Experimental Study and Analysis of the Effect of Phase Change Material (PCM) Mass Variation on Solar Still Desalination Equipment

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Abstract

Water is the most essential element for all human activity on Earth. Clean water is the issue encountered most regularly by all living organisms on earth. The majority of the world's water is in the oceans, thus, it cannot be used for human use. Providing potable water from seawater or contaminated water poses a problem in remote places where grid connectivity is typically unavailable. Desalination technology solutions are highly lucrative and assist in meeting the rising need for clean water. Desalination is the most effective method for meeting clean water needs. In contrast, solar desalination's effectiveness as a water purifier is rather modest compared to other procedures. PCM Phase Change Material (PCM) can be used as a heat storage to boost the water production of a solar still desalination unit. PCM paraffin wax with a melting temperature of 52 °C was put over a basin of 0.95 m by 0.92 m by 0.07 m and filled with PCM paraffin wax in the shape of stainless-steel balls submerged in sea water. This study aims to assess the impact of PCM mass on water production and equipment efficiency in solar desalination systems. Observations were made to assess the influence of PCM mass fluctuations on solar still desalination devices and experiments without PCM were compared to identify the research methodology. Based on test findings without PCM and PCM mass variations of 0.86 kg, 1.72 kg, and 2.58 kg, water production can be increased by an average of 17.03%, 14.53 %, 18.88%, 17.61 %. The use of heat storage material (PCM) can keep a steady temperature for a longer period of time, hence increasing the productivity of each system by 951 ml (without PCM), 811 ml, 1054 ml, and 983 ml, respectively. The decrease in output of 0.86 kg was caused by a continual shift in irradiation intensity, which dropped significantly and was influenced by the low mass of PCM, resulting in less heat energy stored. The rate of heat transmission from PCM to surrounding water is related to the temperature of the water.

Experimental Study and Analysis of the Effect of Phase Change Material (PCM) Mass Variation on Solar Still Desalination Equipment

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Abstracts: - Water is the most essential element for all human activity on Earth. Clean water is the issue encountered most regularly by all living organisms on earth. The majority of the world's water is in the oceans, thus it cannot be used for human use. Providing potable water from seawater or contaminated water poses a difficulty in remote places where grid connectivity is typically unavailable. Desalination technology solutions are highly lucrative and assist in meeting the rising need for clean water. Desalination is the most effective method for meeting clean water needs. In contrast, solar desalination's effectiveness as a water purifier is rather modest compared to other procedures. PCM Phase Change Material (PCM) can be used as a heat storage to boost the water production of a solar still desalination unit. PCM paraffin wax with a melting temperature of 52 °C was put over a basin of 0.95 m by 0.92 m by 0.07 m and filled with PCM paraffin wax in the shape of stainless-steel balls submerged in sea water. This study aims to assess the impact of PCM mass on water production and equipment efficiency in solar desalination systems. Observations were made to assess the influence of PCM mass fluctuations on solar still desalination devices and experiments without PCM were compared to identify the research methodology. Based on test findings without PCM and PCM mass variations of 0.86 kg, 1.72 kg, and 2.58 kg, water production can be increased by an average of 17.03%, 14.53 %, 18.88%, 17.61 %. The use of heat storage material (PCM) can keep a steady temperature for a longer period of time, hence increasing the productivity of each system by 951 ml (without PCM), 811 ml, 1054 ml, and 983 ml, respectively. The decrease in output of 0.86 kg was caused by a continual shift in irradiation intensity, which dropped significantly and was influenced by the low mass of PCM, resulting in less heat energy stored. The rate of heat transmission from PCM to surrounding water is related to the temperature of the water.

Key-Words: desalination, Phase change material (PCM), solar still, water, paraffin wax
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1 Introduction

Water is the most important component for all activities on earth, despite the very uneven distribution of water: only 3% of usable water, only 69% usable in glacial masses, 30% of underground water, less than 1% of lake water, and 97% of the water on earth being sea water, rivers, etc. The problem of clean water is the most frequently encountered by all living things on earth. Most of the water on earth is in the oceans, so it cannot be used for human needs. Desalination technology solutions are very profitable and help meet the increasing demand for clean water [1]. In the past several countries water sources often tasted brackish or salty and contained harmful bacteria, therefore unusable for drinking in its natural form especially in coastal areas where there is scarcity of drinking water [2]. Seawater desalination has two features which are environmentally friendly and solar as an energy source, abundant and renewable. The desalination technique is the most efficient for clean water needs. In the past, the most prominent processes for desalination were reverse osmosis, desalination, distillation, and electrodialysis. The involvement of the whole world in the energy crisis that relies on fossil fuels and the need to use renewable energy sources such as desalination to meet the needs of clean water [3]. Desalination is the process of removing dissolved salts, in which salt water is converted into fresh and clean water by using the sun as an energy source to heat the water. Water vapor will form because it condenses. Desalination is designed with a closed box in a solar still; salty water is evaporated with the help of a tilted glass to obtain fresh water; water droplets are formed and collected with the help of a collector; and the water is stored in a reservoir [4]. Basically, a solar still is a mechanism that uses solar energy to turn impure water into pure water. On the other hand, the ability of solar stills as a water purifier is relatively low compared to other purification techniques. In addition, the solar still process of evaporation and condensation occurs in the same closed gap as the clean water produced. As a result, the yield of diesel has been studied extensively in various studies and has been further improved by carrying out various modifications. For this reason, solar production is affected by various parameters, including water depth, rate of adhesion or close cohesion to prevent moisture outflow, slope of the solar condensing cover, mode of thermal insulation, and the primary design and stationary material itself [5]. There are other ways to improve solar still performance; several other designs have been developed, such as the addition of flat plate solar collectors and the use of phase change materials (PCM) to store solar energy during the day and maintain solar energy for 24 hours [6]. Current phase change materials are used to store solar thermal energy in the form of latent heat and can provide high storage capacities per unit volume and per unit mass at night to obtain heat for desalination. These phase-change materials change the phase from solid to liquid, store solar energy, and radiate absorbed energy [7]. Another review of PCM for energy storage applications varies based on thermophysical properties such as the melting point of the system exposed to constant heat, the density of thermal energy storage, changes in organic and inorganic matter, and changes in the eutectic phase. In previous research, the authors conducted a theoretical study to investigate the effect of various parameters such as solar radiation intensity and ambient weather conditions on variations in water temperature, PCM amount, and unit productivity[8].

2 Problem Formulation

2.1 Water

Water is a H2O compound, which is the most important part of the needs of living things. About 80% of the water contained in the human body is the most important thing in the human body, and the higher the level of activity, the more water is needed so that it cannot be separated from water. The benefits and functions of water as a medium for delivering nutrients, vitamins, minerals, and oxygen to the organs and cells of the body Good or healthy water not only has the characteristics of being colorless, odorless, and tasteless, but is also free from chemical or microbiological contaminants. Water sources come from wells, rivers, lakes, brackish water, and the sea. Dirty, salty, and brackish water have distinguishable characteristics or properties consisting of three parts, namely: [9]

a. Physical characteristics
It is a colorless liquid with a density of 1.02 g/cm3 and a pH of 7.8–8.2. has a freezing point of -2.78 °C and a boiling point of 101.1 °C. The average temperature is 25 °C, the taste is bitter, and the aroma depends on the purity.
b. Chemical Characteristics
Chemical characteristics of clean water: a degree of acidity (pH) between 6 and 8.5 with total hardness *(H)*, consisting of highly aggressive organic matter and $_{CO2}$. The chemical elements contained in brackish well water are Fe $^{++}$Na^{+}, SO$_{4}^{=}$, CI^{-}, Mn^{++}, Zn^{++}.
c. Biological Characteristics
The level of presence of algae, lichens and other microorganisms that can be harmful to health, even in small amounts.

2.2 Solar stills desalination

Solar still desalination is used to convert brackish water or salt water into drinking water by using solar energy. Solar stills consist of a shallow, black-lined pool of saltwater covered by a sloping transparent roof. Sunlight entering through the transparent roof heats the water in the black trough, causing it to evaporate and condense on the bottom of the glass, where it collects in the trough as distilled water and sticks to the glass [7].

2.3 Phase change materials (PCM)

Phase change materials (PCM) are energy storage in the form of latent heat with a heat storage capacity per unit volume [10]. Energy in the form of heat can be stored as sensible or latent heat, or a combination of both. Sensible heat is heat stored in a material due to a change in temperature. The amount of heat storage varies depending on the specific heat of the heat storage material, changes in temperature, and the amount of heat storage material. The amount of heat storage can be calculated using the following formula: [11]

$$Qs = \int_{T_1}^{T_2} m_1 . Cp_1 . dT = m_1 . Cp_2 . (T_2 - T_1) \qquad (1)$$

Where:
Qs = Sensible heat stored (kJ)
T_2 = initial temperature (°C)

T_1 = final temperature (°C)
m_1 = mass of heat storage media (kg)
Cp_1 = specific heat (kJ/kg.°C)
Cp_2 = Specific heat average temperature T_2 and T_1 (kJ/kg.°C)

The difference between sensible heat and latent heat is that as heat increases, the temperature remains constant with heating and when only undergoing a phase change. Thermal storage materials are referred to as phase change materials (PCM). The amount of stored energy is determined by the amount of PCM and PCM latent heat. The amount of stored latent heat energy can be calculated using the following formula:

$$Q_1 = m_2 \lambda \qquad (2)$$

Where :
Q_1= stored latent heat (KJ)
m_2 = mass of PCM (kg)
λ= latency head PCM (KJ/kg)

Latent heat is the amount of heat absorbed when a material transitions from one phase to another. There are two known types of latent heat: the latent heat of melting and the latent heat of vaporization. The latent heat of melting is the heat absorbed when the temperature of the material changes from the solid to the liquid phase and vice versa, while the latent heat of evaporation is where the amount of energy absorbed by a material changes from the liquid phase to the liquid phase or gas phase and vice versa [12]. Phase change materials (PCM) generally utilize the latent heat of phase change to control the temperature of a certain range, there are several materials that are often used as PCM based on their chemical composition, based on chemical composition can be classified as organic, inorganic, and eutectic [13]. Organic phase changers are generally chemically stable, non-supercooling, non-corrosive, non-toxic, and have high latent fusion. Organic PCM can be further divided into two categories: paraffin and non-paraffin. Paraffin is available in a wide melting temperature range from about 20 °C to 70 °C, is chemically inert, has a low vapor pressure in the melt, and there is no phase separation. However, the thermal conductivity of paraffin is low at around 0.2 W/(mK). Non-paraffin organic materials include organic materials such as fatty acids, esters, alcohols, and glycols. These generally have excellent melting and freezing properties but cost about three times the price of paraffin. Inorganic PCM generally has a high melting point, good thermal conductivity, and is cheap and easy to burn. However, some are corrosive to metals, subject to supercooling, and undergo phase separation. Inorganic PCM is generally a hydrated salt and an attractive material for thermal energy storage due to its high storage density of about 240 kJ/kg, relatively high thermal conductivity of about 0.5 W/(mK), and reasonable price compared to paraffin. Eutectics are mixtures of several solids in such proportions that their melting points are as low as possible, their melting points are usually sharp, and their storage densities are higher than those of organic compounds. Eutectics can be divided into three groups: organic-organic, inorganic-inorganic, and inorganic-organic eutectics. The eutectic binary system has a melting point of 18–51 °C and a heat of fusion between 120 and 160 kJ/K [10].

2.4 Paraffin wax as a phase change material (PCM)

Paraffin with the general formula CH_3-(CH_2)n-CH_3 is also known as a straight-chain *n-alkane* mixture; based on 1-4, the number of carbons refers to pure alkanes in the gas phase, 5-17 carbons are liquid paraffin, and more than 17 are known as solid wax. These "waxy" solids refer to mixtures of saturated hydrocarbons such as linear, iso, highly branched, and cycloalkanes. Commercial paraffin contains a mixture of isomers and therefore has a wide range of melting temperatures. From a chemical point of view, paraffin wax is inactive and stable, showing moderate volume changes (10–20%) during melting but having a low vapor pressure.

Fig 1. Paraffin wax
Source: Author documentation, 2022

Paraffin-based PCM usually has high stability for very long crystallization melting cycles. Paraffin wax is a substance that is safe, reliable, inexpensive, non-irritating, and relatively obtainable in a wide range of temperatures. As far as economics is concerned, most technical-grade waxes can be used as PCM in latent heat storage systems. [14] The thermophysical properties of paraffin wax are shown in the following table: [15]

Table 1, ***Thermo-physical properties*** **of** ***paraffin wax***

No	Properties	value
1	Melting	52°C
2	Freezing	52°C
3	Latent heat of smelting	143 kJ/kg
5	Specific heat	2 kJ/kg.°C
6	Density:	
	▪ Liquid	0.88 kg/liter
	▪ Congested	0.76 kg/liter
7	Thermal conductivity (liquid and solid)	0.2 W/mK

2.5 Efficiency of stable solar desalination equipment

Efficiency is the ratio of the heat energy required to evaporate contaminated water into clean water to the amount of solar radiation received by the system through the absorber plate in a certain time interval [16]. To calculate the efficiency value to determine the effect of PCM mass, you can use the following formula:

$$\eta d = \frac{m_k \times h_{fg}}{A_c \times I_r \times t} \times 100\% \qquad (3)$$

Where:
mk = total mass of water production (kg)
hfg = Latent heat of vaporization (kJ/kg)
Ac = Absorber plate area (m2)
Ir = Intensity of solar radiation (W/m2)
t = Length of testing time (S)

3 Research Methodology

In this part of the experimental study, a solar still desalination device with a single slope was designed with a length of 1 m, a width of 1 m, a height of 0.2 m in front, and 0.7 m in back. Solar still desalination is made of aluminum, and the deep basin of the desalination device uses a single basin made of plywood coated with resin and painted black to maximize absorption of solar radiation. Transparent glass is 3 mm thick with a tilt angle of 25°. At the top of the basin is a stainless steel PCM ball with a ball weight of 40 g, an outer diameter of 76.2 mm, and a thickness of 0.5 mm, placed in a basin measuring 0.95 m by 0.92 m by 0.07 m, which is submerged in sea water. In this study, we tested the solar still desalination device with paraffin wax type PCM with a mass variation of 0.86 kg, 1.72 kg, and 2.58 kg, which was then compared to the desalination tool with PCM and without PCM.

Fig.2 Solar still desalination scheme with PCM

In this experiment, a thermocouple device (type K), a digital Lux Meter, is used to measure the temperature and intensity of solar radiation during each experiment. A thermocouple sensor is connected in the desalination device to measure several parameters, namely changes in water temperature, PCM, steam, environment, the resulting amount of water production, and light intensity. The device is set to record temperature and retrieve data manually (hourly).

Fig 3. Solar still desalination equipment

Fig 4. Pictures of each experiment for a solar still desalination device equipped with Phase change material (PCM)

4 Results and Discussion

In each experiment, the amount of PCM used was varied to determine the effect of PCM on changes in the temperature of the solar desalination device. Each series of experiments was carried out in three consecutive days for each PCM mass of 0.86 kg, 1.72 kg, and 2.58 kg. The experiment started at 08.00 until 20.00, each graph of the relationship of water temperature, PCM, steam, environment, and light intensity to time with PCM and without PCM. The mass of water is constant at 24 kg.

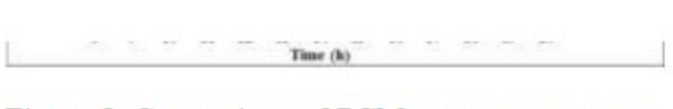

Figure 5: Comparison of PCM temperature, water, steam, environment, and intensity with a PCM mass of 0.86 kg

Based on Figure 5, the results of testing the mass of 0.86 kg PCM with an average irradiation intensity of 295.773 W/m ^{2} indicate that the temperature change of PCM and water, which at 08:00 was constantly increasing until 11:00 a.m. with normal weather conditions, While the decrease in room and environmental temperatures occurred at 11:00–12:00 p.m. due to changes in irradiation intensity, which constantly dropped drastically, The PCM temperature at 0.86 kg mass experienced a maximum temperature increase of 47.2 °C, while the water temperature was 51.9 °C and the maximum steam temperature was 51.2 °C. to reach the phase change point of PCM paraffin wax, which is 52.0 °C, so that the heat storage process does not occur optimally because it is below the melting point of PCM paraffin wax. Heat transfer by conduction starts from the beginning of charging until a solid-liquid phase change is formed. The low irradiation intensity results in slow heat transfer from water to PCM.

Fig 6. Comparison of PCM temperature, water, steam, environment, and intensity with a PCM mass of 1.72 kg

Based on Figure 6, the results of testing the mass of 1.76 kg PCM with an average intensity of 373.393 W/m ^{2}, show that the temperature of the water and room increases from 08:00 to 13:00, the process is constantly increasing faster, this indicates that the rate of heat transfer is greater than water to PCM so that the maximum temperature reached by PCM is 53.8°C. This is due to the high intensity of solar radiation at the beginning of the process. Meanwhile, the maximum water temperature reached 55.2°C and the maximum water vapor temperature reached 53.7°C. To reach the phase change point of PCM paraffin wax, which is 52.0 °C, the PCM heat storage process occurs optimally because it reaches the phase change point of PCM paraffin wax. The process of absorbing energy by PCM is where the charging process occurs. When the water temperature passes through the PCM melting point, the negative temperature difference will reach a peak and then return to a positive value, which indicates the discharging process from the PCM has begun and energy is transferred from the PCM to the water.

Fig.7 Comparison of PCM temperature, water, steam, environment, and intensity with a PCM mass of 2.58 kg.

Based on Figure 7, the results of testing a mass of 2.58 kg PCM with an average irradiation intensity of 395,160 W/m2 show that the temperature rise of water, PCM, and water vapor from the beginning at 08:00 to 14:00 is constantly increasing; this indicates that the heat transfer rate is greater from water to PCM so that the maximum temperature reached by PCM is 57.5 °C, while the water temperature is 58.9 °C, and the maximum steam temperature is also 57.5 °C. This is due to the high intensity of solar radiation at the beginning of the process, so the PCM temperature tends to be higher, resulting in an optimal heat storage process because it reaches the phase change point of PCM paraffin wax at 52.0 °C. Heat transfer by conduction starts from the beginning of charging until a solid-liquid phase change is formed. The high-water temperature causes a large heat transfer in the PCM, so that the temperature is also high.

Fig.8 Comparison of PCM temperature versus time with mass variations of 0.86 kg, 1.72 kg, and 2.58 kg

Fig.9 Comparison of water temperature versus time with variations in PCM masses of 0.86 kg, 1.72 kg, and 2.58 kg

From the results of Figure 8 and Figure 9, Showing the effect of PCM mass on PCM and water temperature variations, it is shown that when the mass number of indigo PCM is greater, the PCM temperature is constant. This can be seen clearly where the temperature remains constant at 08:00–13:30 when the mass value of PCM is 1.72 kg or 2.58 kg. This is because the water temperature is higher than the PCM temperature, so a lot of heat is absorbed during the charging process so that it keeps the temperature constant for a longer time, which increases evaporation. After that, the PCM melts completely and then degrades slowly with time, during which the process of releasing the heat stored in the PCM begins. At a PCM mass of 0.86 kg, the temperature ratio of PCM and water decreased due to the small amount of heat absorbed by the PCM. This is because the temperature of the PCM is proportional to the temperature of the water, and the greater the heat stored, the more the discharging process from the PCM to the water increases.

Fig.10 Comparison of water production results in desalination equipment with and without PCM to the average light intensity

From Figure 10. Based on the graph, it can be seen that the addition of PCM mass has an effect on increasing the productivity of the solar still desalination device when compared to solar testing without PCM. In testing the PCM masses of 0.86 kg, 1.72 kg, and 2.58 kg, the increase in desalination equipment productivity in each test was 951 ml (without PCM), 811 ml, 1054 ml, and 983 ml. Based on the graph results, it can be seen that the difference in PCM mass has an effect on increasing water production in the solar still desalination apparatus with PCM and without PCM, as seen in the mass variation of 1.72 kg; there is an increase in water production of 103 ml compared to without PCM. whereas in testing the PCM mass of 0.86 kg, one tends to experience a decrease in production of 104 ml compared to the test without PCM. The decrease in production is due to the lower mass of PCM and less stored heat energy, so that heat transfer from PCM to the surrounding water is proportional to the water temperature. During testing, the PCM mass of 2.58 kg tended to cause a decrease in production; this was influenced by the addition of excess PCM mass because the large amount of PCM mass present in the system resulted in more energy needed to heat and then melt the PCM. [17] investigated a theoretical model to simulate a solar still connected to an external collector and incorporate sodium thiosulfate pentahydrate as a phase change material (PCM). The result is that loading large PCM masses into the system reduces productivity; increasing the PCM mass to water mass ratio from 10 to 100% reduced production by up to 30%. Meanwhile, introducing the large mass of PCM into the system has kept the basin water temperature higher for a longer time.

Fig.11 Comparison of desalination equipment efficiency with PCM mass variations and without PCM

Based on Figure 11, It can be seen that in testing the PCM mass variation of 0.86 kg, 1.72 kg, 2.58 kg, and without PCM, there was an increase in the efficiency value in the test with the addition of PCM mass of 1.72 kg and 2.58 kg, amounting to 18.88% and 17.61%, respectively, compared to the test without PCM. While testing with a PCM mass of 0.86 kg, we experienced a decrease in efficiency compared to testing without PCM. In this test, the value obtained for each increase in the average efficiency test for each test was 17.03%, 14.53%, 18.88%, and 17.61%.

5 Conclusion

From the test results on a solar still desalination device with a mass variation of PCM, respectively, 0.86 kg, 1.72 kg, and 2.58 kg were compared with those without PCM. This research was conducted with the main objective of increasing the performance of a still-standing solar desalination device with phase change material (PCM) in producing water. Based on the test data and analysis of the influence of the *peraffin wax PCM mass* on the solar still desalination device, a conclusion can be drawn. In each PCM mass test of 0.86 kg, 1.72 kg, and 2.58 kg compared to without PCM, the efficiency values for determining the effect of PCM mass were 17.03%, 14.53%, 18.88%, and 17.61%. The presence of PCM tends to cause the process of charging and discharging, the amount of heat absorbed during the charging process keeps the temperature constant for a longer time. This means that the greater the heat stored, the discharging process increases. The increase in productivity in each testsystem was 951 ml (without PCM), 811 ml, 1054 ml, and 983 ml. In addition, with the addition of PCM, it undergoes a heating process at night due to the release of heat stored in the PCM, so that the total water production is higher than without PCM.

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