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Performance study on solar still with agitator, inbuilt condenser and fans using energy, exergy and economic analysis

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ABSTRACT

Solar still is one of the economic solutions which can address the problem of water scarcity. In the present research, a conventional solar still (CSS) is compared with an inbuilt condenser solar still with an agitator and condensing fans (ICSSAC) having same absorber area where the agitator and condensing fans are powered by a solar PV panel. To study the impact of this excess absorber area of PV panel, another conventional solar still with improved absorber area (SSIAA) was fabricated. Three solar stills were tested under same conditions. Experimentation revealed that ICSSAC have maximum yield of 1.445 L/d followed by SSIAA and CSS with a yield of 0.690 and 0.595 L/d, respectively. Agitation effect, extended condenser area and glass cover cooling had improved the yield of ICSSAC. Energy efficiency of ICSSAC was calculated to be 38.10% and 39.01% more than CSS and SSIAA, respectively. Similarly, exergy analysis revealed that ICSSAC is 2.93% and 3% more efficient than CSS and SSIAA, respectively. Economic analysis was carried out for all three stills, in which ICSSAC was found to be economically viable than counterparts.

Keywords: Solar still; Inbuilt condenser; Agitator; Condensing fan; Exergy; Economic analysis

1. Introduction

Water demand increases every day, as the availability of fresh water depletes, and population increases constantly. Desalination of sea water is one of the promising solutions to address this demand [1]. Basin type solar still is a device which converts the saline water into potable water by using solar energy. Use of this solar energy to desalinate the water helps in reducing the carbon di-oxide emission generated from fossil fuels to produce the fresh water [2]. Solar still works on evaporation and condensation principle for producing fresh water [3]. Low productivity is the major problem associated with these solar stills and makes it uneconomical for commercial use [4]. Various parameters influence the productivity of solar still [5–7]. Many researchers adopted different techniques to improve evaporation and condensation rate of solar stills [8,9]. Design, operational and environmental parameters influence the solar still performance [10,11]. Mohsenzadeh et al. [12] reviewed the performance with respect to new designs and modifications. Optimizing water depth and cover thickness maximizes the productivity of solar still [13,14]. Mohiuddin et al. [15] and Abujazar et al. [16] reviewed the recent progress in internal designs of solar still. Review done by Shoeibi et al. [17] reveals that increasing the water temperature and decreasing the glass temperature improves the productivity. These reviews concluded that improving rate of evaporation and rate of condensation enhances the yield of distillate in solar still.

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Various methods are adopted to improve the evaporation rate of solar still. Porous materials [18], nanoparticles [19,20], nano fluids [21], wick materials [22], natural fibres [23], heat storage materials [24,25], hydrogel materials [26], porous absorbent plate [27] improves the rate of evaporation. Apart from these efforts, breaking the surface layer of basin water has promising impact in improving the evaporation rate. Solar still with rotating parts that gives agitation effect to the basin water was reviewed by Diab et al. [28]. Solar still with vertical rotating wick was compared with conventional solar still by Haddad et al. [29]. Experimental results shows that still with vertical rotating wick yield distillate 14.72% and 51.1% more than the conventional still in summer and winter, respectively. Omara et al. [30] studied the performance of solar still using fan and wind turbine. It was found that solar still with fans enhanced productivity by 17% over conventional solar still at 3 cm depth. Rotating drum coupled with conventional still was experimented by Younis et al. [31]. It was found that yield improved by 198% and 431.1% over conventional still for smooth drum and rough drum, respectively. Eltawil and Zhengming [32] analyzed the performance of wind turbine – inclined solar still. The amount of freshwater yield per m^2 in modified solar still ranged from 26.55% to 29.17% higher than main solar still. Darbari and Rashidi [33] tested the solar stills with porous wick materials. Still with semi-circular shaped tooth wick layers produced more yield than stills with flat shaped and triangular shaped porous wick materials.

Increasing the condensing area and reducing the glass cover temperature improves the rate of condensation [34]. Patel and Modi [35] reviewed the techniques used to enhance the condensation area. Shatar et al. [36] examined a condensing cover with water-based silicone coating. Experiment revealed that the addition of coating improved productivity at 30% coated surface area. Performance of a stepped solar still using a built-in passive condenser was studies by Amiri [37]. Results showed that solar still with built-in condenser had improved yield by 30% to 150%. Including external condenser with rotating drum was experimented by Abdullah et al. [38] which showed increase in productivity by 350% at 0.1 rpm. Rabhi et al. [39] studies the performance of a solar still with pin-fin absorbers and condenser. Still with condenser yields 32.18% more yield than the conventional still. The effect of employing thermoelectric cooling channel and copper oxide nanofluid in solar still was studied by Nazari et al. [40]. Experimental results shows that the maximum enhancement values of productivity, energy and exergy were 81%, 80.6% and 112.5%, respectively. Sadeghi and Nazari [41] investigated the performance of a solar still integrated with evacuated tube and anti-bacterial hybrid nanofluid. Study revealed that the productivity was improved by 218% compared to a traditional still.

The combined effect of improving evaporation rate and condensation rate gives maximum yield. Sathyamurthy et al. [42] analyzed experimentally the portable solar stills with evaporation and condensation chamber. This still has recorded an improved efficiency of 14%. Phase change material and external condenser was used and analyzed in a solar still by Toosi et al. [43]. From experimentation, it was absorbed that still with PCM and condenser had 104% more productivity than still without PCM and condenser. Arun Kumar et al. [44] studied the performance of solar still with agitator and external condenser. Combined effect in modified solar still improved the distillate yield by 39.49% over the conventional solar still. Rajasekaran and Kulandaivelu [34] compared performance of solar still with agitator and inbuilt condenser. Productivity of modified solar still was found to be 98.69% more than the conventional still.

Solar still performance can be analyzed by energy and exergy analysis. Experimentation during summer gives more accurate result of the analysis. Jeevadason et al. [45] reviewed energy-exergy-economics of hybrid solar still and proposed methods with scope for further improvement. Energy and exergy performance of solar still integrated with nanoparticles and nanofluids were carried out by Yousef et al. [46], Sharshir et al. [47] and El-Gazar et al. [48]. Dumka and Mishra [49] have done energy and exergy analysis on conventional and modified solar still with sand berth earth. Exergy analysis reveals that maximum destruction is vested with basin of solar still [50].

Jafaripour et al. [51] review included the economic and environmental aspects in solar desalination units. Many researchers [52–54] carry out economic analysis in their work to study the economic viability of solar still.

Literature review reveals that the maximum exergy destruction in solar still is vested in the basin. Improving rate of evaporation and rate of condensation simultaneously will increase the yield of solar still. Introducing agitation effect will break the surface boundary layer of water leading to increase in rate of evaporation. This further stimulates the heat transfer from basin to water, thus reducing the exergy destruction in basin. Integration of condensing fans over glass cover will remove the heat from glass cover and increases the temperature difference between vapour and glass cover. This will enhance the rate of condensation. Further, the rate of condensation can be enhanced by increasing the condensation area. Introduction of an inbuilt condenser will increase the area of condensation for the same absorber area. This paves way for the vapour to condense at faster rate, which may further make the basin water to evaporate, resulting in overall improvement of condensate yield. Carrying out energy and exergy analysis will help to understand the performance of the solar still in deep and analyze the scope for future research. In our previous study [34], the performance of an inbuilt condenser solar still was compared with conventional solar still by introducing agitation effect. In the current study condensing fans are introduced over the glass cover of an inbuilt condenser solar still with agitator to compare the performance.

2. Experimentation

A single basin single slope conventional solar still (CSS) and modified inbuilt condenser solar still with an agitator and condensing fans (ICSSAC) were fabricated for current research. CSS and ICSSAC have 0.25 m^2 (500 mm ×500 mm) basin absorber area. Agitator and condensing fans in ICSSAC were powered by a solar PV panel which has an area of 0.05 m^2. This makes the cumulative absorber area of ICSSAC as 0.3 m^2. The agitator in ICSSAC is introduced for breaking the surface boundary layer of basin water. This leads to increase in rate of evaporation. The inbuilt condenser and condensing fans are introduced to improve the rate of condensation. Condensing fans reduces the glass cover temperature which increases the temperature difference between vapour and the glass cover. Inbuilt condenser increases the condensing area for the same absorber area as that of CSS. These two effects results in increase in rate of condensation. To compare the impact of this additional absorber area, a third solar still with improved absorber area (SSIAA) of 0.3 m^2 was fabricated. All the three stills were fabricated using 1.5 mm thick galvanized iron. Lower wall of all the three stills were fabricated at 100 mm height with glass cover having inclination angle of 30°. Higher end of ICSSAC was kept at 245 mm with the inbuilt condenser having 0.125 m^2 (250 mm × 500 mm) area. Stills were painted black in the inner side. The side walls and bottom side were insulated with 25 mm thick thermocole to minimize the heat loss. Fig. 1a–c presents the schematic of CSS, ICSSAC and SSIAA, respectively. All the three stills were experimented in same ambient conditions to compare the performance accurately during the month of May, 2022. The experimental setups are shown in Fig. 2a and b. Experimentation was done from 7 AM to 6 PM at Ramco Institute of Technology, Rajapalayam, India (9.4536°N, 77.5433°E). Basin, basin water, glass cover, ambient temperatures were measured along with yield and solar intensity at an interval of 1 h. The experimentation was carried out from 7 AM till 6 PM during the day of experiment. Water level of all the three stills was maintained at 10 mm depth. Details of the instruments used for the experimentation is mentioned in Table 1 along with uncertainties of each instrument. The minimum error of an instrument is the ratio between the least count and minimum value of measured output [55].

3. Energy and exergy analysis of solar still

To analyze the performance of ICSSAC, its energy and exergy efficiency were compared with CSS and SSIAA. Energy efficiency gives the quantitative and exergy efficiency gives the qualitative approach of the solar still. Exergy destruction vested with the major still components' basin, basin water and glass cover was calculated for all three stills. Vaithilingam et al. [56] have studied the energy efficiency, exergy efficiency and exergy destruction [Eqs. (1)–(20)]. Temperature of major components, solar intensity and hourly yield were considered for energy and exergy efficiency. Energy efficiency was calculated [Eq. (1)] by considering total energy in and total energy out from the solar stills. Similarly, exergy efficiency of the stills was calculated [Eq. (5)] by equating total exergy in and total exergy out of the stills. The exergy in and exergy out were equated individually to study the exergy destruction in basin [Eq. (6)], basin water [Eq. (10)] and glass cover [Eq. (15)] of all three stills. The uncertainty vested with energy and exergy efficiencies is represented in Eqs. (19) and (20), respectively.

3.1. Energy analysis of solar still

$$\eta_{\text{energy}} = \frac{m_w \times L}{\left(A_s \times \sum I_t \times 3600\right)} \tag{1}$$

3.2. Exergy analysis of solar still

$$\sum \dot{\text{E}}\text{x}_{\text{sun}} - \sum \dot{\text{E}}\text{x}_{\text{evap}} = \sum \dot{\text{E}}\text{x}_{\text{dest}} \tag{2}$$

where

$$\sum \dot{\text{E}}\text{x}_{\text{sun}} = \left(\left(A_s \times \sum I_t\right)\right) \times \left[1 - \frac{4}{3} \times \left(\frac{T_a + 273}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_a + 273}{T_s}\right)^4\right] \tag{3}$$

$$\sum \dot{\text{E}}\text{x}_{\text{evap}} = \frac{m_w \times L \times \left[1 - \left(\frac{T_a + 273}{T_w + 273}\right)\right]}{3600} \tag{4}$$

$$\eta_{\text{Exergy}} = 1 - \frac{\dot{\text{E}}\text{x}_{\text{dest}}}{\dot{\text{E}}\text{x}_{\text{sun}}} \tag{5}$$

3.3. Exergy destruction of basin, basin water and glass cover

Exergy destruction vested with three major components of the still – basin, basin water and glass cover was calculated based on the exergy in and exergy out in the respective components.

3.3.1. Basin

'Exergy in' of the basin is from Sun's radiation. 'Exergy out' of the basin is from the side walls and bottom of the solar still and the 'exergy in' to the basin water. The exergy destruction vested with the basin of the solar still can be calculated as:

$$\text{Ex}_{\text{des},b} = \left(\tau_g \tau_w \alpha_b\right)\text{Ex}_{\text{sun}} - \left(\text{Ex}_w + \text{Ex}_{\text{ins.}}\right) \tag{6}$$

where

$$\text{Ex}_{\text{sun}} = I_t\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right] \tag{7}$$

$$\text{Ex}_w = h_w\left(T_b - T_w\right)\left(1 - \frac{T_a}{T_b}\right) \tag{8}$$

$$\text{Ex}_{\text{ins.}} = h_b\left(T_b - T_a\right)\left(1 - \frac{T_a}{T_b}\right) \tag{9}$$

3.3.2. Basin water

Sun's radiation and heat transfer from basin provides the 'exergy in' for the basin water. Exergy released from basin water to vapour is the 'exergy out' for the basin water. These exergies are accounted for calculating exergy destruction with basin water and is calculated as:

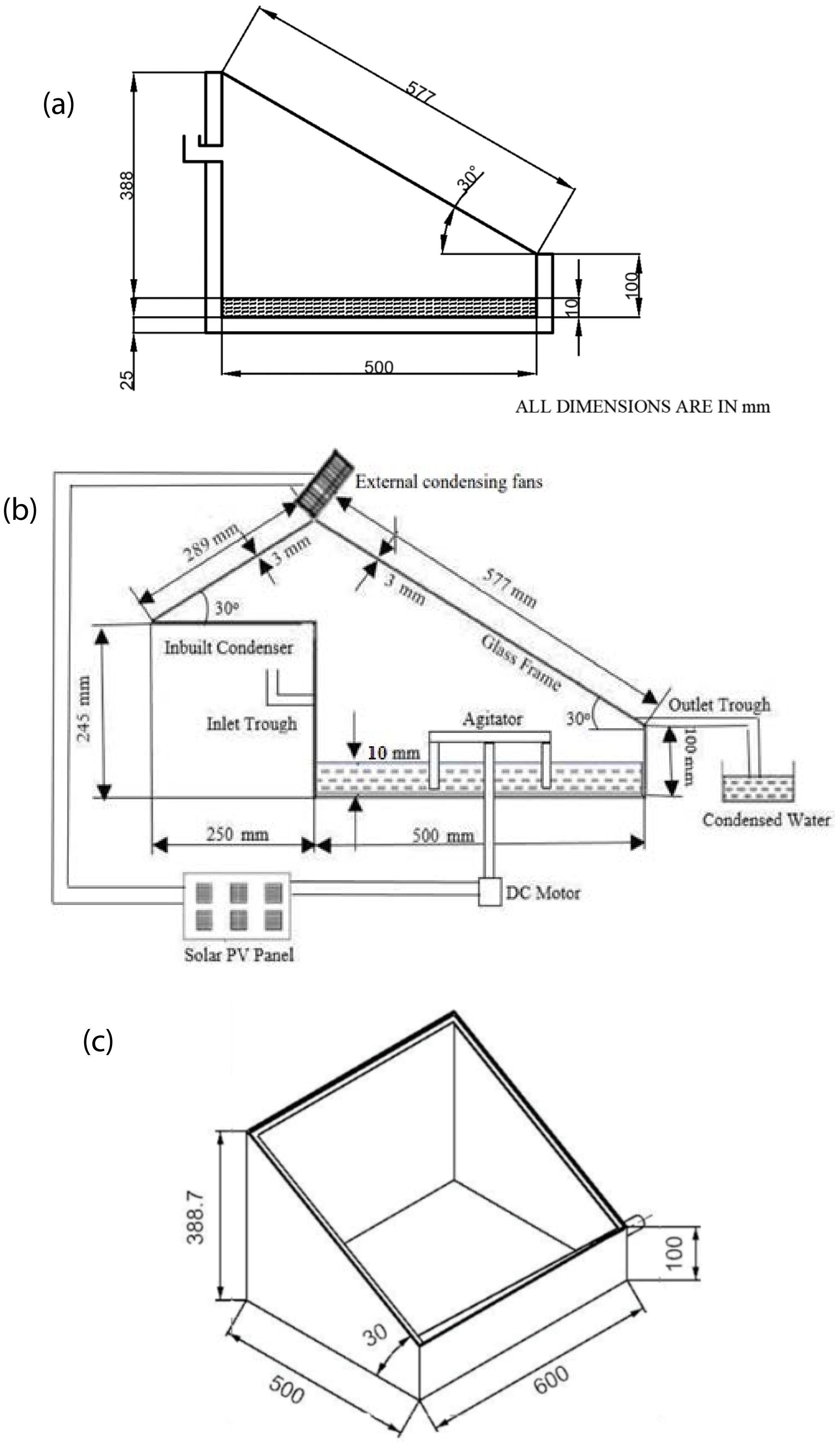

Fig. 1. Design of (a) CSS, (b) ICSSAC and (c) SSIAA.

Table 1
Instruments used for experimentation

S. No.	Instrument	Accuracy	Range	%Error
1	Temperature indicator	+0.1°C	0°C–100°C	0.25
2	PV type sun meter	+1 W/m²	0–2,500 W/m²	2.5
3	Measuring jar	+10 mL	0–1,000 mL	5

$$\mathrm{Ex}_{\mathrm{des},w} = \left(\tau_g \alpha_w\right)\mathrm{Ex}_{\mathrm{sun}} + \mathrm{Ex}_w - \mathrm{Ex}_{t,w-g} \tag{10}$$

where

$$\mathrm{Ex}_{t,w-g} = \mathrm{Ex}_{e,w-g} + \mathrm{Ex}_{c,w-g} + \mathrm{Ex}_{r,w-g} \tag{11}$$

$$\mathrm{Ex}_{e,w-g} = h_{e,w-g}\left(T_w - T_{\mathrm{gi}}\right)\left(1 - \frac{T_a}{T_w}\right) \tag{12}$$

$$\mathrm{Ex}_{c,w-g} = h_{c,w-g}\left(T_w - T_{\mathrm{gi}}\right)\left(1 - \frac{T_a}{T_w}\right) \tag{13}$$

$$\mathrm{Ex}_{r,w-g} = h_{r,w-g}\left(T_w - T_{\mathrm{gi}}\right)\left[1 + \frac{1}{3}\left(\frac{T_a}{T_w}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_w}\right)\right] \tag{14}$$

3.3.3. Glass cover

Exergy from sun and exergy received from latent heat of vapour when it gets condensed are the 'exergy in' for glass cover. 'Exergy out' from the glass cover is during the heat transfer happening due to interaction with ambient air. With these exergies, the destruction vested with the glass cover is calculated as:

$$\mathrm{Ex}_{\mathrm{des},g} = \alpha_g \mathrm{Ex}_{\mathrm{sun}} + \mathrm{Ex}_{t,w-g} - \mathrm{Ex}_{t,g-a} \tag{15}$$

where

$$\mathrm{Ex}_{t,g-a} = \mathrm{Ex}_{c,g-a} + \mathrm{Ex}_{r,g-a} \tag{16}$$

$$\mathrm{Ex}_{c,g-a} = h_{c,g-a}\left(T_{\mathrm{go}} - T_a\right)\left(1 - \frac{T_a}{T_{\mathrm{go}}}\right) \tag{17}$$

$$\mathrm{Ex}_{r,g-a} = h_{r,g-a}\left(T_{\mathrm{go}} - T_a\right)\left[1 + \frac{1}{3}\left(\frac{T_a}{T_{\mathrm{go}}}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_{\mathrm{go}}}\right)\right] \tag{18}$$

3.4. Uncertainties of energy and exergy efficiency equations

Solar intensity, mass of water and basin water temperature are the influencing parameters of uncertainty in energy efficiency whereas the uncertainty in exergy efficiency is influenced by solar intensity, mass of water, ambient temperature and basin water temperature. The uncertainty

Fig. 2. (a) Experimental setup – CSS, SSIAA and ICSSAC. (b) Side view of experimental setup showing the inbuilt condenser in ICSSAC.

values of energy efficiency for CSS, SSIAA and ICSSAC is 0.381, 0.313 and 0.926, respectively and that of exergy efficiency is 0.368, 0.379 and 0.936, respectively.

$$\omega\eta_{\mathrm{energy}} = \left[\left(\frac{\partial\eta_{\mathrm{energy}}}{\partial m_w} \times \partial m_w\right)^2 + \left(\frac{\partial\eta_{\mathrm{energy}}}{\partial T_w} \times \partial T_w\right)^2 + \left(\frac{\partial\eta_{\mathrm{energy}}}{\partial \sum I_t} \times \partial \sum I_t\right)^2\right]^{1/2} \tag{19}$$

$$\omega\eta_{\mathrm{exergy}} = \left[\left(\frac{\partial\eta_{\mathrm{exergy}}}{\partial m_w} \times \partial m_w\right)^2 + \left(\frac{\partial\eta_{\mathrm{exergy}}}{\partial T_a} \times \partial T_a\right)^2 + \left(\frac{\partial\eta_{\mathrm{exergy}}}{\partial T_w} \times \partial T_w\right)^2 + \left(\frac{\partial\eta_{\mathrm{energy}}}{\partial \sum I_t} \times \partial \sum I_t\right)^2\right]^{1/2} \tag{20}$$

4. Results and discussion

Solar intensity, distillate yield, basin temperature, basin water temperature, glass cover temperature and ambient temperature of all the three stills were analyzed for the performance study. The experimental results and their performance comparison are presented below. Exergy efficiency, energy efficiency and exergy destruction in three components were analyzed.

The hourly trend in solar intensity and ambient temperature during the experimentation is shown in Fig. 3. Intensity reaches its maximum during 12 noon with a value of 819 W/m^2. As the solar intensity falls perpendicular to earth's surface during 12 noon, intensity attains maximum value. During post noon time, as the earth's surface re-radiates the heat, ambient temperature seems to be higher between 1 PM and 3 PM. The maximum temperature of ambient condition was recorded as 40.2°C at 1 PM.

The cumulative yield of three stills is compared in Fig. 4. CSS and SSIAA yield were recorded as 0.595 and 0.690 L/d, respectively. The yield that of ICSSAC was 1.445 L/d. The reason for increased productivity in ICSSAC was due to the effect of agitator, inbuilt condenser and condensing fans. Agitator increased the rate of evaporation by increasing the surface area of contact due to breaking of water surface. Inbuilt condenser contributed in increasing the condensation by improving the area of condensation. Condensing fans removed the heat from glass cover which increased the temperature difference between vapour and glass cover leading to increased productivity. Maximum productivity for all the three stills was during 12 PM to 1 PM. During this period, the hourly yield of CSS and SSIAA was 130 and 140 mL, respectively. Yield of ICSSAC was recorded as 230 mL during the same period. The maximum productivity is due to receival of maximum solar intensity during the period.

Energy and exergy efficiency were calculated for all the three stills and are plotted in Fig. 5. Cumulative distillate yield from each still was considered for 'energy out' and solar intensity was considered as 'energy in' for the stills. The solar intensity of the day for CSS and ICSSAC is 1,354.5 W whose absorber area are 0.25 m^2 and that for SSIAA is 1,625.4 W whose absorber area is 0.3 m^2. Energy efficiency of CSS and SSIAA were calculated to be 26.70% and 25.79%, respectively. These efficiencies are found to be closer as both the stills are had same design with varied absorber area. Energy efficiency of ICSSAC was calculated to be 64.80%. The improvisation in efficiency is due to enhanced yield of condensate caused due to simultaneous increase in rate of evaporation and rate of condensation. The exergy efficiency of CSS, SSIAA and ICSSAAC are 1.99%, 1.92% and 4.92%, respectively. As the exergy destruction in basin and basin water of ICSSAC was reasonably reduced due to modifications made, the exergy efficiency had seen a good improvement over the counterparts. The comparison of energy and exergy efficiency for various improvement techniques is presented in Table 2.

Fig. 6 presents the saline water temperature and outer glass cover temperature of three stills. The peak value of both temperatures of all the three stills was recorded at 1 PM during the day of experimentation. ICSSAC, SSIAA and CSS recorded 69.8°C, 64.3°C and 68.7°C as peak saline water temperature, respectively. Similarly, the peak outer glass cover temperature of above stills was measured as 51.8°C, 50.2°C and 54.1°C, respectively. Diffusion of heat from the absorber

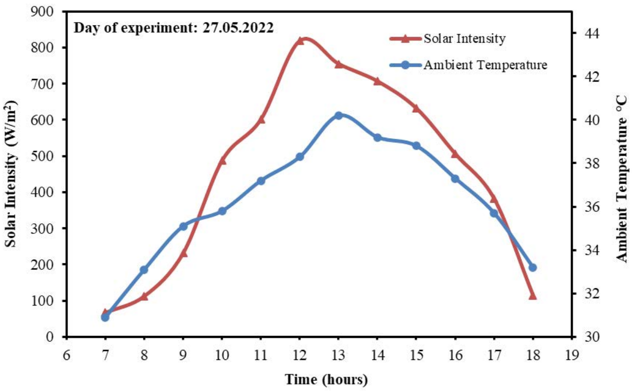

Fig. 3. Solar intensity and ambient temperature vs. time.

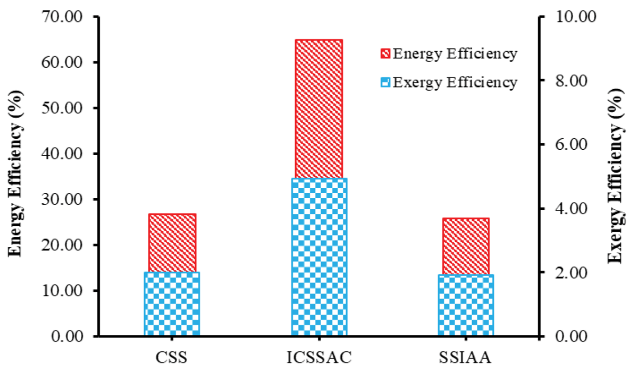

Fig. 5. Energy and exergy efficiency comparison of three stills.

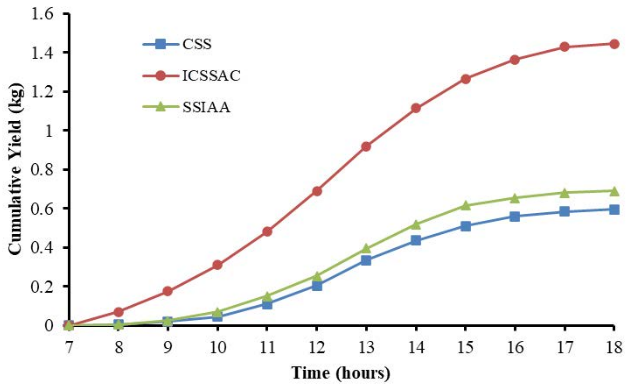

Fig. 4. Cumulative productivity of CSS, SSIAA and ICSSAC.

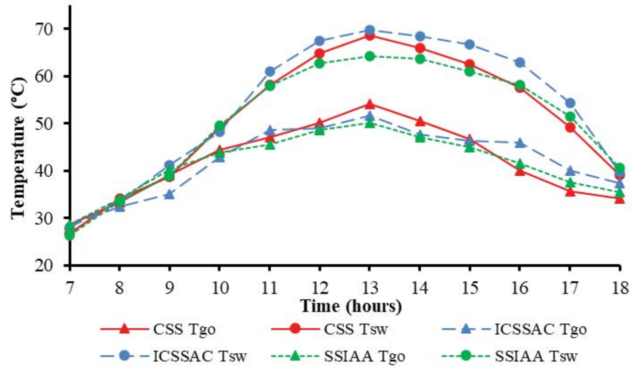

Fig. 6. Saline water and glass cover temperature of CSS, SSIAA and ICSSAC.

plate begins in post noon period after the intensity reaches its peak at 12 noon. This could be the reason for peak attainment during 1 PM. Saline water temperature of ICSSAC is higher than other two stills from 11 AM. The reason could be that the agitation effect had break the boundary layer of saline water surface leading to enhanced heat transfer from absorber plate to saline water. The glass cover temperature of ICSSAC after 3 PM is maximum, which could be due to continued yield of condensate through which latent heat of vapour is transferred to the glass cover.

Exergy destruction of basin with respect to time is presented in Fig. 7. The maximum exergy destruction vested with the basin for all the three stills was recorded during 12 noon. 'Exergy in' to the basin is from sun's radiation. As the intensity of solar radiation is maximum during 12 noon, the destruction is maximum during that time. Exergy destruction peak values were calculated as 527.09, 530.89 and 527.89 W/m^2 for CSS, SSIAA and ICSSAC, respectively. The total exergy destruction with the above-mentioned stills was calculated as 3,510.69; 3,591.83 and 3,477.09 W/m^2, respectively. Exergy destruction of basin in ICSSAC is less than other two stills as the agitation effect had enhanced the exergy out from basin to the basin water.

The hourly exergy destruction of basin water of all the three stills is plotted in Fig. 8. The total exergy destruction of basin water in CSS, SSIAA and ICSSAC are 365.28, 310.54 and 286.67 W/m^2. The condensate yield from ICSSAC is maximum when compared to other two stills which indicate that more basin water gets vaporized. Hence, the exergy destruction vested with basin water in ICSSAC is

Table 2
Productivity and performance comparison of various improvement techniques

S. No.	Author name	Type of solar still	Enhancement techniques	Productivity	Energy efficiency	Exergy efficiency
1.	El-Gazar et al. [48]	Solar still using hybrid nanofluid	Still without hybrid nanofluid	3.80 kg/m^2·d (in summer) 2.55 kg/m^2·d (in winter)	44.013% (in summer) 20.751% (in winter)	2.885% (in summer) 2.430% (in winter)
			Still with hybrid nanofluid	5.52 kg/m^2·d (in summer) 3.11 kg/m^2·d (in winter)	49.541% (in summer) 23.212% (in winter)	3.533% (in summer) 2.756% (in winter)
2.	Rajasekaran and Kulandaivelu [34]	Solar still with inbuilt condenser and agitator	CSS SSICA	2.444 L/m^2·d 4.856 L/m^2·d	31.25% 62.34%	2.04% 4.82%
3.	Vaithilingam and Esakkimuthu [55]	Single slope passive solar still	Passive solar still	1.485 kg	30.97%	3.48%
4.	Sharon [57]	Hybrid solar still	Basin solar still with vertical diffusion still	13.79 kg/d	56.17%	6.93%
5.	Dumka et al. [58]	Single slope solar still augmented with permanent magnets	CSS MSS	0.902 L/d 1.346 L/d	–	–
6.	Tuly et al. [59]	Solar still with nano-particle-mixed phase change materials	Conventional system Conventional system with PCM Modified system with ISR, HCF and nano-PCM	0.995 L/m^2 1.510 L/m^2 1.835 L/m^2	–	–
7.	Rabishokr and Daghigh [60]	Portable solar still with magnetic stirrer and thermoelectric	Modified still	1.550 L/m^2	28%	1.67%
8.	Rahmani et al. [61]	Solar still with external condenser	CSS MSS	2.59 kg/m^2 3.64 kg/m^2	18.25% 23.20%	2.4% 1.9%
9.	Arun Kumar et al. [44]	Solar still using agitation effect and external condenser	Conventional still Modified still	2.380 L/m^2 3.320 L/m^2	–	–
10.	Rabhi et al. [39]	Solar still with pin fins absorber and condenser	Conventional still Still with pin fins and condenser	2.380 L/m^2 3.492 L/m^2	–	–
11.	Present work	Inbuilt condenser solar still with inbuilt condenser and agitator	CSS SSIAA ICSSAC	2.380 L/m^2·d 2.760 L/m^2·d 5.780 L/m^2·d	26.70% 25.79% 64.80%	1.99% 1.92% 4.92%

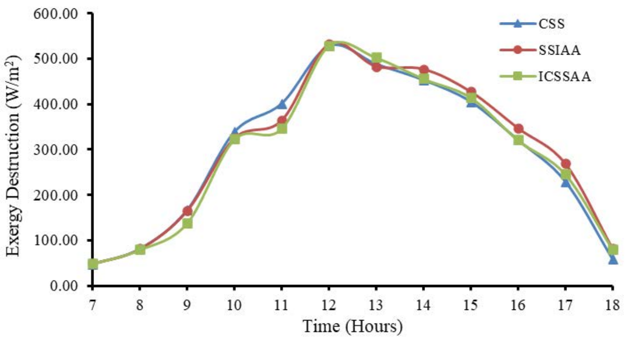

Fig. 7. Hourly exergy destruction of basin in three stills.

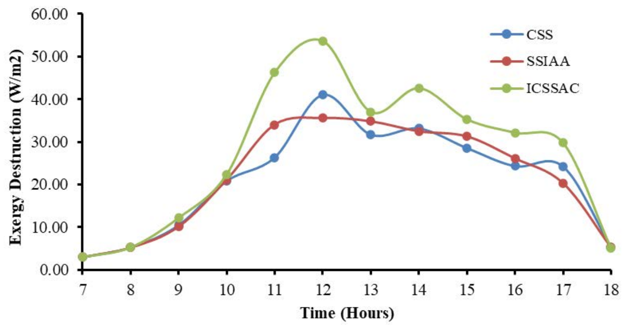

Fig. 9. Hourly exergy destruction of glass cover in three stills.

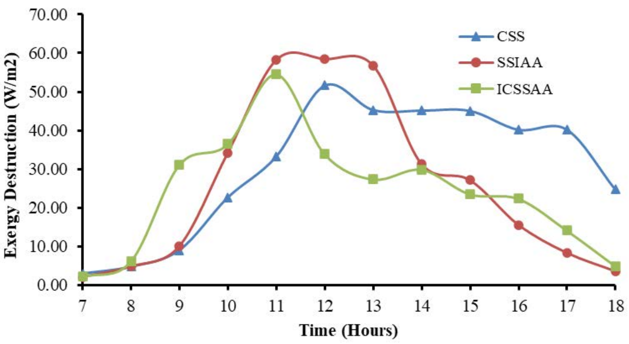

Fig. 8. Hourly exergy destruction of basin water in three stills.

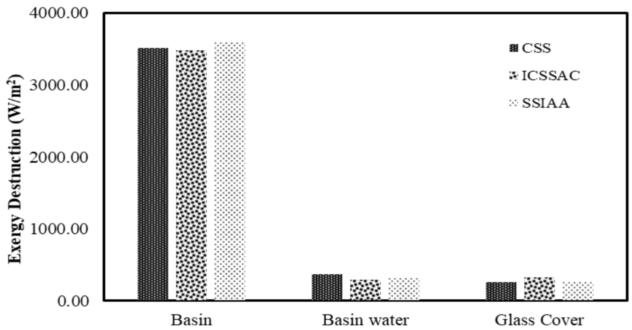

Fig. 10. Overall exergy destruction of basin, basin water and glass cover in three stills.

Table 3
Economic comparison between CSS, SSIAA and ICSSAC ($ value as on 28.06.2023)

Still	Life time (y)	Initial cost ($)	Annual maintenance cost ($) (5% of initial cost) [42]	Annual declination value ($)	Annual salvage value at end of 1st y ($)	Annual operating cost ($)	Yield (mL/d)	Annual profit in 1st year ($)
CSS	10	73.16	3.66	3.90	69.26	7.56	595	14.21
SSIAA	10	85.36	4.27	4.51	80.85	8.78	690	16.83
ICSSAC	10	121.94	6.10	7.93	114	14.02	1,445	38.84

low when compared to CSS and SSIAA. The peak exergy destruction in ICSSAC was during 11 AM which was calculated as 54.54 W/m². The maximum exergy destruction vested with basin water was calculated as 51.65 and 58.55 W/m² for CSS and SSIAA, respectively at 12 PM.

Exergy destruction in glass cover of all the three stills was calculated and is plotted in Fig. 9. The maximum destruction vested in CSS and ICSSAC was 40.99 and 53.67 W/m², respectively recorded at 12 PM. That of SSIAA was recorded at 12 PM was 35.57 W/m². The total exergy destruction of glass cover in ICSSAC was calculated higher than CSS and SSIAA. The reason could be that as the yield in ICSSAC is maximum, the 'exergy in' from condensate through latent heat is high to the glass cover. The total exergy destruction in glass cover of CSS, SSIAA and ICSSAC was calculated as 253.98, 2,259.29 and 324.43 W/m², respectively.

Fig. 10 compares the overall exergy destruction vested in the major components of three stills. As basin is the primary energy receiver from the sun and the conversion into useful energy is minimal, exergy destruction is maximum in basin of the solar stills. Further working on reduction in exergy destruction of basin will improve the productivity of solar still and in turn its efficiency.

5. Economic analysis

Distillate yield, operating cost, maintenance cost and salvage value of respective stills were considered to compare the economic analysis between three stills. Lifetime of the solar stills was considered as 10 y [44]. Economic analysis of three stills was calculated using the following formula [34]:

$$\text{Annual profit in } 1^{st} \text{ year} = \begin{pmatrix} \text{Annual yield} \\ \times \text{Cost of distillate per litre} \end{pmatrix} - \text{Annual Operating Cost}$$

where,

$$\text{Annual Operating Cost} = \text{Initial cost} + \text{Annual maintenance cost} - \text{Annual salvage value}$$

The annual declination value for solar still was considered to be 50% of the initial cost after its lifetime, which is considered as 10 y. The salvage value of glass cover, agitator, condensing fans and PV panel are considered as zero after 10 y. Considering the operational days of solar still to 300 d/y and cost of distillate to be \$0.12/L, economic analysis was carried out [34]. ICSSAC was economically more viable than the SSIAA and CSS. The economic comparison between three stills is shown in Table 3.

6. Conclusion

Conventional solar still (CSS), solar still with improved absorber area (SSIAA) and inbuilt condenser solar still with agitator and condensing fans (ICSSAC) were compared in this work. Agitator and condensing fans in ICSSAC were powered by a solar PV panel. To consider the impact of the absorber area of PV panel in ICSSAC, the absorber area in SSIAA was fixed as 0.3 m^2 whereas that of CSS and ICSSAC was fixed as 0.25 m^2. All the three stills were tested under same ambient. From experimentation, the yield of condensate in CSS, SSIAA and ICSSAC were measured as 0.595, 0.690 and 1.445 L/d, respectively. The increase in productivity of ICSSAC is due to increase in rate of evaporation and rate of condensation. Agitator breaks the surface boundary layer of water surface which leads to increase in evaporation rate. Inbuilt condenser increases the area of condensation for the same absorber area leading to improved condensate yield. The condensing fans fixed over the glass surface, removes the heat from the outer surface leading to increase in temperature difference between glass cover and water vapour. This increase in temperature, improves the rate of condensation in turn. Energy and exergy analysis were carried out for all the three stills. ICSSAC's energy and exergy efficiency were calculated as 64.80% and 4.92%, respectively. Energy efficiency of ICSSAC was 38.10% and 39.01% more than CSS and SSIAA, respectively. Exergy efficiency of CSS and SSIAA was calculated as 1.99% and 1.92%, respectively. Economic comparison reveals that ICSSAC is more efficient when compared to CSS and SSIAA. Exergy destruction analysis in three stills revealed that the maximum exergy destruction is vested with basin when compared to basin water and glass cover. Working on reducing the exergy destruction in the basin will have good scope for improving the performance of solar stills.

Symbols

Ex_{sun} — Exergy from sun, W/m^2
Ex_{w} — Exergy utilized to heat saline water, W/m^2
$\text{Ex}_{\text{ins.}}$ — Exergy loss through insulation, W/m^2
$\text{Ex}_{\text{des.},b}$ — Exergy destruction in basin, W/m^2
$\text{Ex}_{\text{des.},w}$ — Exergy destruction in water, W/m^2
$\text{Ex}_{\text{des.},g}$ — Exergy destruction in glass, W/m^2
$\text{Ex}_{t,w-g}$ — Total exergy associated with saline water and glass cover, W/m^2
$\text{Ex}_{e,w-g}$ — Exergy associated with water and glass through evaporation, W/m^2
$\text{Ex}_{c,w-g}$ — Exergy associated with water and glass through convection, W/m^2
$\text{Ex}_{r,w-g}$ — Exergy associated with water and glass through radiation, W/m^2
$\text{Ex}_{t,g-a}$ — Total exergy associated with glass cover and atmosphere, W/m^2
$\text{Ex}_{c,g-a}$ — Exergy associated with glass cover and atmosphere through convection, W/m^2
$\text{Ex}_{r,g-a}$ — Exergy associated with glass cover and atmosphere through radiation, W/m^2
m_w — Hourly distillate yield, kg
τ_g — Transmittance of the glass cover
τ_w — Transmittance of the saline water
α_b — Absorptivity of the basin
α_w — Absorptivity of saline water
α_g — Absorptivity of glass cover
T_a — Ambient temperature, K
T_s — Temperature of sun, K
T_b — Basin temperature, K
T_w — Basin water temperature, K
T_{gi} — Inner glass cover temperature, K
T_{go} — Outer glass cover temperature, K
I_t — Solar intensity, W/m^2
h_w — Convective heat transfer coefficient between basin and saline water, W/m^2·K
h_b — Convective heat transfer coefficient between basin and atmosphere, W/m^2·K
$h_{e,w\text{-}g}$ — Evaporative heat transfer coefficient between water and inner glass cover, W/m^2·K
$h_{c,w\text{-}g}$ — Convective heat transfer coefficient between water and inner glass cover, W/m^2·K
$h_{r,w\text{-}g}$ — Radiative heat transfer coefficient between water and inner glass cover, W/m^2·K
$h_{c,g\text{-}a}$ — Convective heat transfer coefficient between glass cover and atmosphere, W/m^2·K
$h_{r,g\text{-}a}$ — Radiative heat transfer coefficient between glass cover and atmosphere, W/m^2·K
$\omega_{\eta\text{energy}}$ — Mathematical uncertainty of energy efficiency, %
$\omega_{\eta\text{exergy}}$ — Mathematical uncertainty of energy efficiency, %
η_{energy} — Energy efficiency, %
η_{exergy} — exergy efficiency, %
ΣI_t — Total solar intensity, W/m^2·d

Abbreviations

CSS — Conventional solar still
SSIAA — Solar still with improved absorber area
ICSSAC — Inbuilt condenser solar still with agitator and condensing fans

CRediT authorship contribution statement

Arun Kumar Rajasekaran: Conceptualization, experimentation, analysis of data, writing the first draft.

Kalidasa Murugavel Kulandaivelu: Conceptualization, interpretation of data, writing the final draft.

Declaration of competing interest

The authors do not have any conflict of interest.

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