Performance comparison of solar still with inbuilt condenser and agitator over conventional solar still with energy and exergy analysis

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Abstract
Demand for fresh water increases day by day. Solar desalination is one of the promising technologies to meet this demand in an economical fashion which uses solar still. For the current study, single-basin single-slope conventional solar still and a modified single-basin single-slope solar still with inbuilt condenser and agitator were designed and fabricated. Both the stills were tested under the same ambient conditions to compare the performance. Through experimental results, it was found that modified still with inbuilt condenser and agitator had 98.69% more productivity than conventional solar still. Modified still productivity was recorded as 4.856 L/m²/day and that of conventional still was 2.44 L/m²/day. The agitation effect caused by the agitator in the modified still led to an increase in the rate of evaporation. The increase in condensing area for the same evaporation area of the modified still improved the condensation rate. These two synergized effects resulted in an overall performance improvement of the modified still over the conventional still. An energy analysis revealed that modified still is 24.42% more efficient than its counterpart. The energy efficiency of modified and conventional stills was calculated as 4.82% and 2.04% respectively.

Keywords Solar still · Desalination · Inbuilt condenser · Agitator · Exergy · Energy

Nomenclature

| Symbol | Description |
|--------|-------------|
| 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_g   | Glass Cover Temperature (K) |
| I_t   | Solar Intensity (W/m²) |
| h_w   | Convective heat transfer coefficient between basin and saline water (W/m² K) |
| h_b   | Convective heat transfer coefficient between basin and atmosphere (W/m² K) |
| h_c,w,g | Evaporative heat transfer coefficient between water and inner glass cover (W/m² K) |
| h_c,w,g | Convective heat transfer coefficient between water and inner glass cover (W/m² K) |
| h_r,w,g | Radiative heat transfer coefficient between water and inner glass cover (W/m² K) |
| h_c,g-a | Convective heat transfer coefficient between glass cover and atmosphere (W/m² K) |
| h_r,g-a | Radiative heat transfer coefficient between glass cover and atmosphere (W/m² K) |

Introduction
Demand for fresh water increases exponentially day by day. In spite of being primary need, accessibility to potable water has become a challenge as the population of the world increases. The United Nations High Level Political Programme on Sustainable Development took ‘Water and Sanitation’ as the theme for the year 2018 and reports that over 2 billion people across the world are experiencing high water stress. Though
70% of earth surface is covered with water, humans are not able to access fresh water (El-Samadony and Kabeel 2014). Basin type solar still is one among the promising technologies that can address the water scarcity. The problem associated with solar still is its least productivity. The productivity of solar stills is influenced by various parameters (Muftah et al. 2014; Prakash and Velmurugan 2015; Sharshir et al. 2016). Improving rate of evaporation and rate of condensation increases the distillate production in a solar still. Researchers across the world progress in improving the productivity of passive and active solar stills by adopting different techniques that influence the rate of evaporation and rate of condensation of solar stills (Manokar et al. 2014). Review done by Bhargya and Yadav (2021) revealed that maximum productivity of the still is achieved for minimum water depth. Singh et al. (2021) reviewed the design and operational and environmental characteristics on solar still performance. Performance enhancement techniques associated with new designs and modifications in a passive solar still were reviewed by Mhosenzadeh et al. (2021) and Akkala and Kaviti (2022). The optimized level of four operational parameters (mass of heat storage material, basin water depth, basin cover thickness, and external mirror position) to obtain maximum production in a solar still was identified by Gnanaraj and Ramachandran (2022). Shoeibi et al. (2021) reviewed the techniques adopted for improving evaporation rate and condensation rate simultaneously. Historic review and recent progress in internal designs were reviewed by Mohiuddin et al. (2022). Review concluded that the dynamic modifications to a still give maximum yield.

Use of nanoparticles (Iqbal et al. 2021), wick type solar stills (Jobrane et al. 2021), and natural fibers (Suraparaju et al. 2021a; Suraparaju and Natarajan 2020; Suraparaju and Natarajan 2021b), improve the rate of evaporation reasonably. Fins and energy storage material incorporation too have impact on evaporation rate in solar still (Kabeel and Abdelgaied 2017; Shinde et al. 2020; Suraparaju and Natarajan 2021a). Among various efforts, introducing agitation effects to the saline water is having promising effects on rate of evaporation. Diab et al. (2021) reviewed the solar stills with rotating parts which breaks the surface boundary of basin water. Experimentation works on introducing agitation effect to basin water have proven increase in rate of evaporation. Omara et al.’s (2017) investigation reports that the use of water fan had improved the distillate yield due to increase in rate of evaporation. Essa et al. (2020) have done an experimental study on solar stills with flat and corrugated rotating discs at varying speeds which provided greater areal extent for evaporation. A higher distillate output of 124% was associated with corrugated discs with wick. Among the various integrations to conventional solar stills to improve its performance, Younis et al. (2020) had used a rotating drum within the conventional still to improve the yield. Based on comparison, system with smooth drum and system with rough drum had an improved yield by 198% and 431.1% respectively over the system without drums. The factors favoring the yield are rough surface, increased radius to length ratio, and increased angular speed of rotation of drum.

Increasing the condensing area will also have direct impact on solar still performance. The different techniques to improve the performance of enhanced condensation area in a solar still were reviewed by Patel and Modi reviewed (2020). Inclusion of a fan inside the still can improve evaporation rate by 25% and improved area of condensation had notable impact on productivity (Nayi and Modi 2018). Inclusion of external condenser along with rotating drum and carbon nano particles have increased productivity by 350% over conventional still at 0.1 rpm speed (Abdullah et al. 2019). Addition of inbuilt condenser is one of the methods to improve the rate of condensation for same absorber area.

The combined effect of increasing evaporation rate and condensation rate was investigated by Sathyamurthy et al. (2014). Studies on still with evaporation and condensation chamber showed that the still with PCM is 52% more efficient than still without PCM. Kumar et al. (2016) compared the performance of conventional solar still and still with agitation effect and external condenser. The combined effects led to 39.49% more distillate yield in modified still over conventional solar still. Impact of phase change material and external condenser on stepped solar still was investigated by Toosi et al. (2021). Results concluded that PCM and external condenser effect had improved productivity by 104% when compared to stepped solar still without PCM and external condenser. Rabhi et al. (2017) studied the performance of single basin solar stills with pin fins absorber and condenser. The modified still used in the study had water production gain of 41.95% and efficiency gain of 12.9% over conventional still.

The performance of solar stills can be assessed using various models including mathematical modeling and theoretical modeling. Energy and exergy analysis gives a clear picture about the effectiveness of the solar still. Many researchers have carried out both energy and exergy analysis for the respective experimental set-ups. For a better accuracy in results, studies on solar still were conducted only during summer. Amiri et al. (2021) studies proven that high temperature of ambient are conducive for energy efficiency and cold temperature of ambient is conducive for exergy efficiency. A theoretical performance analysis of a single slope passive solar still for energy and exergy models was carried out by Yousef et al. (2017). Sharshir et al. (2020) and (2018) analyzed the energy and exergy performance of solar still integrated carbon black and copper oxide nanoparticles. Rafeek et al. (2022) did an energy and exergy analysis on inclined solar panel solar still. Energy analysis for a hollow
finned absorber basin solar still with energy storage material was analyzed by Suraparaju et al. (2021c). Energy, exergy, and economic aspects of a solar still with composite material heat storage was analyzed by Kabeel et al. (2019) and Mevada et al. (2021) investigated for solar still with energy storage materials. Dumka et al. (2020) and (2018) too carried out energy and exergy analysis. It has been observed that maximum exergy destruction is with basin of solar still.

Research gap and current study

Literature findings reveal that the maximum exergy destruction is with basin of the solar still. Reducing the same will have an impact on the yield of the solar still. Further, scope for studies in combination of increasing the evaporation rate and condensation rate simultaneously is more. To increase the rate of evaporation and thereby to reduce the exergy destruction of the basin, an agitator is introduced which agitates the basin water, leading to increase in evaporation rate. An inbuilt condenser is introduced in this work for the same absorber area to increase the rate of condensation. To study the impact of combined effect of the modified system in the current work, energy and exergy analysis is done on major three components of the system—basin, water, and glass cover.

Experimentation

A single basin single slope conventional solar still (CSS) and a modified solar still whose performances are to be compared were fabricated. The modified still was designed with an inbuilt condenser and an agitator to agitate the basin water. The modified still is called as solar still with in-built condenser and agitator (SSICA). Both the stills were fabricated with the same absorber area of 0.25 m² (500 × 500 mm) using galvanized iron of 1.5 mm thickness. The lower wall of both stills was designed at 100 mm height and the higher end of SSICA was kept at 245 mm with 30° of inclination. Inbuilt condenser area of modified still is 0.125 m² (250 × 500 mm). SSICA is attached with an agitator coupled with a DC motor and a solar PV panel of area 0.03 m² (200 × 150 mm) which helps the agitator to agitate the surface water. The agitator set up with a length of 150 mm is introduced in the still from the bottom of the SSICA. Stills were painted black inside to ensure maximum absorptivity. Further, 25-mm-thick thermocole is fixed on all side walls and the bottom of both stills to minimize the heat loss. Figure 1a and b shows the schematic of CSS and SSICA respectively used in this work. Figure 2a and b shows the experimental setup used for the study in different views. CSS and SSICA were tested under same ambient conditions to compare the performance accurately. Readings were taken at an interval of 1 h during the experimentation time. Experimentation was carried out at Ramco Institute of Technology, Rajapalayam, India (9.4536°N, 77.5433°E) between 9:00 AM and 5:00 PM during sunny days in the month of June 2021. Water levels were maintained at 10 mm depth in both the stills. Temperatures of basin, basin water, glass cover, and atmosphere were measured along with solar intensity for every hour of experimentation period. The accuracy, range, and error limits of the instruments used are presented in Table 1.

Energy and exergy analysis of solar still components

Energy efficiency, exergy efficiency, exergy destruction of basin, basin water, and glass cover were analyzed for both CSS and SSICA in the current work. The formulae used for energy and exergy analysis (Eqs. 1 to 18) are given below (Vaiithilingam et al. 2022). Energy analysis helped in understanding the quantitative performance of the solar stills and the exergy analysis gives a view on the qualitative performance
each component. Equations 1 and 5 are used for calculating the energy and exergy efficiency of both CSS and SSICA. Equations 6, 10, and 15 are used to calculate the exergy destruction in basin, basin water, and glass cover respectively.

**Energy analysis of passive solar still**

\[ \eta_{\text{energy}} = \frac{m_w \cdot L}{(A_s \cdot \sum I_t \cdot 3600)} \]  

**Exergy analysis of passive solar still**

\[ \sum \dot{E}_{\text{sun}} - \sum \dot{E}_{\text{excp}} = \sum \dot{E}_{\text{dest}} \]  

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

\[ \sum \dot{E}_{\text{excp}} = \frac{m_w \cdot L \cdot \left[ 1 - \left( \frac{T_s + 273}{T_a + 273} \right) \right]}{3600} \]  

\[ \eta_{\text{Ex}} = 1 - \frac{\dot{E}_{\text{dest}}}{\dot{E}_{\text{sun}}} \]  

**Exergy analysis of three main components**

The exergy analysis of three major components of the still—basin, saline water, and glass cover were carried out individually.

**Basin**

The exergy in to the basin is from the Sun and the exergy out from the basin in through the insulation of the solar still and the exergy in to the basin water. Considering these exergies in and out, destruction vested in the basin is calculated.

\[ E_{X_{\text{bas,b}}} = \left( \tau_g \cdot \tau_w \cdot \alpha_b \right) E_{X_{\text{sun}}} - \left( E_{X_{w}} + E_{X_{\text{ins}}} \right) \]  

\[ E_{X_{\text{bas}}} = I_b \left[ 1 + \frac{1}{3} \left( \frac{T_b}{T_a} \right)^4 - \frac{4}{3} \left( \frac{T_b}{T_a} \right)^4 \right] \]  

\[ E_{X_{w}} = h_w (T_b - T_w) \left( 1 - \frac{T_w}{T_b} \right) \]  

\[ E_{X_{\text{ins}}} = h_b (T_b - T_a) \left( 1 - \frac{T_a}{T_b} \right) \]
Saline water

Exergy from the Sun and basin of the still is the input for water. Exergy released from water to vapor is the exergy out from water in the basin. Exergy destruction in water is calculated using these exergies.

\[ E_{x_{\text{des},w}} = (\tau_g \alpha_w) E_{x_{\text{sun}}} + E_{x_{w}} - E_{x_{t,w-g}} \]  

(10)

\[ E_{x_{t,w-g}} = E_{x_{t,w-g}} + E_{x_{t,w-g}} + E_{x_{t,w-g}} \]  

(11)

\[ E_{x_{t,w-g}} = h_{c,w-g} (T_w - T_{gi}) \left(1 - \frac{T_a}{T_w}\right) \]  

(12)

\[ E_{x_{t,w-g}} = h_{c,w-g} (T_w - T_{gi}) \left[1 + \frac{1}{3} \left(\frac{T_a}{T_w}\right)^4 - \frac{4}{3} \left(\frac{T_a}{T_w}\right)\right] \]  

(13)

Glass cover

Glass cover of solar still receives exergy through the Sun and from vapor when it releases the latent heat during its phase change to condensate. The exergy out from the glass cover is during the heat transfer to ambient air. These exergies in and out from the glass cover are considered for exergy destruction calculation in glass cover.

\[ E_{x_{\text{des},g}} = \alpha_g E_{x_{\text{sun}}} + E_{x_{t,g-a}} - E_{x_{t,g-a}} \]  

(15)

\[ E_{x_{t,g-a}} = E_{x_{t,g-a}} + E_{x_{t,g-a}} \]  

(16)

\[ E_{x_{t,g-a}} = h_{c,g-a} (T_g - T_a) \left(1 - \frac{T_a}{T_{go}}\right) \]  

(17)

\[ E_{x_{t,g-a}} = h_{c,g-a} (T_g - T_a) \left[1 + \frac{1}{3} \left(\frac{T_a}{T_{go}}\right)^4 - \frac{4}{3} \left(\frac{T_a}{T_{go}}\right)\right] \]  

(18)

Results and discussion

The temperatures of basin, basin water, glass cover, and atmosphere along with solar intensity and distillate yield were measured and were analyzed for the performance study. Overall energy and exergy study of each major component helped in analyzing the exergy destruction vested in each component which gives the scope for improvement further. The experimental results are presented below.

Trend of ambient temperature and solar intensity along the day of experimentation is shown in Fig. 3. The experimental values of solar intensity were found closer to average solar radiation of the geographic area. The maximum solar radiation falls between 12 PM and 2 PM. Peak value of solar intensity was recorded as 793 W/m² at 1 PM. As the Sun’s radiation falls almost perpendicular to earth’s surface, peak value was recorded at 1 PM. Similarly, the ambient temperature attains its peak value (38 °C) at 2 PM. As the earth re-radiates the absorbed heat during post noon, the maximum temperature falls around 2 PM.
Figure 4 shows cumulative yield of SSICA and CSS which were 4.856 L/m²/day and 2.44 L/m²/day respectively. Improvement in productivity of SSICA over CSS is due to agitator and introduction of inbuilt condenser. Introduction of inbuilt condenser increased the area of condensation for same absorber area. This led to increase in rate of condensation and in turn increase in productivity. Agitation effect caused by agitator increased surface area of contact with surrounding air by forming waves. This led to increase in evaporation rate. Further, stirring effect stimulates movement of water molecules along depth of saline water which may also be the factor for increase in evaporation rate. This increase in evaporation rate accounted in improvement of distillate yield. It was found that the maximum hourly yield of both the stills were between 12 and 3 PM as the Sun’s radiation was maximum during that time.

The temperatures of saline water and glass cover in both CSS and SSICA were measured and are presented in Fig. 5 with respect to time. The maximum temperature of saline water for CSS and SSICA were 64 °C and 72 °C respectively. Saline water of both the stills registered their maximum temperature at 2 PM during which the basin temperature was also at its peak. The reason for attainment of peak value around 2 PM could be the diffusion of heat from the absorber plate surface, after the solar intensity began to decrease around 1 PM after reaching its peak value. The highest glass cover temperature recorded in CSS and SSICA were 62 °C and 66 °C respectively. The glass temperature values of SSICA are higher than the glass temperature values of CSS after attaining its peak temperature. This reflection can be due to more rejection of latent heat from vapor to glass cover in SSICA when compared to CSS.

Energy and exergy efficiency of CSS and SSICA is compared in Fig. 6. SSICA comparison is made by including and excluding the solar PV area. Energy analysis was computed by considering the output distillate yield and input solar intensity to the solar stills. Total energy output from CSS during experimentation period is calculated as 369.69 W and the input received is 1183 W. The energy extracted from SSICA is calculated as 737.54 W. The input to SSICA including the PV area is 1324.96 W. The energy and exergy efficiency of CSS were calculated as 31.25% and 2.04% respectively. The values of the same for SSICA by including the solar PV area are computed as 55.67% and 4.31% respectively. The agitator in SSICA is powered through solar PV which also an absorber with an area of 0.03 m². By considering the solar PV area, the energy and exergy efficiencies of SSICA are found as 62.34% and 4.82% respectively. The combined effects of agitator and inbuilt condenser led to increase in energy and exergy efficiencies of SSICA over CSS.

Basin exergy destruction of CSS and SSICA for every hour is plotted in Fig. 7. The destruction of exergy in CSS and SSICA attains its maximum at 1 PM respectively. Peak values were calculated as 525.45 W/m² and 505.748 W/m² respectively for CSS and SSICA. Basin exergy destruction of SSICA is minimum than CSS during most of the time. This indicates that the agitation effect in SSICA had paved way for more energy transfer from basin to saline water than in CSS, leading to increase in productivity of distillate. At 12 noon, exergy destruction of basin in SSICA is higher than CSS because exergy out from basin of CSS to its insulation area is higher when compared to SSICA. This is due to higher temperature difference between basin temperature (62 °C) and ambient temperature (36 °C) at that time. The total exergy destruction of SSICA and CSS are 3044.68 W/m² and 3132.71 W/m² respectively.
Figure 8 pictures the exergy destruction of saline water of both the stills. The peak destruction of the stills was found around 1 PM of the day. The exergy destruction at 1 PM is calculated as 48.259 W/m² and 50.44 W/m² for SSICA and CSS respectively. As the solar intensity is maximum at 1 PM, the total input energy available to the saline water at the time is maximum and thus the exergy destruction reaches peak around 1 PM for both the stills. Exergy destruction sees a change in trend after 2 PM in which destruction in SSICA is more than CSS. The reason is that, the ‘exergy in’ to the water from basin in SSICA is higher when compared to CSS during the post noon period. The total exergy destruction of water in SSICA and CSS is 314.42 W/m² and 326.93 W/m² respectively.

Exergy destruction of glass covers in SSICA and CSS is figured in Fig. 9, which reached their respective peak value 48.72 W/m² and 40.15 W/m² close to 2 PM. The total exergy destruction of SSICA and CSS were calculated as 215.24 W/m² and 210.52 W/m². As the productivity of SSICA is maximum than CSS, the heat gained by the glass through latent heat from vapor will be more. Thus, total exergy destruction of glass in SSICA is greater than CSS.

Total exergy destruction of solar still components basin, water, and glass are shown in Fig. 10. It can be seen that the maximum exergy destruction is seen in basin of solar stills when compared to the others. Basin is the prime receiver of input solar energy in a solar still. As only a minimal portion of received energy is converted as useful energy, the destruction is maximum in basin. Agitation effect which led to increase in evaporation rate had reduced the exergy destruction in basin and water of SSICA. From the graph, it is evident that working on decreasing the exergy destruction in basin will help in improving the productivity of solar still.

![Exergy destruction of basin](image1.png)

**Fig. 7** Trend in basin exergy destruction of CSS and SSICA along the day

![Exergy destruction of water](image2.png)

**Fig. 8** Trend in saline water exergy destruction of CSS and SSICA along the day

![Exergy destruction of glass](image3.png)

**Fig. 9** Trend in glass exergy destruction of CSS and SSICA along the day

![Total exergy destruction](image4.png)

**Fig. 10** Total exergy destruction of solar still components
## Table 2 Comparison between the productivity for various evaporation and condensation improvement techniques

| Sl. No. | Author name                  | Type of solar still                                      | Enhancement techniques                                         | Productivity | Exergy destruction |
|---------|------------------------------|----------------------------------------------------------|----------------------------------------------------------------|--------------|--------------------|
| 1       | (Attia et al. 2021a)         | Single slope solar still with energy storage material    | - Conventional still                                           | 3.80 kg/m²   | –                  |
|         |                              |                                                          | Solar still with ESM                                          | 5.27 kg/m²   | –                  |
| 2       | (Attia et al. 2021b)         | Hemispherical and single-slope solar still               | - Single-slope solar still                                    | 3.640 L/m²   | –                  |
|         |                              |                                                          | Hemispherical still                                          | 5.380 L/m²   | –                  |
| 3       | (Dubey and Mishra 2021)      | Double slope solar still augmented with dye, pebbles and metal chips | - Double slope solar still                                    | 1.567 kg     | Basin–289.72 W Water–17.00 W Glass–21.72 W Basin–322.13 W Water–17.54 W Glass–24.46 W |
|         |                              |                                                          | Modified double slope solar still                             | 2.012 kg     | –                  |
| 4       | (Vaithilingam et al. 2022)   | Acrylic solar still with and without copper fins         | - Acrylic solar still without copper fins                      | 3.75 kg/m²   | Basin–392.33 W/m² Water–70.41 W/m² Glass–30.50 W/m² Basin–424.33 W/m² Water–42.25 W/m² Glass–39.58 W/m² |
|         |                              |                                                          | Acrylic solar still with copper fins                          | 5.08 kg/m²   | –                  |
| 5       | (Suraparaju et al. 2021b)    | Solar still using ball marbles                           | - Sunny days                                                 | 2.950 kg/m²  | –                  |
|         |                              |                                                          | Cloudy days                                                  | 2.150 kg/m²  | –                  |
| 6       | (Suraparaju and Natarajan 2021c) | Single-slope solar still with PCM                  | - Conventional still                                          | 2.885 L/m²   | –                  |
|         |                              |                                                          | Solar still with hollow finned absorber inserted in energy storage | 4.085 L/m²   | –                  |
|         |                              |                                                          | Solar still with solid finned absorber inserted in energy storage | 3.485 L/m²   | –                  |
| 7       | (Natarajan et al. 2021)      | Solar still (SS) with low-cost and eco-friendly materials | - Conventional still                                          | 2.250 L/m²   | –                  |
|         |                              |                                                          | Molasses powder                                              | 2.383 L/m²   | –                  |
|         |                              |                                                          | Rice husk                                                    | 2.467 L/m²   | –                  |
|         |                              |                                                          | Saw dust                                                     | 3.033 L/m²   | –                  |
|         |                              |                                                          | Bamboo straw                                                 | 2.700 L/m²   | –                  |
|         |                              |                                                          | Banana leaf stem                                             | 2.683 L/m²   | –                  |
|         |                              |                                                          | Rice straw                                                   | 3.367 L/m²   | –                  |
| 8       | (Dhivagar et al. 2021)       | Solar still using block and disc magnets                 | - Conventional still                                          | 2.15 L/m²    | –                  |
|         |                              |                                                          | Still using block magnets                                    | 3.15 L/m²    | –                  |
|         |                              |                                                          | Still using disc magnets                                     | 2.82 L/m²    | –                  |
| 9       | (Balachandran et al. 2021b)  | Solar still with and without insulation                 | - Conventional still                                          | 1.93 L/m²    | –                  |
|         |                              |                                                          | Still with polystyrene insulation                              | 2.58 L/m²    | –                  |
|         |                              |                                                          | Still with fibre insulation                                   | 3.26 L/m²    | –                  |
| 10      | (Balachandran et al. 2021a)  | Single slope novel stepped absorbable plate solar stills | - Conventional still                                          | 2.47 L/m²    | –                  |
|         |                              |                                                          | Stepped absorbable plate solar still                          | 3.05 L/m²    | –                  |
| 11      | (Sathyamurthy et al. 2015)   | Portable solar still with evaporation and condensation chamber | - Still without PCM                                           | 1.053 kg     | –                  |
|         |                              |                                                          | Still with PCM                                               | 1.600 kg     | –                  |
| 12      | (Kumar et al. 2016)          | Solar Still using agitation effect and external condenser| - Conventional still                                          | 2.380 L/m²   | –                  |
|         |                              |                                                          | Modified still                                               | 3.320 L/m²   | –                  |
| 13      | (Toosi et al. 2021)          | Stepped solar still with phase change material and external condenser | - Single stepped solar still                                  | 665 ml/day   | –                  |
|         |                              |                                                          | Stepped solar still with an external condenser                | 797 ml/day   | –                  |
|         |                              |                                                          | Stepped solar still with PCM                                  | 878 ml/day   | –                  |
|         |                              |                                                          | Stepped solar still with PCM and external condenser           | 1300 ml/day  | –                  |
| 14      | (Rabhi et al. 2017)          | Solar still with pin fins absorber and condenser        | - Conventional still                                          | 2.380 L/m²   | –                  |
|         |                              |                                                          | Still with pin fins and condenser                              | 3.492 L/m²   | –                  |
Through exergy destruction analysis, it is evident that the destruction in exergy lies maximum with basin. Improvements ensuring decrease in exergy destruction in basin can lead to performance improvement in solar still. Few efforts taken in increasing the performance of solar still is presented in Table 2 and the same is compared with present work.

### Economic analysis

The economic analysis between the CSS and SSICA were compared by considering the yield of distillate, operating cost of both solar stills, maintenance cost of the stills, and the salvage value of the stills after life time. The average life time of the solar stills are considered as 10 years. Economic analysis is made using the following formula: (Kumar et al. 2016)

\[
\text{Annual profit in 1st year} = (\text{Annual yield} \times \text{Cost of distillate per liter}) - \text{Annual operating cost}
\]

where,

\[
\text{Annual operating cost} = \text{Initial cost} + \text{Annual maintenance cost} - \text{Annual salvage value}
\]

Annual maintenance cost of both the stills CSS and SSICA were considered as 5% of initial cost. The maintenance cost was calculated as Rs.300 and Rs.475 for CSS and SSICA respectively. Considering the salvage value of still after 10 years of life as 50% and that of glass cover, agitator, and PV panel are considered to zero after life time. The annual declination value of CSS and SSICA is Rs.320 and Rs.570 respectively. Rs.620 and Rs.1045 is the annual operating cost of CSS and SSICA respectively. Considering the market price of distilled water as Rs.10 per liter and operational days in a year as 300, the annual profit at the end of year 1 is calculated as Rs.1210 for CSS and Rs.2600 for SSICA. The economic analysis gives a conclusion that SSICA is having more economic significance than CSS. The economic comparison between the stills is shown in Table 3.

### Conclusion

Conventional solar still (CSS) and solar still with inbuilt condenser and agitator (SSICA) were compared. Introducing in-built condenser increased the condensation area for same evaporation area. Agitator increases evaporation rate by agitating basin water to increase its surface area of contact with surroundings. Both stills were fabricated and experimented at Ramco Institute of Technology, Rajapalayam, India (9.4536° N, 77.5433° E) with a water depth of 10 mm. Experiment was carried out under same ambient condition to assess the performance exactly. SSICA yields 4.856 L/m²/day distillate and CSS yields 2.444 L/m²/day. The improvised yield in SSICA was due to agitation effect and introduction of inbuilt condenser. Performance of SSICA and CSS were analyzed by comparing their energy and exergy efficiency. Energy analysis revealed that SSICA is 24.42% more efficient than CSS when considering solar PV area and 31.10% more efficient when excluding the solar PV area. Exergy efficiency of CSS is 2.04%. The same for that of SSICA is 4.31% when solar PV area is included and 4.82% when solar PV area is excluded. Exergy analysis reveals that minimizing the exergy destruction in basin is having more scope to improve the efficiency of the still. Total daily exergy destruction of basin in SSICA and CSS were calculated to be 3044.68 W/m² and 3132.71 W/m² respectively. Exergy destruction of water and glass in CSS are 326.93 W/m² and 210.52 W/m² respectively and that of SSICA are 314.42 W/m² and 215.24 W/m² respectively. Economic analysis was carried out in the work, which revealed that economic significance is more with the modified SSICA when compared to CSS.
Author contribution Arun Kumar carried out the experimentation for evaluating the performance of the system and prepared the first draft of the manuscript. Kalidas Murugavel contributed to the designing of system and experimentation and reviewed and prepared the final draft of the manuscript.

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