Mekanika: Majalah Ilmiah Mekanika

Usage of Phase Change Material as Heat Storage in Water Desalination

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Abstract

Phase Change Material (PCM) refers to substances that can absorb or release heat, making them effective for heat storage applications. PCMs can be categorized by chemical composition into three primary types: organic, inorganic, and eutectic. In Indonesia, a nation characterized by extended periods of sun exposure, selecting the most suitable PCM for solar still desalination experiments poses a challenge in reducing inefficient practical outcomes. This study investigates the properties of various PCMs and analyzes the essential factors to consider when choosing a PCM for heat storage. The research employs a review method using previously published literature from the Scopus database that incorporates PCM in solar still desalination. The results highlight five critical parameters for evaluation: physical properties, chemical properties, thermal properties, kinetic properties, and economic cost. For optimal compatibility with tropical environments, paraffin wax and soybean wax are the most appropriate choices, whereas coconut oil and beef tallow, which melt faster than wax, are better suited for subtropical regions.

1 Introduction

Indonesia, as a nation surrounded by oceans, has significant potential to use seawater to address its water supply challenges. However, this opportunity has not yet been fully realized. Seawater is abundant in minerals, with salt being the most predominant. One of the most straightforward methods for extracting these minerals from seawater is through desalination. Desalination is the process of purifying water by separating dissolved minerals. Several mechanisms are employed for desalination, including evaporation-condensation, filtration, and crystallization. In the desalination process, water is heated to its boiling point, causing it to evaporate into pure H_2O vapor while leaving the minerals behind as residue. The simplest method of water desalination, often used for small to mid-range applications, is the evaporation-condensation mechanism. This process can be implemented in various ways using different devices, with the solar still being one of the most common devices. However, as sunlight is available for only about 12 hours each day, the desalination cycle using a solar still is also limited to sunlight hours. This limitation has driven innovations in the water desalination industry. Solar stills have been modified in structure and functionality, often incorporating an external medium to enhance their practical efficiency.

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Researchers have been exploring the use of Thermal Energy Storage (TES) materials to extend the operational duration of the desalination cycle. TES materials can store heat for later use, allowing for heat storage without the need for electricity [1]. The long practical duration extends into the night, aided by the release of heat from TES into the seawater. The release of heat is known as the discharging process [2,3]. An experiment conducted by Mahsa Rousta et al. assessed solar still performance across Conventional Solar Still (CSS), pure soybean wax PCM, and soybean wax-enriched cobalt and aluminum (nano-enhanced PCM). Results indicated that the solar still incorporating nano-enhanced PCM and aluminum produced 350 ml of water after 10 hours of operation, which is 0.8% more than the conventional solar still [4]. Another study by Prasad et al. compares the productivity of a passive single-slope solar still with a rectangular basin and a pyramid solar. Initially, each solar still was tested without PCM. In the subsequent phase of the experiment, 10 kg of paraffin wax was added as PCM to each solar still. The results demonstrated that incorporating PCM significantly increased water productivity. For the rectangular conventional still, the water output was 2,940 ml, which increased to 3,490 ml upon adding PCM. In the case of the pyramid, still, the initial production was 3,410 ml, but this rose to 4,130 ml with the addition of PCM [5]. In Figure 1, we observe that PCMs are classified into three distinct groups. The first category is organic PCMs, which include paraffins, with paraffin wax and soybean wax commonly used. This group also encompasses fatty acids such as stearyl alcohol and stearic acid, as well as various other options. The second category consists of salt hydrates, including lithium chlorate trihydrate ($LiClO_3 \cdot 3H_2O$) and magnesium chlorate hexahydrate ($MgCl_2 \cdot 6H_2O$), while the metals are usually $AlSi1_2$. The third type is eutectic PCMs, which typically represent a combination of both organic and inorganic materials [6]. A previous study detailing PCM applications in solar desalination is outlined in Table 1.

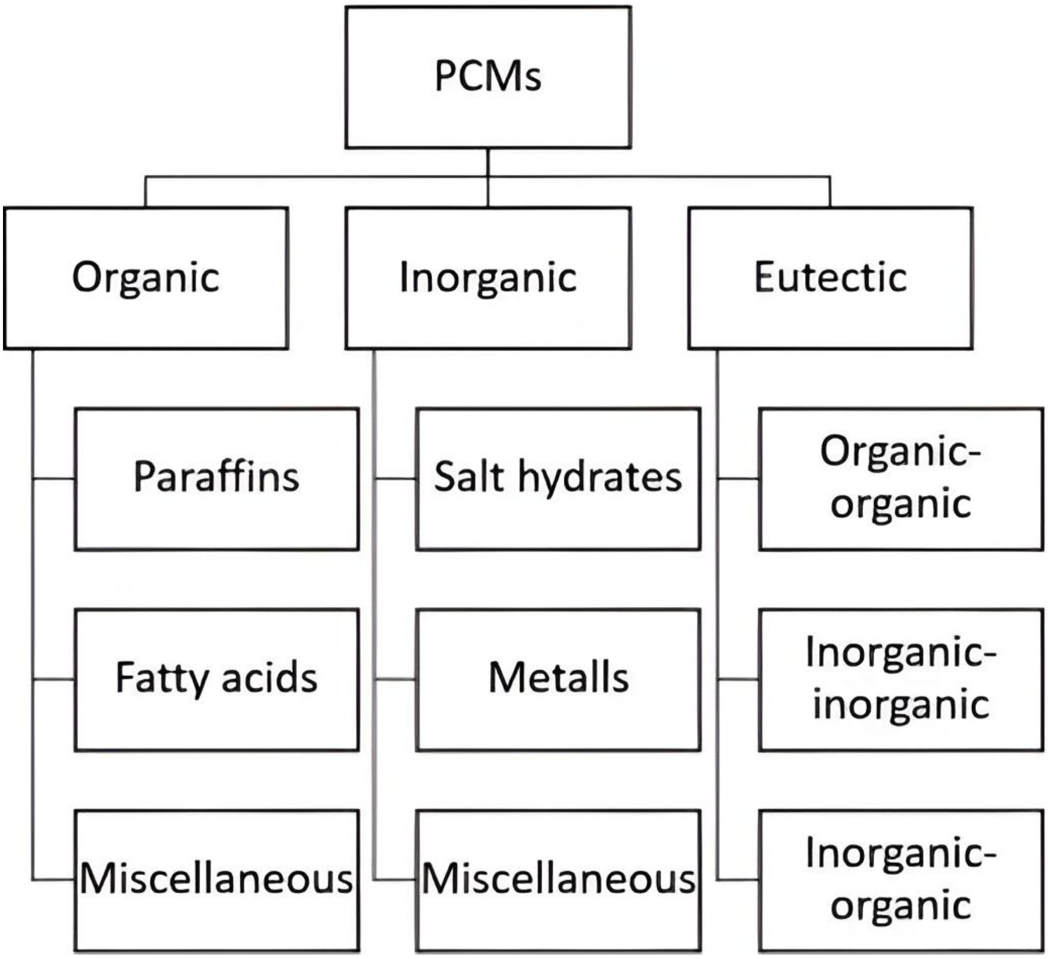

Figure 1. Classification of PCM

Table 1. Previous study on phase change material

Authors	PCM used in paper	Methodology	Conclusion
A. Reyes et al. [7]	coconut oil paraffin wax	comparative study between CSS, SS with coconut oil, and SS with paraffin wax, both inserted inside 18 copper tubes	CSS • 5.55 kg produces 0.148 kg/day • 8.25 kg produces 0.151 kg/day • 11 kg produces 0.143 kg/day CO-SS • 5.55 kg produces 0.15 kg/day • 8.25 kg produces 0.163 kg/day • 11 kg produces 0.15 kg/day PW-SS • 5.55 kg produces 0.123 kg/day • 8.25 kg produces 0.153 kg/day • 11 kg produces 0.132 kg/day
P. M. Kumar et al. [8]	a combination of sodium acetate trihydrate and MgO nanoparticles	comparative experiment between n-PCM modified solar still, PCM modified solar still, and conventional solar still	the modified solar still produces higher distilled water, as the n-PCM modified system yields 2.9 L, the PCM modified system yields 2.5 L, and the traditional system yields only 1.9 L of distilled water
A. R. Prasad et al. [5]	paraffin wax	comparative experiment between 2 conventional solar stills and 2 PCM-modified solar stills	conventional solar stills produce 2.9 L and 3.4 L of distilled water, while the modified ones produce 3.4 L and 4.1 L of distilled water
J. Seifi et al. [9]	paraffin wax	comparison between 3 PCM modified solar stills, with flow rates of 1.9, 3.1, 4.2 L/min, and a conventional solar still	the 3 PCM modified solar still produces different amounts of distilled water, which are: 1. 1.9 L/min produce 350 L/m^2 2. 3.1 L/min produce 570l/m^2 3. 4.2 L/min produce 710 L/m^2 as for the conventional solar still, it produces only 650 L/m²

Table 2. *Cont.*

Authors	PCM used in paper	Methodology	Conclusion
Naim and A. El Kawi [10]	paraffin wax	Comparative experimental study between a conventional solar still with PCM (mixture of paraffin wax, paraffin oil, and water) and a modified multi-basin solar still	The modified solar still produces 4.5 L/m², while the conventional solar still produces more than the conventional one
M. Bady et al. [11]	Algeria	Comparative experimental study between the Conventional Conical Solar Distiller (CCSD) and two modified Conical Solar Distillers (CSD), which are copper tubes-CSD and copper tubes + Copper Plate Material (CPM) CSD	• CCSD produced 4.85 L/m^2 /day • copper tubes-CSD produced 6.75 L/m^2 /day • copper tubes+CPM CSD produced 7.50 L/m^2 /day
W. I. A. Aly [12]	Egypt	Comparative experimental study between Oval Turbular Solar Still (OTSS) with different modifications: conventional, with cooling water, and with PCM	• conventional OTSS produces 5.21 L/m^2 /day • cooling water-modified OTSS produces 6.34 L/m^2 /day • PCM modified OTSS produces 6.78 L/m^2 /day
L. Afolabi et al. [13]	encapsulated paraffin wax with zinc nanoparticle	Comparative experimental study between Conventional Double Slope Solar Still (DSSS) and PCM-Modified Double Slope Solar Still (PCM-DSSS)	• average DSSS production is at 2.8 L/m^2 • average PCM-DSSS production is at 4.5 L/m^2 • The PCM-DSSS operated 3 hours longer than DSSS due to the addition of PCM, and had 4°C higher solar still temperature and 2°C higher saline water temperature

Each PCM possesses distinct thermo-physical properties. With the wide variety of PCMs available, selecting the appropriate one for thermal energy storage in water desalination can be challenging. In tropical regions where the average ambient temperature rarely exceeds 35°C, choosing a PCM with a low melting point is crucial to gain maximum performance. Conversely, in subtropical areas, the frequent seasonal fluctuations often render PCMs unsuitable for consistent use. This variability is part of the reason why most PCM applications are concentrated in tropical zones. This paper provides parameters to consider when selecting the most suitable PCM for solar desalination and aims to enhance the reader's understanding. Consequently, researchers can identify the most suitable PCM material for thermal energy storage in water desalination for local demographics.

2 Parameter of Phase Change Material

2.1 Physical properties

The physical properties of PCM are crucial when selecting them for Thermal Energy Storage (TES) in water desalination applications. Solar stills, which are commonly employed for this purpose, have limited volume and fixed space. Therefore, it is essential to choose a PCM that balances mass and volumetric capacities. As the phase change material transitions between solid and liquid states, significant changes in its volumetric or mass properties can affect its thermal energy storage capabilities, ultimately impacting the optimization of distilled water production. Another important criterion is the material's vapor pressure. PCMs with low vapor pressure tend to exhibit better chemical stability compared to those with high vapor pressure, which are more prone to evaporation. Lastly, the density of the PCM should also be considered. Each material has its own density; as density increases, the mass required decreases, allowing less space to house the material and enabling higher heat storage capacity within the PCM. Table 2 presents the physical properties of various PCMs across different categories [14].

Table 2. Physical properties of organic and inorganic PCM

Category	Product	Melting point	Boiling point	Density	Thermal conductivity
organic PCM	paraffin wax	58°C - 62°C	322°C	0.82 g/ml at 20°C	0.2 W/m·K
organic PCM	capric acid	31.6°C	268.7°C	0.89 g/ml at 20°C	0.372 W/m·K (solid) 0.141 W/m·K (liquid)
organic PCM	lauric acid	44°C	298.9°C	0.965 g/ml	0.147 W/m·K [15]
inorganic PCM	potassium chloride	770°C	1420 °C	1.98 g/ml	-
inorganic PCM	Al_3Cu_2	548°C	-	3.424 g/ml	130 W/m·K (solid) 80 W/m·K (liquid) [16]

2.2 Thermal properties

To optimize water distillation production, it is essential to select an appropriate PCM with favorable thermal properties. An effective PCM should have high thermal conductivity, significant latent heat, and high specific heat capacity. Using a PCM with a high specific heat capacity allows for greater heat storage compared to one with lower thermal conductivity. Additionally, it is essential to consider the material's latent heat of fusion; a PCM with a high latent heat can store more thermal energy from solar radiation. Lastly, the temperature range over which the material undergoes a phase change is another critical factor to evaluate when choosing an appropriate PCM [17]. From Figure 2, we observe that heat absorption is most pronounced within specific temperature intervals, particularly during phase changes. At the melting point, the material maintains a constant temperature as it absorbs heat to transition from solid to liquid. Once the material has completely melted, its temperature will begin to rise again. It is crucial to select the appropriate PCM for each specific application. For instance, a PCM with a high phase change temperature may be effective for heat storage. However, it may not be suitable in environments where ambient temperatures are significantly lower than the PCM's minimum temperature required for solid-to-liquid transition. In such cases, the PCM may not melt, thereby failing to store heat. These conditions can result in insufficient heat for water evaporation, ultimately reducing productivity. This concept is illustrated by Equation 1.

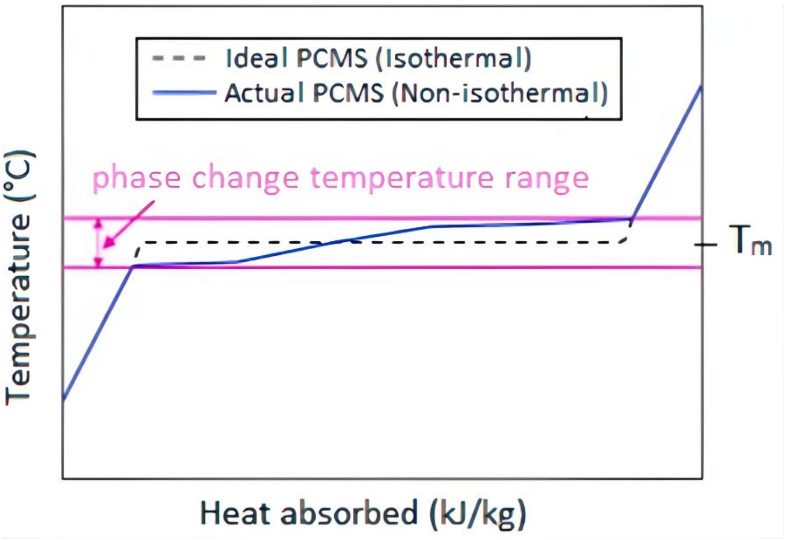

Figure 2. Relationship between the amount of heat absorbed and its temperature

$$Q_{cond,PCM-basin} = \frac{M_{eq}}{A_{PCM}} \times \frac{dT_{PCM}}{dt} \tag{1}$$

In the equation, we can identify three factors that influence the amount of heat transfer between the PCM and the basin in a solar still. The amount of heat transferred depends on the heat already stored in the PCM. For PCMs with a large phase-change interval, the equivalent mass (Meq) will be greater, allowing for more heat storage and the ability to deliver this stored heat to the basin for an extended period when sunlight is unavailable. This principle also holds for PCMs with a smaller phase-change temperature interval; a narrower interval corresponds to reduced heat-storage capacity. When utilizing a phase change material PCM for water desalination, there is a potential risk of errors leading to instability after several thermal cycles. The addition of certain substances can mitigate this instability. A study conducted in Hungary by Omar explored the effects of composite and nano-additives on the thermal properties of paraffin wax. The results indicate that incorporating a hybrid of 1.0% mass Multi-Wall Carbon Nanotubes (MWCNTs) and 1.0% mass Al_2O_3 into RT-65HC paraffin wax significantly enhances thermal stability by 89%, increases latent heat temperature by 80%, and boosts thermal conductivity by 32% [18].

2.3 Kinetic properties

When selecting the appropriate material for Latent Heat Storage (LTES), the ideal PCM should not exhibit supercooling. Supercooling is a phenomenon where a liquid material solidifies below its melting point, leading to crystallization [19]. This occurrence can diminish the PCM's performance by hindering its ability to release stored heat effectively. While nearly all PCM materials may experience some form of supercooling to facilitate the transition from liquid to solid, excessive supercooling can disrupt the system's efficiency. For instance, the crystallization temperature of paraffin wax ranges from approximately 24.78°C to 48.38°C, depending on the presence of additives such as nanoparticles. If severe supercooling occurs, paraffin wax may begin to solidify at a lower temperature, which delays the latent heat release process and prolongs the overall heat transfer duration [20]. As illustrated in Figure 3, there is a distinction between the melting temperature (Tm) and the supercooling temperature (T_s). If the supercooling temperature increases, the PCM requires more heat to raise its temperature sufficiently to melt. This scenario could result in the loss of more heat during the melting process than is effectively stored. Such complications can burden the system, preventing the water in the basin from reaching the necessary temperature for evaporation while simultaneously impeding the optimal melting of the PCM, rendering it ineffective for heating the water at night.

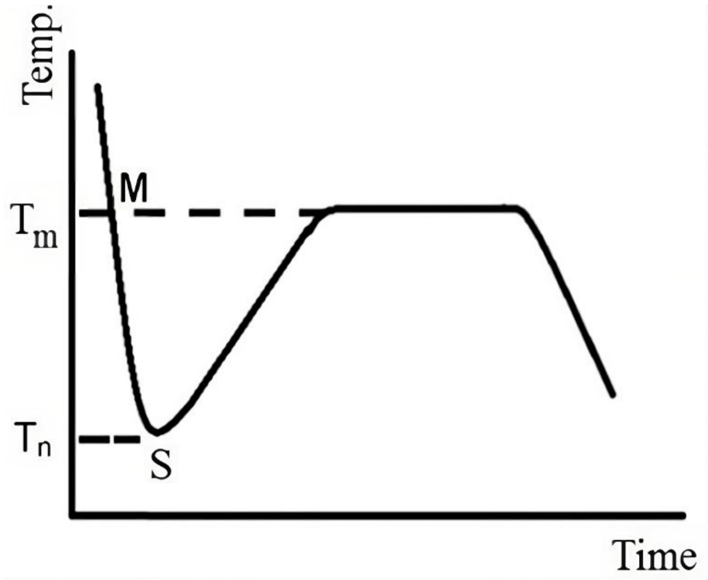

Figure 3. Time-temperature diagrams in PCM in the supercooling phase

Supercooling in PCM can be mitigated by incorporating surfactants, provided the surfactant is used at an appropriate ratio to the PCM mass. While the addition of surfactants can effectively reduce supercooling, it may also decrease the latent heat. In addition to surfactants, the inclusion of silica nanoparticles can enhance the crystallinity of PCMs [21].

2.4 Chemical properties

PCMs possess a unique atomic structure that greatly influences their quality. When selecting PCMs based on their chemical properties, three critical factors should be considered. Firstly, it is essential to examine their toxin levels. In a solar still, the bulk water is stored above the basin liner, while the PCM is placed below it. Although the entire chamber is designed to be isolated to prevent any mixing of the PCM and water, it remains crucial to ensure that no toxic materials contaminate the water. The second factor to assess is the material's corrosiveness and flammability. When dealing with inorganic or metallic PCMs, it is vital to ensure they do not corrode when stored in a closed, damp environment, as this can compromise their integrity. Additionally, they should not easily ignite due to high temperatures or chemical reactions occurring within the chamber [22]. A chemical reaction in the system should be a concern as it could affect the performance of PCM. This chemical reaction may occur after the PCM's first thermal cycle. Due to the heated PCM, the space between the basin layer and the PCM will be at elevated temperatures, leading to corrosion. This will affect the PCM because when the basin corrodes, corrosion can mix into the PCM, reducing its phase-change capability. Another chemical reaction may occur during the manufacturing process. When preparing the PCM, it is essential to ensure that no water is trapped in the PCM, that no bubbles are present in the solid PCM, and that the PCM is not contaminated. Air bubbles or water droplets will reduce heat storage capacity and create a vapor layer between the basin layer and the PCM, which disturbs the system.

2.5 Economic value

The use of PCM as a heat storage medium encourages researchers to account for both the system's manufacturing costs and the PCM's cost. Typically, the amount of PCM required for one square meter of basin area ranges from 10 to 25 kilograms, necessitating a significant financial investment. Additionally, the cost of using PCM includes transportation fees, primarily because water desalination often occurs in remote areas, such as beaches or deserts. The economic value of PCM affects users and their maintenance costs. More complex PCM mixtures may incur higher expenses and require more intricate maintenance procedures compared to less expensive alternatives [14].

3 Results and Discussion

When using a PCM for thermal energy storage, several fundamental considerations must also be taken into account. These fundamentals are the temperature difference and the basin thickness. Equation 2 is used to calculate the heat transferred and stored between the basin layer and the PCM. Several factors influence this process, including thermal conductivity, temperature difference, and basin area. Typically, the basin's thermal conductivity is high, enhancing efficient heat transfer to the PCM.

$$Q_{cond,b-n-PCM} = \frac{k_{basin}(T_b - T_{PCM})}{basin\ thickness} \tag{2}$$

The temperature difference between the basin layer and the PCM also plays a crucial role in determining the amount of heat that can be stored; a larger temperature differential enables a greater heat storage capacity. Furthermore, the thickness of the basin layer affects the energy stored; a thicker basin can retain more heat but may ultimately reduce the total heat stored. In contrast, a thinner basin layer requires less heat, facilitating more efficient energy transfer. This equation is similarly applied to calculate the heat transferred from the PCM back to the basin, as demonstrated in Equation 3 [23].

$$Q_{cond,b-n-PCM} = \frac{k_{PCM}(T_{PCM} - T_B)}{PCM\ thickness} \tag{3}$$

It is crucial to assess the manufacturing quality of PCM, as it is a key factor in determining its overall performance. The inherent characteristics of pure PCM can lead to insufficient thermal stability, resulting in challenges such as supercooling, limited thermal cycling capability, and the high risk of potential contamination. To address these challenges and enhance PCM quality, integrating nanoparticles into the material presents a viable solution. The addition of nanoparticles significantly improves the thermal stability of PCMs [24,25]. Furthermore, it is imperative to consider environmental conditions. An ideal location for PCM application is one that is hot and exposed to sunlight, as the material enhances energy storage capabilities while minimizing thermal heat loss to the surrounding environment by maintaining a smaller temperature differential. Conversely, when solar stills operate in colder conditions, the PCM remains functional; however, heat dissipation to the surrounding environment increases due to the larger temperature differential. This issue can be effectively mitigated by installing a layer of glass wool or another suitable insulating material beneath the outer basin. In terms of chemical stability, commonly used PCMs include nonreactive substances such as soybean wax and paraffin wax. Although these materials are inherently non-reactive, some researchers are actively exploring encapsulation techniques to prevent unintended reactions between PCMs and seawater. This approach also helps reduce PCM leakage during the phase transition from solid to liquid during the charging process, without the need for chemical bonds, as demonstrated in composite PCMs that feature cross-linked polymer structures or mesoporous frameworks created through hydrolysis and calcination [26]. Chen et al. found that physical stability is influenced by capillary forces, surface tension, and the chemical arrangement of structures, such as n-octadecane dispersed within modified polymer networks [27] or molten salts encapsulated in ceramic frameworks [28].

According to Table 3, engineers can select the most suitable PCM type for their research needs. In small-scale water desalination using solar stills, a low-maintenance system is essential to keep costs down and ensure access to water for target users. Consequently, organic PCMs, such as paraffin wax, are often preferred. Paraffin wax is not only readily available but also compatible with conventional structures and nonreactive. These characteristics make it advantageous for individuals who may not be familiar with complex systems. In contrast, middle-scale water desalination targets higher daily water production, aiming for approximately 150 liters per day. Researchers in this area often combine PCMs with external heat sources to optimize output. Various experiments indicate that enhancing the thermal stability of the PCM is vital for improving both its quality and lifespan. One common approach is to incorporate nanoparticles, such as Al_2O_3 and CuO, into the PCM to achieve this enhancement.

For large-scale water desalination, relying solely on PCM is insufficient for producing the desired volume of water. Therefore, the system typically requires additional components such as heaters, condensers, or the integration of solar stills with a Humidification-Dehumidification (HDH) mechanism.

Table 3. Characteristic of the PCM

	Organic	**Inorganic**	**Eutectic**
advantage	1. melt congruently 2. less supercooling phase 3. compatible with conventional structure 4. chemically stable 5. high sustainability 6. non-reactive materials	1. sharp melting point 2. high volumetric heat storage capacity 3. high thermal conductivity 4. low cost	1. sharp melting point 2. high material density 3. suitable for customizing substance 4. high melting temperature 5. good chemical and thermal stability
disadvantage	1. low thermal conductivity 2. leaves residue 3. low value of enthalpy when phase change occurs	1. high volumetric changes 2. easily gets into the supercooling phase 3. low thermal stability	1. low thermal conductivity 2. prone to leakage during phase changes 3. high temperature corrosion

4 Conclusions

From this study, four conclusions can be drawn regarding the use of PCM in solar desalination. which are:

1. PCM serves a crucial role in solar desalination as an LTES solution. By incorporating PCM or non-PCM, heat from solar radiation can be more effectively absorbed, allowing bulk water to retain heat even in the absence of sunlight
2. To choose a suitable PCM as LTES, five parameters must be considered, such as thermal stability, physical and chemical properties, economic values, and the sustainability of the PCM.
3. For small-scale water desalination, paraffin wax is the most recommended PCM due to its excellent thermal stability, low thermal conductivity, and widespread availability, making it a cost-effective choice. For medium-and large-scale water desalination, it is advisable to incorporate nanoparticles or an external condenser/heater to enhance the system's productivity.
4. In the future, experimenting with paraffin wax and salt hydrates, which are encapsulated, may prove to be the most effective method for identifying compatible types of LTES materials. Encapsulated PCMs can reduce the rate of supercooling and offer additional advantages, such as minimizing mass loss, lowering contamination risks, and decreasing PCM leakage.

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