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ENHANCEMENT PYRAMID SOLAR DISTILLER PERFORMANCE USING THERMAL STORAGE MATERIAL

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ABSTRACT. This study aims at enhancing the freshwater from saline water via pyramid solar stills (PSS). Experimental work for sand beds PSS was conducted to enhance its performance; the sand was used as thermal storage materials. The effects of sand bed height on the performance of pyramid SS were studied. Experimental results revealed that the sandy layer improves the pyramid SS productions. In addition, the maximum increase in accumulated production of sandy pyramid SS was obtained at sand beds height of 1 cm. At 1 cm height of sand beds the accumulated productivity of the PSS and sandy PSS were 3000 and 4650 mL /m^2. day, with improvement of 55%, The environmental parameter of black SSS with vapor withdrawal and reflectors was 23 tons CO_2 per year.

KEYWORDS: Solar stills; Pyramid solar stills; Thermal storage materials; Sand; Reflectors.

NOMENCLATURE

A	area, m^2
E_{in}	embodied energy, kW.h
E_{out}	energy output, kW.h
$\dot{m}$	water production, kg/s
h_{fg}	vaporization latent heat, J/kg
i	interest rate, %
I(t)	solar radiation, W/m^2
M	average annual yield, l/year
n	life time, years
P	capital cost of solar still, $
S	salvage value, $
t	time, Sec
T	temperature, °C
z_{CO_2}	the carbon cost, $/ton
Z'	the enviroeconomic parameter
η_d,	daily efficiency, %
Abbreviations	
AMC	annual maintenance and operating costs, $
ASV	annual salvage value, $
CPL	cost of fresh water, $/lit
CRF	capital recovery factor
FAC	
SFF	sinking fund factor
SS	solar still
PSS	Pyramid solar still
TAC	total annual cost, $

1. INTRODUCTION

Due to the rapidly rising demand and the limited supply of resources, freshwater scarcity is one of the most significant issues that humanity is currently dealing with. Water needs are anticipated to rise by 130% and 400% from home and manufacturing consumption, respectively, by 2050, notwithstanding the stability of global water resources. It was reported that exclusively 0.01% of the earth's water can be reachable [1]. SS is suggested for smaller requirements due to its cheapness and simplicity [2]. Because of their low production, solar distillers are small units of desalination devices that can be utilized to meet the freshwater needs of small families. So, various shapes of SS systems have been tested under different design and operating conditions such as CSS, stepped SS [3], pyramid SS [4], pyramidal absorber SS [5], conical absorber SS [6], tubular SS [7], drum tubular SS [8], convex tubular SS [9], trays SS [10], corrugated trays SS [11], finned trays SS [12], hemispherical SS [13]. and half barrel SS [14]. Also, phase change material [15], various wick materials [16], sensible heat storage [17], nanoparticles [18], wire mesh absorber SS [19], reflectors [20], elevated basin SS [21], solar collectors SS [22], hybrid SS [23] cords SS [24], rotating wick SS [25], rotating discs SS [26], rotating drum SS [27], fan SS [28], parabolic solar concentrator SS [29] and ultrasound waves SS [30].

The water depth in the SSs inversely affects the production of the SSs. Maintaining the minimum depth in the SS is very difficult. For maintaining minimum depth, wick [31], plastic water purifier [32] and stepped SS [33] were utilized. Studies have found that a decrease in the SS's salinity depth increases output, primarily because the basin's water is warmer. The performance of the modified SSS with reflectors (internal and external) studied by Omara et al. [34]. The results indicated that, freshwater production of SSS enhanced by about 125% over conventional SS, with mirrors and external condenser. An experimental study of SSS with external condenser and reflectors (internal and external) was conducted by El-Samadony et al. [35]. The results indicated that, production of SSS enhanced by about 165% over conventional SS. Kabeel et al. [36] studied effect of varying both widths and depths and of trays on the performance of Pyramid SS. The step width was constant and equal100 mm. They found that, at a tray depth 5mm and tray width 120mm the maximum production of SSS is achieved, which is about 57.3% over conventional SS.

The solar still efficiency is dependent on the energy of sun. The sun is most intense between 12:00 and 13:00. As a result, SS ought to produce more fresh water between 12:00 and 13:00. However, the water temperature inside the SS remains greater, and water vapour formation is also higher, because to the increased amount of solar rays impacted on the basin water at this time. So, the temperatures of the mixture of air vapor increased and which increases the glass cover temperature. The productivity of SS depends on the difference of temperature between temperature of glass cover and temperature of saline water, so due to higher glass cover and temperature of saline water, improvement in production is not increased. The use of thermal energy storage materials, which store surplus thermal energy and release it during non-sunny hours, enables an increase in production and thermal efficiency, is thus necessary to make use of the extra energy. Omara and Kabeel [37] investigated conventional solar still with sand beds in detail, taking into account numerous characteristics such as depth and sand type. They found that black sand was the most efficient of the different sands tested. Murugavel et al. [38]. Velmurugan et al. [39] utilized pebbles, sponges, sand and black rubber in the finned SS for enhancing the daily productivity. They indicated that sand in the SSs improves the SS productivity by around 14%. Srithar [40] utilized sand, pebble and sponge to improve the daily distillate of the traditional SS. The experimental results indicated that maximum daily production of 32.3% improvement was obtained with sponge and sand. Suha et al. [41] conducted experimental study to evaluate the influence of inclined rectangular perforated fins, hollow cylindrical perforated fins, and nanocomposites on the yield of a pyramid solar stills. The results indicated that, inclined rectangular perforated fins and hollow cylindrical perforated fins, improving the productivity by 55.9% and 31.3%, respectively, compared to that of the conventional PSS. Additionally, utilizing nanocomposites with inclined rectangular perforated fins improved the daily yield by 82.1%.

From this review, it is very important to conclude that the sand as thermal storage material inside solar stills play a vital role in its performance. In addition, the effect of sand on the Pyramid solar stills performance is not recognized. So, the aim of this study is to improve the performance of the pyramid solar still via exploiting different types of sand as thermal storage material. Given the prior research, the following may be said about this work's novelty:

1. Yellow sand was studied.
2. Three heights of the sand beds were investigated.

2. Materials and Procedures

2.1. Setup elements

Two solar stills were fabricated; conventional pyramid PSS and sand pyramid solar still (SPSS) to evaluate and compare the tested SSs performance. Fig. 1 show a photograph and of the experimental test rig. The setup consists of two solar distillers, saline water tank, and some auxiliary instruments as shown in Fig. 2. One of both solar distillers had the proposed modifications (modified still) and the other was used as a reference for comparison (reference still). The saline water tank had the dimensions of 50 cm × 50 cm × 100 cm, and it was used to provide the distillers with the saline water. The conventional PSS was created from the galvanized steel (1.5 mm) with the base dimensions of 70 cm × 70 cm and height of 15 cm. This basin was covered by four glass sheets tightened together to form the pyramid shape as illustrated in Fig. 1. The thickness of the glass sheets was 3 mm. Moreover, the basin was contained and rounded by a fiberglass to prevent the heat losses from the basin to ambient. In addition, four troughs were welded roundly at the end edges of the glass sheets. The troughs were utilized to cumulate the condensed droplets and guide them outside of the distiller into the graded bottles. Besides, all edges of sides and walls were sealed by silicon to prevent the leakage. Additionally, there was one pipe connecting between the saline water tank and solar distiller to feed the still by the required feed water. Also, there was another pipe at the bottom of the distiller to control the basin water as wanted. Finally, the distillate of the distiller was collected at two points inside the distiller and guided to the outside of the still into the flasks through a plastic hose.

2.2. EXPERIMENTS PROCEDURES

In order to measure the solar intensity, temperatures, air velocity, and productivity, all measuring instruments were then attached to the setup. The beginning and ending times of testing were 08:00 and 18:00, respectively. The processes of tests were resumed into: (a) effects of two different types of sand (black and yellow sand) on the performance of SSS were studied, (b) three height of sand bed (1, 2, 3 cm) with zero water height above the sand beds level were investigated, according to Omara and Kabeel [42] the maximal productivity increase was obtained at zero depth of water over sand beds, (c) the effect of adding internal and external (top and bottom) reflectors on the performance of the sand SSS.

2.3. MEASURING TOOLS AND ERROR ANALYSIS

Sunlight intensity, glass and water temperatures, ambient temperatures, wind speed, and water productivity all affect the SS's performance. A solarimeter was used to measure the radiation. As well, the temperatures were measured by thermocouples. The basin water temperatures were measured at all steps then the mean value was taken. Also, air velocity was measured by anemometer. What is more, the yield was recorded by graded bottles. Table 1 provides the unit, accuracy, resolution, and range characteristics of the measuring equipment.

The error analyses are executed regarding the method of Holman [43]. The error in a result of parameter was found as following.

$$W_R = \left[\left(\frac{\partial R}{\partial X_1}W_1\right)^2 + \left(\frac{\partial R}{\partial X_2}W_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial X_n}W_n\right)^2\right]^{\frac{1}{2}} \quad (1)$$

Where W1, W2, W3, ..., Wn are the uncertainties of the independent parameters. All calculated errors for the used tools are found in Table 1.

$$\eta_{th} = f(\dot{m}, I_R, \Delta T_{w-g}) \quad (1)$$

Then, the efficiency uncertainty is determined by,

$$W_{\eta_{th}} = \left[\left(\frac{\partial \eta_{th}}{\partial m}W_m\right)^2 + \left(\frac{\partial \eta_{th}}{\partial I_R}\right)^2 + \left(\frac{\partial \eta_{th}}{\partial \Delta T_{w-g}}\right)^2\right]^{\frac{1}{2}} \quad (2)$$

Fig. 1. Photo of experimental test rig.

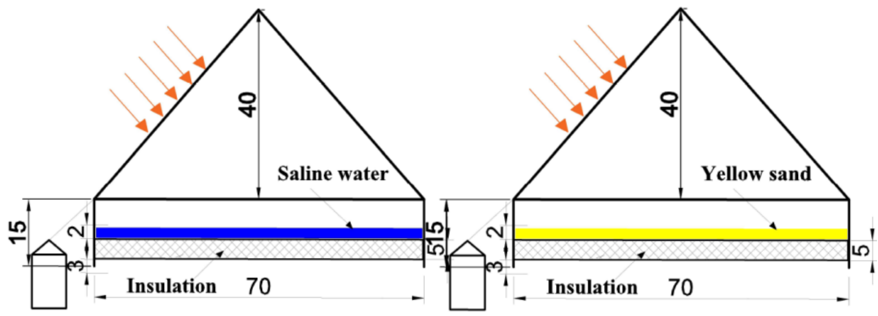

Fig. 2. Schematic view of experimental test rig.

Table 1. The characteristics of the measurement tools.

Device	Dimension	Unit	Resolution	Accuracy	Range
Solarimeter	Irradiance	W/m²	0.1	± 1	0 – 5000
K-type thermocouple	Temperature	°C	0.1°C	± 0.5	0 – 100
Anemometer	Wind velocity	m/s	0.01	± 0.1	0.4 – 30
Graded bottles	Productivity	L	0.5mL	± 5mL	0 – 1

3. RESULTS AND DISCUSSIONS

3.1. PERFORMANCE OF SOLAR STILLS AT 1 CM SAND HEIGHT

The average temperature of the sand-water mixture in sand trays, the salinity of the pyramid and SPSS waters, and the productions all rise with exposure to the sun. Figs. 3 and 4 show that they rise until the afternoon, when they peak, and then decline the rest of the day as the sun's irradiance and surrounding temperature decrease.

Glass and water temperatures of PSS and SPSS and solar climatic conditions were measured at 1 cm trays height, as shown in Fig. 3. From Fig. 3, it can be indicated that the sand-water temperature (average value) of SPSS are greater than that of PSS by a range of 0–3°C. This is owing to that sand has a large capacity for storing sensible heat. The peak value of sun radiation of 1160 W/m² was achieved at 12:00. Additionally, at 13:00, the highest sand-water mixture temperature was 67, and 64 °C for SPSS and PSS, respectively.

The glass cover temperature of for SSS, YSSS and BSSS was found to be more than that of conventional SS by 0 – 3 °C. This is brought on by an increase in SSSs' rates of condensing and vaporizing relative to conventional SS. Moreover, the maximum temperature of glass was recorded at 13:00 where the temperatures of glass cover of SPSS and PSS were 46 and 43 °C, respectively.

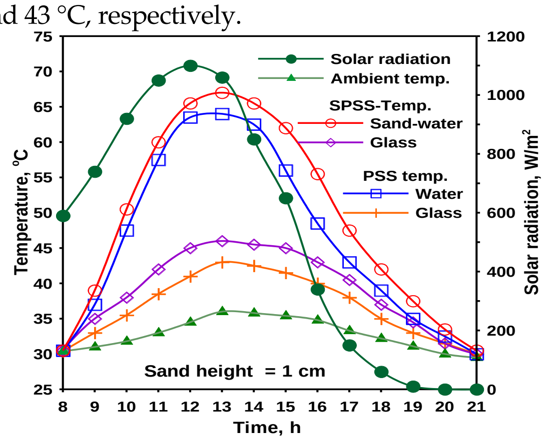

Fig. 3. Temperatures and solar irradiation for SSs at sand height 1 cm.

Also, from Fig. 4 the water production for sand SPSS is superior to that of the PSS. The growth of both sensible heat and the area that absorbs sun irradiation increases the productivity of fresh water. Additionally, Sand in SSS reduces the amount of time needed to pre-heat the water in the basin until it evaporates, where the specific heat of saline water (average value 4050 J/kg °C) is approximately five times than that of sand (average value 830 J/kg °C), Therefore, compared to the conventional PSS, the sand PSS requires lesser time to heat up before yield for the same depth. . Additionally, Fig. 4 indicates the production of the CSS, black SSS, yellow SSS and SSS, were 3050 and 4700, mL /m². day, with improvement of 55%,for the SPSS higher than PSS.

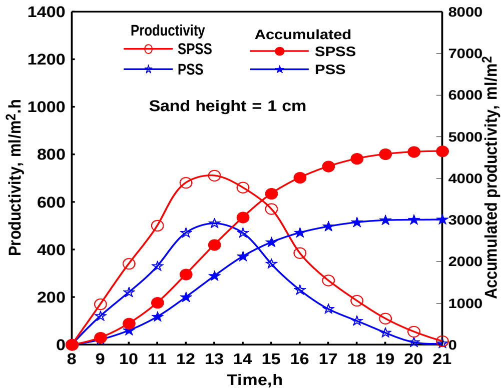

Fig. 4. The changes of total and hourly yields for stills at sand height 1 cm.

3.2. EFFECT OF SAND BEDS HEIGHT ON THE PYRAMID SS PERFORMANCE

According to Fig. 5, the measured variations in the daily production increase's percentage (productivity rise, %) for yellow sand pyramid SS with different sand heights. According to Fig. 5, the greater quantity of heat transported and stored within the tested sand beds sunlight, results in a drop in daily production rise when the height of the sand beds is increased. The SPSS has greater production for all heights, due to its high capacity of heat. From Fig. 5 at 1 cm sand beds height, the daily productivity rises of freshwater of the yellow SPSS and PSS was 57% over PSS. While at 3 cm sand beds height, the daily productivity rises of freshwater of the SSS, YSSS and BSSS were 53%, over PSS.

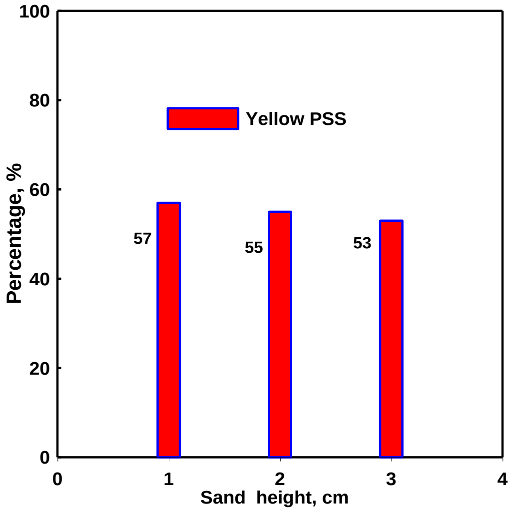

Fig. 5. The production rise of basin stills.

The daily thermal efficiency is formulated as;

$$\eta_d(\text{thermal efficiency}) = \frac{\sum \dot{m}\ (\text{distillate}) \times h_{fg}\ (\text{latent heat})}{\sum A\ (\text{area}) \times I(t)\ (\text{solar radiation})} \quad (4)$$

So, Fig. 6 shows the distiller's daily efficiency at varying sand bed height. Fig. 6 shows that the lowest (41.5 %) and highest (43 %) efficiencies of pyramid SS were found at 3 and 1cm sand bed. Fig. 6 indicated that the daily thermal efficiency declines with raising the height of sand beds for the tested sand beds trays solar still similar to the productivity rise. Furthermore, the PSS's efficiency was about 35–33.5%.

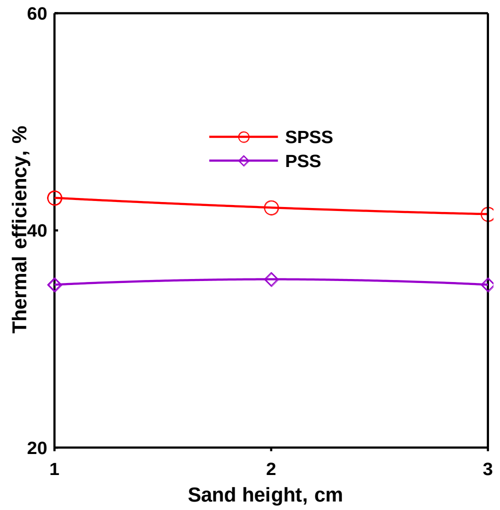

Fig. 6. Efficiency of stills at different sand bed height.

4. Economic analysis of freshwater

Economic analysis is done to ensure the comparability of distillers' performance is accurate. Table 2 shows the specifics of the fixed costs for PSS and SPSS. The formulae in Table 3 are utilized to calculate the expenses of the desalinated water based on the previously mentioned information. Additionally, Table 4 lists the presumptions and estimates for a few factors used in the economic analysis. Some of these assumptions include the system lifetime, the number of working days in a year, the interest rate and costs of annual maintenance and cleaning. So, the costs of freshwater are 0.026 and 0.019 \$/L for PSS and SPSS.

5. Environmental analyses

The environmental analyses of the proposed system are evaluated. It is well known that the world, recently, is paying close attention to the environmental analyzes of the systems in order to know the greenhouse gas emissions that come out of these systems especially CO_2 and life cycle assessment (Mousavi and Mehrpooya [45]). This interest came because the use of fossil fuel sources leads to disasters and environmental risks including the emission of greenhouse gases to the surroundings. This helped the scientists and decision makers to utilize the renewable energy sources for the systems instead of the fossil fuel sources in order to obtain the goals of preservation of environmental and sustainability. The governing equations stating the mitigation and emission of CO_2 by SS are proposed as following.

The solar distiller annual energy output (kW.h/year) is

$$E_{out} = \frac{365 \times \dot{m}(\text{hourly yield}) \times h_{fg}(\text{latent heat of vaporiz}}{3600} \quad (8)$$

The yearly amount of CO_2 emitted in kg/year is (Parsa et al., 2021).

$$CO_{2,emitted} = \frac{2 \times E_{in}}{n} \quad (9)$$

Where, E_{in} is the embodied energy of components.

Then, the amount of CO_2 emitted through the system lifetime is.

$$CO_{2,emitted} = 2 \times E_{in} \quad (10)$$

Besides, the amount of CO_2 mitigated in kg/year through the year is.

$$CO_{2,mitigated} = \frac{2 \times E_{out}}{n} \quad (11)$$

Also, the amount of CO_2 mitigated through the system lifetime in kg is.

$$CO_{2,mitigated} = 2 \times E_{out} \times n \quad (12)$$

Finally, the environmental parameters (ϕ_{CO_2} and Z') are evaluated as following.

$$\phi_{CO_2} = \frac{2 \times \left((E_{out} \times n) - E_{in}\right)}{1000} \quad (13)$$

And,

$$Z' = z_{CO_2} \times \phi_{CO_2} \quad (13)$$

Where, z_{CO_2} is the carbon cost in the international market (14.5 \$/ton) (Parsa et al. [46]).

The embodied energy of the system components,

Table 5, following the above equations. Additionally, the enviroeconomic and environmental analyses for lifetime 20 years and 365 days are obtained in Table 5. So, the environmental parameter of black SSS with modifications (vapor withdrawal and reflectors) was 23 tons CO2 per year. Also, the enviroeconomic parameter (Z') was 348 per year for the black SSS with modifications, for lifetime 20 years and 365 operating days, Table 4.

Table 2. Fixed costs of fabricated PSS and SPSS for 1m².

Unit	CSS ($)	Black SSS ($)
Iron sheet	30	30
Tray's sheet	-	15
Glass sheet	10	10
Paint	10	10
Support legs and ducts	25	25
Fiber glass (insulation)	7	7
Production	20	45
Sand	-	3
Total fixed cost (F)	102	145

Table 3. Calculations for cost analyses [44].

No.	Description	Relation
1	**Fixed annual cost**	$FAC = F\ (CRF)$
2	**Capital recovery factor**	$CRF = \frac{i\ (1+i)^n}{(1+i)^n - 1}$
3	**Sinking fund factor**	$SFF = \frac{i}{(1+i)^n - 1}$
4	**Annual salvage value**	$ASV = \mathrm{S\ (SFF)}$
5	**Salvage value**	$S = 0.2\ F$
6	**Total annual cost**	$TAC = \mathrm{FAC + AMC - ASV}$
7	**Costs of annual maintenance**	$AMC = 0.15\ \mathrm{(FAC)}$
8	**Distilled water cost**	$CPL = TAC/M$

Table 4. Premises utilized in the economic analyses.

No.	Variable	Mean	Value	Unit
1	***N***	**Working days of year**	340	Day
2	***i***	**Interest rate**	15	%
3	***n***	**System lifetime**	20	Years
4	***F***	**System fixed cost**	187 for SPSS 102 for PSS	$
5	***M***	**Average yearly productivity**	2550 for SPSS 1080 for PSS	L/m².year
6	**CPL**	**Costs of the desalinated freshwater**	0.012 for SPSS 0.022 for PSS	$

Table 5. Embodied energy of the components of the system.

Component	Materials	Energy density kW.h/kg	Mass of component (kg)	Embodied energy, E_{in} (kW.h)
Body	**Galvanized iron**	13.8	10	138
Trays	**Galvanized iron**	13.8	6	81
Cover	**Glass**	4.16	6.1	25.4
Insulation	**Fiberglass**	2.6	0.4	1.1
Coating	**Black paint**	25	0.2	5
Valves	**Brass**	17.22	0.22	3.8
Total				**255**

Table 6. Environmental and enviroeconomic analysis for 365 days and lifetime 20 years.

Type of SS	Embodied energy = E_{in} (kW.h))	E_{out} yearly (kW.h)	E_{out} for lifetime (kW.h)	Environmental parameter, (ϕ_{CO_2}. year)	Enviroeconomic parameter, (Z' .year)
SPSS	255	620	12400	23	348

6. CONCLUSIONS

The production of the sand's SSs is improved by incorporating sandy beds over the basin plate of PSS. The sandy beds are regarded as a practical heat-storage media, so the freshwater production is increased. The aforementioned findings and justifications lead to the following conclusions.

1. The daily distillate of the sand pyramid SS was inversely proportional to the heights of sandy beds.
2. The highest daily production of sandy pyramid SS is obtained at 1 cm height of sand beds
3. At 1 cm height of sand beds the daily yield of freshwater productivity of the PSS, and SPSS were 3000 and 4650, with improvement of 55%, higher than PSS.
4. The anticipated cost of 1 l of the freshwater for SPSS and PSS are around 0.019$ and 0.026$.
5. The environmental parameter of black SPSS with vapor withdrawal and reflectors was 23 tons CO2 per year.

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