Thermodynamic analysis of single slope solar still using graphite plates and block magnets at seasonal climatic conditions

R. Dhivagar, M. Mohanraj, Praveen Raj and Radha Krishna Gopidesi

ABSTRACT

In this research, the thermodynamic (energy and exergy) analysis of a single slope solar still using graphite plates and block magnets (GPBMSS) was investigated during summer and winter climatic conditions of Coimbatore city (latitude: 11°01'68"N and longitude: 76°95'58"E), in India, 2019. The results observed in GPBMSS were compared with a conventional solar still (CSS) under the same climatic conditions. The outcomes observed that the hourly productivity in GPBMSS was 19.6% and 22.8% higher in summer and winter days, respectively, when compared to CSS. The cumulative productivity in GPBMSS was found to be about 3.93 kg/m² and 3.56 kg/m² respectively, for 12 h observations during summer and winter days. Furthermore, the energy and exergy efficiencies of GPBMSS were substantially improved by 20.6% and 18.1% when compared to CSS during summer days. Similarly, the energy and exergy efficiencies of GPBMSS were increased by 18 and 19% compared to CSS in winter days. In addition, the maximum basin exergy destruction was observed in CSS compared to other solar still components. The results observed that the heat storage ability of the graphite plates and water magnetization in GPBMSS greatly decreased the exergy destructions. Finally, the water quality analysis proved that the distillate collected from both GPBMSS and CSS satisfied the requirements recommended by the Bureau of Indian Standards.

Key words | block magnets, graphite plates, productivity, solar still, thermodynamics

HIGHLIGHTS

● Graphite plates and block magnets are attached in a solar still basin (GPBMSS) and improved the productivity by 3.93 kg/m² and 3.56 kg/m² respectively, in summer and winter climatic days.
● The energy efficiency of GPBMSS was substantially improved by 20.6 and 18%, respectively, compared to CSS during summer and winter days.
● The exergy efficiency in GPBMSS was enhanced by 18.1 and 19%, respectively compared to CSS in summer and winter days.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (http://creativecommons.org/licenses/by/4.0/).

NOMENCLATURE

\( A \)  \hspace{1cm} \text{solar still area, m}^2 \hspace{1cm} a \hspace{1cm} \text{absorptivity} \\
\( C_p \)  \hspace{1cm} \text{specific heat capacity, kJ/kg.K} \hspace{1cm} r \hspace{1cm} \text{transmissivity} \\
\( E \)  \hspace{1cm} \text{energy, W} \hspace{1cm} \eta \hspace{1cm} \text{efficiency} \\
\( E_x \)  \hspace{1cm} \text{exergy, W} \\
\( I(t) \)  \hspace{1cm} \text{solar irradiation, W/m}^2 \\
\( h \)  \hspace{1cm} \text{heat transfer coefficient, W/m}^2 \text{K} \\
\( L \)  \hspace{1cm} \text{latent heat of vaporization, kJ/kg} \\
\( K \)  \hspace{1cm} \text{thermal conductivity, W/mK} \\
\( m \)  \hspace{1cm} \text{hourly productivity, kg} \\
\( P \)  \hspace{1cm} \text{pressure, N/m}^2 \\
\( T \)  \hspace{1cm} \text{temperature, K} \\
\( U \)  \hspace{1cm} \text{overall heat transfer co-efficient, W/m}^2 \text{K} \\
\( v \)  \hspace{1cm} \text{wind velocity, m/s} \\
\( x \)  \hspace{1cm} \text{thickness} \\

Greek symbol \\
\( \varepsilon_{\text{eff}} \)  \hspace{1cm} \text{effective emissivity} \\
\( \sigma \)  \hspace{1cm} \text{Stefan-Boltzmann constant, } 5.67 \times 10^{-8} \text{ W/m}^2 \text{K}^4 \\
\( \tau \)  \hspace{1cm} \text{radiation} \\

Subscripts \\
a \hspace{1cm} \text{atmospheric air} \\
b \hspace{1cm} \text{basin} \\
c \hspace{1cm} \text{convection} \\
ch \hspace{1cm} \text{charge} \\
d \hspace{1cm} \text{destruction} \\
eva \hspace{1cm} \text{evaporation} \\
g \hspace{1cm} \text{glass} \\
ge \hspace{1cm} \text{gained energy} \\
gp \hspace{1cm} \text{graphite plate} \\
ins \hspace{1cm} \text{insulation} \\
mg \hspace{1cm} \text{magnet} \\
o \hspace{1cm} \text{overall} \\
out \hspace{1cm} \text{output energy} \\
r \hspace{1cm} \text{radiation}
In this world, pure water is a fundamental necessity for humans. The increase in industrialization rapidly increases the pure water demand. The rise in human population has also played a vital role in reducing pure water availability in recent times. Many developing countries are facing difficulties in supplying potable water to their people due to the increase in globalization. Even though several water purification techniques such as simple disinfection treatment, reverse osmosis (RO) and the ion exchange process exist, desalination using solar energy is the good option to purify brackish or saline water. The reason behind this is that it has simple working operation with low investment compared to other water purification techniques. The system used for this technique is called a solar still and it can be fabricated using materials that are readily available.

The key benefit of this solar desalination technique is that there is zero fuel cost and no skilled labor is needed. Many studies have been performed on solar stills to enhance the productivity using different heat storage materials. The outcomes proved that the productivity was significantly improved by heat storage materials such as fins, nanoparticles, stones, jute cloths and PCM (Dhivagar & Sundararaj 2018). Rabhi et al. (2017) increased the solar still area by integrating the pin-fin absorber and obtained significantly improved productivity by about 14.5%. In addition, they have used a condenser in a solar still, which results in improved productivity of about 32% compared to CSS. They observed that the thermal efficiency improved with the use of a pin-fin absorber and condenser.

Jani & Modi (2017) used square and circular type fins in a double acting solar still to improve the thermal performance. They reported that the thermal efficiency improved by 26.8% and 54.2%, respectively. They also reported that the reduction in water depth has significant improvement in productivity. Sharshir et al. (2018) found improved productivity using copper oxide and graphite nanoparticles in a solar still basin compared to a simple solar still. They reported that the improvement in productivity was observed to be about 41 and 32%, respectively, for the use of copper oxide and graphite nanoparticles under sunny climatic conditions. Dumka et al. (2019) used sand-filled cotton bags in a solar still basin to enhance the energy efficiency during summer climatic conditions. The experiments were conducted with different masses of sand and compared the outcomes with CSS. They found that the increase in energy efficiency was observed as 31.3% (40 kg) and 28.9% (50 kg), respectively. They also stated that the increase in sand quantity reduced the productivity considerably. Modi & Modi (2019) reported significant improvement in solar still performance when jute and cotton cloths were used in the basin. The outcomes observed in the jute cloth solar still were significantly higher than the results observed in the use of cotton cloth. They also found that the jute cloth solar still increased the productivity to 18% (1 cm depth) and 24.5% (2 cm depth), respectively, compared to cotton cloth solar still. In addition, the lower saline water depth in the solar still basin has a significant role in heightening the productivity. Gnanaraj & Velmurugan (2019) used different types of sensible heat storage materials like fins, granite, wick, reflector and modifications done internally and externally in a double acting solar still and reported the productivity improvement as 58.4%, 69.8%, 42.3%, 93.3% and 171.4%, respectively, compared to CSS. Omara et al. (2020) assessed the productivity improvements in both passive and active solar stills using paraffin wax phase change material during sunny days. They reported that the productivity improved by 120 and 700%, respectively, in both passive and active solar stills under nocturnal observations. The results also reported that paraffin wax has been widely used in many research works. Even though many researchers have used this material, it has poor thermal conductivity compared to other heat storage materials. El-Saida et al. (2020) reported the productivity and thermal efficiency improvements in a tubular solar still using porous packed wire mesh media as 4.2 kg/m² and 34%, respectively, when the results were
compared with CSS. Munoz et al. (2020) reported the thermal efficiency comparison between fiberglass and concrete solar stills under similar climatic conditions. The results confirmed that the fiberglass still has 8% improved thermal performance compared to a concrete still. Panchal et al. (2020) used inclined and vertical fins in a solar still basin and reported that the improvements in productivity were observed as 2.37 kg/m² and 2.32 kg/m², respectively. They also reported that the use of inclined and vertical fins increased the thermal efficiency to 26.7% and 24.1%, respectively. Kabeel et al. (2020) used red bricks (cement-coated) in the basin of a solar still and found that the energy efficiency has improved significantly to 45%. Furthermore, the productivity improvement observed in this proposed model was 38.8% higher than the productivity observed in a double acting solar still. Similarly, Dhivagar et al. (2021) numerically analyzed the parameters in a coarse aggregate assisted solar still using computational fluid dynamics and reported that the productivity performance deviation between experimental and simulation observations was ±14%.

Numerous researchers have concentrated on estimating the energy and exergy efficiencies of solar stills to quantify the heat regeneration and losses. Deniz (2016) found significant improvements in energy and exergy efficiencies of a solar flat plate collector assisted still as 48.1% and 2.76%, respectively, compared to CSS. The results reported that the decrease in water depth improves the productivity significantly. Dumka & Mishra (2018) found a thermodynamic performance improvement in CSS by adding various earth heat storage materials. They reported that the coal powder solar still covered with polythene increased the energy and exergy efficiencies by 5.06 and 76%, respectively, compared to CSS with simple earth oil. Dhivagar & Sundararaj (2019) used a sensible heat storage bed in a coarse aggregate material to improve the thermodynamic performance of CSS. They found that the enhancements in energy and exergy efficiencies were around 28% and 5.5%, respectively. Furthermore, the observed productivity improvement is 11% higher than CSS. Hassan (2019) found the energy and exergy improvements in a parabolic collector assisted solar still as 49.9% and 2.6%, respectively, when compared to CSS. Furthermore, it was reported that the thermodynamic performance observed in an active solar still was significantly higher than in CSS. Sakthivel & Arjunan (2019) reported the energy and exergy efficiency improvements using cotton cloth in a solar still basin during summer climate conditions in Chennai. The results reported that the use of 6 mm thickness in the basin improved the energy and exergy performances by 23.8% and 2.6%, respectively. In addition, the cotton cloth significantly improved the productivity by 24.1% compared to CSS. Similarly, in an extended work, Dhivagar et al. (2020) found the productivity, energy and exergy efficiency improvements in a coarse aggregate assisted solar still by 4.21 kg/m², 32% and 4.7%, respectively, at lower water depth (1 cm). The results confirmed that the improvements in productivity were significantly influenced by basin water depth. Erfan et al. (2020) improved the exergy efficiencies of PV/T collector and PCM assisted double slope solar still by 27 and 2%, respectively, during summer and winter climatic conditions. They also reported that the proposed model has improved productivity of about 10.6% compared to CSS.

Researchers have carried out extensive research on the impact of the rate of evaporation in the basin by adding graphite and magnetic materials. Cai et al. (2009) found that saline water surface tension was significantly minimized using a magnetic field. Amor et al. (2017) reported that magnetization considerably reduced the saline water surface tension by 24%. Wang et al. (2018) reported that the impact of magnetization gave significant improvement in the evaporation rate and also reduced the surface tension. Dumka et al. (2019b) used ferrite ring magnets in a solar still basin and reported that the improvements in productivity were 49.2% higher than for CSS. They also reported that the improved energy and exergy performance was observed as 49.1% and 110.2%, respectively. In a similar work, Dubey & Mishra (2020) used ring magnets and galvanized iron sheet in a solar still basin and reported that the improvement in productivity was observed to be about 21.7%. Furthermore, the improvements in energy and exergy efficiencies were 31.3% and 22.6%, respectively, compared to CSS. Sharshir et al. (2017) used graphite nanoparticles, film cooling and phase change materials in a solar still basin and reported that the improvement in productivity was 73.8% higher than for CSS. Kabeel et al. (2018) used graphite nanoparticles in a solar still basin and reported an improved efficiency of 65.1% for 20% mass concentrations. Kabeel et al. (2019) performed experiments in an evacuated tube collectors assisted solar still with phase change materials. The improvements in productivity and energy efficiency were 21.05% (14.42 kg/m²) and 21.64%, respectively, when compared to CSS. Through this, it is clearly observed that the graphite materials and water magnetization significantly improved the productivity of solar stills.

The literature review above shows that there has been a great deal of experimentation on enhancing the
thermodynamic performance in various solar still configurations. It was found that in order to achieve the productivity improvements, the more important adjustments and modifications were made in the solar still basin. Nevertheless, the work on the solar still also has a gap in the basin using graphite plate and block magnets. Therefore, an experimental work to test the thermodynamic efficiency with the impact of ambient parameters has been performed in summer and winter climatic conditions. The results observed in GPBMSS were compared with CSS. In addition, the water quality parameters of the obtained distillate were checked and compared with BIS.

**EXPERIMENTS**

The experimentations have been carried out in both GPBMSS and CSS under the same climatic conditions during the year 2019.

**Experimental setup**

The schematic views and photographs of GPBMSS and CSS are illustrated in Figure 1. The solar still is fabricated using galvanized iron sheet which has 1.5 mm thick and the entire system area is $0.65 \times 0.78 \, \text{m}^2$. The basin is

---

**Figure 1** | (a) Schematic view of GPBMSS, (b) schematic view of CSS, (c) photographic view of GPBMSS and CSS, (d) graphite plates and block magnets arrangements in basin. (continued.)
attached with 20 graphite plates and 16 block magnets, respectively, and painted black to increase the heat absorption rate during peak sunshine hours. A glass cover of 3 mm thickness is placed over the top surface of the solar still and this has a higher transmissivity of about 0.9 and a lower absorptivity of about 0.05. The solar still angle is kept at 12° according to the latitude of Coimbatore city. In addition, silicon rubbers are used to close the solar still tightly without any vapour losses to the surroundings. The condensate is collected using a collection tray mounted at the bottom of the glass cover. The absorptivity of solar irradiation is maximized by keeping the solar still in the east-west direction. The basin saline water depth is observed at each one-hour interval and a consistent range is maintained. The salt accumulation in the basin is removed regularly.

The dimensions of graphite plates and block magnets are 40 mm × 25 mm × 10 and 100 mm × 25 mm × 5 mm, respectively. It is ideally positioned in the basin to confirm the steady flow of heat transfer and magnetic fields. These graphite plates and block magnets are not only used for saline water heating and magnetization. They can further act as good sensible heat storage material in higher solar irradiations. The thermo-physical properties of graphite plates and block magnets are listed in Table 1.
Instrumentation

The different temperature measuring locations in both GPBMSS and CSS are shown in Figure 1. These temperatures were measured using calibrated thermocouples with an accuracy of ±0.2 °C. A digital temperature indicator was used to connect these thermocouples with a resolution of 0.1 °C. During experimentation, the intensity of solar irradiations was observed using a solar intensity meter (accuracy ±5 W/m²). The fluctuation observed in ambient wind velocity was recorded by a cup-type anemometer (accuracy ±0.1 m/s). A digital Gaussmeter (precision ±1 mT) was used to observe the magnetic field. The hourly productivity was calculated using a collection bottle. The saline water depth was measured by measurement scale. The specifications of measuring instruments are listed in Table 2.

Experimental procedure

The experiments were conducted in both summer and winter climatic conditions during the year 2019. The findings obtained in this study were reported on April 24 (summer day) and November 14 (winter day). Before the experimentations, the saline water was filled in the solar still basin to warm up and achieve the steady state condition. The glass cover top portion was unsoiled, using a smooth cloth to eliminate the accumulation of dust particles, which affects the thermal performance of the entire system. The ambient parameters were measured at one-hour interval from 9:00 hours to 21:00 hours during the experimental observations. Ten experimental trials were made in solar stills to evaluate the correctness of the results. Finally, these results were used to estimate the thermodynamic efficiency of GPBMSS and compared to CSS.

Uncertainty analysis

During the experimentations, the observed uncertainties in all the measuring instruments are evaluated mathematically by the following relation (Holman 2007):

\[ w_r = \left( \frac{\partial R}{\partial x_1} w_1 \right)^2 + \left( \frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left( \frac{\partial R}{\partial x_n} w_n \right)^2 \]  

(1)

Here, the function and total uncertainty are R and \( w_r \), respectively. x and w are independent variables. The uncertainties observed in estimation of energy and exergy efficiencies were ±2.1% and ±1.2%, respectively.

THERMODYNAMIC ANALYSIS

The thermodynamic (energy and exergy) performance in GPBMSS and CSS are estimated using the following mathematical relations. The energy and exergy balance equations of all the solar still components are given in this section.

Energy analysis

According to the first law of thermodynamics, the energy balance equation is estimated by:

\[ E_{in} + E_{ge} = E_{out} + E_{st} \]  

(2)

To perform the energy analysis, the following assumptions are considered and listed below (Dhivagar & Mohanraj 2021):

- The glass cover inclination is negligible.
- The saline water depth is constant.
- The glass cover and insulation are having no specific heat capacity.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Accuracy</th>
<th>Range</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermometer</td>
<td>±0.2 °C</td>
<td>0–100 °C</td>
<td>±0.492</td>
</tr>
<tr>
<td>Thermocouple (K-type)</td>
<td>±0.1 °C</td>
<td>0–200 °C</td>
<td>±0.487</td>
</tr>
<tr>
<td>Digital temperature indicator</td>
<td>±0.1 °C</td>
<td>0–200 °C</td>
<td>±1.195</td>
</tr>
<tr>
<td>Solar intensity meter</td>
<td>±5 W/m²</td>
<td>0–1,000 W/m²</td>
<td>±1.491</td>
</tr>
<tr>
<td>Cup type anemometer</td>
<td>±0.1 m/s</td>
<td>0–15 m/s</td>
<td>±9.712</td>
</tr>
<tr>
<td>Gaussmeter</td>
<td>±1 mT</td>
<td>0.1–2,400 mT</td>
<td>±1.198</td>
</tr>
<tr>
<td>Measuring jar</td>
<td>±10 ml</td>
<td>0–1,000 ml</td>
<td>±9.814</td>
</tr>
</tbody>
</table>
• The solar still model is in quasi-static condition.
• The solar still has no potential, kinetic and chemical impacts.
• The saline water temperature is constant.
• There is no vapor leakage in the solar still.
• The overall heat transfers are linear with temperature.
• During the one hour observation, the forces of all heat transfers are constant.
• The thermo-physical properties of glass cover and saline water are constant.
• The saline water absorptivity is lower and transmissivity is higher.

The basin energy balance is given by (Elango et al. 2015):

\[ \alpha_b T_g I(t)A_b = m_b C_{pb} \frac{dT_b}{dt} + h_c b-w (T_b - T_w) + U_o b-a (T_b - T_a) \]  

(3)

The graphite plate energy balance is estimated by:

\[ \left( \frac{k_{gp}}{x_{gp}} \right) (T_b - T_{gp}) = \left( \frac{k_{ins}}{x_{ins}} \right) (T_{gp} - T_a) + m_{gp} C_p, gp \frac{dT_{gp}}{dt} \]  

(4)

The block magnet energy balance is estimated by:

\[ \left( \frac{k_{mg}}{x_{mg}} \right) (T_b - T_{mg}) = \left( \frac{k_{ins}}{x_{ins}} \right) (T_{mg} - T_a) + m_{mg} C_p, mg \frac{dT_{mg}}{dt} \]  

(5)

The basin with graphite plate and block magnet energy balance is estimated by:

\[ \alpha_b T_g I(t)A_b = m_b C_{pb, gp, mg} \frac{dT_b}{dt} + h_c b-w (T_b - T_w) + \left( \frac{k_{gp}}{x_{gp}} \right) (T_b - T_{gp}) + \left( \frac{k_{mg}}{x_{mg}} \right) (T_b - T_{mg}) \]  

(6)

The saline water energy balance is given by (Elango et al. 2015):

\[ \alpha_w T_g I(t)A_w + h_c b-w (T_b - T_w) = m_w C_p, w \frac{dT_w}{dt} + U_o w-g (T_w - T_g) \]  

(7)

Overall heat transfer coefficient (Elango et al. 2015):

\[ U_o w-g = (h_c w-g + h_{eva} w-g + h_r w-g) \]  

(8)

Convective heat transfer coefficient (Elango et al. 2015):

\[ h_{c, w-g} = 0.884 \left[ T_w - T_g + \frac{(P_w - P_g) T_w + 273}{268, 900 - P_w} \right]^{\frac{1}{2}} \]  

(9)

Here, \( P_g \) and \( P_w \) are:

\[ P_g = \exp \left[ 25.317 - \frac{5, 144}{T_g + 273} \right] \]  

(10)

\[ P_w = \exp \left[ 25.317 - \frac{5, 144}{T_w + 273} \right] \]  

(11)

Evaporative heat transfer coefficient (Elango et al. 2015):

\[ h_{eva w-g} = 0.016 h_c w-g \left( \frac{P_w - P_g}{T_w - T_g} \right) \]  

(12)

Radiative heat transfer coefficient (Elango et al. 2015):

\[ h_r, w-g = \sigma \varepsilon_{eff} [(T_w + 273)^2 - (T_g + 273)^2](T_w + T_g + 546) \]  

(13)

Here,

\[ \varepsilon_{eff} = \frac{1}{\varepsilon_w + \varepsilon_g - 1} \]  

(14)

The glass cover energy balance is given by (Elango et al. 2015):

\[ \alpha_g I(t)A_g + U_o w-g (T_w - T_g) = m_g C_p, g \frac{dT_g}{dt} + (h_c g-sky + h_r g-sky) (T_g - T_{sky}) \]  

(15)

Convective heat transfer coefficient between glass cover and sky (Elango et al. 2015):

\[ h_{c, g-sky} = 2.8 + 3.0 V \]  

(16)

Radiative heat transfer coefficient between glass cover and sky (Elango et al. 2015):

\[ h_{r, g-sky} = \varepsilon_{eff} \sigma \left( T_g^4 + T_{sky}^4 \right) \]  

(17)
The sky temperature is given by (Belyayev et al. 2013):

\[ T_{sky} = 0.0552T_a^4 \]  \hfill (18)

Latent heat of vaporization (Belyayev et al. 2013):

\[
L = 2.4955 \times 10^6 \times \left[ 1 - 9.4779 \times 10^{-4} T_w \right] + 1.3132 \times 10^{-7} \times T_w^2 - 4.794 \times 10^{-9} \times T_w^3
\]  \hfill (19)

The solar still hourly productivity is given by (Belyayev et al. 2013):

\[
m_w = \frac{h_{eva} (T_w - T_a) \times 3600}{L}
\]  \hfill (20)

Solar still energy efficiency (Belyayev et al. 2013):

\[
\eta_{E, ss} = \frac{m_w \times L}{A_{ss} \times \sum (I_{ss}) \times 3600}
\]  \hfill (21)

The theoretical calculations are solved using C program and are mentioned in the appendix.

**Exergy analysis**

The second law of thermodynamics estimates the energy losses (exergy) in both the GPBMSS and CSS. The general exergy balance equation is given by:

\[ Ex_d = Ex_{in} - Ex_{out} \]  \hfill (22)

To estimate the exergy efficiency, the following equations are used (Hepbalsi 2006):

\[
Ex_{out} = Ex_{eva} = \frac{\sum m_w \times L \times \left( \frac{T_a + 273}{T_w + 273} \right)}{3600}
\]  \hfill (23)

\[
Ex_{in} = Ex_s = A_{ss} \times \sum I_s \\
\times \left[ 1 - \frac{4}{3} \times \left( \frac{T_a + 273}{T_s} \right) + \frac{1}{3} \times \left( \frac{T_a + 273}{T_s} \right)^4 \right]
\]  \hfill (24)

\[
\eta_{Ex} = \frac{\sum Ex_{eva}}{\sum Ex_s}
\]  \hfill (25)

**Basin exergy destructions**

The basin exergy destruction is given by (Piyush et al. 2018):

\[
Ex_{d,b} = (h_e \times h_w \times \alpha_b)Ex_s - (Ex_{b,s} + Ex_{ins})
\]  \hfill (26)

Here, \(Ex_{b,s}\) and \(Ex_{ins}\) are given by following equations:

\[
Ex_{b,s} = h_{c,b} \times (T_b - T_a) \times \left( 1 - \frac{T_a}{T_b} \right)
\]  \hfill (27)

\[
Ex_{ins} = h_{c,b} \times (T_b - T_a) \times \left( 1 - \frac{T_a}{T_b} \right)
\]  \hfill (28)

**Graphite plate exergy destructions**

The graphite plate exergy destruction is estimated by the following equations:

\[
Ex_{d,gp} = Ex_s + Ex_{st} - Ex_{t,gp-a}
\]  \hfill (29)

The stored exergy is given by:

\[
Ex_{st} = Q_{ch} \left( 1 - \frac{T_a}{T_{gp}} \right)
\]  \hfill (30)

\[
Q_{ch} = m_{gp}C_p \frac{dT_{gp}}{dt}
\]  \hfill (31)

The total exergy destruction between graphite plate and ambient air is given by:

\[
Ext_{gpa} = Ex_{c,gpa} + Ex_{r,gpa}
\]  \hfill (32)

Here,

\[
Ex_{c,gpa} = h_{c,gpa} \times (T_{gp} - T_a) \left( 1 - \frac{T_a}{T_{gp}} \right)
\]  \hfill (33)

\[
Ex_{r,gpa} = h_{r,gpa} \times (T_{gp} - T_a) \left( 1 + \frac{1}{3} \left( \frac{T_a}{T_{gp}} \right)^4 - \frac{4}{3} \left( \frac{T_a}{T_{gp}} \right) \right)
\]  \hfill (34)

**Block magnets exergy destructions**

The block magnets exergy destruction is estimated by following equations:

\[
Ex_{d,mg} = Ex_s + Ex_{t,mg-a}
\]  \hfill (35)
The stored exergy is given by:

\[ Ex_{st} = Q_{ch} \left( 1 - \frac{T_a}{T_{mg}} \right) \]  
(36)

\[ Q_{ch} = m_{mg} C_{p,mg} \frac{dT_{mg}}{dt} \]  
(37)

Total exergy destruction in block magnets and atmosphere:

\[ Ex_{t,mg-a} = Ex_{c,mg-a} + Ex_{r,mg-a} \]  
(38)

Here,

\[ Ex_{c,mg-a} = h_{c,mg-a}(T_{mg} - T_a) \left( 1 - \frac{T_a}{T_{mg}} \right) \]  
(39)

\[ Ex_{r,mg-a} = h_{r,mg-a}(T_{mg} - T_a) \left( 1 + \frac{1}{3} \left( \frac{T_a}{T_{mg}} \right)^4 - \frac{4}{3} \left( \frac{T_a}{T_{mg}} \right) \right) \]  
(40)

**Exergy destructions in basin with graphite plates and block magnets**

The exergy destruction in the basin with graphite plates and block magnets is estimated by:

\[ Ex_{d,bp-mg} = (\alpha_b \times \alpha_a \times \alpha_b) Ex_s - (Ex_{b-wg} + Ex_{b-gp-mg}) \]  
(41)

Here, \( Ex_{b-gp-mg} \) is given by the following equation:

\[ Ex_{b-gp-mg} = \left( \frac{k_w}{\lambda_{gp}} \right) (T_b - T_{gp}) \times \left( 1 - \frac{T_a}{T_b} \right) \]
\[ + \left( \frac{k_{mg}}{\lambda_{mg}} \right) (T_b - T_{mg}) \times \left( 1 - \frac{T_a}{T_b} \right) \]  
(42)

**Saline water exergy destructions**

The exergy destruction in saline water is estimated by:

\[ Ex_{d,w} = (\alpha_w) Ex_s \]  
(43)

\[ Ex_{b-wg} = Ex_{b-wg} \]  
\[ Ex_{t,w-g} = Ex_{t,w-g} \]  
(44)

The exergy destruction in heat transfers are estimated by (Dhivagar & Mohanraj 2021b):

\[ Ex_{eva w-g} = h_{eva, w-g}(T_w - T_a) \left( 1 - \frac{T_a}{T_w} \right) \]  
(45)

\[ Ex_{c w-g} = h_{c, w-g}(T_w - T_a) \left( 1 - \frac{T_a}{T_w} \right) \]  
(46)

\[ Ex_{r w-g} = h_{r, w-g}(T_w - T_a) \left[ 1 + \frac{1}{3} \left( \frac{T_a}{T_w} \right)^4 - \frac{4}{3} \left( \frac{T_a}{T_w} \right) \right] \]  
(47)

**Glass cover exergy destructions**

The exergy destruction in the glass cover is estimated by:

\[ Ex_{d,g} = \alpha_g Ex_s + Ex_{t,g-w} - Ex_{t,g-a} \]  
(48)

Total exergy destruction in glass cover and atmosphere:

\[ Ex_{t,g-a} = Ex_{c,g-a} + Ex_{r,g-a} \]  
(49)

Here,

\[ Ex_{c,g-a} = h_{c, g-a}(T_g - T_a) \left( 1 - \frac{T_a}{T_g} \right) \]  
(50)

\[ Ex_{r,g-a} = h_{r, g-a}(T_g - T_a) \left[ 1 + \frac{1}{3} \left( \frac{T_a}{T_g} \right)^4 - \frac{4}{3} \left( \frac{T_a}{T_g} \right) \right] \]  
(51)

The radiation and thermo-physical properties of solar still materials are listed in Table 3

**RESULTS AND DISCUSSION**

The observed results in GPBMSS and CSS experimentations are discussed in this section. The comparative analysis has been made in both summer and winter climatic conditions.

**Experimental observations**

Figure 2 depicts the variations of solar irradiation and wind velocity during the summer and winter days. The observed maximum solar irradiation in morning to afternoon hours were about 925 W/m² and 804.1 W/m² respectively,
Table 3 | The radiation and thermo-physical properties of solar still materials (Belyayev et al. 2019):

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorptivity in glass cover ($\alpha_g$)</td>
<td>0.05</td>
</tr>
<tr>
<td>Absorptivity in saline water ($\alpha_w$)</td>
<td>0.05</td>
</tr>
<tr>
<td>Absorptivity in basin ($\alpha_b$)</td>
<td>0.9</td>
</tr>
<tr>
<td>Saline water mass ($m_w$)</td>
<td>20.5 kg/m²</td>
</tr>
<tr>
<td>Glass cover mass ($m_g$)</td>
<td>10.1 kg/m²</td>
</tr>
<tr>
<td>Mass of basin ($m_b$)</td>
<td>15.6 kg/m²</td>
</tr>
<tr>
<td>Mass of graphite plate ($m_{gp}$)</td>
<td>12.01 kg/m²</td>
</tr>
<tr>
<td>Mass of magnets ($m_{mg}$)</td>
<td>0.032 kg/m²</td>
</tr>
<tr>
<td>Transmissivity in saline water ($\tau_w$)</td>
<td>0.95</td>
</tr>
<tr>
<td>Transmissivity in glass cover ($\tau_g$)</td>
<td>0.9</td>
</tr>
<tr>
<td>Specific heat of saline water ($C_{pw}$)</td>
<td>4.178 kJ/kg.K</td>
</tr>
<tr>
<td>Specific heat of glass cover ($C_{pg}$)</td>
<td>0.8 kJ/kg.K</td>
</tr>
<tr>
<td>Specific heat of basin ($C_{pb}$)</td>
<td>0.48 kJ/kg.K</td>
</tr>
<tr>
<td>Specific heat of graphite plate ($C_{pgp}$)</td>
<td>0.72 kJ/kg.K</td>
</tr>
<tr>
<td>Specific heat of magnet ($C_{p, mg}$)</td>
<td>0.36 kJ/kg.K</td>
</tr>
<tr>
<td>Effective emissivity ($\varepsilon_{eff}$)</td>
<td>1</td>
</tr>
<tr>
<td>Sun temperature</td>
<td>6,000 K</td>
</tr>
<tr>
<td>Thermal conductivity of basin ($k_b$)</td>
<td>16.3 W/m² K</td>
</tr>
<tr>
<td>Thickness of basin ($x_b$)</td>
<td>0.002 m</td>
</tr>
<tr>
<td>Thermal conductivity of water ($k_w$)</td>
<td>0.57 W/m² K</td>
</tr>
<tr>
<td>Thickness of water ($x_w$)</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Thickness of graphite plate ($x_{gp}$)</td>
<td>0.025 m</td>
</tr>
<tr>
<td>Thickness of magnets ($x_{mg}$)</td>
<td>0.025 m</td>
</tr>
<tr>
<td>Thermal conductivity in insulation material ($k_{ins}$)</td>
<td>0.039 W/m² K</td>
</tr>
<tr>
<td>Thickness of insulation ($x_{ins}$)</td>
<td>0.03 m</td>
</tr>
<tr>
<td>Heat transfer coefficient in basin and saline water ($h_{c, b-w}$)</td>
<td>135 W/m² K</td>
</tr>
<tr>
<td>Overall heat transfer coefficient in basin and atmosphere ($U_{b-a}$)</td>
<td>14 W/m² K</td>
</tr>
</tbody>
</table>

during summer and winter days. It decreased to 30–18.7 W/m² during the evening hours in both summer and winter climatic conditions. Although the sunshine period was found to be around 12 hours during the daytime, the successful sunshine availability (more than 250 W/m²) for the experiment was only about 8–10 hours. It is also observed that the fluctuation in ambient wind velocity was very effective with respect to time. In order for this, the temperature of the glass cover has decreased, which results in higher condensation. The maximum wind velocities of about 2.9 m/s and 2.8 m/s were observed at 17:00 hours in both summer and winter days. The variation between the ambient wind velocities were observed to be about 1.6 m/s and 2.9 m/s during experiments.

The variations of different temperatures during the summer and winter days are illustrated in Figure 3. During summer days, the ambient temperature increases in afternoon hours (14:00 hours) and attains the maximum of about 39.8 °C. During evening hours, it was reduced to around 25 °C as solar irradiation decreased. Similarly, during winter days, the observed maximum and minimum ambient temperatures were 38.2 °C and 25.7 °C, respectively. The maximum glass cover temperature of about 52.3 °C was observed in afternoon hours and decreased slowly to 30.1 °C during summer days. Similarly, the observed maximum and minimum glass cover temperatures were 51.2 °C and 29 °C in winter days. It was observed that the graphite plates and block magnet temperatures increased in noon hours and reached 70.2 °C and 68.5 °C, respectively during summer days. In night hours (21:00
hours), the temperature observed in graphite plates and block magnets fell to 41.4 °C and 40.1 °C, respectively. Similarly, during the winter days, the maximum temperatures observed in graphite plates and block magnets were 69.1 °C and 65.8 °C, respectively. During 21:00 hours, it dropped to 39.4 °C and 38.1 °C, respectively. It is known that, compared to the impact of block magnets, the graphite plates had the greater heat absorption and heat storage capacity. Graphite plate heat storage capacity was 2.4% and 4.7% higher than the block magnets' heat storage capacity in summer and winter days. However, the usage of graphite plates and block magnets in basin has improved the temperatures significantly. During summer days, the maximum observed water temperature in GPBMSS and CSS were about 67.4 °C and 55.1 °C, respectively. In winter days, the maximum water temperature in GPBMSS and CSS were 64.2 °C and 53.3 °C respectively. The reason behind the improvements of water temperature in GPBMSS is the heat storage capacity of graphite plates and magnets in the basin. During the experimentation, the heat accumulated in graphite plates and block magnets are stored and released during off sunshine hours. The observed saline water temperature in GPBMSS was 18.2% and 16.9% higher than CSS in summer and winter days. The average saline water temperature in GPBMSS was 16.3% and 17.1% higher than CSS during summer and winter days. Finally, it is clearly observed that the usage of graphite plate and block magnets in solar still basin have significantly improved the saline water temperature (Balachandran et al. 2019).

The variations of evaporative and convective heat transfer coefficients during the summer and winter days are depicted in Figure 4. During summer days, the observed maximum evaporative heat transfer rate of GPBMSS and CSS were about 27.3 W/m²K and 18.1 W/m²K respectively, at 14.00 hours. In winter days, the maximum evaporative rate of GPBMSS and CSS were found to be around 26.1 W/m²K and 17.5 W/m²K, respectively. The evaporative heat transfer rate of GPBMSS was 33.6% (summer days) and 32.9% (winter days) higher than CSS. The average evaporative heat transfer rate of GPBMSS has been significantly enhanced by 39.7% and 41.5% compared to CSS during summer and winter days. It happens due to heat energy accumulated in graphite plates and block magnets in the solar still basin. Finally, it is confirmed that, the magnetization of water enhances the evaporation rate as confirmed in the literature (Wang et al. 2018). In summer days, the observed maximum convective heat transfer rate of GPBMSS and CSS were 2.01 W/m²K and 1.46 W/m²K, respectively. During winter days, the maximum convective heat transfer coefficient of GPBMSS and CSS were observed to be about 1.98 W/m²K and 1.44 W/m²K, respectively. The difference in the convective heat transfer rate of the both GPBMSS and CSS were 0.55 W/m²K (summer days) and 0.54 W/m²K (winter days) during noon hours. From this, the observed convective heat transfer rate of GPBMSS was 27.3% and 27.2% higher than CSS during summer and winter days. The average convective heat transfer rate of GPBMSS has been significantly enhanced by 27.9% (summer days) and 29.2% (winter days) than CSS. This enhancement confirmed that, there is a good variation in the saline water density and surface tension when graphite plates and block magnets are used in basin (Amor et al. 2017).

Evaluation of theoretical observations

The energy balance equations of the solar stills were theoretically solved using the fourth order Runge-Kutta method and a numerical algorithm was developed using C language. The initial conditions of all the solar still components were assumed to be at ambient temperature conditions. Convective, radiative heat transfer coefficients and temperatures in various regions of solar stills were calculated using physical properties. The predicted theoretical productivity in summer and winter climatic days are compared with experimental productivity and illustrated in Figure 5(a). It is observed that the theoretical evaluated productivity values followed the same pattern observed in experimental productivity with the maximum deviations of ±8%. 

Figure 4 | Variations of evaporative and convective heat transfer coefficients during the summer and winter days.
Productivity performance

Figure 5 depicts the hourly, cumulative and monthly average productivity of GPBMSS and CSS during the summer and winter days. The maximum evaporation process in both the solar stills were observed during the afternoon hours (13.00–15.00 hours) in both summer and winter days. In Figure 5(a), during summer and winter days, the maximum productivity observed in GPBMSS and CSS were 610 and 570 ml, respectively. It happens due to increase in evaporation process with the heat harvested in graphite plates and block magnets in the solar still basin. In addition, it occurs due to temperature difference between the inner glass cover and surface of saline water. In CSS, the enhanced productivity of about 490 ml (summer days) and 440 ml (winter days) were collected with the low saline water temperature. The observed productivity in GPBMSS was 19.6% and 22.8% higher than CSS during summer and winter days. The average productivity in GPBMSS was 23.8% (summer days) and 25.9% (winter days) higher than CSS. The GPBMSS has 39.4% and 31.1% (summer and winter days) of productivity improvements than the earlier work reported in solar still using graphite nano-particles and phase change materials (Kabeel et al. 2019). In Figure 5(b), during summer times, the cumulative productivity of both GPBMSS and CSS were about 3.93 kg/m² and 2.54 kg/m², respectively. Similarly, in winter times, the cumulative productivity of the GPBMSS and CSS were observed to be about 3.56 kg/m² and 2.24 kg/m², respectively. In Figure 5(c), in monthly average productivity, it is noticed that the maximum productivity was observed during April (summer) and November (winter) months, respectively.

Energy and exergy performance

Figure 6 illustrates the energy efficiency of GPBMSS and CSS during the summer and winter days. From this, the observed maximum energy efficiency in GPBMSS was found at noon hours. Energy efficiency of both the solar
stills were increased with increase in saline water temperature. The maximum energy efficiency in GPBMSS and CSS were about 29.1% and 23.1%, respectively, during summer days. Similarly, the maximum energy efficiency of the GPBMSS and CSS were observed to be about 27.1% and 22.2%, respectively during winter days. The energy efficiency observed in GPBMSS was 20.6% (summer days) and 18% (winter days) significantly enhanced compared to CSS. In exergy efficiency, it is noticed that the exergy performance is enhanced during the morning to noon hours for both the solar stills. The maximum exergy efficiency of the both GPBMSS and CSS were about 4.4% and 3.6%, respectively, during summer days. Similarly, the maximum exergy efficiencies of the GPBMSS and CSS were observed to be about 4.2% and 3.4%, respectively, during winter days. It is also observed that the exergy performance of GPBMSS was 18.1% (summer days) and 19% (winter days), significantly higher than CSS. The average exergy efficiency of GPBMSS was also 18.7% and 21.4% maximum compared to CSS during summer and winter days.

Figure 7 illustrates the exergy destructions of both the solar stills during summer and winter days. In Figure 7 (a), the exergy destruction observed in the basin was comparatively higher than the exergy destruction observed in the saline water. In summer and winter days, the exergy destruction observed in the GPBMSS basin was 6.9% (674.2 W/m²) and 6.1% (621.4 W/m²) lower than CSS during 14.00 hours. Similarly, during noon hours, the exergy destruction observed in GPBMSS saline water was 16.2% (68.2 W/m²) and 13.9% (59.5 W/m²) lower than CSS in summer and winter days. Finally, it is observed that the usage of graphite plates and block magnets in the solar still basin has significantly minimized the exergy destruction compared to CSS (Dumka et al. 2019b).

In Figure 7(b), during summer days, the exergy destruction observed in the glass cover, graphite plates and block magnets reached the maximum of about 46.3 W/m², 134.2 W/m² and 26.4 W/m² respectively. Similarly, in winter days, the exergy destruction observed in the glass cover, graphite plates and magnets attained the maximum of 36.4 W/m², 120.1 W/m² and 22.3 W/m² respectively. The exergy destruction observed in the graphite plate was 80.3% and 74.8% higher than the exergy destruction observed in block magnets during summer and winter days. The average exergy destruction in the graphite plate was 84.5% (summer days) and 79.2% (winter days) higher than block magnets.

**Distillate analysis**

Two samples of saline water and distillate collected in summer and winter days were checked in chemical
laboratory for the analysis of water quality parameters. The results of pH, hardness, alkalinity, chloride and fluoride concentration are listed in Table 4. The observed values are compared with the required level recommended by BIS. It is seen that all the required water quality parameters of distillate are of acceptable values given by BIS. The distillate collected from this GPBMSS and CSS is maximum suitable for drinking when the required minerals are added.

CONCLUSIONS

The experimentation was conducted in GPBMSS to heat and magnetize the saline water in a basin during the summer and winter days. This results in significantly improved convective and evaporative heat transfer rates. The observed results are compared with CSS. The following main conclusions are drawn:

(a) The observed heat transfer coefficients in GPBMSS are comparatively higher than CSS. During summer days, GPBMSS has improved average evaporative and convective heat transfer coefficients of 39.7% and 41.5%, respectively, compared to CSS. Similarly, the maximum observed average evaporative and convective heat transfer coefficients in GPBMSS were 27.9% and 29.2%, respectively, higher than CSS during winter days. The maximum observed average productivity in GPBMSS was 23.8% and 25.9%, respectively, higher than CSS during summer and winter days.

(b) The energy efficiency in GPBMSS has improved by 20.6 and 18%, respectively, compared to CSS on summer and winter days. The exergy efficiency in GPBMSS has enhanced to 18.1 and 19%, respectively, compared to CSS during summer and winter days. In summer days, the maximum observed exergy destruction in basin, saline water and glass cover were 724.1 W/m², 81.4 W/m² and 46.3 W/m², respectively in CSS. During winter days, the highest observed exergy destruction in basin, saline water and glass cover were 675.5 W/m², 75.2 W/m² and 36.4 W/m², respectively, in CSS. The GPBMSS has significantly minimized the exergy destructions of basin and saline water compared to CSS.

(c) The observed maximum exergy destruction in graphite plate and block magnets were 134.2 W/m² and 26.4 W/m², respectively during summer days. Similarly, the observed highest exergy destruction in graphite plates and block magnets were 120.1 W/m² and 22.3 W/m², respectively during winter days.

(d) Finally, the distillate observed from GPBMSS and CSS has met the quality level recommended by BIS.

FUTURE SCOPE

The performance analysis of single slope solar still using graphite plates and magnets have gaps in evaluating the impact of dust accumulation on the glass cover and its shadowing effects.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Amor, H. B., Elaoud, A., Salah, N. B. & Elmoueddeb, K. 2017
Improvising the efficiency of single sloped solar still using


First received 5 February 2021; accepted in revised form 12 April 2021. Available online 22 April 2021