Exploration and investigation of energy harvesting from organic PCM- paraffin wax and coconut oil

Selvam R[1]*, Prakash R*[1]**, Devanathan C*[2] *and Kumar A*[3]

[1]Department of Mechanical Engineering, Saveetha Engineering College (Autonomous), Chennai, India.
[2]Department of Mechanical Engineering, Rajalakshmi Engineering College (Autonomous), Chennai, India.
[3]Department of Chemical Engineering,Saveetha Engineering College (Autonomous),Chennai, India.

Abstract. The preservation of the environment through eco-friendly systems is crucial in various industries such as food, cosmetics, lifestyle, and storage. In recent times, there have been significant technological advancements in cooling systems that provide specific cooling for different applications while reducing electricity consumption. A critical consideration in these methodologies is the reduction of electricity usage. This study focuses on the use of an additional setup or system to maintain temperatures or provide cooling when electricity is not available. Specifically, it explores the usage of latent heat storages, including PCM, in various applications, their properties, types, and selection criteria. Additionally, it provides guidelines for calculating the necessary quantity of PCM for load and other cold storage applications.

1 Introduction

Practically, the phase of phase change materials (PCMs) can be controlled through three parameters: temperature, electric current, and strain. This characteristic presents an opportunity to create versatile and dynamic cooling devices that can be utilized for free space modulation and electronic devices.Phase transitions in PCMs involve structural transformations that lead to notable alterations in electronic structure and refractive indices [1]. As phase change materials (PCMs) transition from the amorphous state to the crystalline state, a significant reconfiguration of chemical bonds occurs. This transition causes pronounced changes in the material's properties and behavior.In recent studies, PCMs have been successfully incorporated into innovative platforms such as meta surfaces, color printing, and integrated modulators, expanding their range of applications [2]. Silicon (Si), a commonly utilized material in the semiconductor and emerging photonics industry, possesses approximately 83% of the desirable characteristics of a phase change material. Silicon exhibits a stable chemical composition even during repeated modulation, and both crystalline and amorphous resonators derived from silicon have found extensive use in diverse applications [3]. The latent of fusion will be increased if coconut oil is mixed with

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[*] Correspondingauthor:prakash@saveetha.ac.in, prakash8781@gmail.com

PCM as the oil absorbs significant amount of heat when it turns from solid to liquid keeping the surroundings cool.

1.1 Phase change material's (PCMs)

Phase change materials (PCMs) possess the remarkable capability to store thermal energy in the form of latent heat within their structure. PCMs find extensive application in solar energy systems and building materials, such as plaster, to absorb excess heat in buildings. Furthermore, phase change microparticles have been employed to enhance the effectiveness of cool colour coatings. These microparticles are integrated into coatings that utilize infrared-reflecting pigments doped with PCMs. By incorporating these phase change microparticles, the coatings can exhibit improved properties related to heat reflection and thermal management [4].

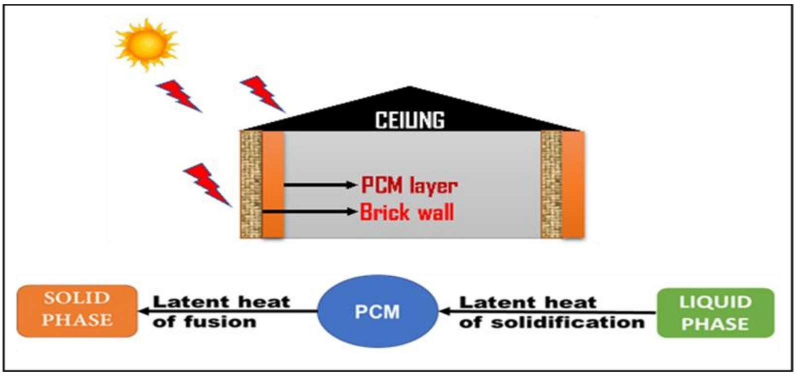


Fig. 1. Phase change materials (PCMs) application and principle.

Microencapsulated PCMs available in the market typically have a particle size ranging from 17 to 20 µm. These microparticles consist of a core that contains a phase change material, usually paraffin, and an outer shell composed of a polymer or plastic material. The melting temperature of phase change materials (PCMs) can be precisely tailored to meet the specific requirements of various applications [5]. PCMs with phase-change temperatures exceeding 100°C are classified as medium- and high-temperature materials. These specialized PCMs are utilized across a diverse array of fields, including industrial surplus thermal utilization, concentrated solar power (CSP) generation, power peak regulation, and other processes that demand efficient medium- and high-temperature thermal storage systems. To optimize temperature management, the PCM is integrated within a matrix of solid materials characterized by high thermal conductivity, ensuring effective heat transfer and enhanced performance. This configuration enables the PCM to maintain a consistent temperature near its melting point. As the internal temperature decreases, the PCM releases stored thermal energy to maintain a comfortable environment within the system. The process is visually represented in Figure 1.

PCMs are also applicable in solar walls, which generally comprise a transparent layer facing outward, an air chamber, and an opaque wall. The opaque wall absorbs solar radiation on its external surface and subsequently transmits the acquired heat. In order to enhance absorptivity, the external surface of the opaque layer is typically coated with a dark color [6]. Following conduction through the opaque layer, the heat is disseminated to the interior space through radiation and convection from the interior surface.

1.1.1 Storage of latent heat

Phase Change Materials (PCMs) derive their name from their unique ability to store latent heat during the transition between solid and liquid states. This remarkable property enables them to absorb and release energy efficiently, making them invaluable in various thermal management applications. This phase change involves the absorption of heat during solid-to-liquid melting, known as the heat of fusion, and the release of heat when the liquid solidifies. These transitions occur at the material's specific melting temperature (Tm). During that temperature, the materials experience melting upon the addition of heat, without an increase in temperature, a phenomenon known as latent heat. The primary advantage of employing latent heat storage systems is their ability to store energy within a narrow temperature range, closely aligned with the phase change temperature [7]. This characteristic enhances the efficiency of energy storage and retrieval, making it a valuable approach in various application.

More specifically, a substance absorbs or releases heat without changing its temperature when it changes from a liquid to a solid and vice versa. Latent heat is the term used to describe this particular heat exchange. It takes place at the melting point of the substance (Tm). The benefit of using latent heat storage devices is that energy may be stored in a narrow temperature range that is near the phase change temperature. Because it involves the heat of fusion, it is significant to remember that even a change in a material's crystalline form without a physical phase shift. It can be seen as storage of latent heat [8, 9]. To visualize this process of melting and solidification in a PCM, please refer to Fig. 1.

It is important to note that the choice of a appropriate PCM for a particular application be contingent on various features such as the desired operating temperature choice, the temperature of fusion, the thermal conductivity, the stability, and the cost. Diverse categories of PCMs are available, including eutectic mixtures, inorganic PCMs, and organic PCMs. Organic PCMs are naturallyresulting from hydrocarbons such as paraffin wax or fatty acids and their derivatives. Inorganic PCMs are often based on sodium sulphate decahydrate or salt hydrates such as calcium chloride hexahydrate. Eutectic mixtures are binary or ternary mixtures of organic and/or inorganic compounds that have a lower melting point than their individual components. They can be designed to have specific melting temperatures and enthalpies of fusion tailored to a particular application [10, 11].

The energy that a substance absorbs or releases during a phase transition, like changing from a solid to a liquid or from a liquid to a gas, is referred to as latent heat. What makes latent heat unique is that this energy exchange occurs without any accompanying change in temperature. The latent heat of vaporization (for liquid-to-gas transitions) or the latent heat of fusion (for solid-to-liquid transitions) are the amounts of energy required to cause a phase shift in a substance. Paraffin and salt hydrates are commonly employed as phase change materials (PCMs) for applications requiring temperatures up to 150°C [12].These applications include the thermal management of electronic devices, transportation containers, pocket heaters, as well as heating and cooling systems in clothing and buildings. However, it is important to consider certain critical aspects when using organic PCMs at temperatures exceeding 120°C. These aspects include ensuring long-term thermal stability, resistance to oxygen reactivity, and maintaining low vapor pressure. Alternative material classes are usually more suited to attaining the intended performance at higher temperatures.On the other hand, for low-temperature PCM applications such as cooling water or ice in buildings, water-salt (brine) and water-glycol slurries are commonly used [13].

1.1.2 Selection criteria of phase change material

Phase transition materials come in a variety of forms and can be divided into three primary categories. Organic (such as paraffin and non-paraffin), inorganic (including salt hydrates and metallic alloys), and eutectic (a mixture of organic and inorganic PCM ingredients). When choosing a PCM, it is important to consider its thermal properties, including an appropriate melting point, high latent heat of fusion per unit volume, and good thermal conductivity in both solid and liquid phases. Physical properties such as high density to occupy less space in containers, minimal volume change during phase transition, and low vapor pressure to prevent containment issues are also significant factors to consider [14]. Kinetic properties, such as avoiding supercooling during freezing, promoting rapid nucleation and growth, and facilitating efficient heat transfer, should also be considered. Several techniques have been proposed to improve heat transfer in PCM-based thermal control units (TCUs). These include the use of conducting routes or materials such as metal matrices or foams, the addition of metal and metal oxide fillers in micro- and nano-sized sizes, the use of discrete components such fins and pins, the use of graphite, carbon nanotubes, or fibers, and the use of exfoliated graphite [15].

1.1.3 Application of PCM

PCM finds frequent use in thermal storage, particularly for preserving temperature-sensitive food during transportation. By leveraging the thermal energy storage properties of PCM, food can be kept at the desired temperature to avoid spoilage and ensure optimal quality. PCM also offers promising applications in the medical field, including the transportation of blood and organs. In addition, PCM can be utilized to regulate the temperature of medical equipment, like MRI machines, and maintain consistent temperatures for medications during storage and transportation.

We have successfully developed a phase change material (PCM) that exhibits exceptional performance and a virtually infinite lifespan, particularly in the human comfort range of 18˚C to 29˚C (64˚F to 84˚F), as well as in electronic applications at higher temperatures. In our study on the use of PCM in domestic refrigerator applications, we generated graphs plotting the melting time and melting point of the PCM, as well as the freezing time and freezing point of the material. These values were measured in minutes and degree centigrade, respectively, and were plotted for two different PCM thicknesses (2mm and 5mm) to compare their effects. The experiments were conducted using a specially designed setup, and the results were compared to theoretical data obtained from computational fluid dynamics (CFD) analysis. Our findings revealed that larger thicknesses of the PCM yielded superior results when compared to thinner layers.

1.2 Performance improvement of a domestic refrigerator by using PCM

The performance of a household refrigerator was studied through experiments conducted with water as the phase change material (PCM) under specific thermal loads. The impact of introducing 5 liters of PCM on the refrigerator's performance parameters was analyzed. The number of on-off compressor cycles was observed over a certain period of time, with and without PCM. Results indicated that the use of water as PCM had a significant impact on the coefficient of performance (COP) improvement at specific thermal loads.

2 Methods and Materials

The schematic flow of the experimental study is represented in the Figure 2. It involves the preparation of PCM and blending with the calculated quantity of cocunt oil for the desired amount of heat removal. The validation of the prepared sample is the successive methodology of testing viz., micro and macro encapsulation methods.

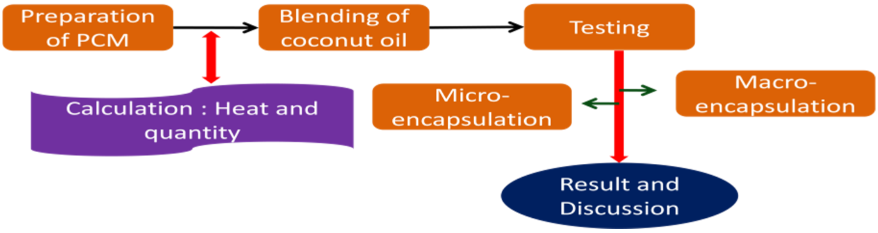


Fig. 2. Schematic flow of the experimental study.

The experimental setup depicted in Figure 3 includes the following components: 1) Aluminum sheet metal, 2) Paraffin wax, 3) Coconut oil, 4) Temperature sensor, and 5) Stop watch. Aluminum is a versatile and commonly used material for sheet metal due to its cost effectiveness, flexibility, and various properties. Four of the most frequently used aluminum grades for sheet metal are available. This metal exhibits excellent chemical and weather resistance, can be drawn deeply, and is weldable, though it has relatively low strength. Due to its favorable characteristics, paraffin wax is widely used as a phase change material (PCM) in electronic thermal management. It possesses a high heat of fusion per unit weight, a wide range of melting points, reliable cycling performance, and is non-corrosive and chemically inert.

Fig. 3. Paraffin Wax and Coconut Oil.

Table 1. Paraffin Wax's Physical Characteristics.

Property	Range
Température of transition	55°C to 58°C
Potential for Latent Heat	206 kJ/kg

Density	789kg/m³

Table 2. Physical Properties of Coconut Oil

Property	**Value**
Melting point(°C)	26.78
Latent heat (J/g)	110.4
Thermal conductivity (W/m ºC)	0.321

The soft, colorlessmaterialknown as paraffin wax is made fromcoal, shale oil, or petroleum. With a carbonatom count rangingfromtwenty to forty, itis made up of a combination of hydrocarbonmolecules, usually straight-chain n-alkaneswith the general formula CH_3- $(CH_2)_n$ -CH_3. Paraffin wax is a soft, colorlesssolidthatisderivedfrompetroleum, coal, or shale oil. It consists of a mixture of hydrocarbonmolecules, typicallycomposed of straight-chain n-alkaneswith the general formula CH_3- $(CH_2)_n$-CH_3, where the carbonatom count ranges fromtwenty to forty. At room temperature, paraffin wax is in a solid state but starts to meltaround 37 °C (99 °F), and itsboiling point exceeds 370 °C (698 °F). On the other hand, coconutoilis a recentlydeveloped bio-based phase change material (PCM) thatexhibits favorable thermophysicalproperties. In a study, itwasnoticedthatwithout the use of PCM, the cooling process from 22 to 20 °C tookapproximately 1.4 hours, whereaswith the incorporation of PCM, ittookaround 3.5 hours. Temperature serves as a fundamental and widelymeasuredparameteracrossvarious aspects of life [16].

A temperature sensor is an instrument that measures the temperature of a body, indicating whether it is hot or cold. These sensors typically detect temperature by measuring a change in the physical property of the sensor or material. Thermocouple alloys, which are often available in the form of wire, are commonly used as temperature sensors and can measure temperatures ranging from -200ºC to 2000ºC. A stopwatch, on the other hand, is a portable timepiece designed to measure the duration between its activation and deactivation.

2.1 Expérimentation

Cube Storage System Design and Micro-encapsulated Storage System Figure 5, this is the primary system which is made of aluminum sheet metal to store the Phase Change Material (PCM) (Figure 4).

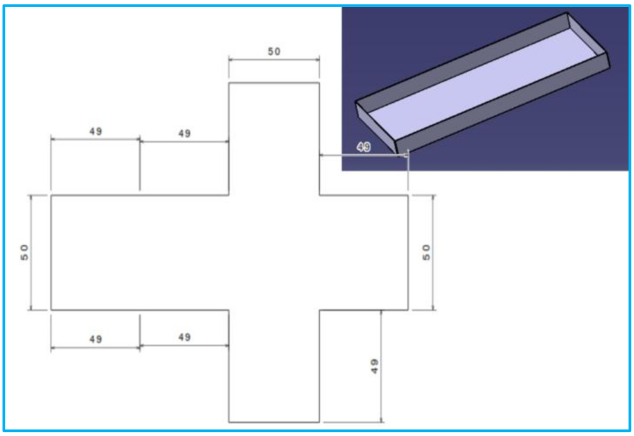


Fig. 4. Rectangular Storage System Design

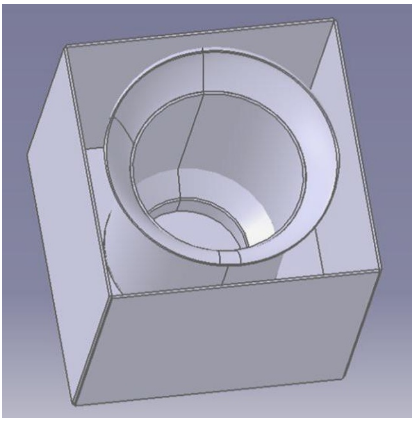


Fig. 5. Micro-encapsulated Storage System

Table 3. Thermal Storage Performances of Heating and Freezing of PCM

Sample	Melting Point (°C)	Latent Heat (J/G)	Rate Of Change (%)	Freezing Point (°C)	Latent Heat (J/G)	Rate Of Change (%)
Coconutoil	26.78	110.4	25.4	14.76	105	26.1
Palm oil	17.26	127.3	39.4	8.55	53.75	37.5
Coconutoil/ xGnP SSPCM	26.93	82.34	-	14.95	77.64	0
Palm oil/ xGnP SSPCM	18.33	77.18	-	9.2	33.58	-

Coconutoilexhibits certain physicalproperties, including a melting point of 26.78°C, a latent heat of 110.4 J/g, and a thermal conductivity of 0.3210 W/m ºK.In the case of paraffin wax, itundergoes a transition fromsolid to liquidwithin the temperature range of 55°C to 58°C. It has a latent heatcapacity of 206 kJ/kg and a density of 789 kg/m³.

Theseproperties are listed in Table 3. Following steps shows the calculation of heatcapacity of PCM material: For 1 Grams of PCM.

$$Q = mC_p, \Delta T + mL_s \tag{1}$$

Where, Q- HeatCapacity, C_p-Specific heat capacity,
m – Mass of PCM, Ls-Latent heat of fusion of PCM

$$Q = 0.001\text{kg} \times 2100\text{J/kgk} \times (305\text{-}296) + 1\text{g} \times 110.4\text{J/g}$$
$$Q = 129.3 \text{ J}$$

Thus, in order to phase change a liquidcoconutoil to solid or vice versa, heat to beremovedis 129.3J.Calculation of total conduction heattransferis as follows.

$$\frac{Q}{A} = \frac{T_a - T_3}{\frac{1}{h_a} + \frac{L_1}{k_1} + \frac{L_2}{k_2}} \tag{2}$$

Q - Heattransfercapacity (w), h_a – Heat Transfer Coefficient of air= 30 W/m^2 ºK;K_1, K_2- Thermal Conductivity of Aluminum and coconutoil (W/m ºK), L_1 and L_2 – Thickness of Aluminum (0.001m) and coconutoil (0.05m), A – Area normal to heat (0.01m^2).

$$\frac{Q}{0.01} = \frac{33 - 18}{\frac{1}{30} + \frac{0.001}{205.0} + \frac{0.05}{0.3210}}$$

Q = 0.7932W.

2.1.1 TestingProcedure

Fig. 6. Macro capsulated System.

The test can be done in two types of system: macro capsulated system and micro capsulated system.In this scenario, a phase change material (PCM) is stored in a separate system that is placed in a room or environment that requires cooling and temperature maintenance. The PCM material is first supercooled in an aluminum system for analysis. The aluminum box, containing the PCM, is then placed in a thermocol-insulated environment, which is a 30 × 30 × 30 cm on each wall. After recording the ambient and ambient temperatures, the temperature change in the environment as a result of the PCM's influence is tracked over time. This procedure is shown graphically in Figure 6. [17]. The ambient temperature and the temperature of the environment are recorded, and then the temperature change in the environment due to the effect of the PCM is monitored over time. Figure 6 provides a visual representation of this process. [17].

2.1.2 Properties of outersurroundings made up of thermocol

Thermal Conductivity of thermocol is 0.047 w/m ºC, and Density is 35kg/m^3, which is made in the dimensions of 30 × 30 ×30 cm as shown in Figure 7.

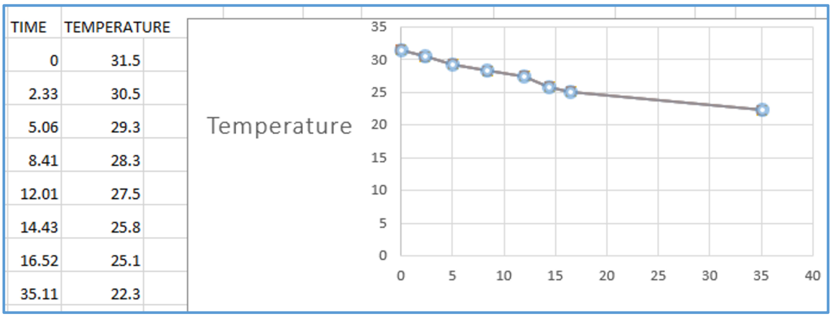
Fig. 7.Thermocol Surrounded system

2.1.3 Aluminum Cube Box

Fig. 8. Aluminium Cube Box

The aluminum cube box isshown in the Figure 8. The variousdetails of the cube box are as follows. (a). Thermal Conductivity: 205.0 W/m˚K, (b). Density: 2710kg/m3, (c). Dimensions: 100mm x 100mm x 100mm, (d). Thickness: 1mm, (e). PCM Quantity: 434 ml. In this setup, PCM volume isbased on the container size and isenclosedwithinwalls, which can be made of composite materials or a mixture of multiplecomponents. The process involvespouring PCM between the walls made of aluminium and coppermaterials and then super-coolingit for experimentalpurposes. The entire setup isthenexposed to direct sunlight. The temperature of the room and the coppervessellocated at the centre of the system isrecordedwith respect to time. The surface iscoveredwith aluminium sheets, and the innerwalls are insulatedwithparaffin wax for specificpurposes. The innerwallmaterial of the coppervesselis 300ml in quantity, has a thermal conductivity of 385.0 W/m˚K, a thickness of 1mm, and the amount of PCM usedis 434ml.

3 Result and Discussion



TIME	TEMPERATURE
0	31.5
2.33	30.5
5.06	29.3
8.41	28.3
12.01	27.5
14.43	25.8
16.52	25.1
35.11	22.3

Fig. 9. Time Duration Chart - Tabulation and Graphs of FreezingCharacteristicsParaffin

3.1 Macro-encapsulated test results.

The results of macro encapsulation test are shownbelow. In Figure 10 for cube system the temperature of 32.5˚C dips to a minimum of ~30˚C at 5 minutes. Whereas forcube storage system the drop of 2.5˚C happens at 7 minutes as shown in Figure 12. The rectangular system (Test 3)isdepicted in Figure 11 has more or lesssame pattern of Test 1.

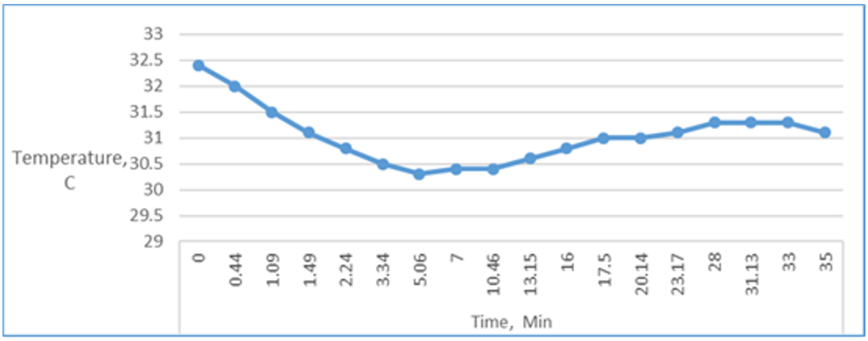


Fig. 10. Time Duration Chart - Tabulation and Graphs of FreezingCharacteristicsParaffin (Test 1: Cube system)

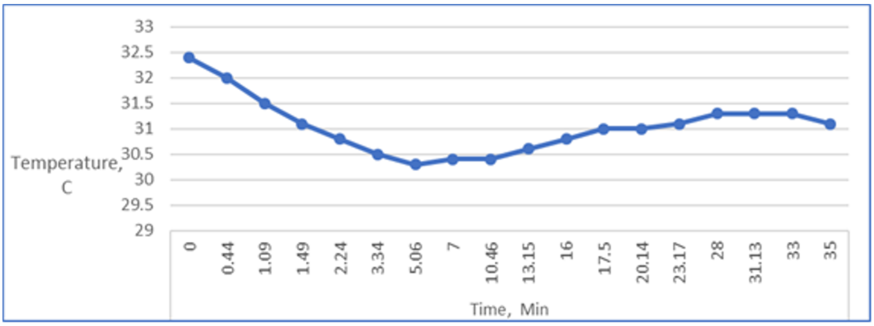


Fig. 11. Time Duration Chart - Tabulation and Graphs of FreezingCharacteristicsParaffin (Test 2:Rectangular system).

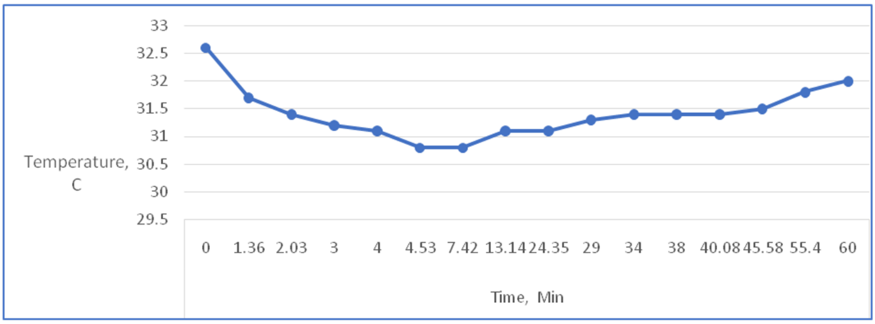


Fig. 12. Time Duration Chart - Tabulation and Graphs of FreezingCharacteristicsParaffin (Test 3 - Cube Storage System).

3.2 Micro-Encapsulated System results

Encapsulating PCM in wallsis a commonmethodused for thermal energystorage. In thisparticularexperiment, the walls are made of aluminium and copper, with the PCM pouredbetweenthem. The PCM issupercooled for experimentalpurposes and the entire setup isplaced in direct sunlight. The room temperatureismeasured first, followed by recording the temperature of the coppervessel in the centre of the system with respect to time. The surface iscoveredwith aluminium sheets, and the innerwalls are insulatedwithparaffin wax for specialpurposes. This setup allows for the testing of the effectiveness of the encapsulated PCM in storing and releasing thermal energy.

Outside Wall Material : Aluminium
Dimension : 100mm × 100mm ×100mm
Thickness : 1mm
Thermal Conductivity : 205.0 W/m˚K
Inside Wall Material : COPPER
Quantity : 300 ml
Thermal Conductivity : 385.0 W/m˚K
Thickness : 1mm
PCM Quantity : 434ml

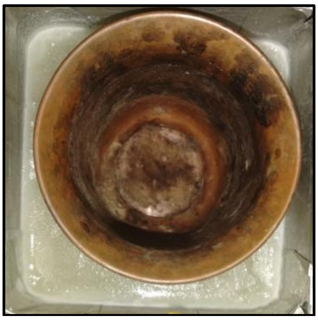


Fig. 13. Micro-encapsulated System.

$$Q/A = T_a - T_b / ((1/h_a) + (L_1/k_1) + (L_2/K_2) + (L_3/K_3) + (1/h_b)) \tag{3}$$

$$= 38-23/((1/30)+(0.001/205.0)+(0.018/0.3210)+(0.001/385)+(1/30))$$

$$= 1.22\ \mathrm{W}$$

Q - Heattransfercapacity(w), ha – Heat Transfer Coefficient of air= 30 W/m^2˚K;K1, K2, K3 - Thermal Conductivity of Aluminium, coconutoil and copperrespectively(W/m˚K) ; L1,L2 & L3 – Thickness of Aluminium(0.001m) , coconutoil(0.05m) &copper(0.001m) respectively ; A – Area normal to heat (0.01m^2) ;SurroundingTemperature: 33˚ to 40°C.

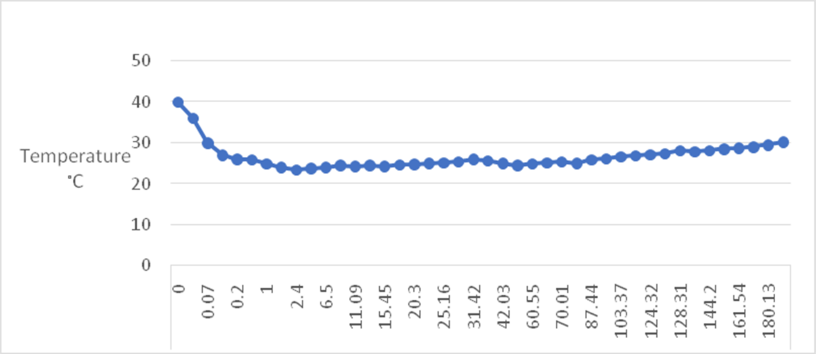


Fig. 14. Micro-encapsulated System (Test 1).

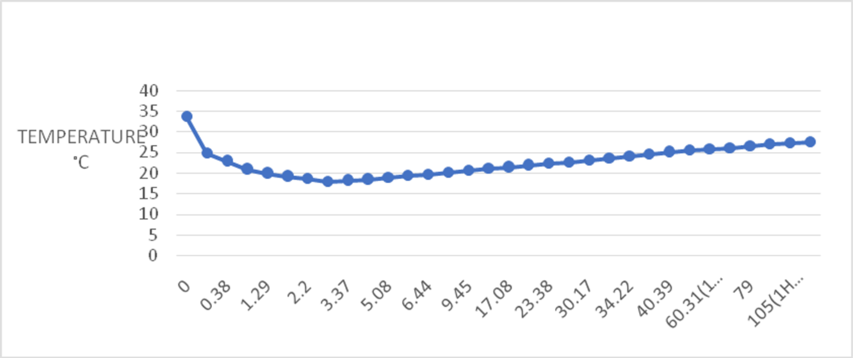


Fig. 15. Micro-encapsulated System (Test 2).

It isseenthat the microencapsulation system is not as efficient as the macro encapsulation system in maintaininglowtemperatures. The microencapsulation system able to lower the system temperature by up to 2°C and maintainit for a short period of time. On the other hand, the macro encapsulation system was able to achieve a temperaturedifference of 15 to 20°C and maintainit for a longer period of time.In Test 4 and 5, the microencapsulated system was able to achieve the desiredresult of reaching the lowesttemperature of 21 to 24°C whenexposed to a hot sunwith a temperature of 40°C. The system was able to maintain the lowtemperature for almost 3 hours and keep the system temperaturelessthan or equal to 27°C for almost 2 hours. Overall, the resultssuggestthat macro encapsulation is a more effective method for maintaininglowtemperaturescompared to microencapsulation. However, bothmethods can beuseful in different scenarios depending on the specificneeds and requirements of the system.

Conclusion

Thus, thisresearchworkgives us a clearanalysis of the coconutoil PCM that can beusedeven as a macro encapsulated system, but itislow efficient as thereisa 2°C temperature change lasting 30 minutes. Whenitcomes to the microencapsulation system, itgives the desiredresultwith a difference of more than 15 °C and can beused for more than 2.5 hours. Overall, the use of PCM has showngreatpotential in reducingenergyconsumption and improving the performance and reliability of varioussystems. The selection of the appropriate PCM depends on the specific application and the required thermal and mechanicalproperties. The researchconducted on the coconutoil PCM in thisproject highlights itspotential use in refrigerated transport containers, whereit can maintain a lowtemperature for a longer periodwithout the need for electricity. Furtherresearch and development in thisfield can lead to more efficient and sustainableenergystoragesystems, reducing the carbonfootprint and contributing to a greener future.

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