Thermal performance enhancement of the wick-type solar still using Titanium dioxide nanoparticles embedded in paraffin wax as a phase change storage material

Ali Ibrahim  
Tanta University Faculty of Science

Ahmed El-Sebaii  
Tanta University Faculty of Science

Saad Aboul-Enein  
Tanta University Faculty of Science

Mohamed Hegazy  
Tanta University Faculty of Science

Assem Fleafl  
Tanta University Faculty of Engineering

A.M. Khallaf (✉️ amakhallaf@yahoo.com)  
Tanta University Faculty of Science  https://orcid.org/0000-0002-0399-4755

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Abstract

In this study, the performance of the wick-type solar still was investigated using phase change storage material (PCM) with titanium dioxide nanoparticles. Therefore, two solar stills were fabricated one of which was operated with pure PCM and the other one was operated with PCM incorporated with TiO$_2$ nanoparticles. The use of the nanoparticles was to enhance the thermal conductivity of the PCM and hence improve the productivity and the efficiency of the studied solar still. The proposed design was investigated with jute and cotton as wick materials. The results revealed that the addition of the nanoparticles boosted the thermal conductivity of the PCM by 9.6%. Moreover, the daily productivity was found to be 1058 and 1226 ml/m$^2$/hr for cotton and jute, respectively in case of the presence of the PCM-nanocomposite.

Introduction

Nowadays, access to fresh water is one of the most crucial challenges facing the world. As a result, experts offered several methods of extracting drinkable water from salt water as the sole way to solve the world’s drinking water crisis. Solar stills are one of the most important applications used to obtain fresh water [1]. One of the advantages of solar stills is the low operating cost in addition to the fact that they require simple maintenance [2]. Nevertheless, the biggest problem with these distillers is their low productivity, especially at night. Therefore, most researchers resorted to use several methods to increase the productivity of these stills. One of these methods is the use of a phase change material (PCM), which is a material that can store heat during the sunrise and release this heat after sunset. Thus, the process of heating the water remains, and the process of distillation and productivity continues during the night [3]. One of the drawbacks of the PCM is its low thermal conductivity, so researchers used a mixture of nanoparticles with PCM to enhance its thermal conductivity, which leads to an increase in the productivity of the solar still [4]. There is another way to raise the performance efficiency of solar stills, which is to use a wick material such as jute, cotton, etc., in order to increase the evaporation area and the preheating time of basin water inside the still, which increases water production [5]. Haddad et al. [6] made an attempt to improve the productivity of the conventional solar still using a vertical rotating wick belt to act as an additional absorption-evaporation area. They investigated the proposed still during summer and winter seasons. The experimental outcomes illustrated that the daily productivity of the still during summer was 7.17 kg/m$^2$ with an enhancement of 14.72% in comparison with the conventional still. On the other hand, the daily productivity was 5.03 kg/m$^2$ during winter. Essa et al. [7] improved the performance of the tubular solar still experimentally using convex absorber, wick material and nanocomposites. The convex absorber was used to increase the surface area of the still which in turn leads to enhance the vaporization inside the still. They studied two different wick materials as well as they investigated the effect of using TiO$_2$ and graphene nanocomposites on the performance of the still. The experimental results showed that the vaporization surface area was enhanced by 21.3%. Moreover, the maximum daily productivity was 9000 (ml/m$^2$.day) by using the wick materials and nanocomposites. Abdelaziz et al. [8] tested experimentally five modifications on the tubular solar still to improve its performance. They
recorded that the best modification was by using v-corrugated plate on which wick material and carbon black (CB) nanoparticles and paraffin wax mixed with CB nanoparticles positioned under the absorber plate. The results indicated that the best modification improved the productivity the still by 88.8%. Additionally, they found that the best design could save the cost by 22.4% compared with the conventional still. Kabeel et al. [9] carried out experiments to enhance the productivity of the tubular solar still using graphene oxide nanoparticles mixed with paraffin wax as PCM. The experimental data showed that there is no enhancement in the thermal conductivity of the nano-PCM beyond 0.3% of the concentration of the nanoparticles. After comparing the performance of the conventional tubular still, tubular still with PCM and the tubular still with nano-PCM, they found that the total cumulative yield per m² was 2.59, 3.35 and 5.62 kg, respectively. The performance of the tray solar still was improved through several stages by Abdullah et al. [10]. Firstly, using reflectors lead to an enhancement in the productivity by 57%. Additionally, they used reflectors along with painting the surfaces of the still by CuO nanoparticles, which resulted in improving the productivity by 14%. The third modification was by combining the reflectors and the nano-painting and the result showed an increase in the productivity by 70.7%. Finally, the effect of using paraffin wax mixed with CuO nanoparticles was investigated. This mixture boosted the productivity by 108% [10]. Behura and Gupta [11] tried to enhance the productivity of the v-corrugated solar still using paraffin wax as PCM embedded with CuO nanoparticles. The experimental study was performed for different concentrations of the nanoparticles started from 0.1–0.3%. The results showed that the best concentration was 0.3%, which gave productivity about 510 (ml/m².day). They concluded that the productivity was enhanced by 62.7% in comparison with the conventional still. The productivity of the wick-type solar still was enhanced by the addition of nickel oxide nanoparticles in the saline water according to Lawrence et al. [12]. A concentration of 12% of nickel oxide nanoparticles was the optimum value for increasing the productivity of a still containing 50 kg of water. They prepared nickel oxide nanoparticles from the stem and leaf of a plant called Acalypha Indica. The experimental results depicted that the productivity of the proposed still was 5.81 and 5.75 (l/m².day) for stem and leaf, respectively. Kumar et al. [13] conducted experiments to improve the performance of the conventional solar still. Three different designs were tested in India; namely, the conventional still, the still with PCM, and the still incorporated with mixture of silica nanoparticles and PCM. The results revealed that the still with PCM and nano-PCM enhanced the production of fresh water by 51.22 and 67.07%, respectively. A study performed by Rufuss et al. [14] in which three different types of nanoparticles (CuO, TiO₂ and GO) were added individually with paraffin wax to improve the output of solar stills. The addition of CuO, TiO₂ and GO improved the thermal conductivity of the paraffin wax by 28.8, 25 and 101%, respectively. Moreover, the results showed that the annual productivity was 660, 617 and 453 liters, respectively for the used nanoparticles. Kabeel et al. [15] enhanced the performance of the pyramid solar still through the usage of PCM and fins made of copper. They tested the performance of the conventional pyramid still and compared the results with that of the modified stills. One of the modification methods was by adding copper fins while the other method was done by placing the PCM below the absorber plate. They concluded that the copper fins increased the productivity to 5.75 (L/m².day), whereas the addition of the PCM boosted the productivity to 8.1 (L/m².day). Murali et al. [16]
enhanced the solar still productivity by using Al$_2$O$_3$ nanoparticles and paraffin wax as an energy storage medium. The mixture of the NPCM was faded into 12 tubes made of copper which are immersed beneath 1 cm of water in the basin. The experimental results revealed that the use of the NPCM boosted the efficiency and the productivity of the still by 9.5% and 19.4%, respectively, as compared with the use of the PCM only. The productivity of the stepped solar still was improved by Safaei et al. [17]. They focused on using graphene oxide (GO) nanoparticles dispersed in paraffin wax with different concentrations. They concluded that the use of GO with PCM increased the solar still efficiency by 25% compared to the still with only PCM. Moreover, the results showed that the productivity was 2.5 kg/0.4 m$^2$ with 0.6 wt% of GO.

A study made by Younes et al. [18] to investigate the performance of the wick solar still with corrugated plate (CWSS) and half barrel absorber (BWSS). The vertical sides of the stills were covered by a wick material to increase the evaporation area. Moreover, PCM mixed with CuO nanoparticles was placed below the absorbers. The experiments revealed that the daily productivity was increased by 154% and 139% for the BWSS and CWSS, respectively, over the conventional solar still.

From the previous review it is obvious that the single basin wick-type solar still with TiO$_2$ as nanoparticles incorporated in paraffin wax as a PCM material is still need further investigation in an attempt to improve the overnight productivity of wick-type solar stills. Therefore, the objective of this study is to improve the thermal performance of the wick-type solar still and raise its productivity. Accordingly, in this study, the wick solar still was investigated using paraffin wax as a PCM for energy storage. Due to the low thermal conductivity of paraffins, TiO$_2$ nanoparticles have been added to the PCM to improve its thermal conductivity, which leads to an increase in the productivity of the solar still. Experiments were performed using cotton and jute as wick materials. Some results and conclusions were drawn.

**Experimental Procedure**

A schematic diagram of the wick-type solar still with the PCM is presented in Fig. 1. The system can be used with and without nanoparticles embedded in the PCM. Experimental measurements were made in Tanta city (Lat. 30 deg 47′ N), Egypt, during summer 2021. Two identical stills were manufactured with the dimensions illustrated in Fig. 1. They composed of aluminum sheets with a thickness of 0.005 m. Two other boxes of galvanized iron, thickness of 0.005m, are inserted inside the external aluminum boxes separated by an insulating foam of 0.03 m thickness. Two containers were made of galvanized iron, with dimensions of 0.99 x 0.99 x 0.15 m, to work as the basins of the stills. These basins needed about 13.5 kg of paraffin wax to fill them. Each box containing the wax has two tubes upright on both sides of the basins with a diameter of 0.15 m that allow the wax to expand through them to accommodate the increased volume of the liquid PCM (see Fig. 1). There is a back slot in the still to insert the wick material to cover the surface of the absorber plate. The other side of the wick material is immersed in a water container outside the still. The external end of the wick material immersed in water allows for spreading a thin layer of water through the whole wick material by the capillary action. Each solar still has a 0.003m thick glass cover acts as the condensation surface which makes an angle of 30° with respect to the horizontal almost equal the latitude of Tanta. The temperatures of the glass cover, the absorber plate, the
paraffin wax with and without nanoparticles and the ambient air were measured using temperature sensors connected directly to a computer software from 8 am to 8 pm with a time step of five minutes and then the recorded data were averaged and drawn every one hour. The solar radiation was measured using an Eppley PSP pyranometer. The values of the productivity were recorded on the second day at 8 am and added to the value of the previous daylight productivity to give the daily productivity of the still.

Results And Discussion

Experimental investigation of thermal performance of the single basin wick solar still with paraffin wax as a phase change storage material (PCM) and nanoparticles incorporated with the PCM has been performed. Figures 2 and 3 present the hourly variations of temperatures of the still water ($T_w$), storage material ($T_{pcm}$), glass cover ($T_g$) and ambient air ($T_a$) and solar radiation ($I$) when the length and width of the still equal 1 m with jute and cotton as wick materials and paraffin wax with nanoparticles on 13/9/2021 and 14/9/2021, respectively. All temperatures and solar radiation increase with time until they achieve their maximum values of 61.1, 53.3, 44.3, 37.3 °C and 805 W/m² for $T_w$, $T_{pcm}$, $T_g$, $T_a$ and $I$, respectively for the still with jute then decrease with time when the ambient air temperature and solar radiation decrease. When the still operates with Cotton as a wick material, the maximum values of the temperatures and solar radiation are 58.3, 55.7, 44.7, 36.8 °C and 825 W/m² for $T_w$, $T_{pcm}$, $T_g$, $T_a$ and $I$, respectively.

Hourly variations of the temperatures and solar radiation jute, as a wick material, and PCM with and without nanoparticles has been illustrated in Fig. 4. Firstly, $T_w$ for the still with PCM and nanoparticles is less than that without nanoparticles due to the increased thermal conductivity of the PCM with nanoparticles until 2.0 PM. This behavior is reversed afterwards with variations of 6.49%. For the temperature of the storage material ($T_{pcm}$), it is seen that $T_{pcm}$ for the PCM with nanoparticles is more than that without nanoparticles because of the increased effective thermal conductivity of the PCM-nanoparticles composites. It is seen from the figure that the temperatures of the PCM with and without nanoparticles slightly increase during the period from 12 PM to 6 PM during the period of phase change of the PCM material. The enhancement in $T_{pcm}$ with using the nanoparticles. When the still operates with cotton as a wick material (see Fig. 5), $T_w$ and $T_{pcm}$ exhibit the same behavior as same as that with Jute. The daily average values of $T_w$ are 44.8 and 45.6 °C for the PCM with and without nanoparticles, respectively. For $T_{pcm}$, they are 44.6 and 41.2 °C for the PCM with and without nanoparticles, respectively. Figure 6 presents comparison of $T_w$ for the still with PCM-nanoparticles composites using jute and cotton as wick materials. It is seen that $T_w$ with jute is more than that with cotton by about 3.82ls% may be due to the difference in capillary action for the two materials and due to the difference in the amount of the absorbed solar radiation for the individual material. The daily average values of $T_w$ are found to be 46.2 and 44.5 °C using Jute and Cotton as wick materials, respectively.
Variations of the hourly productivity \((P_h)\) for the solar still using the PCM with and without nanoparticles for jute and cotton as wick materials are depicted in Figs. 7 and 8, respectively. It is obvious that, for both wick materials, values of \(P_h\) using the PCM with nanoparticles are more than that without nanoparticles due to the enhanced thermal conductivity of the PCM with nanoparticles that increases the evaporation rate from the still water. Figure 9 presents comparison of \(P_h\) of the still with PCM-nanoparticles composites using jute and cotton. It is seen that \(P_h\) with jute is more than that with cotton by about 9.1%.

Table 1 summarizes the values of the daytime, overnight and daily productivities for the still using jute and cotton under different operational conditions on 13 and 14/9/2021. It can be concluded from the results of Table 1 that using the nanoparticles with PCM for jute enhances the daytime, overnight and daily productivities by 20.6%, 23.0% and 21.5%, respectively. The corresponding values with using cotton are found to be 32.9, 25.0 and 30.8% respectively compared to the case without nanoparticles.

Figures 10 and 11 show the hourly variations of the evaporative heat transfer coefficient \((h_{ewg})\), calculated using Eq. 1 [19] for the still using the PCM with and without nanoparticles when it operates with jute and cotton, respectively.

\[
h_{ewg} = 9.15 \times 10^{-7} \left[ \frac{h_{cwg}(P_w - P_g)L_w}{(T_w - T_g)} \right]
\]

(1)

<table>
<thead>
<tr>
<th>Daytime productivity (ml/m² hr)</th>
<th>Overnight productivity (ml/m² hr)</th>
<th>Daily productivity (ml/m² hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jute (with Paraffin wax)</strong></td>
<td>678</td>
<td>285</td>
</tr>
<tr>
<td><strong>Jute (with Paraffin wax and Nano)</strong></td>
<td>856</td>
<td>370</td>
</tr>
<tr>
<td><strong>Cotton (with Paraffin wax)</strong></td>
<td>522</td>
<td>210</td>
</tr>
<tr>
<td><strong>Cotton (with Paraffin wax and Nano)</strong></td>
<td>778</td>
<td>280</td>
</tr>
</tbody>
</table>

Where \(P_w\) and \(P_g\) are the partial vapor pressure at temperatures of the still water and glass cover, respectively. \(h_{cwg}\) is the convective heat transfer coefficient between the still water and glass cover, \(L_w\) is the latent heat of vaporization of water (J/kg). It is calculated using the following correlation [20]

\[
L_w = 3044205 - 1670.1109T_w - 1.14258T_w^2
\]

(2)
Due to the increased effective thermal conductivity of the PCM-nanoparticles composite, $h_{cwg}$ for the still with PCM and nanoparticles is more than that without nanoparticles for the still for both jute and cotton. The daily average values of $h_{ewg}$ for the still with jute as a wick material are found to be 11.59 and 9.87 W/m$^2$K using the PCM with and without nanoparticles, respectively. With cotton, the corresponding values of $h_{ewg}$ are 10.92 and 10.35 W/m$^2$K with and without the nanoparticles, respectively. The hourly variations of the $h_{ewg}$ with the PCM-nanoparticles composite when the still operates with jute and cotton are presented in Fig. 12. It is clear that $h_{ewg}$ with jute is more than that with cotton by 6.1%. The daily average values of $h_{ewg}$ for the still with the PCM and nanoparticles are found to be 11.58 and 10.92 W/m$^2$K for jute and cotton as wick materials, respectively.

The daily efficiency ($\eta_d$) of the wick solar still represents one of the most important parameters affecting the performance of the still. It is calculated by the following equation [21]

$$\eta_d = \frac{P_d L_{ave}}{A_p (\sum I)} \times 100$$  \hspace{1cm} (3)

where $A_p$ is the surface area of the absorber plate (m$^2$), $L_{ave}$ is the average latent heat of vaporization of water (J/kg), $P_d$ is the daily productivity (ml/m$^2$ d) and $\Delta t$ is the time interval (s). The values of $\eta_d$ for the still using jute and cotton as wick materials with PCM are found to be 14.63% and 10.75%, respectively and the values using PCM-nanoparticles composite are 18.45% and 15.54%, respectively.

To verify the above-mentioned results, when using the PCM-nanoparticles composite to improve the productivity and efficiency of the wick-type solar still, measurements of the thermophysical have been performed for the paraffin wax with and without TiO$_2$ nanoparticles. Table 2 summarizes the results of the measured different thermophysical properties using the technique of the Hot Disk Transient Plane Source (TPS). From the measured results, the addition of TiO$_2$ to the paraffin causes an increase in the thermal conductivity and the thermal diffusivity by 9.6% and 18.9%, respectively. However, the specific heat of the PCM decreased from 1044 to 933 J/kg K. These results confirm the improvement in the thermophysical properties of the used nanoparticles and hence the daily productivity and efficiency of the solar still.
Table 2

the measured different thermophysical properties using the technique of the Hot Disk Transient Plane Source (TPS).

<table>
<thead>
<tr>
<th>Thermal properties</th>
<th>Paraffin wax with Tio$_2$ nanoparticles</th>
<th>Pure paraffin wax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity (W/m K)</td>
<td>0.354</td>
<td>0.320</td>
</tr>
<tr>
<td>Specific heat (J/kg K)</td>
<td>933</td>
<td>1044</td>
</tr>
<tr>
<td>Thermal Diffusivity (m$^2$/s)</td>
<td>$3.79 \times 10^{-7}$</td>
<td>$3.07 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Conclusions

Based on the obtained results, it may be concluded that; the still water temperature ($T_w$) with jute as a wick material is more than that with cotton. Using the nano-oxides with PCM when the still operates using the Jute and cotton as wick materials enhances the daytime, overnight and daily productivities. The evaporative heat transfer coefficient ($h_{ewg}$) between the still water and the glass cover for the still with jute is more than that with cotton. Using nano-oxides incorporated with the PCM causes an increase in thermal conductivity and diffusivity and a decrease in the specific heat of the PCM. From the results obtained from this study, it is recommended to operate the wick solar still with jute as a wick material and using the phase change storage material (PCM) with nano-oxides to improve the daily and efficiency of the solar stills.

Declarations

Informed Consent Statement:

Not applicable.

Research Data Policy and Data Availability Statements:

The data presented in this study are available in the article.

Conflicts of Interest:

There are no conflicts to declare.

Author Contribution:

Ali Ibrahim, Ahmed El-Sebaii, Saad Aboul-Enein: Conceptualization, Methodology, Investigation, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision, Resources, Funding acquisition. Ahmed El-Sebaii, Abd El-Monem Khallaf, Mohamed Hegazy, Assem Fleafi: Methodology, Validation, Writing - Original Draft, Writing, Investigation, Resources. Funding acquisition.
Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Funding Declaration:

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References


**Figures**

![Figure 1](image)

**Figure 1**

The schematic diagram of the wick-type solar still with PCM/nano-PCM
Figure 2

Hourly variations of temperatures of the still water ($T_w$), storage material ($T_{pcm}$), glass cover ($T_g$) and ambient air ($T_a$) and solar radiation ($I$) for the still with jute and PCM with nanoparticles.
Figure 3

Hourly variations of temperatures of the still water ($T_w$), storage material ($T_{pcm}$), glass cover ($T_g$) and ambient air ($T_a$) and solar radiation ($I$) for the still with cotton and PCM with nanoparticles.
Figure 4

Hourly variations of temperatures of the still water ($T_w$) and the storage material ($T_{pcm}$) for the still with jute and PCM with and without nanoparticles.
Figure 5

Hourly variations of temperatures of the still water ($T_w$) and the storage material ($T_{pcm}$) for the still with cotton and PCM with and without nanoparticles.
Figure 6

Variations of the still water temperature ($T_w$) for the still with jute and cotton as wick materials and PCM-nanoparticles composite.
Figure 7

Variations of the hourly productivity ($Ph$) for the still with jute using the PCM with and without nanoparticles.
Figure 8

Variations of the hourly productivity ($Ph$) for the still with PCM with and without nanoparticles with cotton.
Figure 9

Hourly variations of the hourly productivity \((P_h)\) for the still with jute and cotton as wick materials using PCM- nanoparticle composite.
Figure 10

Hourly variations of the evaporative heat transfer coefficient \((h_{ewg})\) for the still with jute and PCM with and without nanoparticles.
Figure 11

Hourly variations of the evaporative heat transfer coefficient \((h_{ewg})\) for the still with cotton and PCM with and without nanoparticles.
Figure 12

Hourly variations of the evaporative heat transfer coefficient ($h_{ewg}$) using jute and cotton as wick materials for the still with PCM-nanoparticles composite.