V-Type solar still integrated with hybrid solar concentrator

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Abstract: In this paper, the experimental performance of a “V” type solar still coupled with a hybrid solar concentrator (HSC) and Heat exchanger (HX) are presented. A high yield, inexpensive solar desalination system is constructed almost entirely from salvaged components. Even though it requires a mild maintenance, the necessary skills of operation are rudimentary and the cost of maintenance is low. The HSC focuses the solar radiation to a particular area and it offers a higher concentration ratio than conventional linear focus types. The HX is placed on the focus of the HSC and is connected to the basin of the “V” type solar still. A higher basin water temperature will be achieved by the “V” type solar still due to the additional heat from the HX, causing the brackish water to evaporate leaving behind all the contaminants. When comparing the performance analysis of “V” type solar still to that of the same still incorporated with the HSC, the efficiency of the latter improved from 20% to 36%, the amount of distillate production per unit area increased 4.17 kg/m² to 7.42 kg/m² and the latter also experienced an 80% more total distillate productivity. The cost per liter of the distillate was also found to be 0.0027 $/ which is significantly cheaper than that from other conventional solar stills.

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We are currently working on perfecting a solar desalination system for economically disadvantaged areas where pure water is scarce. Different materials for PCM (phase change materials) and the effects of incorporating PCM to the still are being experimented and studied. Our primary aim is to increase the efficiency to more than 45% and to lower the overall cost. This research and those to ensue will contribute to the design and construction of recycled desalination units and in extrapolating it to a larger scale.

PUBLIC INTEREST STATEMENT

Construction of desalination plants usually requires substantially high investment which are a big hurdle to desalination in poor countries, where limited funds are already stretched too thin. The present study is an adequate starting point in fabricating an eco-friendly and effective desalination system from salvaged scraps, which runs on essentially endless solar energy to solve the drinkable water shortage in economically backward areas. The solar desalination system consists of a solar still and a hybrid solar concentrator. The solar still distils brackish water into drinking water by vaporization using the solar radiation and by condensation. The price per litre of desalinated water from this system was found to be a lot cheaper than that from conventional solar stills and is only about one tenth of the cost of typical bottled water in India.
1. Introduction

Areas without access to clean water are usually poverty stricken and do not have the necessary infrastructure to create and support large scale water purification plants. Since it is typically expensive to transport clean water to coastal regions and remote areas suffering from water scarcity, a reliable yet cost effective method of purifying brackish water is necessary. The objective is to construct an efficient and inexpensive desalination system which could solve the water crisis in these areas.

Ajay Vardhan et al., (2013) studied the efficiency of parabolic dish collectors under different seasons in Bhopal (M.P) India. They also reported the influence of meteorological parameters (such as Direct Normal Irradiance (DNI), wind, ambient air temperature, humidity etc.) on the performance of parabolic dish collectors. The concentrated solar thermal power system constructed follows that of conventional design of a parabolic concentrator with the receiver placed along the line between the center of the concentrator and the sun. The authors reported that the collector’s efficiency is maximum (90%) in the month of June at hour angle ~30°. Sharshir et al., (2016) conducted a detailed study of the influences affecting the solar still productivity, such as intensity of solar radiation, wind velocity, environmental temperature, glass—water temperature difference, glass cover angle, and area of absorber plate. A significant enhancement in solar still production (up to 273%) was felt when sponge cubes were used in the basin water, whereas using cuprous oxide nanoparticles increased the distilled yield by 133.64% and 93.87% with and without the fan respectively. Annual and seasonal performance analysis of a single slope passive solar still with different water depths and different inclinations of condensing cover have been analyzed by Anil & Tiwari, (2007a) and they reported that the combination of minimum water depth and 15° inclination of the condensing cover leads to maximum annual distillate yield.

Suneesh, Jayaparakash, Arunkumar et al., (2014) studied the “V” type solar still alongside a Cotton Gauze Top Cover Cooling (CGTCC) for water desalination with and without air flow over the glass cover. The results showed that the water production rate increased when the still was integrated with CGTCC (air-flow) and with CGTCC (water-flow), where the latter showed the highest production rate. Arunkumar et al., (2012) used a pyramid solar still coupled with a non-tracking compound parabolic concentrator (CPC) with the help of insulated pipes. The concentrator increased the water temperature up to 95°C and the assistance of concentrators increased yield to 3500 mL/m²/day. Suneesh, Jayaparakash, Kumar et al., (2017) studied the design, implementation and performance evaluation of a “V”—type solar still with the effect of wick tilt and coverage. The tilted wicks with partial coverage increased the temperature of the evaporating surface and the glass temperature was independent of the tilt angle. Arunkumar et al., (2017) have reported distillate yield of 7346 mL/m²/day with a compound parabolic concentrator-concentric circular tubular solar still (CPC-CCTSS) with phase change material. Kumar Sharma et al., (2022) studied the experimental investigation of a solar energy-based water purifier (SEBWP) of single slope type by incorporating N similar evacuated tubular collectors (ETCs) having series connections. They evaluated different parameters like energy metrics, productivity, cost of producing 1 kg of fresh water, and exergoeconomic and enviroeconomic parameters. The values of per kilogram cost of producing fresh water, energy payback time and exergy loss per unit Rs. were evaluated to be Rs. 0.95/kg, 1.72 years, and 0.128 kWh/Rs. respectively. Chaouchi et al., (2007) developed a theoretical model to calculate the absorber average temperature and the distillation flow rate. The results indicated that the distillate flow rate reached an average relative error of 42% and also showed that the design of the desalination unit...
needs to be improved with special emphasis on the absorber. Compared with the common parabolic trough solar concentrators, (Riffat & Karim Mayere, 2013) studied a new concentrator with two parabolic troughs which form a V-shape with the focal line at the bottom of the troughs. The collector system can have thermal efficiency up to 38% at 100°C operating temperature and the modelling showed that the collector is promising for small to medium scale desalination. A solar desalination unit was built by Otero Prado et al., (2016) by taking a dish concentrator as the heat source. For the mentioned dish, an external receiver was installed. The yield of distilled water varied between 4.95 kg/m²/day to 4.11 kg/m²/day. This simplified distillation system's yield per square meter provided sufficient drinking water to meet the daily needs of at least 2 adults. Davani et al., (2017) investigated the performance of a multi-staged water desalination still connected to a solar parabolic trough with focal pipe and simple HX (Al serpentine). The system produced about 3.6 kg of fresh water in 5 hours. Elsafty et al., (2008) developed a mathematical model for a solar still that uses parabolic reflector-tube absorber desalination technology. The mode is used to study the still production in different cases. The study revealed that by increasing the solar intensity, ambient temperature, reflector aperture area, efficiency of reflector material and evaporation increases the unit productivity. On the other hand, increasing wind velocity, saline water depth, condenser emissivity and condenser thickness have a small effect on productivity. The effects of dissimilarity of mass flow rate (mf) on energy metrics of double slope solar based water purifier (SEBWp) by incorporating N equal partially covered photovoltaic thermal (PVT) compound parabolic concentrating collector (NPVT-CPCs) having series connection keeping water depth 0.14 m were studied by Bandhu Singh et al., (2021). They reported that the value of energy payback time for double slope type SEBWp in active mode increased, while the life cycle conversion efficiency (LCCE) for the system diminished with the enhancement in the value of mf at a given value of water depth of 0.14 m. The effects of the variation of N on productivity of solar energy based single slope water purifiers integrated with alike partly covered compound parabolic concentrating solar collectors were studied by Raturi et al., (2021). They reported that the value of productivity increased with the increase in the number of collectors at given values of water depth and fluid flow per unit time. Negi et al., (2021) studied active and passive solar using phase change materials (PCM). They reported that the PCM along with nanomaterials have the capacity to improve the cost effectiveness and thermal performance as a whole and to enhance the overall productivity. Sanjay & Sinha, (1996) thermally analyzed a concentrator assisted regenerative solar distillation unit in forced circulation mode. The yield of the concentrator assisted regenerative solar still was much higher than passive/active regenerative or non-regenerative solar distillation system and the overall thermal efficiency increased with the flow rate of the cold water over the glass cover. To enhance the solar desalination productivity, (Emin Argun & Afsin Kulaksiz, 2017) developed a new system composed of a sequential flat plate and parabolic dish solar collector. The maximum desalinated water productivities were 1038 mL/m².h in autumn and 1402 mL/m².h in summer. Bhargya & Yadav, (2020) developed a modified solar still: a copper tube HX is installed in the still basin and waste engine oil is utilized as a working fluid in the evacuated tube collector (ETC) and HX circuit. The modified still was experimentally investigated at distinct water depths of 4 cm, 5 cm and 6 cm. The experimental results showed maximum daily productivity of 7.38 L/m².day and daily efficiency of 30.5% for the modified still at 4 cm water depth. Pearce & Denkenberger, (2006) modelled a compound parabolic concentrator (CPC) augmenting the solar radiation falling on a solar still. For reflector height 2.5 times the width of the still, the output per unit area per day roughly triples with only ~10% increase in cost and moderate maintenance (weekly tilts), so CPCs have a significant economic advantage in producing solar distilled water.

An effective yet cheap solar desalination system made almost entirely from scraps which could bring relief to water stressed areas suffering from an economic disadvantage is yet to be perfected. The present study is only a starting point to improve the performance of recycled desalination units and to extrapolate to a larger scale. This research and those to follow will
contribute to the design and construction of desalination systems made from salvaged parts. Future work includes incorporating bitumen as a phase change material (PCM) and multiple mirrors into the still. It is expected that nocturnal output and the efficiency will increase significantly.

The experimental study here involves (i) design and construction of the solar concentrator, a heat exchanger (HX) and the “V” type solar still (ii) comparison and performance analysis of the “V” type solar still with and without the HSC.

2. Experimental setup
The Hybrid Solar Concentrator (HSC) works by combining linear focus collector type technologies and point focus type technologies; it focuses the solar radiation reflected to a particular area instead of a point or a line as in the case of a trough type or a dish type concentrator, respectively. The HSC also offers a comparatively higher concentration power than a parabolic trough and a larger acceptance angle than a conventional dish type. This results in a reduced need of adjustments to track the sun without sacrificing the concentration of solar radiation. The HSC is an elliptical paraboloid (Figure 1), i.e. it is an ellipse in the x-z plane and a parabola in the x-y and y-z planes. The collector is designed with simple parabolic equations in Cartesian coordinates,

\[ y^2 = 4fx \]  

Figure 1. Different cross sections of HSC.

Figure 2. Geometrical parameters of HSC.
From equation (1), the height “h” of the parabola in terms of the focal length “f” and aperture diameter “a” is:

\[ h = \frac{a^2}{16f} \]  

(2)

The geometrical parameters of HSC are shown in Figure 2. The HSC was fabricated from salvaged metal pieces and has dimensions of major axis, minor axis and depth of 0.36 m, 0.17 m and
0.09 m, respectively. The surface was polished for better reflection. The joints connecting the base, rod and the concentrator were made as in Figure 3 so that the orientation and the inclination of the solar concentrator can be changed by adjusting the screws (dual axis tracking).

The HX (Figure 4) works as a receiver to the solar concentrator and is used to transfer heat from the solar concentrator to the saline/brackish water flowing through it. The HX can be oriented in different ways using screws and nuts in the two joints of the stand. It is made using condenser coils from a refrigerator salvaged from junkyard. The condenser coil is made from Bundy tube, which is a type of double-walled low-carbon steel tube manufactured by rolling a copper-coated steel strip through 720° and resistance brazing the overlapped seam in a process called Bundy welding. The “U” shaped ends of condenser coils are sawed off, stacked on top of each other and are interconnected. All surfaces except the bottom are coated with epoxy putty to minimize thermal loss while the bottom part is painted black for maximum radiation absorbance. The HX is 0.09 m long, 0.05 m wide, 0.04 m thick and has an inlet and an outlet.

The “V” type solar still consists of four main parts: steel basin, double glass cover, inlet and distillate collecting channel (see, Figure 5). The stainless-steel basin is painted black for maximum solar radiation absorbance. The bottom of the basin is rectangular in shape and has a length of 0.8 m, a breadth of 0.5 m and an area of 0.4 m². The basin has a height of 0.2 m at the two ends and 0.15 m at the middle. The double glass cover of length 0.41 m, breadth 0.5 m and thickness 3 mm is inclined at an angle of 15° horizontally. This inclination is used so that the maximum amount of incident solar radiation can reach the basin without the condensate falling before the collection trough. The collection trough of 0.06 m width is inclined towards the outlet and is attached 0.02 m below the place where the two pieces of glass meet. The glass is sealed airtight to the basin using silicone sealant. As the water inside the still heats up, the rate of evaporation
increases. The warm water vapor rises up and gets condensed as water droplets on the underside of the double glass cover. These droplets are free from nearly all impurities, as the contaminants are left behind in the basin. Due to the presence of gravity and inclination of glass cover, the water droplets trickle down into the collection trough, and are then channeled into an external storage container. The advantage of “V” type solar stills is that the trickle distance is only half of that of a conventional single slope solar still of similar dimensions. The efficiency “η” of a single basin solar can be calculated using,

$$\eta = \frac{ML}{1AT} \times 100\% \quad (3)$$

Where, “M” is the mass of the distilled output water in kg, “L” is the latent heat of evaporation of water in kJ/kg, “I” is the average solar irradiance experienced by the solar still in W/m², “A” is the sum of area of the base of the solar still and the area of collector surface in m² and “t” is the total time in seconds for which the solar still has operated.

The solar still is placed on an elevated platform, while the HX is placed at a lower elevation. Inlet and outlet pipes of 0.02 m diameter are welded in the bottom of the still as shown in Figure 6. The other ends of the pipes are connected to the inlet and the outlet of the HX. The HX placed at the focus of the HSC gets heated by absorbing the solar radiation falling on it. This heat is then transferred into the brackish water flowing inside the HX from the solar still. Since the HX is placed at a lower elevation than the base of the still, water circulation due to the density difference is generated. The cold water (higher density) will flow into the HX while the hot water (lower density) from the exchanger will flow up to the solar still placed at a higher elevation. The water circulation increases the temperature inside the still, thereby increasing its distilled water production. This configuration eliminates the need for a water pump, making the system passive.

3. Experimental procedure
The experimental study was conducted between 8.00 AM and 6.00 PM on the sunny days of December 2019 to February 2020 at the MES College of Engineering, Kuttippuram, Kerala, India. The experimental setup was suitably instrumented to measure different parameters. A vane type digital anemometer was used to measure the wind velocity with an accuracy of ±0.1 m/s. In the first part, a thermocouple was inserted inside the tube of the HX placed at the focus of the HSC and the variation of temperature with solar irradiance was recorded without connecting it to the solar still. The “V” type solar still was filled with brackish water up to 5 mm—10 mm and was maintained at a constant level. The long dimension of the still was placed in a north-south direction. The temperatures of the ambient, water and glass cover were gauged using a calibrated K type thermocouple connected to a digital temperature indicator. Thermopile pyranometer was used to measure the total solar irradiance and the conical flasks to measure the amount of distillate. These parameters were observed in 1-hour intervals between 8.00 and 18.00. Overnight cumulative yield was also determined. Similar performance analysis of the “V” type solar still without the HSC was also studied. Photographic and schematic views of the “V” type solar still with HX and HSC are shown in Figure 7a, b.

4. Results and discussion
Only the days with similar weather conditions are considered in the study. The wind speed varied from 0.1 to 4 m/s. The ambient temperature ranged between 27°C and 37.5°C. The interference from the clouds was minimal. The solar irradiance varied between 216 W/m² and 1115 W/m². Figure 8 shows the hourly variation of solar irradiance and temperature inside the dry HX with the average solar radiation received during the day being 356 W/m². The temperature of the HX ranged between 29°C and 218°C with the average value being 137°C and the peak occurring at
Figure 6. Schematic representation of water circulation inside the “V” type solar still.

Figure 7. (a) Photographic view of the “V” type solar still with HX and HSC (b) Schematic representation of the “V” type solar still with HX and HSC.
It can be clearly observed that the temperature of the HX increases as the solar irradiance increases until they reach their maximum values at noon and then starts to decrease with the decrease in solar irradiance.

Figure 9 shows the hourly variation of solar irradiance, the glass temperature and the water temperature of the “V” type solar still without HSC. The average solar radiation received during the day was 365 W/m². It can be observed that the temperatures of the system increase as the solar radiation increases until they achieve their maximum values around noon and then starts to decrease with decrease in solar radiation. The glass temperature ranged between 29.2°C and 50.4°C with the average value being 37.9°C and the water temperature ranged between 33.8°C and 50.4°C.
and 69.1°C with the average value being 51.2°C. Both the glass and the water temperatures peaked at 1.00 pm and the solar noon was observed to be at 12.35 pm.

Figure 10 shows the hourly variation of solar irradiance, the glass temperature and the water temperature of the “V” type solar still with the HSC connected. The average solar radiation received during the day was 362 W/m². The glass temperature ranged between 30.1°C and 56.3°C with the average value being 42.5°C and the water temperature ranged between 34.3°C and 79.7°C with the average value being 61.5°C. As observed before, both the temperatures peaked at 1.00 pm. As expected, the water and glass temperatures of the “V” type still without the HSC are lower than...
those of the “V” type still with HSC. Since the brackish water passing through the HX gets heated up, the overall temperature of the brackish water inside the basin attains a higher temperature, thus a higher evaporation rate is achieved. Consequently, the HSC leads to an increased productivity. The average glass temperature and the average water temperature of the “V” type still with the HSC were higher than that without it by about 4°C and 10°C, respectively.

Figure 11 shows the comparison of hourly variation of distillate yield of the “V” type solar still with and without the HSC. The water productivity increased from zero in the morning and reached its maximum value at 1.00 pm. The delay from solar noon is due to the thermal mass in the system. As expected, the maximum productivity occurs when the temperature of brackish water is maximum. Also, it can be observed that the fresh water productivity for the “V” type solar still with the HSC is greater than that without it. Experimentally, the daytime (8.00 to 18.00) yields for the “V” type solar still with and without the HSC were found to be 2620 ml and 1435 ml and the overnight (18.00 to 8.00 of the next day) yields were found to be 348 ml and 233 ml respectively. It can also be inferred from the data that the presence of the HSC has significantly increased the performance. The peak yield increased from 275 ml/h to 405 ml/h and the total yield increased from 1668 ml to 2968 ml with the coupling of the HSC to the still. Results also indicated that the efficiencies of the “V” type solar still with (M = 2.968 kg, L = 2260 KJ/kg, I = 362 W/m², A = 0.59 m², t = 86400s) and without (M = 1.668 kg, I = 365 W/m², A = 0.4 m², t = 86400s) HSC were 36% and 20% respectively. The integration of the HSC and the HX to the “V” type solar still increased the output by about 80%. The amount of water production per unit area of the “V” type solar still with and without the HSC are 7.42 kg/m² and 4.17 kg/m² respectively.

Single basin solar stills have a life expectancy of about 20 years if properly designed, constructed and maintained (Tiwari & Sahota, 2013; Kristoferson & Bokalders, 1986). Since this solar still is made from scraps, a conservative estimate of its lifetime should be about 10 years. Figure 12 shows the cost estimation for the components of the desalination system. Total cost of construction was 39.33 $. The estimated maintenance and repair cost over solar still’s lifetime were 13.20 $. The cost over solar still’s lifetime was estimated to 52.53 $. If average cumulative solar distilled water per day is 2.7 litres and India have 300 sunny days each year, the average solar distilled water over the solar still’s lifetime will be 810 litres. So, the price per litre of the solar distilled water will be 0.0027 $/l, which is very affordable. To put into perspective, the average cost of bottled water in India is about 0.26 $/l. Kabeel et al., (2010) studied 17 solar still configurations and found that the lowest cost of distilled water was obtained from the pyramid-shaped solar still (0.0135 $/l) while the highest cost was from the

| Components                        | Cost ($) |
|-----------------------------------|----------|
| Concentrator dish                 | 1.98     |
| Reflective window tint            | 1.06     |
| Silicone sealant                  | 2.77     |
| Matt black paint                  | 1.98     |
| Glass                             | 4.09     |
| Hoisting mechanism and other auxiliaries | 3.30 |
| Basin                             | 14.52    |
| Condenser coil                    | 2.51     |
| Aluminium tubes from old refrigerator | 0.53 |
| Labour                            | 2.64     |
| miscellaneous parts               | 3.96     |
modified solar stills with sun tracking (0.23 $/l). Emphatically, the cost per litre of distillate from these stills are higher than the cost per litre of distillate from the “V” type solar still with HSC.

5. Conclusion
From the performance analysis of “V” type solar still with and without the HSC and HX, following conclusions could be drawn:

(1) ) The temperature of the glass and the brackish water of the still with the HSC were higher than without it by about 4°C and 10°C.
(2) ) The total yields of the “V” type solar still with and without HSC were found to be 2968 ml and 1668 ml respectively
(3) ) With the incorporation of HSC and HX to the “V” type solar still, the efficiency increased from 20% to 36%, the amount of distillate production per unit area from 4.17 kg/m² to 7.42 kg/m² and an 80% more total distillate productivity
(4) ) The price per liter of desalinated water from this system was found to be 0.0027 $/l which is cheaper than that from conventional solar stills and is only about one tenth of the cost of a typical bottled water in India.

The present study is an adequate starting point in fabricating an eco-friendly and effective desalination system to solve the drinkable water shortage in economically backward areas and further work is needed to improve the yield and affordability of the desalination system.

6. Geolocation information
The still and all the systems were designed, fabricated, and tested in the Faculty of Fabrication, Department of Physics, MES College of Engineering, Kerala, India (Latitude 10.8299 °N & longitude 76.0228 °E).

Disclosure statement
No potential conflict of interest was reported by the author(s).

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