Performance assessment of double Slope Solar Still with Pebbles & Cooling water jacket for performance enhancement

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Abstract

The unavailability of fresh drinking water can sometimes compel people to drink unclean water which causes illnesses and other health issues. This research work aims to develop & study a cost-efficient desalination technique employing thermal energy of solar irradiance. This device popularly known as passive solar still has been studied for a district in Jaipur, India for three solar still configurations i.e., 1) Conventional double slope solar still; 2) Still incorporating Pebbles as naturally available energy storage material & 3) cooling water jacket for glass cover for higher clean water production. Along with the experimental work, Energy & Exergy efficiency calculations were also performed for the entire system. In this study it has been concluded that the double slope solar still incorporating water cooling jacket for glass cover resulted in highest water production, Energy & exergy efficiency followed by still with Pebbles & conventional solar still. The total water yield for the above configurations being 1.9, 2.3 and 2.9 Liters respectively.

Keywords: Solar Desalination, Solar Thermal Power, cost efficient, Double Slope Solar Still, Energy Storage Material.

1. Introduction

Clean water is one of the basic necessities of different lifeforms to survive on the planet. In fact, scarcity of water also affects food, livestock management, industries etc. The demand for this resource has escalated over time due to the increase in population & growth in different sectors like agriculture & industries. Often direct use of this resource is not advisable due to the presence of harmful organisms or high TDS. Out of the various methods available such as reverse osmosis, fossil fuel based thermal desalination etc., most of these are highly energy intensive and expensive (Kariman et al., 2023). Hence a need for an alternative solution is generated for production of clean water at very low cost following a simple process.

Passive Solar Desalination technique using a solar still is a promising solution as it is cheap & follows a simple process of evaporation and condensation utilizing solar thermal power. Solar still is a simple device that can be used to convert saline, brackish water into potable water (Tarazona-Romero et al., 2022) . The construction of a solar still comprises of a basin containing brackish water covered with a transparent media such as glass (Murugavel et al., 2010). The solar irradiance when passing through transparent cover, is absorbed by water & basin which increases the temperature of brackish water inside the still due to greenhouse effect. This gives water enough thermal energy to evaporate in a saturated state at a slow rate leaving behind the impurities and rising towards Transparent cover. Once encountering the inner side of cover, due to temperature difference between water vapor and glass cover, the water vapor condenses on the inner side of glass cover. This condensed water then flows along the inner surface of glass cover due to gravity and is collected in a collection tank via a drainage channel. This clean water can be used directly without the need for any further treatment. An important point to keep in mind is that this type of setup can be easily fabricated using locally available materials without the need for any fabrication expertise.

In India, many areas of Gujarat, Rajasthan & Haryana have been facing a problem of freshwater scarcity. Luckily these areas are blessed with ample solar irradiance which can be utilized to desalinate salty ground water. Findings of one such study conducted by (Khanna et al., 2008) for Chui, a remote village of Rajasthan reported that people

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of this village have been facing a lot of difficulty getting a fresh water source. A water sample testing done at Guru Kripa Test House; district of Ajmer revealed that quality of drinking water is not appropriate. The author's findings also indicate that the local people of this village were optimistically looking for a low-cost water purification device which can fulfill the basic water demands. Conventional desalination methods such as reverse osmosis, multistage flash and electro-dialysis are expensive and use conventional energy sources which negatively pollute the environment. Application of solar stills in India stands a good chance of success due to availability of both solar irradiance and need for fresh water at low cost.

Some of the known development cases of Solar distillation in India include installation of first solar based distillation plant by Central Salt and Marine Chemical Research Institute (CSMCRI) in Bhavnagar to supply drinking water in Awania village and Chhachi lighthouse in 1978 (Natu et al., 1979). This facility consists of 90 stills each having an evaporation surface area of 20.74 m^2. With a production capacity of 5000L per day. After regular use of desalinated water, residents of this village understood the quality difference between desalinated water & water available in ponds/wells. Although Solar still are of great advantage they also require regular cleaning due to accumulation of salts which settle down during desalination process. Also, the production capacity of such systems is very low hence such systems are generally uneconomical for mass adoption. Recently a lot of work has been carried out to enhance the water yield of a solar still.

It has been established that air or water flow over still cover enhances the productivity of still. This is because when cover temperature drops, it creates higher temperature difference between saturated water & condensing surface (Dimri et al., 2008, Dutt et al., 1993). Efforts were made to understand the effect of cover slope angle on still productivity, it was realized that for locations with latitude higher than 20◦, single-sloped stills were found preferable whereas for lower latitudes, double-sloped stills facing north and south directions and having a cover inclination equal to the latitude angle received near normal sun rays throughout the year (Murugavel et al., 2008). Studies for brine depth for still suggested that higher outputs and efficiencies occur at lower depths of brine (Badran, 2007, Tiwari & Tiwari, 2007). (Kalidasa Murugavel et al., 2008, Tripathi & Tiwari, 2005) reported that productivity of still is inversely proportional to brine depths for daytime but for nighttime the reverse is true. This inverse effect was attributed to the energy storage effects of brine during nighttime. The productivity of solar stills can also be enhanced by utilizing phase change materials. (Ayoub & Malaeb, 2012) in their work have integrated a thin layer of stearic acid beneath basin as Phase change material. During the day, PCM charges up and release this same energy during night, hence extending the evaporation duration even in night until next day morning. Although daytime productivity of still dropped a little but overall productivity for entire duration of working increased significantly.

The objective of the present work is to fabricate and analyze a cost-efficient double slope solar still utilizing naturally available pebbles as sensible heat storage material and water jacket for cooling of glass cover to enhance yield of potable water. All three different configurations have been studied for their water output for a water depth of 2cm in basin. An additional attempt has been made to analyze theoretical energy and exergy efficiency of all still configurations. The obtained results have then been compared. Energy & Exergy values have been determined for temperature values starting from 08:00 hr. to 17:00 hr. While the total water output has been determined for a period of 24hrs, entire duration of operation.

2. Location, Materials and Method

As various designs have been explored by researchers for solar still optimization and analysis, for the present work, a single basin double slope solar still is fabricated for the investigation of all the proposed configurations. As many previous research works are based on methods which generally increase the unit cost of water yield. The solar still configurations selected for this study are such that it keeps the unit cost of water yield very low while enhancing the yield greatly.

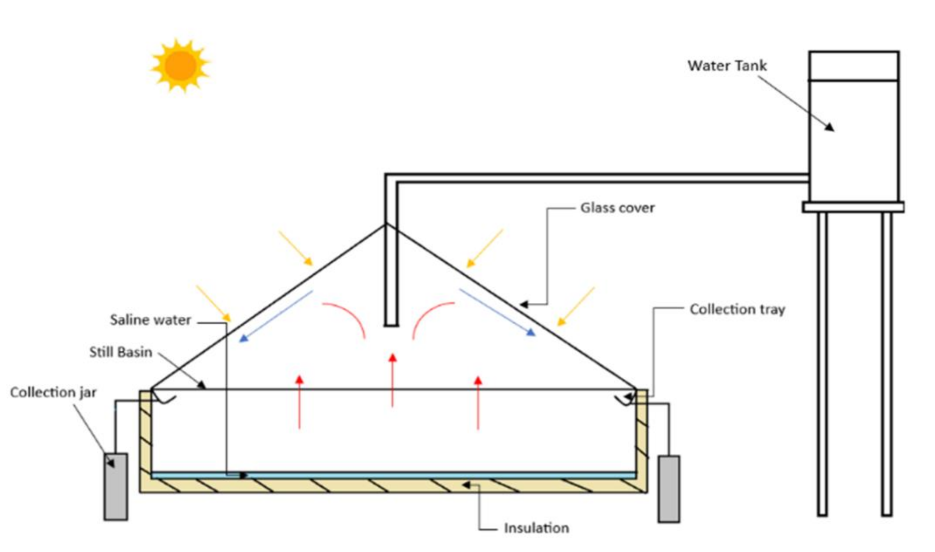


Figure 1: Schematic diagram of Double Slope, single basin passive solar still showing working mechanism.

The schematic diagram shown in Fig.1 showcases the solar still design and its working mechanism. Generally, such systems consist of common components such as basin, transparent cover such as glass, collection tray, collection tanks and refill tank to maintain saline water level in basin. The working mechanism of this system is such that upon the incidence of solar irradiation onto the transparent cover, the irradiance gets transmitted to the basin. This increases the internal temp of solar still due to which the water molecules at the surface, start to show slower rates of evaporation. The water vapor produced flows and get accumulated on to the inner surface of glass cover where vapor loses its latent heat of vaporization and gets converted to liquid which then flows along the inner surface of glass cover to collection tray and then to collection tank for use. Saline water treated in such a manner can be used directly without any requirement of further treatment.

Figure 2: A photograph of double-slope, passive solar still (MUJ, Jaipur, India)

The orientation of solar still is in a manner that tilted glass covers face north-south direction (vertical side glasses face east-west direction) so that both the glass covers receive similar irradiance. Also, the basin liner was painted black for maximum absorption of solar irradiance. As not many studies are available for the Indian state of Rajasthan, the experimental work has been performed for a district of Jaipur, Rajasthan (India). The designed solar still is presently operational and maintained by the Department of Mechanical Engineering at Manipal University, Jaipur. The climatic and operational parameters considered for this study are for Jaipur (26.8439° N, 75.5652° E) as mentioned in the Table. 3, 4 &5.

Table 3: Climatic specifications for double slope solar still.

Time	G_s (W/m^2)
08:00	352
09:00	569
10:00	730
11:00	852
12:00	922
13:00	925
14:00	861
15:00	738
16:00	558
17:00	358

Table 4: passive solar still materials specification.

Component	Material
Transparent cover	Glass
Basin	Aluminum, (grade- 6082)
Insulation	Glass wool
Collection tray	PVC
Tanks	10 L, HDPE container
Stands	Mild steel
Energy storage material	Pebbles
Thermocouples	K-type

Table 5: Design specifications of passive solar still.

Parameter	Value
Glass cover tilt angle from horizontal, θ	45°
Glass cover thickness	0.003 m
Basin dimension	0.9 m × 0.9 m × 0.2 m
Area of basin, A_b	0.81 m^2
Thickness of basin	0.003 m
Insulation thickness	0.01 m
Thermal conductivity of insulation material (Hung Anh & Pásztory, 2021)	0.03 W/m-K
Depth of brine in basin, d	0.02 m
Latent heat of vaporization, h_{fg} (Ranjan et al., 2016)	2260 × 10^3 J/Kg

For the research work proposed in this article, the assumptions considered for energy and exergy analysis are as mentioned below:

(i) The double slop solar still with 'θ' tilt angle (with horizontal) operates in a quasi-static (steady) state.
(ii) Incident solar irradiance is uniform throughout the transparent cover.
(iii) No temperature gradients across any component of solar still (except glass cover) and saline water.

(iv) Material composition is uniform throughout for all components of still.
(v) Solar still is water and vapor leak proof.
(vi) Heat transfer coefficient being temperature dependent.
(vii) Temperature difference in inner and outer glass cover temperature ($T_{gi} \neq T_{go}$).
(viii) Heat leakages have been neglected.
(ix) Saline water level is maintained in still at a constant level throughout the experiment.
(x) Saline water properties considered are like water for simplification of calculations.
(xi) Phenomena of reflection and absorption of solar irradiance due to glass cover have been neglected.

The solar still configurations under study for the present work are 1) conventional solar still, 2) solar still with pebbles and 3) solar still with cooling water jacket for glass cover. The conventional solar still consists of common parts like basin glass cover, tank etc. as described previously. This is the most common design, and its results will be used as datum values for comparison. The second configuration of solar still incorporates pebbles (as thermal energy storage material). While these pebbles are naturally available and very cheap, the role of pebbles here is to act as thermal energy storage medium to extend the time-period for desalination. Utilization of pebbles also keeps the cost of production very low. The third configuration utilizes a cooling water jacket to lower the glass cover temperature.

3. Expression for theoretical productivity, energetic and exegetic efficiency of solar still.

A very important aspect of any solar-based system is its efficiency. With lower system efficiencies, lower amounts of distillate are produced for any solar still. Energy analysis is often employed to study the system energy efficiency which also helps in determination of distillate output (Ranjan et al., 2016). A drawback of this approach is that as energy analysis is based on the first law of thermodynamics, it only gives an estimate of the qualitative aspects of the system. To have a thorough understanding of the system losses, exergy analysis is performed (Singh et al., 2000). Being based on the second law of thermodynamics, this tool gives true estimate of system losses along with its location. The principles of energy and exergy can be utilized to fabricate effective solar stills with reduced irreversibility's hence giving highest distillate output per unit cost of production (Vaithilingam et al., 2021). As there are not many papers available utilizing exergy technique for passive solar still. An attempt has been made to utilize these complementary thermodynamic tools and validate the different configurations of double slope solar still proposed in this work.

Given below is the expression for hourly distillate output (m_d) for passive solar still (Kg/m^2-h) (Aghaei Zoori et al., 2013, Yousef et al., 2017):

$$\mathrm{m_d} = \frac{\mathrm{h_{e,w-g}} \times (\mathrm{T_w} - \mathrm{T_{gi}})}{\mathrm{h_{fg}}} \times 3600 \qquad \text{(eq. 1)}$$

Here $h_{e,w-g}$ (W/m^2-K) is the evaporative heat transfer coefficient between inner glass cover and saline water and h_{fg} (J/Kg) is the latent heat of vaporization of water.

The expression for thermal energy efficiency on hourly basis of passive solar still can be regarded as the ratio of energy available in distillate output to input solar irradiance (Aghaei Zoori et al., 2013, Yousef et al., 2017)

$$\eta_{en} = \frac{m_d \times h_{fg}}{G \times 3600} \qquad \text{(eq. 2)}$$

Where, m_d is the hourly distillate output (Kg/m^2-h) and G is global solar irradiance (W/m^2).

The exergy efficiency of a solar still can be regarded as the ratio of desired solar still output exergy to input exergy efficiency single slope solar still (Kumar & Tiwari, 2011, Yousef et al., 2017)

$$\eta_{ex} = \frac{E_{x_{e,w-g}}}{E_{x_{sun}}} \qquad \text{(eq. 3)}$$

While the equations for $E_{x_{e,w-g}}$ and $E_{x_{sun}}$ are as follows:

$$E_{x_{e,w-g}} = h_{e,w-g} \times A_b \times (T_w - T_{g_i}) \times \left(1 - \frac{T_a+273}{T_w+273}\right) \quad \text{(eq. 4)}$$

$$E_{x_{sun}} = A_g \times G_s \times [1 + \frac{1}{3}\left(\frac{T_a+273}{6000}\right)^4 - \frac{4}{3}\left(\frac{T_a+273}{6000}\right)] \quad \text{(eq.5)}$$

4. Results and discussion

The focus of investigation for this study is to analyze the performance of the double slope solar still for three distinct configurations. Hourly variation of the solar irradiance for the test site is as shown in Fig. 3. It can be interpreted from the data that during the first half of the day, the solar irradiance gradually increases reaching the maximum value of 925 W/m^2 at 13:00 hr. and after which it gradually decreases. Although for the present study the solar still was operational for an entire duration of 24 hr., solar irradiance and temperature data were captured for the time interval of 08:00 hr. to 17:00 hr.

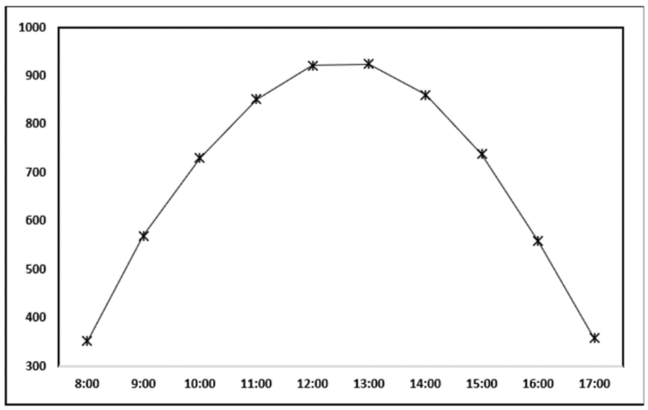
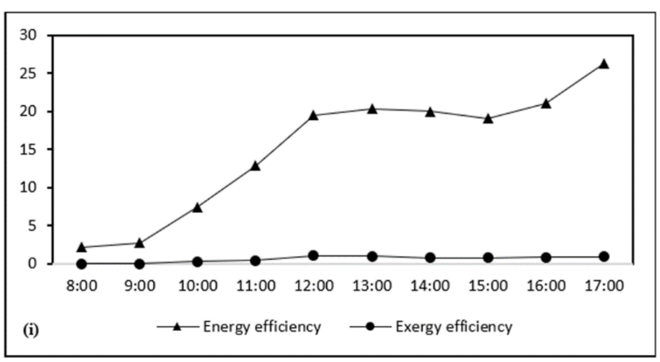
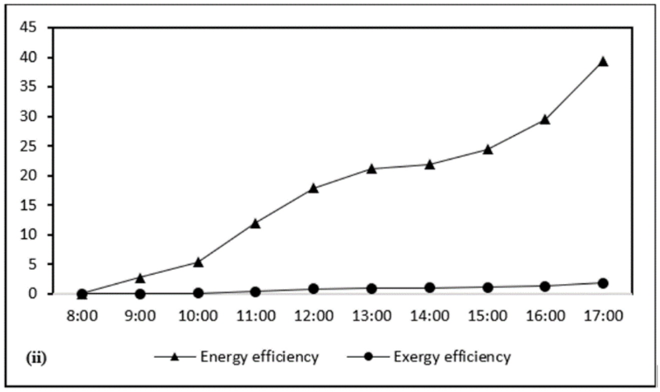


Figure 3: Hourly variation solar irradiance.

From Fig. 4 it can be understood that even though energy and exergy graphs are following the same trend, the efficiency of energy is comparatively much higher than efficiency of exergy. This can be attributed to the fact that saline water's temperature is much lower than sun's temp which is about 6000K. Also, it gives clear indication of the possibility of presence of irreversibility's in different components of the system. It can also be understood from the data that the slope of the characteristic curve is generally positive which is due to temperature dependent properties of the system. The above findings are also in good agreement with the results published in (Kumar & Tiwari, 2011, Ranjan et al., 2016, Yousef et al., 2017).





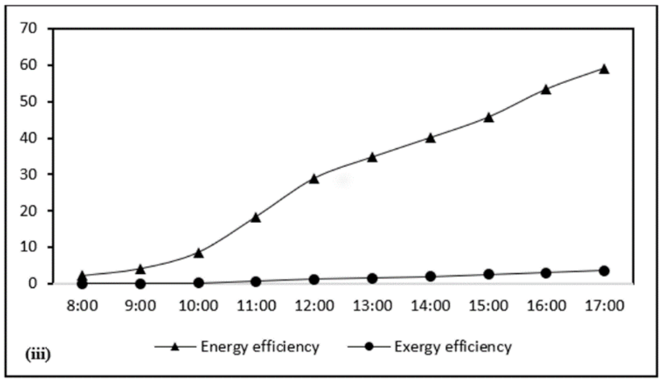


Figure 4: Hourly variation of energy and exergy efficiency for (i) Conventional solar still, (ii) Pebbles based solar still and (iii) solar still with cooling cover.

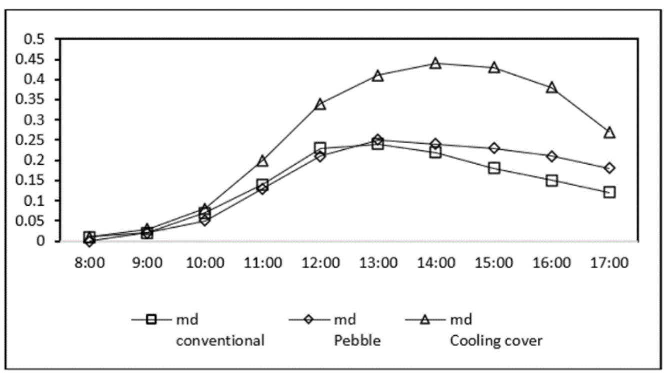


Figure 5: hourly variation of solar still productivity.

The data in Fig. 5 shows the hourly variation of water yield for the three configurations of double slope solar still. It can be understood that initially in comparison to conventional solar still design, the productivity of pebble based solar still is generally lower. This can be attributed to the fact that in the first half of the day, solar thermal energy is being utilized by both the saline water as well as pebbles. It was after 13:00 hr. that once pebbles have stored enough thermal energy; the remaining energy was supplied to saline water. Also, during the end of the day, productivity of pebbles-based system is higher than conventional system due to the utilization of thermal energy stored in pebbles. Application of pebbles lead to prolonged duration of desalination of saline water. For the case of cooling cover, as established in several research works (Ranjan et al., 2016) higher temperature difference between inner glass cover and saline water, leads to higher water yield and exergy efficiency. It is evident from the data that application of cooling cover for solar still enhances hourly productivity significantly. The joint effect of colling cover and solar irradiance greatly enhances productivity. Glass cover being regarded as a solar still component with highest exergy efficiency (Ranjan et al., 2016), any modification in its temperature leads to immediate change in the results. The Overall water yield for the conventional still, pebble based still and still with water cooling jacket for glass cover was recorded as 1.9, 2.3 and 2.9 Liter respectively.

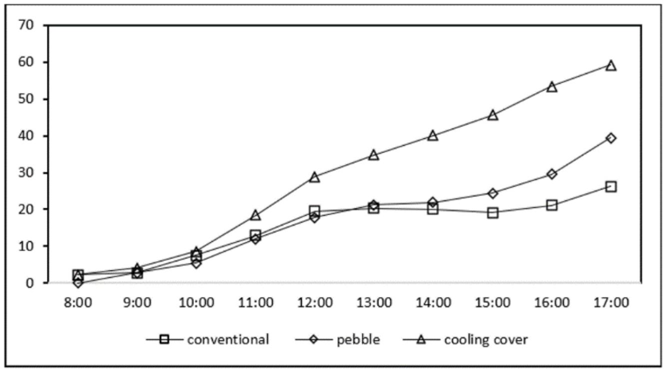


Figure 6: Energy efficiency for conventional, pebble and Cooling cover configuration of still.

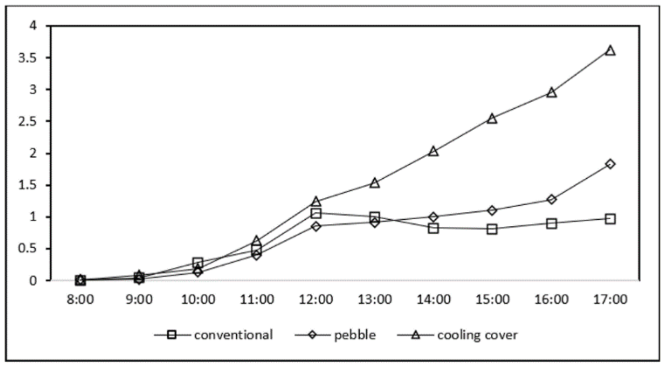


Figure 7: Exergy efficiency for conventional, pebble and Cooling cover configuration of still.

The findings of this study also include the energy and exergy comparison for all the configurations. Fig. 6 &7 shows a comparison of energy and exergy efficiency of solar still for all the three configurations. It is clear from that that energy and exergy efficiency of the system for all configurations are generally tracing a positive trend which can also be seen in the work done by (Kumar & Tiwari, 2011, Ranjan et al., 2016). Analysis of the present study suggests that before 13:00 hr., the efficiency of solar still with cooling cover is highest followed by conventional solar still and then solar still with pebbles. However, after 13:00hr., the order of energy and exergy efficiency is such that it is highest for still with cooling cover followed by still with pebbles and then conventional solar still. The increase in the efficiency of solar still pebbles after 13:00 hr. is because the pebbles have been thermally charged enough and the complete solar irradiance is being supplied to solar still while pebbles maintain the temperature of water even after sun sets leading to prolonged desalination.

5. Conclusions and recommendations

A single basin, double slope solar still is fabricated and tested for different configurations. The main aim of this work being to improve solar still productivity, energy and exergy efficiency without increasing the cost of production. Namely three configurations were selected i.e., conventional still, still with pebbles for thermal energy storage and still with cooling water jacket for reducing the glass cover temperature. From the study it was determined that the solar still configuration with cooling water jacket for glass cover proved to be the highest performing solar still amongst all the configurations. While this configuration has a productivity of 2.9 L/day, productivity for still with pebbles and conventional solar still has come out to be 2.3 and 1.9 respectively. It can also be seen that the energy and exergy efficiency of still with cooling cover is higher than the remaining two configurations. The reasoning behind this can be understood as by lowering the glass cover temperature, higher temperature difference is created between water vapor and inner glass cover leading to higher productivity for the same basin area. It has also been understood that for solar still the exergy efficiency is much lower than energy efficiency, a fact which is also confirmed by various researchers in the field. So, the research work undertaken by the authors has yielded some satisfactory results in terms of improvement in productivity, energy and exergy efficiency. Though an attempt has been made by the authors of this article to improve upon the productivity of solar still. It is well understood that more collaborative efforts are needed in this area of research to help make this an economical product for practical use and mass adoption.

6. Nomenclature:

A_b	Area of basin (m^2)
A_g	Area of Glass cover (m^2)
d	Depth of brine (m)
$E_{x_{e,w-g}}$	Output exergy for solar still (W)
$E_{x_{sun}}$	Input exergy for solar still (W)
G_s	Solar Irradiance (W/m^2)
$h_{e,w-g}$	Evaporative heat transfer coefficient between water and glass cover (W/m^2-K)
h_{fg}	Latent heat of vaporization (J/Kg)
m_d	Solar still productivity (L/h)
T_a	Ambient temperature (˚ C)
T_{g_i}	Temperature of inner glass cover (˚ C)
T_w	Temperature of saline water in basin (˚ C)
η_{en}	Energy efficiency
η_{ex}	Exergy efficiency

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8. Citation / References

Aghaei Zoori, H., Farshchi Tabrizi, F., Sarhaddi, F., & Heshmatnezhad, F. (2013). Comparison between energy and exergy efficiencies in a weir type cascade solar still. *Desalination*, *325*, 113–121. https://doi.org/10.1016/j.desal.2013.07.004

Ayoub, G. M., & Malaeb, L. (2012). Developments in Solar Still Desalination Systems: A Critical Review. *Critical Reviews in Environmental Science and Technology*, *42*(19), 2078–2112. https://doi.org/10.1080/10643389.2011.574104

Badran, O. O. (2007). Experimental study of the enhancement parameters on a single slope solar still productivity. *Desalination*, *209*(1–3), 136–143. https://doi.org/10.1016/j.desal.2007.04.022

Hung Anh, L. D., & Pásztory, Z. (2021). An overview of factors influencing thermal conductivity of building insulation materials. *Journal of Building Engineering*, *44*, 102604. https://doi.org/10.1016/j.jobe.2021.102604

Kalidasa Murugavel, K., Chockalingam, Kn. K. S. K., & Srithar, K. (2008). Progresses in improving the effectiveness of the single basin passive solar still. *Desalination*, *220*(1–3), 677–686. https://doi.org/10.1016/j.desal.2007.01.062

Kariman, H., Shafieian, A., & Khiadani, M. (2023). Small scale desalination technologies: A comprehensive review. *Desalination*, *567*, 116985. https://doi.org/10.1016/j.desal.2023.116985

Khanna, R. K., Rathore, R. S., & Sharma, C. (2008). Solar still an appropriate technology for potable water need of remote villages of desert state of India - Rajasthan. *Desalination*, *220*(1–3), 645–653. https://doi.org/10.1016/j.desal.2007.01.060

Kumar, S., & Tiwari, G. N. (2011). Analytical expression for instantaneous exergy efficiency of a shallow basin passive solar still. *International Journal of Thermal Sciences*, *50*(12), 2543–2549. https://doi.org/10.1016/j.ijthermalsci.2011.06.015

Murugavel, K. K., Sivakumar, S., Ahamed, J. R., Chockalingam, K. K. S. K., & Srithar, K. (2010). Single basin double slope solar still with minimum basin depth and energy storing materials. *Applied Energy*, *87*(2), 514–523. https://doi.org/10.1016/j.apenergy.2009.07.023

Natu, G. L., Goghari, H. O., & Gomkale, S. D. (1979). Solar distillation plant at awania, Gujarat, India. *Desalination*, *31*(1–3), 435–441. https://doi.org/10.1016/S0011-9164(00)88548-3

Ranjan, K. R., Kaushik, S. C., & Panwar, N. L. (2016). Energy and exergy analysis of passive solar distillation systems. *International Journal of Low-Carbon Technologies*, *11*(2), 211–221. https://doi.org/10.1093/ijlct/ctt069

Singh, N., Kaushik, S. C., & Misra, R. D. (2000). Exergetic analysis of a solar thermal power system. *Renewable Energy*, *19*(1–2), 135–143. https://doi.org/10.1016/S0960-1481(99)00027-0

Tarazona-Romero, B. E., Campos-Celador, A., & Maldonado-Muñoz, Y. A. (2022). Can solar desalination be small and beautiful? A critical review of existing technology under the appropriate technology paradigm. *Energy Research & Social Science*, *88*, 102510. https://doi.org/10.1016/j.erss.2022.102510

Tiwari, A. Kr., & Tiwari, G. N. (2007). Thermal modeling based on solar fraction and experimental study of the annual and seasonal performance of a single slope passive solar still: The effect of water depths. *Desalination*, *207*(1–3), 184–204. https://doi.org/10.1016/j.desal.2006.07.011

Tripathi, R., & Tiwari, G. N. (2005). Effect of water depth on internal heat and mass transfer for active solar distillation. *Desalination*, *173*(2), 187–200. https://doi.org/10.1016/j.desal.2004.08.032

Vaithilingam, S., Gopal, S. T., Srinivasan, S. K., Manokar, A. M., Sathyamurthy, R., Esakkimuthu, G. S., Kumar, R., & Sharifpur, M. (2021). An extensive review on thermodynamic aspect based solar desalination techniques. *Journal of Thermal Analysis and Calorimetry*, *145*(3), 1103–1119. https://doi.org/10.1007/s10973-020-10269-x

Yousef, M. S., Hassan, H., Ahmed, M., & Ookawara, S. (2017). Energy and exergy analysis of single slope passive solar still under Egyptian climate conditions. *Energy Procedia*, *141*, 18–23. https://doi.org/10.1016/j.egypro.2017.11.005