-liter volume of PCM required, the experiments were carried out on a KIC KBF 525/1 ME refrigerator with an average daily power consumption of 0.567 kWh. With a heat transfer rate of 5 W and a total of 80 kJ of energy, the PCM took 2.5 days to fully solidify. It was then able to maintain the frigerated compartment at a temperature below 5 ° C for close to 25 hours, resulting in a 8W output power and a total of 90 kJ of energy being released. For power consumption analysis, 1.4175 kWh was used during the charging phase and 0.567 kWh was saved during the discharging phase. Heat transfer during the charging phase needs to be improved to better optimise the TESS.**

***Keywords: thermal* energy storage, refrigerator, phase change material, eutectic salt / water solution.**

NOMENCLATURE

A_s	heat transfer area	[m^2]
B_{air}	beta	[1/K]
cp	specific heat capacity	[J/kg °C]
d	internal diameter	[m]
D	outer diameter	[m]
g	gravitational acceleration	[m/s^2]
Hm	heat of fusion	[kJ/kg K]
h	heat transfer coefficient	[W/m^2K]
k	thermal conductivity	[W/mK]
L	length of the tube	[m]
m	mass	[kg]
Pr	Prandtl number	
T	temperature	[°C]
t	time	[s]
T_{film}	film temperature	[K]
ν_{air}	kinematic viscosity	[m^2/s]
μ	dynamic viscosity	[kg/ms]
ρ	density	[kg/m3]

I. INTRODUCTION

The thermal energy storage system (TESS) can be incorporated with other existing systems to improve the system for better efficiency. Over the years, TES systems have been seen to provide energy supply security in places such as hospitals, computer centres, and other areas where they are needed. They can provide thermal inertia and thermal protection in the construction industry. They help to store energy and its consumption in the solar energy and cogeneration industries [1], [2].

TESSs are considered to be diverse technological systems that have inherent characteristics. This enables them to be implemented in varying applications and makes them more or less suitable for an application [3].

Cold Thermal Energy Storage (CTES) is a representation of cool and cold TES. Materials such as glycol, eutectic salts, and pure water can be used as cooling storage for TESS [4]. These materials can be used in the cold chain for freezing products or for chilling.

Although this technology has existed for more than half a century, it has received only much attention recently due to major changes in electric rate structures, increases in maximum power demands, and utility-sponsored incentive programmes. Utility companies have higher demand charges for peak demand periods to discourage energy consumption during these peak demand periods. The CTES systems can then be used to shift peak cooling loads to off-peak periods by operating during peak hours during the day and fully recharged during peak hours during the night [4].

[5] showed that household refrigerators were one of the main consumers of residential electricity, they consume up to 26%

and have an additional 17% greenhouse gas emissions. In an effort to save energy, the need to improve the refrigerators efficiency was addressed by incorporating a phase change material (PCM) into the compartment. This study presents the design of a low-cost potassium chloride saltwater PCM unit to maintain a household refrigerator compartment below 5 ° C. This can be beneficial in saving electricity and preserving food products during power outages.

A. *Application of PCM in household refrigerators*

Phase-change materials (PCMs) have been used inside refrigerators with the main purpose of reducing temperature fluctuations during operation. [6] showed that due to the opening and closing of the refrigerator door, the temperature tends to fluctuate and this dramatically affects the quality of frozen foods. [7] also showed that temperature fluctuations during refrigerator operation are not desirable. They could cause stress damage and other harmful effects, such as fat oxidation and changes in the colour and texture of the frozen product. [8] showed that these temperature fluctuations can be reduced by placing PCM inside the refrigerated compartment. He used readily available low-cost PCM for his experiments.

[9] showed that a Eutectic plate can be used in a refrigerated warehouse with a refrigeration unit in place. The refrigerator consisted of a compressor, a condenser and an evaporator, which was licked parallel to the eutectic plate by tubes. The authors aimed to reduce electricity costs during the peak-valley price mechanism by running a refrigeration unit during the valley period of 23:00 to 07:00. When the refrigeration system was running during the valley period, it simultaneously charged the PCM. Eutectic plate were allowed to maintain the temperature inside the warehouse for 16 hours during the peak period from 07:00 to 23:00. The maintained temperature ranged between 0 – 5 ° C. The entire project benefited from savings of 323.6 CNY per year.

PCMs are easily incorporated into domestic refrigerators. The PCM can be configured as a heat storage device mounted on the condenser and as a cold storage device mounted on the evaporator. The aim is to improve the performance of the entire refrigerator. A freezer integrated with a eutectic plate showed energy savings of 12% with an improvement in COP of up to 19% [10].

[5] showed that household refrigerators were one of the main consumers of residential electricity. Consumes up to 26% and has additional 17% greenhouse gas emissions. To save energy, the need to improve the refrigerator's efficiency was addressed by incorporating a PCM inside the compartment.

Placing a PCM slab on one side of the evaporator improves global heat transfer because PCMs can maintain lower temperatures. This proved to be a cheaper solution than installing variable-speed compressors (VSCs) and variable-capacity compressors (VCC). These devices control the refrigeration capacity by matching the compressor speed with the thermal load. This solution was also better than improving cabinet and door insulation to prevent heat loss [5].

Applying a similar method [11], a 25% increase in performance coefficient was observed with a decrease in the number of starts/stops. [12] went further and placed the PCM in the evaporator and the condenser of two different types of refrigerator. Their study observed 8.8% and 9.4% in savings. This figure could be further improved by optimising the PCM configurations in contact with the evaporator and the condenser. In their conclusion, they showed from their economic and environmental analysis that PCMs incorporated in refrigerators are beneficial to the end user, national economies and the global environment [13].

B. *Full storage CTES*

In a full-storage CTES, during off-peak hours, the CTES system is being recharged, and during off-peak hours the CTES system is fully operational. This shifts the entire peak cooling load to off-peak hours by decoupling the operation or cooling generating equipment from the peak cooling load. The CTES system discharges the cooling load while the generating equipment is idle, making this strategy ideal when peak demand charges are high or the peak period is short [4].

[14] further elaborated that this strategy is economically advantageous when:

- The surges in the peak load curve are of short duration.
- Energy rates at time-of-use are based on short-duration peak periods.
- There are short overlaps between peak loads and peak energy periods.
- Large cash incentives are offered for using TES
- High peak demand charges apply.

C. *Design Criteria*

TES systems are considered diverse technological systems that have inherent characteristics. This enables them to be implemented in varying applications and makes them more or less suitable for an application [3].

A study by [3] focused on TES, which is used for high temperature ranges. However, some of the parameters used by the authors are applicable to low-temperature range TES systems. [3] identified that to have a successful integration of the TES system, the interaction between the parameters of the TES system and the process must be met. The inherent diversity of processes becomes a challenge when designing a TES system, as one system cannot be adjusted to all the needs of an application. The relationship between technical and economic parameters of the TES system against the analysis of the process is shown in Fig. 1.

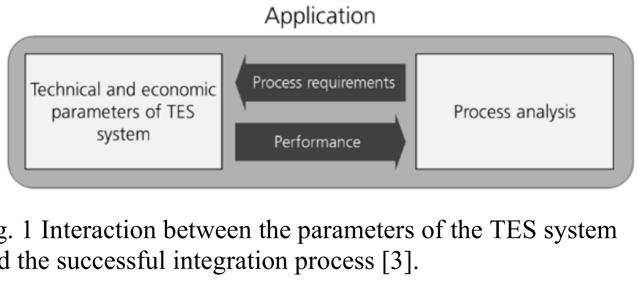


Fig. 1 Interaction between the parameters of the TES system and the successful integration process [3].

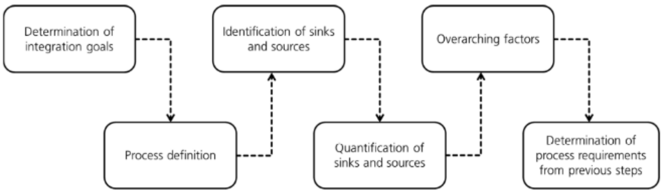


Fig. 2 Steps in the process analysis guidelines [3].

[3] provided a guide for designing an TES system.

The guideline shown in Fig. **2** follows a six-step systematic approach that collects and analyses relevant data to integrate different thermal storages. The determination of integration goals of a TES system can be made from an analysis of the existing non-TES system. The definition of processes and boundaries defines the boundaries of the analysis. The identification of thermal sinks and sources would determine the CTES systems as thermal sinks, while the sources could be identified as the heat load surrounding them. Thermal sink and source quantification consists of three main groups that are used to quantify the potential use of sinks and sources for the integration of TES, general factors, thermodynamics, and physical properties. The analysis of the overarching factors considers information related to the overall process. The summary and determination of the process requirements from previous steps determine whether the expected goal of integrating TES can be achieved and also determine whether the required results are feasible [3].

A proper TES system will take into account two main parameters when selecting a suitable storage material, the storage capacity, and the storage density. The storage application is determined by the power rating during charging and discharging, together with the total energy storage capacity. The optimal design of the TES system will minimise the amount of material used for the PCM, the enclosure, and the entire TES system and will also minimise weight and size for better economic benefit while maintaining the storage application requirements and specifications. The optimal design must also overcome the PCM shortfall, such as low thermal conductivity [15], [16].

In heat exchangers, the magnitude of the difference in temperature between two fluids determines the rate of heat transfer. This temperature difference varies along with the heat exchanger [17]. The heat transfer rate has been identified as one of the major setbacks with TES systems, specifically the latent heat energy storage system (LHESS). Longer charging and discharging times result from the low thermal conductivity of the PCM, leading to small heat transfer rates [15]. To assess the peak performance of an LHESS, different authors use common parameters such as the energy stored in the system, the charging and discharging time, the melting fraction of the PCM over a certain period, and finally the heat transfer rate. [16] highlighted that the results of these parameters were not comparable between different geometries. They further elaborated that the results were not comparable between the geometries used by different authors. [15] identified factors that must be considered when designing an LHESS such as:

- The total energy storage capacity required
- Charging and discharging heat transfer rates
- The operating temperature range
- Thermal fluid used in the exchange process
- Other constraints are size, weight, compatibility, safety requirements, and costs.
- Determining the LHESS Application
- PCM selection and incorporating its constraints, such as corrosion, low thermal conductivity, volumetric expansion, thermal stability, etc., into the system.
- Consider the thermal fluid of the LHESS

[15] highlighted that due to the complex modelling of the phase change and heat transfer process within the PCM, the LHESS design methodologies are based on experimental tests and also on the characterisation of the heat exchange process. [15] further elaborated that computational methods cannot fully account for the complete modelling of a full LHESS. These methods currently cannot account for the total energy conserved, heat-transfer characteristics including conduction and natural convection, and the changing properties of the PCM during the charging and discharging process.

D. PCM selection

[18] made a comparison between Eutectic water-salt solutions, Noneutectic water-salt PCM, and ideal common PCMs. Although there are no ideal common PCMs, six thermal properties are crucial in determining the type of PCM to be used. In Fig. **3**, six thermal properties are compared on a radar chart. Three advantageous thermal properties, thermal conductivity, fusion heat, and density, are compared, with three disadvantages, corrosion, supercooling, and flammability. As the shaded area extends along the arrow, the better the performance along that direction. However, [18] further elaborated that these diagrams are not scale-based, but designed to provide a general idea of the ideal common PCMs needed.

From Fig. **3**, eutectic water-salt solutions have higher thermal conductivity, fusion heat, and density. They are less flammable, but they are very corrosive and undergo supercooling compared to other categories. Noneutectic water-salt PCMs have less thermal conductivity and Fusion heat; however, alcohol solutions have relatively high Fusion heat and high density, while different types of paraffin have little supercooling effects and are less corrosive [18], [19].

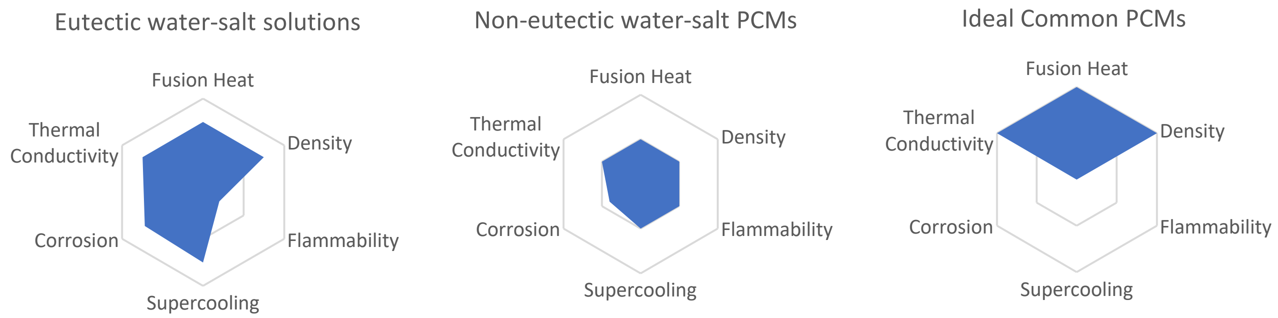


Fig. 3 *Comparison of the thermal properties of common PCMs* [18].

[18] and [20] indicated that the desirable properties of LHTESS were:

- Have high latent heat and specific heat per unit volume and weight.
- Have a desirable melting point for the designed system
- Have a low vapour pressure below 1 bar at operating temperature;
- Be chemically stable and be noncorrosive towards the material case
- Not to be hazardous, highly flammable, or poisonous.
- Reproducible crystallisation without degradation
- They have a small degree of subcooling and a high rate of crystal growth.
- Have a small volume variation when the solidification process is undergoing.
- They have high thermal conductivity.
- Be available in abundance.

Table I and Table II showed that it is desirable to use inorganic PCM for a low-temperature system despite the disadvantage encountered.

TABLE I
COMPARISON *OF ORGANIC AND INORGANIC PCM* [20]

	Organic	Inorganic
Adv..	No corrosive Low or no subcooling Chemical Stability	Greater phase change enthalpy
Disadv..	Low phase change enthalpy Low thermal conductivity Flammability	Subcooling Corrosion Phase Separation Phase segregation, lack of thermal stability

TABLE II
COMPARISON OF PCM TYPES [20]

	Organic Fatty		Inorganic metals		
	Parraffins	Fatty acids	Salt hydrates	Metals	Eutectics
Formula	$C_nH_{2n+2}\ (n = 12 - 38)$	$CH_3(CH_2) \cdot COOH$	$AB \cdot nH_2O$	-	-
Melting Enthalpy	190 - 260 kJ/kg	130 - 250 kJ/kg	100 - 200 kJ/kg	25 - 90 kJ/kg	100 - 230 kJ/kg
Cost	Expensive	2 to 3 times more expensive than paraffins	Low cost	Costly	Coslty

II. METHODOLOGY

A. Experimental setup - PCM

The salt particles were mixed with deionised water according to the salt to water ratio of Table 3 to reach the desired phase change temperature. The container was then fitted with a Pt100 temperature probe connected to a GL820 Graphtec data logger to measure the uniform temperature throughout the container by dampening the temperature fluctuations, thus increasing the accuracy of the results.

B. Experimental Setup Refrigerator

The experiments were carried out on a KIC KBF 525/1 ME Refrigerator, the configuration of the setup is shown in Fig. 4, with the PCM container placed at the top and the thermocouple placed near the bottom. The PCM container used was not optimised for maximum heat transfer rate between the PCM and the surrounding refrigerated air. The standard household and 5 litre PVC bottle container were used to simulate the resources available within a domestic household. The refrigerator had a gross capacity of 257 litres and a net capacity of 239 litres. The upper compartment had interior dimensions of 700 x 450 x 650mm with insulation of approximately 30mm thick. With the thermostat set to maximum, the temperature of the refrigerator compartments was measured to be 0.6°C near the bottom of the compartment and 5.1°C near the top of the compartment, while the evaporator coil was measured close to -24°C. The temperature of the freezer compartments was measured to be -24.1°C with the evaporator coil at a temperature of -31.6°C. The atmospheric temperature surrounding the refrigerator was measured to be 22.6°C. A watt measure was used to measure electrical consumption; the refrigerator had an average power consumption of 0.567 kWh per day.

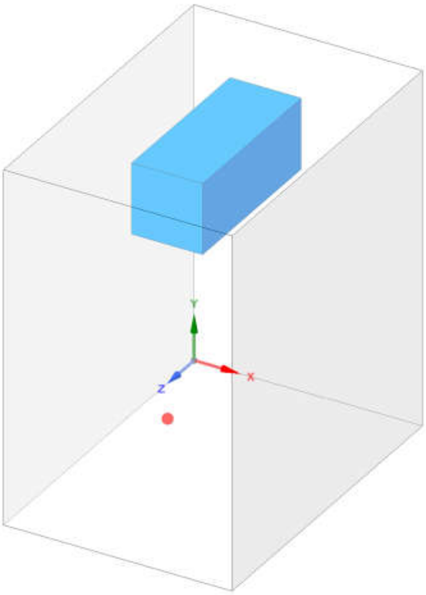


Fig. 4 Configuration

C. Material

Table III presents the properties of the potassium chloride saltwater solution. These solutions cost only \$9.36 per 500 g. They also have high density and latent heat when compared to other PCM solutions.

TABLE III
PROPERTIES OF POTASSIUM CHLORIDE SALT WATER SOLUTION

	KCl
Salt to water (%)	19.5/80.5
Phase change temperature(°C)	-10.7
Density (kg/m3)	1980
Latent heat (kJ/kg)	153.240
Quantity used (g)	950
Price per 500 g (\$)	9.36

D. Sizing of PCM needed

$$V_{PCM} = \frac{t_{off} \cdot Q}{\rho\, H_m}$$

Eq. 1

Eq. 1 determines the amount of PCM needed to maintain the compartment at a constant temperature. The amount obtained in a previous study [21] was 1.5 litres and 5 litres, which were sufficient to maintain the refrigerated compartment below 5 ° C during the load-shedding period.

E. Determining the Heat Transfer of the System

$$Ra_D = \frac{g \cdot \beta \cdot (T_s - T_\infty) \cdot D^3}{\nu^2} \cdot Pr$$

Eq. 2

Since the Rayleigh number is determined in Eq. 2 is less than 10^12, the natural convection Nusselt number is obtained in Eq. 3. The natural heat coefficient and the PVC container surface area are determined in Eq. 4 and Eq. 5. The heat transfer rate and the total accumulated energy are determined in Eq. 6 and Eq. 7. It was assumed that the inside temperature of the measured unit was the same as the surface temperature of the PVC container.

$$Nu = \left\{ 0.6 + \frac{0.387 {R_D}^{1/6}}{\left[1 + \left(\frac{0.559}{Pr} \right)^{9/16} \right]^{8/27}} \right\}^2$$

Eq. 3

$$h = \frac{k}{D} Nu$$

Eq. 4

$$A_s = \pi \mathrm{DL}$$

Eq. 5

$$\dot{Q} = h A_s (T_\infty - T_s)$$

Eq. 6

$$Q = \int_0^t \dot{Q}$$

Eq. 7

F. The energy efficiency

Energy efficiency is the relationship between the heat released by the TESS to the environment during the discharging process and the energy absorbed by the system during charging. It is expressed in Eq. 8,

$$\varepsilon_{sys.xt} = \frac{|Q_{sys.discharge}|}{|Q_{sys.charge}|}$$

Eq. 8

III. RESULTS & DISCUSSION

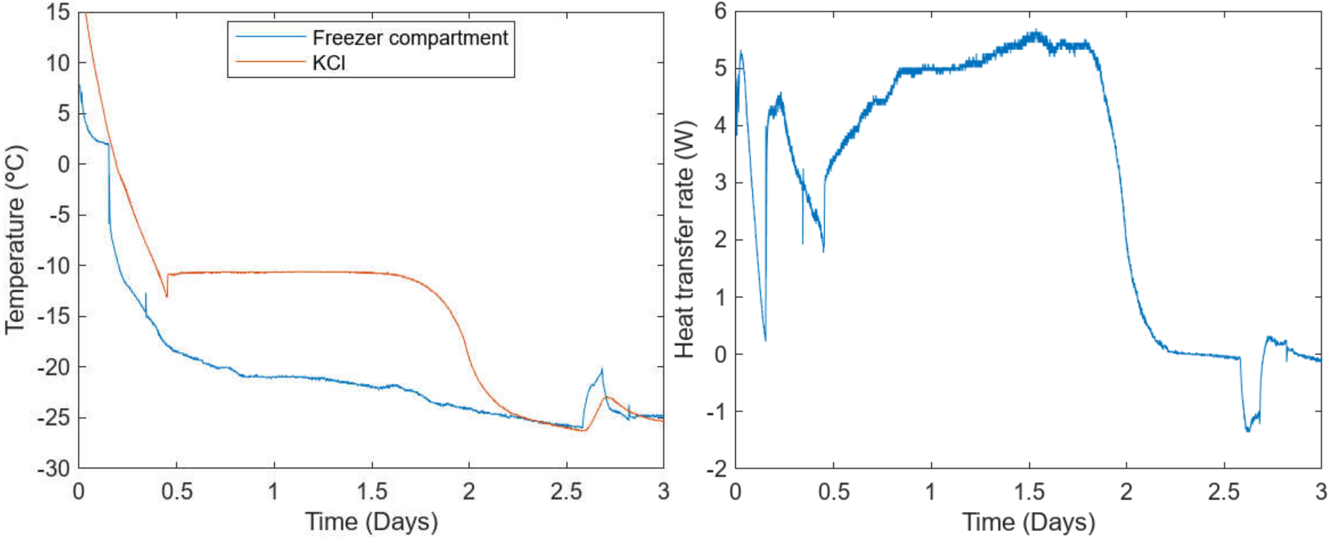
A. Charge phase

For the charging phase, the 5-litre unit was filled with a salt water solution of potassium chloride and placed in the freezer compartment of the household refrigerator to determine the time to freeze the PCM solutions. A Pt100 thermocouple was placed in the centre to capture the temperature. In Fig. **4** (a), the temperature of the freezer compartment increased when the compartment was opened. The saltwater potassium chloride solution was initially at room temperature. In Fig. **4** (a), the PCM took close to 2.5 days to reach the operating temperature of the freezer. The PCM took half a day to reach the latent heat region. And the latent heat region took 1 day and a half for the solution to fully solidify.

Due to the small temperature difference between the freezer atmosphere and the PCM, the heat transfer was relatively low, as seen in Fig. **4** (b). A maximum of 5.5W was reached during the latent heat region. Once the solution had fully solidified, the temperature of the compartment was the same as that of the PCM, hence the sharp decline in Fig. **4** (b)

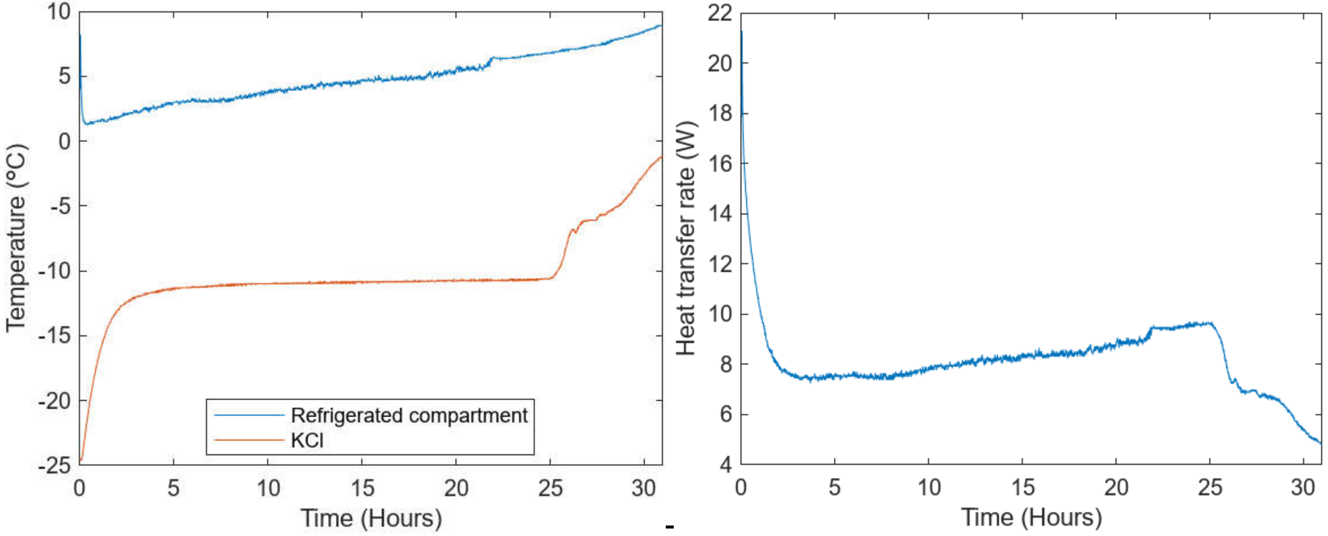
B. *Discharge phase*

For the discharge phase, the unit at an initial temperature of -24 ° C a was placed inside the refrigerated compartment having an initial temperature of 8 ° C upon opening, as seen in Fig.5 (a). The compressor was then turned off. The saltwater potassium chloride solution had a response time of 2 hours before reaching a stable latent heat region at a temperature of -11 ° C. This region was maintained for 22 hours before the solution was fully liquid. The compartment temperature was kept below 5 ° C for the duration of the latent heat region. In Fig. 5 (b), the heat transfer rate during the latent heat region was 8W. Despite the time taken to freeze the solution, the performance of the discharging phase is better than that of the charging phase. To improve the charging time, different methods can be implemented, such as the addition of nanoparticles in the solution. PCM embedded with highly thermally conductive nanoparticles has been identified as a potential solution to overcome the limitation of low thermal conductivity [22].



(a) (b)

Fig. 4 Performance during the charging phase (a) temperature analysis [21] (b) heat transferred to the PCM



(a) (b)

Fig. 5 Discharge phase (a) Temperature analysis [21] (b) Heat transferred to the refrigerated compartment.

Nanoparticles are solids, therefore having a higher thermal conductivity than the surrounding PCM liquid. Incorporating them into the PCM solution will increase the effective thermal conductivity, thus increasing the rate of heat transfer [23]. This effect not only increases the rate of heat transfer but also reduces supercooling in aqueous solutions as nanoparticles behave as nucleating agents [24]. The specific heat of the base PCM can also increase [25]. However, by increasing the heat transfer rate, the total melting time is also decreased [24]. This can be seen as a drawback since the latent region is shorter; thus, the temperature of the PCM will increase rapidly. Despite all these technological advancements to be made in nanoenhanced PCM, [15] expressed that such initiatives do not lead to satisfactory production. Research has shown that from an energetic point of view and from an economic and long-term stability point of view, this approach is not beneficial.

C. *Energy analysis*

To effectively analyse the system, the energy input and output should be determined. Fig. 6 presents the cumulative energy of the charging phase and the discharging phase. The total energy required for the potassium chloride saltwater solution to fully solidify was 78 kJ over a time span of 50 hours. The total energy released into the refrigerated compartment was 90 kJ for 30 hours. Improvements in the charging phase are needed to run the system more efficiently. For power consumption, the system consumed 1.4175 kWh for the charging phase and only saved 0.567 kWh for the discharging phase. Currently, this system is good for maintaining the refrigerated compartment during power outages, but for energy savings, it needs to be optimised.

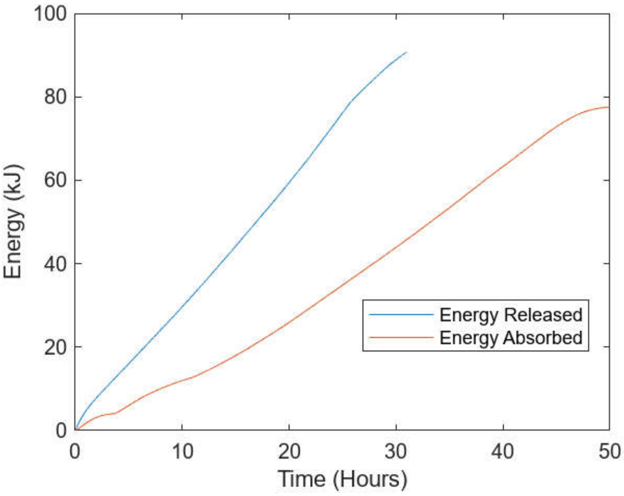


Fig. 6 Energy analysis

D. *Pulldown Performance*

Further experiments were carried out to determine the pull-down performance of the unit. The power was turned off and the temperature of the refrigerated compartment was allowed to reach 30 °C, then the unit was inserted. Fig. 7 presents the performance of the unit if inserted into an unrefrigerated compartment with an initial temperature of 30 ° C.

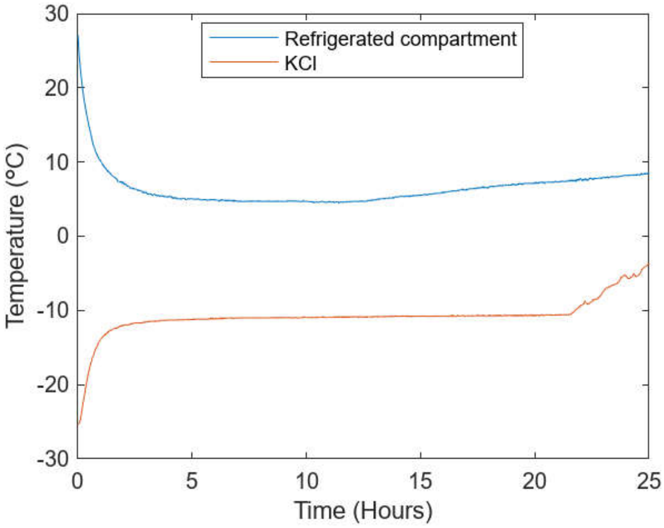


Fig. 7 Pulldown performance [21]

Since the unit was at an initial temperature of -25 ° C, it was able to reduce the compartment temperature to 5 ° C and maintain it for more than 10 hours before the compartment temperature gradually increased to 10 ° C after 25 hours. These units can be used in areas where food and pharmaceutical products need to be maintained for a certain period.

IV. CONCLUSIONS

Major changes in electric rate structures, increases in maximum power demands, and utility-sponsored incentive programmes allow TES to be integrated into existing systems to improve their energy efficiency, leading to power savings. This study integrated a saltwater potassium chloride solution into a home refrigerator. The PCM took 2.5 days to fully solidify, with a heat transfer of 5 W, it consumed 80 kJ of energy. Then the frigerated compartment was able to remain at a temperature below 5 ° C for close to 25 hours, resulting in an 8W output power and a total of 90 kJ. For power consumption, 1.4175 kWh was used during the charging phase and 0.567 kWh were saved during the discharging phase.

The overall energy storage capacity, the charging and discharging heat transfer rates, the operating temperature range, the thermal fluid used in the exchange process, and other constraints such as size, weight, compatibility, safety requirements, and costs need to be evaluated before the PCM is integrated into an existing system. The selection of PCMs and the incorporation of their constraints, such as corrosion, low thermal conductivity, volumetric expansion, thermal stability, etc., into the system also have to be factored in to make the system more efficient.

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