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RESEARCH ARTICLE

Experimental investigation on thermal augmentation methods for high-yield solar desalination systems

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Abstract

For saline or wastewater, solar distillation is a suitable, environmentally friendly technique for purifying water. The problem is that there is no distillation process that produces salt water, and that salt water used on plants may cause plant death. The techniques described in this work aim to enhance the solar distillation process using solar stills with a steam generator and a condenser. The distilled water was heated between 11 am and 4 pm, with best output of 1200 ml at 80-90°C. One method used to achieve faster evaporation is to increase the heating rate so that the temperature changes rapidly, such as 100°C/min, which results in lower total yields due to overheating. The novelty of this work is that the heating rate to the steam generator is increased, thereby increasing the overall temperature and the surface water temperatures of the solar still and the water surface. The other advantage of the extended heating for three hours was that it also resulted in higher yields, and sunlight alone did not guarantee that high temperatures were equivalent to moisture-loss temperatures above 41°C.Various thermal enhancement techniques were used in the study, including sensible heat storage synthesis, warming in an aquatic basin, and altering surface absorptivity. Furthermore, external thermal support to increase heat supply and improve thermal conduction pathways to the basin was designed to keep high temperatures throughout the low-light availability period. This study examined the effect on system efficiency and the performance comparison of different approaches to increase the efficiency of the solar dehydration process under realistic operating conditions. This study provides a scalable, energy-efficient, and renewable-energy solution to locally produce freshwater for the benefit of global health and climate goals.

Keywords: Solar still; distillation; evaporation; saline water; augmentation; cleaner energy; SDG goals

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1. Introduction

Distillation is one of the most important methods for obtaining fresh water from salt, brackish, or contaminated water. The process might use solar energy, a natural resource and a source of heat. Among the advantages of sunlight are zero fuel cost and its status as an environmentally friendly energy source, but more land is needed to produce distilled water, and the device is generally expensive to reach high temperatures [1]. No need to boil large volumes of water to distill it. Once collected, the wastewater undergoes an oxidation process to produce clean water. This saline water is usually directed into a gardening" steam generator, where it generates steam in a single container under pressure. The history of Solar water distillation is very long. The process began at the start of the 1700s, and solar stills were built 2000 years ago [2]. Solar distillation is the basic principle of solar stills. They are mainly used for purifying water. Several solar stills are used to treat seawater into potable water. Technology is a powered still that evaporates salt water and condenses it to yield clean water, which can be used for agriculture and small-scale irrigation. The solar still has no moving parts and is very simple. Solar stills are used

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to generate water when no rainwater or well water is available in remote houses or when power is off. It is used in conjunction with a parabolic concentrator and a plain plate collector and is part of a wastewater treatment plant. A set of different solar still designs was developed by several researchers [3,4]. They have used a single-slope solar still in comparison to a double-slope solar still. Various other researchers have also studied a flat-plate collector/solar still system. Our solar still consists of a steam condenser unit connected to a steam generator, which generates hot flue gases to raise the solar still's temperature. When the term 'intrusion' is used, however, it is not referring to fuel combustion – be it electrical or instantaneous – in the system that exists. It is the recovered low-quality heating energy combined with ultraviolet rays, directed to the reservoir water body. It is possible to use solar still input instead of waste electricity and wastewater. The gases emitted by the atmosphere are extremely polluting: CO_2, Hydrocarbons (HC), Nitrogen oxides (NOx), Carbon monoxide (CO), and Sulfur compounds. These types of flue gases will be hotter, making it easier to heat the solar still for distilled water production. The scientists have compared the productivity of a single-effect solar still with that of a multi-effect solar still under various conditions, design specifications, and operating parameters in Oman. In this experiment, brackish water is used to analyses a solar still [5]. The brackish water is stored in a basin with two sloping covers, both found at the Centre of the basin. There are two types of solar stills: single-basin and double-basin. In the present study [6], the use of single solar still basins for potable water distillation in the water-scarce region of Syria is explored. The study consisted of the conceptualization, fabrication, and testing of the solar stills, and it was found that the daily production of distilled water depends on the volume of water in the reservoir. The post-desalination water quality assessment showed the water was acceptable. The results of the study show that solar still basins can be a cost-effective way of producing potable water. They studied the design, manufacture and efficiency of an Active Solar Still coupled with a Solar collector for desalination in their research work [7]. The solar still has been changed to incorporate some of the most important features, including the stepwise basin, the heat storage pebbles and the water dispersion spray system. The outcomes show that solar still efficiency was 60% and that the average was 2.24 L/m^2/day. The amount of water in the basin and the amount of sunlight was also influential on water production in distilled water. In their study [8 ,9]. The study proves that a solar still with an octagonal-pyramidal shape can achieve twice the distillation rate of a conventional solar still. Various materials of different latent and sensible heat capacities are added to the octagonal-pyramid solar still to increase its performance [10]. The efficiency of the solar still is clear from its octagonal shape, which is superior to that of the traditional still under all conditions [11,12].

The absorber is installed in the still, with a yield of 2.85 litre/m^2, and without any installed part in the still, the yield is 2.1 litre/m^2. Also, the study found that the higher the water level in the basin, the more distilled water would be produced. The best basin depth was determined to be 4 cm, and the best result was obtained with the parabolic concentrator and a still at 5 cm depth, yielding a 35.7% increase in distillate yield. Based on the research outcomes, this unit can be installed in the Vijayawada area, India, as it receives adequate solar radiation. [13]. Research was carried out to perfect a solar distillation unit using an experimental approach. The purpose of this paper is to investigate the influence of various parameters on distillate production, including the type of system, water depth, heat storage material and salt content. Its results show that adding heat storage materials charcoal and reducing the salt concentration can substantially increase production. The use of charcoal as a heat-retaining and thermal-storage material in the experimental solar still system is due to its desirable physicochemical and economic properties. The research findings show that solar distillation can be one solution to the problem of inadequate drinking water supply in regions where freshwater sources are scarce. A thorough scientific analysis was conducted comparing the MSSS with the standard cylindrical distiller across four parameters: Energy, Efficiency, Economics, and Environment. Design variables chosen were the rotation rate (0.2-1.2 rpm) of the sphere and the material used to coat the sphere, and the material used underneath, which served as thermal storage material such as desert soil, minerals, or a combination of both. The constituent with 58% efficiency and a rotating velocity of 0.8 rpm 40% increase in production shows better performance, and, when combined with the above factors, yields a distillate with 76% efficiency and 59.5% [14]. The first solution was to bring in the spinning ball into the rotating sunlight still, thus making a rotary ball-sphere sunlight still, in contrast to the common circular sunshine still. The thermal power, activity and profitability of these two sunlight-powered stills have been investigated. The effects of different revolving accelerations and the presence or absence of the wick substance spread on the spinning ball have been examined. It was found that the best spin of the ball sphere in sunlight was 1 revolution per minute, and the maximum production was obtained. The ball sphere in sunlight was already proving a tremendous increase in effectiveness (37%) and (51%), while a spinning ball globe proved a 33% increase in effectiveness. Even with 1 revolution per minute and a rotary ball sphere [15], production increased by 57 per cent.

The study focuses on the performance enhancement of the conical solar heating device when the materials used for energy storage, such as glass spheres, steel, sandstone and black crushed stone, are added to the device. The results of the study show that aluminum balls are the best material to store energy in the cylindrical solar still. This increases the system's productivity and water production. The study offers a practical, cost-effective, energy-efficient solution to the challenge of water scarcity worldwide through solar desalination. Further research is needed to evaluate the addition of new materials and mixtures to enhance the distillation of renewable energy [16,17]. A detailed empirical study is carried out to evaluate the synergy of the focused solar thermal technologies by combining CSP technologies in rectangular daylight photothermal systems using honey extract as the phase change material heat collector. The split dataset consists of experimental controls: no PCM, PCM integrated, and data collection stages, which are iterative evaluations of the different results of the solar condensation systems [18]. The system's end efficiency (54%) and productivity (66.10%) show room for improvement. To achieve high efficiency and water production rates in solar desalination systems, a combination of PTC-enhanced thermal storage and metallic heat absorbers with phase change material is a promising approach. Academic interest in these thermodynamic and ultraviolet factors that enable this maximization of effectiveness stays [19,20]. A deterministic relationship between productivity and controlled temperatures under real conditions with variable temperatures. Most laboratory tests report continuous/false diurnal conditions. It is essential to conduct experiments to decide the effects of hourly short-term temperature fluctuations, driven by cloud cover, on the daily and weekly production and quality of groundwater. Proposed approach: very correct measurement of warmth and yield in 1-5 minutes over a wide range of hours and time periods [21,22]. A passive thermal storage system is not meant to store energy, but rather to increase the temperature. The bulk of studies on thermal mass research focus on increasing overnight output, while a smaller number focus on deciding how best to heat the stored energy to enhance conditions in the basin/glass during the most desirable afternoon. Propose an experiment to test various locations for the phase change materials, below the reservoir in the absorbent and near the glass and record the relative temperatures of the windshield and reservoir and exchange of the vapor [23,24]. A literature survey of methods for improving solar still performance is presented in Table 1.

Table 1. Literature review on solar still performance enhancement methods

S. No	Enhancement Technique	Research Gap Identified	Key Findings	References
1	Solar still with auxiliary heating	low-cost heating	Freshwater yield	[25]
2	Hybrid solar desalination systems	Scalability and energy utilization challenges	Improved overall efficiency	[26]
3	Basin-type solar still optimization	Limited focus on external heat integration	Improved productivity	[27]
4	Inclined glass cover optimization	Limited integration with steam condensation units	Better condensate collection efficiency	[28]
5	Nanofluids and PCM integration	Higher material cost and operational complexity	Enhanced thermal storage and evaporation rate	[29]

This is an experimental study that proposes a new hybrid distillation technique coupled with a solar still, a steam condenser, and a steam generator to boost freshwater production. This is compared to conventional solar stills, which rely exclusively on solar radiation. In this system, saline water (145 ppm) is heated in a steam generator, and the steam is forced through a steam separator and then a steam condenser. When hot flue gases are added to the condenser, the operating temperature of the solar still increases, thereby increasing the evaporation and condensation rates. Furthermore, the paper is unique in considering the impact of varying input current levels on the system's temperature, the efficiency of the condensation process, and the amount of distilled water produced. Through systematic experimentation and graphical analysis, this work has found a new relationship between thermal and electrical enhancement techniques, which can substantially improve the energy efficiency and productivity of traditional solar designs. The project is to develop a hybrid solar distillation system that will consist of a solar powered still, a steam generator, steam separation, and steam condensation, with maximum heat recovery and clean water production.

The reason is that the research aims to decide the effects of different electrical input currents (70 A, 80 A, 90 A, and 100 A) on the temperature distribution, evaporation rate, and distillate yield of the solar distillation system. To view the effect of the high level of emissions on the hot steam condensing, and the effect of strengthening the heating and temperature capacity of the PV cell while running. The operational scenarios include purified water produced from processed feeding water at 145 ppm, along with different scenarios to decide the drinkability and profitability of the purified water. To compare and display measurements taken at various amperages to decide the best conditions for maximizing energy use and yielding the most freshwater. The new work is an experimental demonstration of a tapered solar still consisting of a steam generator-condenser unit, where the steam condenser serves as a secondary heat augmentation to the solar still. The proposed design takes advantage of the recovered thermal energy from steam condensation to improve basin temperature and evaporation rates compared with a flat-plate or evacuated-tube collector in the earlier active solar still design. This system has been integrated to enable distillate production even in low-solar-intensity conditions and after cooling down the heating processes; hence, the system's productivity has been enhanced. The proposed design is a simple, low-cost, and scalable system that does not require solar collectors, pumps, or phase change materials. This innovation differs from conventional active solar stills that use active plates or electric fireplaces for heating, as it uses waste flue gases from abroad. The incorporation takes advantage of a second-hand heat exchanger under the storage tank, without requiring any circulation to be pumped or any extra space that needs to accept the sun. The results show that modifications to the still geometry, steam flow rate, and thermal storage units, as well as the integration of the whole system with solar thermal energy, could improve system performance.

2. Methodology

The experimental approach is illustrated in Figure 1. The assembly and fabrication were carried out at Vel Tech University. All experiments were run from 11 am to 4 pm, with an evaporation area of 0.066 m^2 at this normal productivity. From the point of view of radiation intensity, this is a period during which good results are obtained. A detailed method for designing, constructing, experimentally studying and reliability testing the PV still in the interconnection with the steam source and condensing is described in this section.

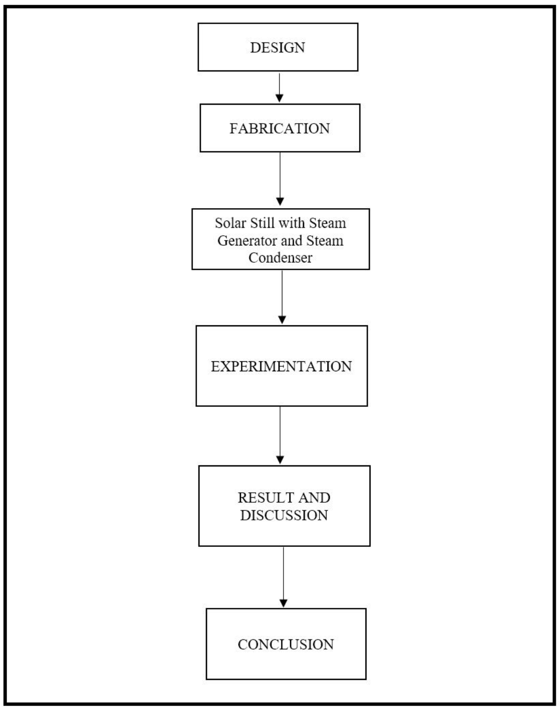

Figure 1. Flowchart of workflow

2.1. Design

The main condensation operations were performed with an easily accessible rectangle steaming evaporator. Conventional condenser technologies with correct angle conical configuration were used to reduce steam contamination. This conical condensate differs from the traditional unit as it's designed to prevent vapor from escaping at the connections. The next section describes the advanced solar cell layout in detail to increase the production of potable water. The determination procedure is complex and is designed to maximize the blend of absorbent sheet substrate, angle of covering glass and insulation coatings. An analysis is conducted on scientific premises of as well as heat transport that governs sunlight, vaporization, wetness creation, and rainfall. The condensing unit and vapor generating systems are designed for efficient use with the solar still, maximizing the temperatures and the transfer of steam in rainfall. The solar energy still is made up of elements that meet the strength and cost requirements of recognized design specifications. Special focus is given to the use of vapor-proof gaskets to prevent evaporation, and proper assembly and adequate thermal insulation.

2.2. Schematic diagram

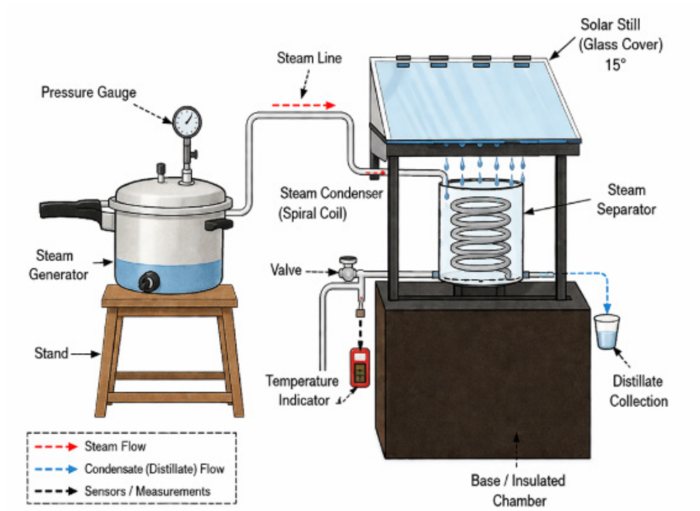

Figure 2. Schematic diagram

The layout design of exploration of the sun's still, the power source outside ultraviolet, however, proves in Figure 2. This is a construction forming of moisture inside the engine and a tension gauge to measure internal pressure. The gas is delivered by a moisture line, and an ownership valve controls the circulation of the gas. The outcome moisture is compelled to a spiral-coil condenser in the sunlight nevertheless room. The suns still protect is cocked at fifteen degrees with encourage effective condensing and distillates rainfall. The moisture flows through the condensers which lose heat in the process, thus offering a way to condense onto the cooler, inner components and the window surround. The liquid droplets have been further decreased along with will be moved to the willing surface, lower to the distillates the outlet. The system also involves a moisture separator to guarantee successful division about the water and additionally shipping for the power source steam. The thermostat is equipped to constantly see the personal warmth. Insulating in the based space allows minimizing heat reduction as well as boosting heat effectiveness. It is a hybrid structure designed to optimize operation parameters of steam-assisted solar extraction and enhance production of existing waters.

3. Experimental setup

3.1. Solar still assembly

Sheet metal was rolled, and tungsten inert gas and gas welding were used to construct the solar still. The first step was to form a sheet metal panel to fit the requirements of the solar remains (560 mm × 560 mm). Later, it was combined with a cone-shaped solar distillation unit. The basin dimensions of 560 mm × 560 mm were selected to maximize the use of resources and to make the academic building easy, as well as to get an acceptable area of basins of 0.313 m². This kept the test equipment relatively compact and helped to produce a significant amount of distillation. The reduction in the size of the lower basin will help evaporation processes as the amount of thermal energy being stored is reduced, thus allowing the water to heat up faster. The selected size guarantees an even exposure of the basin surface to the Sun and reduces loss of thermal energy from the rim of the basin. The 560 mm diameter is easy to handle considering the conventional matrices and therefore reducing production and loss. The rectangular design provides for the efficient conveyance of heat and is esthetically appealing. The surface thickness of an aluminum sheet is 2 mm, and its size is 75 x 75 mm, which was cut into a measurement length of 310 mm and a circumference of 240 mm and then rolled into a rectangular shape with the help of rotating machinery. The steel sheets were stretched to create a cylindrical shape. A right-angle cone from the barrel was TIG welded to an existing steam-powered condensate. The solar generating still was connected to the heat condensation by TIG welding method. The heat inlet/outlet pipe and heat splitter were installed for the steam generating condensation. This results in steam being produced by the generating device and is reduced to obtain from the apparatus. The top portion of the sunlight was covered with an acrylic substrate, which was bonded with a standard bonding and rubber bonding.

Figure 3. Pictorial view of assembled solar still

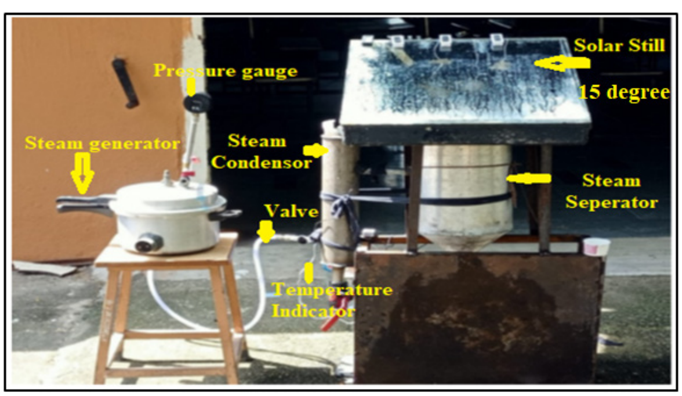

Figure 4. Pictorial view of solar still with steam generator

The distilled water is discharged from the steam condenser through a pipe. The distilled water is discharged from the steam condenser through a pipe known as the discharge pipe. The upper and lower parts of the pipe are welded, and dummy parts are used to attach a steam separator to both ends with a length of 400 mm and a diameter of 30 mm. The steam separator has a valve at the bottom to allow water generated in the steam generator to pass through the separator. This is a schematic diagram of a solar still and a steam generator connected, with the steam generator coupled to a steam separator via a pipe. The large, inclined metal plates at the top are likely a screen to warm the water or a collector of sunlight, as shown in Figure 3. The gradient is used to get the maximum exposure. When distilling, allow the distillation to drip. The dark color is more efficient in absorbing the heat. If there is too much rain or moisture, water droplets will be created. On the roof, there are 4 small, oblong shapes. This is like adiabatic but shows circuits/detectors. The clear temperatures of the water and steam appear to be what they are seeing. The major operating compartment can be the spherical barrel at the bottom of the plating. The tasks could include Water storage to harvest and store solar energy, a heated storage tank, and a research vessel with an evaporator, heater, and bubbles. The bottom is the spherical form to allow accumulation and reprocessing of aqueous effluents. The foundation is a rectangle and is rust colored. Builds Dependability, removes the lower conical part, provides easy access, and conducts investigations. The prototype is a hybrid solar heating system where steam generation is done by solar heat and controlled by supercharging steam to enhance the purification efficiency of water, as shown in Fig. 4. The pressure generated by the steam in the device is measured by a sensor and fed into a controlled thermostatic valve sign system to keep the operating conditions in the meteorological field. This flow then goes to the oxygen separator, where the water is separated, leaving only dry, hot steam, which is sent to the condensate collector, allowing added heat exchange and increasing the efficiency of the condensation process. The fluid flowing in the photoelectric still and the condensed sunlight are, therefore, further enhancing the spirit production and purity in the photoelectric still. This will ease the estimation of heat and energy efficiencies and mass transfer during operation for different heating modes, compared with conventional independent solar stills. The amount of thermal energy transferred to the steam generator is not necessarily shown by the electric current (I). Warming will depend on the availability of power (P), not on that of electricity (E). So, the amount of heat that is added by processed water can't account for the amperage. The experiments were conducted at 60 W, 80 W, and 100 W power supplies to the steam generator, varying the current at a 230 V AC supply voltage. The equation [1] relation given in [30] was used to calculate the electrical power input needed in the steam generator

$$P = V \cdot I \tag{1}$$

Therefore, the electric power inputs for the three operating conditions were approximately 13.8, 18.4 and 23.0 kW, respectively.

3.2. Solar radiation

The test system was exposed to natural sunlight in an outdoor environment, and the glass cover of the test system with a slope was appropriately exposed to sunlight. A standardized observatory was employed to accurately measure solar reflected power, which was continuously checked, allowing solar radiation to be measured in a direction like the suspended covering. The intensity of the Sun's radiation is not measured directly in the experiment. However, the experiments were done on all days and in clear conditions during the day in Chennai, India. According to historical climatological data of the city of Chennai, the average level of global solar radiation for March and April is 900–1100 W/m². The high solar intensity [31] shows good weather for solar still operation. The fact that most of the thermal input into the system was supplied by steam-assisted heating means there is not a significant risk that the amount of solar radiation falling on the system will have a large impact on the system's relative performance if solar radiation changes rapidly.

4. Experimental working

The experimental apparatus consists of a conventional single-slope solar still with an added steam generator and some steam condensation. The steam engine process includes evaporation, which uses a thermal steam process outside the basin to raise the basin's temperature and, so, the rate of perspiration. This coordination enables it to continuously distill even as solar radiation changes, and it also enhances the thermal efficiency of the entire structure. A solar still is coupled to a steam condenser, and the steam condenser is coupled to a steam generator. Water treated in the treatment plant has 145 parts per million (ppm). This is water collected at the treatment plant, which is further used to produce distilled water. Saline water at 145 parts per million (ppm) is introduced into the steam generator, and heating begins. At the boiling point, the temperature of the water rises to the point where it changes state from liquid to gas. The wet steam is then fed into a steam separator to remove the water. The hot flue gases from the solar still and the steam from the steam condenser are heated by injecting steam into them, thereby increasing the temperature of the solar still. Separation efficiency and distillate production under different conditions were used to assess the results. The empirical results are analyzed to find critical performance indicators, including clean water generation, evaporation, frequency, and temperature performance. The results are compared to the energy balance calculation and the temperature-dependent phase change. The impact of steam supplementation and improved condensation on the system's reliability is investigated and compared with available solar power-increase techniques.

4.1. Calibration

The pre-investigation of the measurements including the pressure measurement of the atmosphere, the temperature measurement and the flow measuring device have been done with the aid of known referencing instrumentation. The calibration step was used to minimize intentional errors and provide quality and consistency of the experimental results. Calibrated thermocouples were used to measure all the temperatures. The uncertainty analysis is used to estimate the uncertainty of temperature measurement. Table 2 is Calibration of solar still.

Table 2. Calibration of solar still

Component	Parameter	Instrument Used	Range	Accuracy	Standards	Remarks
Valve	Flow Control	Flow Meter	0 – 100 m^3/s	± 1.5 %	Volumetric	Smooth operation
Steam Condenser	Temperature	Thermometer	25 -105°C	±0.2°C	Boiling Point Method	steady flow
Temperature Indicator	Temperature Accuracy	Thermometer	25 -110°C	±0.3°C	calibrated thermometer	No lag
Pressure Gauge	Pressure Reading	Pressure Gauge	0 - 6 bar	±0.05 bar	Comparison Method	Error checked
Steam Generator	Pressure	Pressure Gauge	0 - 6 bar	±0.1 bar	Dead Weight Tester	No leakage
Steam Separator	Separation Efficiency	Measurement	—	—	Condensate Method	Insulated properly
Solar Still	Tilt Angle	Protractor	0 -35°	± 2°	Mechanical Angle Measurement	15°

5. Results & discussion

5.1. Thermal augmentation

In the current study, the solar still system was enhanced through thermal augmentation, and the experiment described previously was conducted to increase heat transfer, achieve a higher operating temperature, and boost the freshwater production rate. It is a technique used in conjunction with traditional solar heating that adds latent heat, further enhancing the evaporation process. The steam thus generated will circulate around the condenser set and into the solar still, where the space will absorb the thermal power. A steam separator is used to distribute vapors evenly and to prevent excess moisture from being carried over or causing an unstable thermal condition. The inclined glass cover (15°C) also helps improve thermal augmentation by allowing proper condensation and rapid distillate condensation. Furthermore, heat transfer to the outside atmosphere will be minimized by the insulated base chamber, conserving the heat generated in the system. Continuous pressure and temperature measurements are used to optimize thermal input and run efficiently and safely.

5.2. Evaluation of solar still with steam generator

The evaluation of a solar still with a steam generator is conducted with continuous heating for 1 hour at 80A. We conducted this experiment using a steam generator and recorded the values every 12 minutes. The Solar Still results are shown in Table 3.

T1= Ambient Temperature

T2= Temperature of Water

T3= Base Surface (Middle) Temperature

T4= Base surface (Corner) Temperature

T5= Steam Separator Inlet Temperature

T6=Steam Separator Outlet Temperature

Table 3. Solar still with steam generator on day 1 at 80A during evaporation

Time	T1°C	T2°C	T3°C	T4°C	T5°C	T6°C	Water Condensed
10:00	46.5	39.6	38.8	39.8	45.2	44.0	No
10:32	57.4	56.0	62.2	55.6	76.9	86.2	Yes
10:44	65.6	65.3	71.1	66.4	76.2	89.0	Yes
10:56	67.8	68.6	74.5	70.6	76.2	89.1	Yes
11:10	68.1	69.1	75.5	71.8	77.2	89.3	Yes
11:30	69.1	70.1	76.1	72.9	78.3	89.4	Yes

The heating was performed under constant steam at 100 °C, and the inlet steam temperature to the steam condenser should be kept at 88 °C for the first 20 minutes. The pressure gauge showed a significant change after this time, showing that the steam flow direction shifted to the condenser, where the temperature was kept at 88 °C. The amount of water condensed in about 1 hour was about 750 milliliters. The steam produced was used to provide a good temperature difference for efficient heat transfer and condensation before entering the condenser, achieving a maximum temperature of 145 °C [28]. Table 4 shows a solar still with a steam generator on day 2, when evaporation is at 80 A.

Table 4. Solar still with steam generator on day 2 at 80A during evaporation

Time	T1 °C	T2°C	T3°C	T4°C	T5°C	T6°C	Water Condensed
11:20	33.0	33.1	33.2	33.4	33.7	31.9	No
11:50	39.1	41.4	46.6	40.7	71.0	87.9	Yes
12:00	43.4	46.3	51.1	45.9	70.0	88.0	Yes
12:10	47.5	49.6	54.2	49.3	69.5	88.6	Yes
12:20	51.3	55.1	61.4	54.5	70.7	88.6	Yes

The experimental design for the heating process was to keep a steady heating rate, with the steam fed to the condenser at 88 °C during the first 20 minutes. After a certain time, a difference in pressure reading on the pressure gauge was seen, suggesting that the steam was flowing in a different direction, that is, towards the steam condenser [29] at 88 °C. About 600 milliliters of water condensed in the water condenser in about 60 minutes. Importantly, condensation began about 1 hour after the heat started, while evaporation began at 70 °C and was complete in 30 minutes. Table 5 shows a Solar Still with a Steam Generator on Day 3 at 100A Evaporation. The Values of the Solar Still on Day 4, 60A Evaporation with the Steam Generator are shown in Table 6. Table 7 shows a Solar Still with a Steam Generator on Day 5 at 60A Evaporation.

Table 5. Solar still with steam generator on day 3 at 100A evaporation

Time	T1°C	T2°C	T3°C	T4°C	T5°C	T6°C	Water Condensed
9:40	31.2	31.4	31.1	31.6	30.8	31.6	No
9:50	31.3	31.3	31.4	31.8	30.8	30.7	No
10:00	31.6	31.5	31.5	32.0	32.0	53.0	No
10:10	36.6	38.8	51.2	35.0	71.4	88.1	Yes
10:50	37.1	39.1	52.2	37.0	72.1	89.1	Yes

The experimental setup involved keeping a continuous heating process, in which the steam temperature in the steam condenser was held at 100 °C, and the steam entering the condenser was held at 88 °C for the first 20 minutes. After the above time interval, a noticeable difference in the pressure gauge was seen, and steam was diverted to the steam condenser, which was always kept at 88 °C. About 30 minutes after this changeover, 200 milliliters of water were condensed in the water condenser. The evaporation started at approximately 70 °C, and the full initiation period was approximately 30 minutes. Condensation occurred about 30 minutes into the first heating period.

Table 6. Values of solar still with steam generator on day 4 at 60A evaporation

Time	T1°C	T2°C	T3°C	T4°C	T5°C	T6°C	Water Condensed
11:50	36.7	35.6	35.5	36.2	35.2	34.9	No
12:00	37.3	37.4	41.3	38.2	71.8	87.8	No
12:10	38.5	39.6	43.3	40.2	70.0	89.8	Yes
12:20	41.6	42.8	46.6	43.8	69.5	89.5	Yes
12:30	45.8	47.1	49.5	47.9	68.0	80.5	Yes

Table 7. Solar still with steam generator on day 5 at 60A evaporation

Time	T1°C	T2°C	T3°C	T4°C	T5°C	T6°C	Water Condensed
11:00	34.5	37.8	43.5	36.9	78.8	90.3	Yes
11:45	37.3	40.0	41.3	39.4	79.0	90.1	Yes
11:55	38.9	41.7	43.3	41.5	79.5	90.3	Yes
12:05	40.1	43.2	44.5	42.8	79.8	90.7	Yes
12:15	41.5	44.7	46.0	44.3	80.0	90.7	Yes

In one hour, the water in the water condenser changed to condensate by nearly 100 milliliters. Evaporation began at about 70 °C, took about 30 minutes to get going, and condensation followed about half an hour after heating started [32,33]. This is a well-planned experiment in which a constant heating program was used, with the steam temperature kept at 100 °C and the feeding to the steam condenser at 91 °C during the first 20 minutes. After this period, the pressure gauge showed a change, writing down that the steam was diverted to the steam condenser, and the temperature was held constant at 91 °C. Table 8 illustrates a Solar still which has a steam generator on day 6 at 80A. When a perceptible change in the pressure gauge was seen after the first 20 minutes [34], it showed that the steam was being channeled to the steam condenser, which was always kept at 88 °C. The amount of condensate generated by the water condenser was approximately 100 milliliters after an hour [35. After the first heating phase ended, condensation began around 30 minutes later.

Table 8. Solar still with steam generator on day 6 at 80A evaporation

Time	T1	T2	T3	T4	T5	T6	Water Condensed
10:30	26.0	25.6	25.5	26.1	25.6	26.4	No
11:00	35.0	34.0	41.9	33.7	71.2	78.1	Yes
11:20	47.3	45.5	54.3	47.5	73.0	77.5	Yes
11:30	46.9	45.0	64.3	58.3	74.8	79.6	Yes
11:40	60.5	58.7	65.4	62.5	74.2	77.8	Yes

In the experiment, the system was cooled after being heated for approximately 3 hours [36]. Table 9 is Solar Still with Steam Generator Day 7 at 60A Evaporation. The following day at 10.00 a.m., 10 milliliters of collected water was found. The solar still showed no leakage, and significant efforts were made to improve efficiency [37,38]. These upgrades included replacing an acrylic sheet with a glass sheet, using a fitting tray to catch the bag, and adding a secure closure to seal any side openings. The changes were made to perfect the operational efficiency of the solar still and enhance its water-harvesting capacity in the research [39,40].

Table 9. Solar still with steam generator on day 7 at 60A evaporation

Time	T1°C	T2	T3	T4	T5	T6	Water Condensed
12:30	25.9	26.1	25.6	26.5	30.5	29.0	No
12:40	27.2	27.5	33.3	28.3	72.3	71.0	No
12:50	29.0	29.9	35.6	30.6	73.8	68.0	Yes
1:00	31.2	32.5	38.9	33.1	75.0	85.7	Yes
1:10	33.0	34,7	40.1	35.3	75.5	87.9	Yes
1:20	35.0	36.9	42.0	37.6	76.0	89.2	Yes
1:30	36.5	38.5	43.4	39.2	76.5	89.6	Yes
1:40	37.8	39.9	44.6	40.5	76.8	89.6	Yes
1:50	37.6	39.7	43.6	40.5	77.2	89.4	Yes
2:00	37.7	39.8	44.1	40.6	77.5	89.8	Yes
2:10	38.2	40.2	44.4	40.9	77.7	89.8	Yes
2:20	38.2	40.3	44.4	40.9	77.8	89.8	Yes
2:30	37.9	40.0	44.1	40.6	78.0	89.8	Yes
2:40	38.0	40.1	44.5	40.8	78.2	89.4	Yes
2:50	39.3	41.9	46.4	42.5	78.5	89.9	Yes
3:00	40.0	42.3	43.0	42.8	78.7	89.9	Yes

5.3. Saline water temperature test during heating

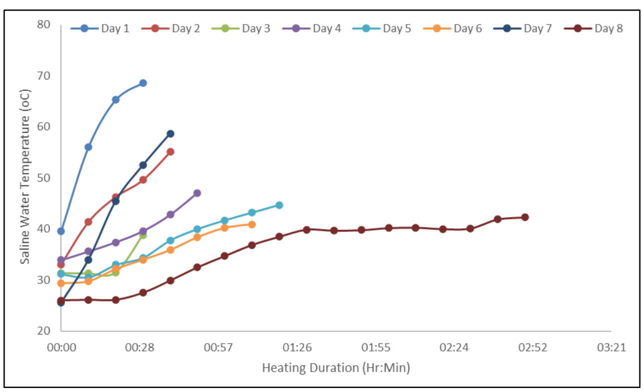

Figure 5. Saline water temperature during heating

The temperature of the water increases with the amperage during the heating process. The experimental manipulation is the amperage, set at three levels: 60 A, 80 A, and 100 A. It is seen that the water temperature varies over time and with different amperage levels. The graph below shows the change in water temperature over many days [41]. In Figure 5, the saline water temperature is shown during heating.

The data shown in Figure 5 show the varying temperature of the saline water throughout the 8 days of testing, the temperature increases of the saline water, the increases in effectiveness over the days of testing, and the key changes in the stability of the saline water based on the different exposure to warm/steam and sunlight.

This best thermal response was seen during the first hour of operation, with peak temperatures of about 70-75 °C, 55-60 °C, and 60-62 °C on day 1, 2, and 7, respectively. On the other hand, Days 6 and 8 recorded the lowest warming, with temperatures below 35 and 45 degrees Celsius during the cycle. When Day 8 was used as the base, the maximum warmth on Day 1 was an impressive 97 per cent improvement, but Days 2 and 7 improved by 53 and 63 per cent, respectively. A test of the heaters' preliminary operation revealed considerable differences: an almost spiking increase in heat consumption was seen during the first 30 minutes of operation on Day 1, compared to Day 8, which showed a very high difference in energy consumption under best conditions.

5.4. Ambient temperature during heating

The ambient temperature rises in response to the heating process, compared to the temperature showed in amperes. The experiment is carried out at several amperage levels, namely 60A, 80A, and 100A. The temperature fluctuates at different intervals depending on the specific amperage used. In Figure 5 the variations in water temperature during several days and time periods are shown

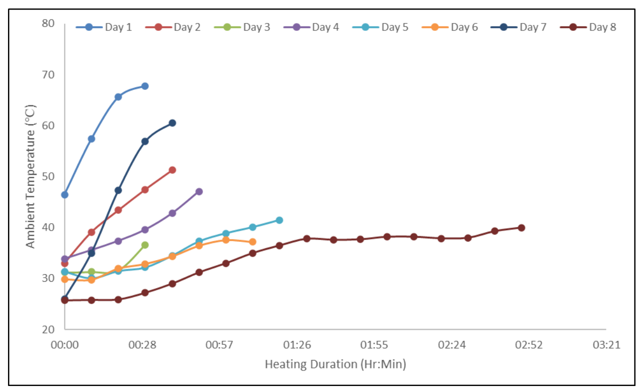

Figure 6. Ambient temperature during heating

As shown in Figure 6, the average temperature inside the apparatus's containment traces a temporal pattern over eight weeks of the experiment, with two distinct operational levels related to variations in solar radiation and steam-induced warming. Days 1, 2, and 7 have a much steeper rise in temperature, with the highest temperatures of about 65-70 °C, 50-52 °C, and 60-62 °C, respectively, in the first forty and forty-five minutes. On the other hand, Day 8 shows the weakest thermal response, with the temperature staying at approximately 40 °C throughout the long warming period, thus providing a basis for evaluating the relative increase. Compared with this first point, Days 1 and 7 show a substantial mean rise of approximately 75 per cent and 55 per cent, respectively, and Day 2 proves a satisfactory increment of 30 per cent. The difference, especially in the warming rate, was that Day 1 was more than 9 times hotter in the first 30 minutes than Day 8, showing that, under the best conditions, the efficiency of heat transfer has improved significantly.

5.5. Surface temperature middle test during heating

The steam generator is heated to 100 °C and the pressure begins to increase. The steam intake valve is opened, and steam flows from the steam generator to the steam condenser. This illustrates the significance of the structural modifications of solar stills compared to conventional stills: the stepped solar stills have significantly larger evaporation surface area and freshwater production rate than the conventional ones. [42]. The steam is not quite cool and is used to heat the solar still. As the steam temperature rises, the solar still gets hotter. This is a good reason why the current study includes innovative design improvements to increase desalination efficiency [43]. The data collected were plotted in a graph to display the correlation between time and the heating period. The middle surface temperature of the solar still is proportional to the change in the temperature of the steam [44,45].

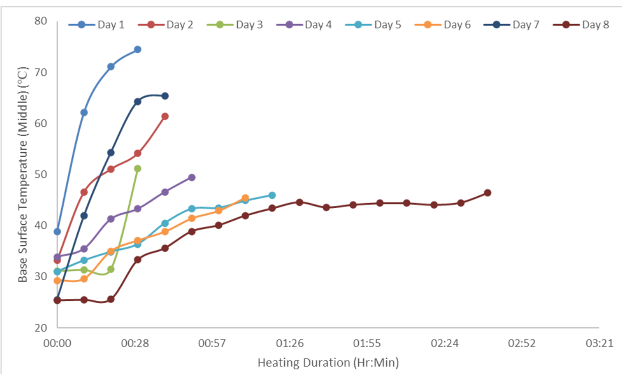

Figure 7. Base surface temperature (middle) during heating

Figure 7 illustrates the temporal evolution of the substrate thermometer at the central point in the sunlight for 8 test days and confirms that there is a clear difference in the thermodynamic response of the substrate in the different warming conditions, both ambient and via steam. Days 1, 2, and 7 show the greatest increase in humidity, with the highest foundation-surface temperatures of approximately 72 -75 °C, 60 -62 °C, and 65 -67 °C, respectively, in the first 40 minutes. These calculated temperatures were significantly higher than the 35-45 °C kept on Day 8 as a reference. The size of the change is clear: the realization of Day 1 is about 75-85 % more peak warmth than on Day 8, and the observations of Days 2 and 7 about 35 and 50 per cent greater. Days 3-6 present little production; it is a dormant period due to sporadic precipitation and variable steam flow.

5.6. Surface temperature corner test during heating

When the steam generator internal temperature reaches 100 °C and the pressure begins to rise, the intake valve opens to allow steam to flow from the steam generator to the steam condenser. This vapor is used to heat the solar still. The higher the solar still's temperature is above the steam temperature, the higher it is [46]. A correlation chart of time spent versus time spent in heating was plotted with the results. The data obtained was plotted on a graph to show the correlation between the time spent and the time spent in heating. The surface temperature of the solar still increases with higher steam temperature. The center surface of the solar still, however, will take longer to heat than the corner surface [47].

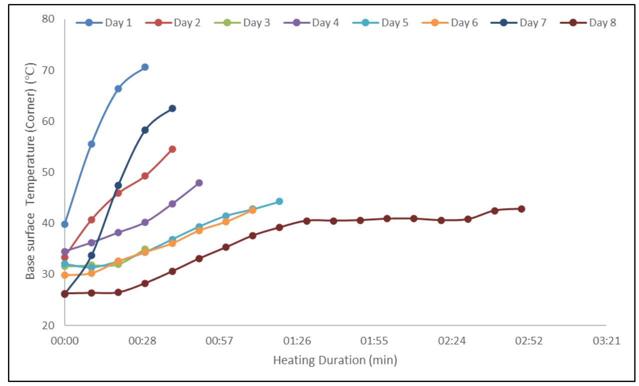

Figure 8. Base surface temperature during heating

The time-dependent development of the outermost base-surface temperature of the solar-power still is shown in eight experimental runs as shown in Figure 8, and the development is clearly different depending on the thermally responsive behavior of the sun's warming conditions and the steam supplied. The first and seventh days are the maximum thermal responses, with the thermometers reaching approximately 32-34 °C and 75-78 °C, respectively, at the beginning of the 40-minute period. A clear upward trend is visible on Day 2, where a maximum of 55°C was recorded during the same period; a steady increase is seen on Days 3 and 4, with temperatures of 45-50°C. Days 5 and 6 show less uniform heating profiles, showing either less heat input or greater convection heat loss in these corner regions. The initial point is defined for Day 8, and the temperature increases rather linearly during the heating phase from approximately 27oC to 40oC, which is the smallest metabolic gain of any of the experiments.

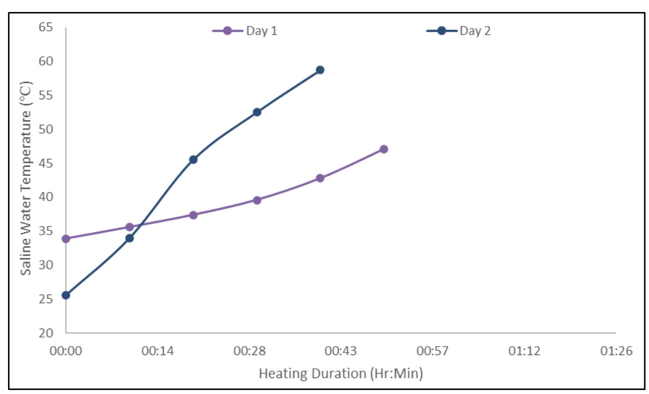

Figure 9. Comparison of day 1 vs Day 2 during heating at 60 W for 1h 15 min

The difference between the salinity and water temperature was graphed for two situations as shown in Figure 9. Day 1 means there are clouds on the day. Day 2 means there is a sunny day. Heating on a cloudy day was slower because the sun's radiation was reduced. This led to a slow rise in temperature of salty water. Salinity of water increased much faster during the daytime, though [48]. The amount of solar radiation received was directly proportional to the best temperature of salty water. This suggests that the amount of sunlight received by a solar still will influence its evaporation potential [49]. If salinity and water temperature change on Day 1 and Day 2, as in Figure 9, then these two days prove differences in thermal sensitivity between the two working conditions. Day 2 reveals that the temperature has risen much more rapidly, by some 60°C in just 45 minutes, suggesting greater efficiency of heat input, likely the result of a combination of the sun's increased brightness and increased heat transfer from the sedimentary layer to the briny water. Day 1, on the other hand, shows a more stable increase with temperature, rising approximately from 34 °C to 48 °C, suggesting slightly reduced heating stimuli and increased overall energy loss. The temperature difference recorded on Day 2 suggests that the exchanges by aerodynamics and conduction under the saltwater layer were enhanced, and that the time to reach conditions favorable to perspiration was shorter.

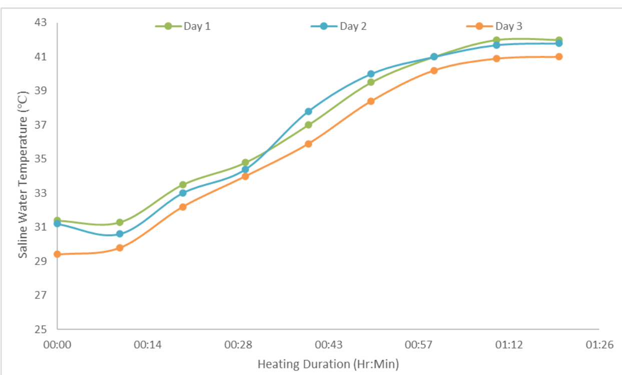

Figure 10. Comparison of day 1 vs day 2 vs day 3 during heating at 60W for 1 h 15 min

Figure 10 shows the temperature difference between the saline water under both 60W active heating and 1 hr 15 mins. The heating process was repeated three times to verify the data. Saline water was seen to heat during the heating process [50]. The temperature of the saline water was constant after 10 minutes. This amount of heat was used during this time to raise the aluminum solar still's temperature. Time was needed to release heat energy by conduction to the walls of the solar still. Then, heat transfer by convection occurred. In this, the heat generated by the solar sides still used to heat the saline water. It was estimated that the saline water temperature increased by 2 °C in an hour. This implies that sensible heating of the saline water was performed over a period of 1 hour. The temperature rose to 41° C. It was later seen that the temperature remained constant throughout the time. This fact is the basis of the idea that there was some evaporation during this time interval. Latent heating occurred in the salty water, stabilizing the temperature. It can therefore be concluded that the evaporation of saline water can be improved to a minimum of 1 hour using a heat of 60W. The amount of heat supplied was kept throughout the experiment. Passive heating involves sunlight, which must raise the temperature to at least 41 °C to ease evaporation. After conducting the experiment three times, it was noted that the trend in temperature change in the saline water was similar. The experimental design proved that results could be reproduced with high accuracy.

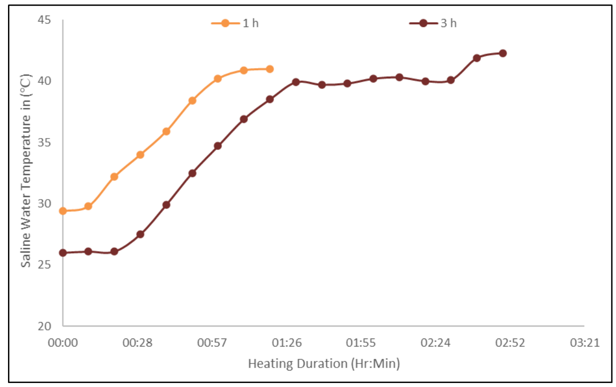

Figure 11. Comparison of 1hr vs 3hr during heating

Two different temperatures were used to start the experiments. In both instances, it was discovered that the temperature fluctuations were in the same direction. The heating process continued with the senses until the temperature reached 41 °C. The heating rate was then kept constant at 2° C / 10 minutes. Latent heating continued for almost an hour. Replaced with the use of sensible heating. This means that, if the air is to be heated to saturation, 1 hour of heating at 60W is needed.

Figure 11 shows the temperatures of salt water under two working conditions 1 and 3 hours of heating and immersion. A greater increase in the thermodynamic value is seen for the 1-hour condition, where water temperatures change from approximately 29 °C to 41°C, showing better heat transfer and greater resistance to temperature changes. On the other hand, the 3 h curve would start at a lower temperature, 26 °C, and have a slower rate of heating, taking about 2.5 h to reach similar temperatures. Thus, long periods of sunshine can be correlated with lower sun brightness, higher aerodynamic losses, and/or higher cooling due to evaporation, which can lead to less overall heat loss. The two curves show a significant drop in the scorching rate after about 2 hours, and the water reaches a quasi-steady state as it balances with the surrounding temperature [51].

The comparison of changes in temperature over time in saline water heated by 60 W, 80 W, and 100 W is presented in Figure 12. At a low heating rate (60W), the temperature rose slowly. On the contrary, when the heating rate was at the maximum of 100 W, the temperature of the saline water rose so quickly. The total heat used was 80W, which produced a moderate rise in temperature over time. Such a moderate heating rate is desirable, as it minimizes the time needed to reach evaporation and ensures sufficient air saturation in the solar still. The 60-watt heater heats up to 35°C in 1 hour, the 80-watt heater heats up to 55°C in 45 minutes, and the 100-watt heater heats up to 70°C in 43 minutes. Thus, the 100 W heater will require 70°C, which is 21.5 per cent higher than the 80 W heater and 50 per cent higher than the 60 W heater.

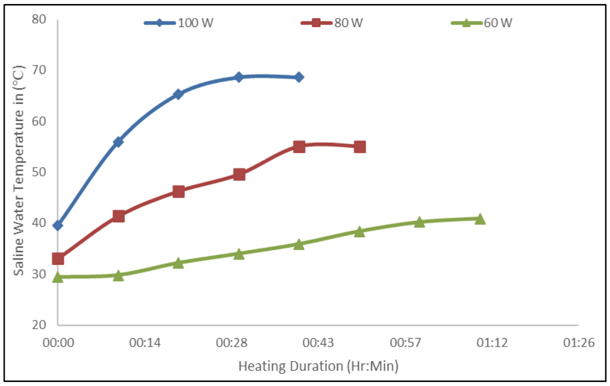

Figure 12. Comparison of 100W vs 80W vs 60W during heating

6. Uncertainty analysis

The significance of uncertainty analysis in the present research study is to enhance the operating conditions of the solar still, as the performance of a specific solar still depends on many uncertain variables, such as electrical current, voltage, solar irradiation conditions, and distillation weight. Each piece of equipment in the set-up has a fundamental measurement error, which manifests in the calculated values of thermal performance, energy usage, and productivity. A comprehensive risk assessment is performed to ensure that the identified temperature rises, and yield advances are technically correct and within tolerance. This analysis attests to the credibility of the results, follows the ASME empirical standards, and supports the research's general credibility and predictability. The items in Table 10 are the instruments and the Uncertainty measure. Volumetric yield is shown in Table 11.

Table 10. Uncertainty in the instruments

Variable	Instrument	Typical Accuracy	Purpose
Time	Stopwatch	±0.02 s	Time calculations
Flow Rate	Flowmeter	±1–3%	cooling flow
Water Volume	Measuring Cylinder	±2%	Output yield
Water Mass	Digital Weighing	±0.2g	Output yield
Irradiance	Pyranometer	±6%	Solar energy input
Voltage	Voltmeter	±0.6–1.1%	Electrical power input
Pressure	Bourdon Gauge	±2–3% FS	Steam pressure
Temperature	Digital Thermometer	±0.6°C	Heat losses
Power	Wattmeter	±0.6%	power measurement
Current	Ammeter	±1–2%	Electrical power

Table 11. Volumetric yield

Run No.	Operating time	Heating Conditions	Feed water type	Operating temperature (°C)	Condensate Collected volume milli Litres	mass Collected grams	Volume Litres
1	11 am to 4 pm	Steam-assisted heating	Distilled water	80–90	1200	1200	1.2

7. Conclusion

The efficiency and productivity of the freshwater production system using a solar steam generator with a steam generator were higher than those of the solar still alone. The significant increase in the evaporation rates was achieved by generating steam in the generator and using it as the heat source for the solar still. The maximum productivity, with best output, was achieved by heating distilled water from 11 am to 4 pm to a temperature range of 80 °C to 90 °C. The 100 A favored evaporation, but total yields decreased due to the high heat. The surface temperature, water temperature in the solar still, and ambient temperature increased with increasing heating rate of the steam generator. This observation suggests that heat was transferred better. A minimum heating rate must be reached for evaporation to begin and to continue at 60 W/h. Further yield improvements were achieved with extended heating periods of up to 3 hours. The scientists decided that temperatures wouldn't always be above 41°C, which is needed for evaporation to occur. It was found that the water temperature would not exceed 41°C at any time when heated solely by sunlight. A regular supply of thermal power was provided by the steam generator Future studies can use these design parameters, which include solar still size and shape, steaming rate of flow, thermal storage system integration and solar thermal apparatus. Such developments in distillation techniques have enhanced the efficiency of the processes and applied the technology practically to perfect production. The use of external power generation with steam generators and condensing rooms is a substantial improvement over the current inactive solar reactors which require energy. The apparatus produces elevated basins with eyeglasses.

They are heated by added heat from steam and exhaust gases. This results in high amounts of evaporation and the production of distillates in the absence of adequate sunlight.

Warming and maturation of solar energy is tightly coupled with the warming of basins, as driven by electronic inputs. Keeping high sustainable levels reduces energy losses and increases daily groundwater production. All the exhaust gases from the steam producer are used in the solar power still, and the same gases are diverted to the steam condensation to heat the solar power still, thereby using any exhaust heat that might otherwise be lost, improving the energy efficiency of the entire process.

Trials can be conducted at different amperage levels. This allows careful control of the heat rate. If Day 8 had been the start date, then Days 2 and 7 had 53 per cent and 63 per cent, respectively, while Day 1 had an amazing 97 per cent increment. Days 1, 2, and 7 show a much more pronounced rise in temperature, reaching approximately 65 °C- 70 °C, 50-52 °C, and 60oC-62oC, respectively, in the first forty-five to forty minutes. Conversely, on the 8th day, the minimum temperature was around 40°C, and the thermal action was the least, thus setting a standard for comparing relative rises.

This difference is further highlighted in the first warming rate, where Day 1 achieved over 9-fold higher temperatures in the first 30 minutes than Day 8, showing a significant improvement in heat transfer efficiency in the best environment.

Baseline surface temperatures in the middle days 1, 2, and 7 show the highest growth in humidity, which is recorded to reach the highest foundation-surface temperatures of approximately 72°C -75°C, 60°C-62°C and 65- 67°C, respectively, within the first forty minutes of the heating. The recorded temperatures are also significantly different from those on Day 8, when temperatures remained constant at 35-45°C, providing a basis for comparing and analyzing the results. The magnitude of the shift is readily apparent: Day 1 is already seeing a change of about three-quarters to three-fifths of the increase in peak warmth, The initial temperature rise would also confirm this comparison: in the first half an hour of Day 1, the surface temperature is almost 9 times higher than that of Day 8, indicating that surface propagation and absorption of infrared radiation are nearly 9 times more efficient.

The heating pattern is lessened and comparable on Days 5 and 6, and hence the heat input is also lower, or convection dissipation is more intense in such corners. On Day 8, the first position shows a relatively linear, cold increase in temperature, and the temperature increases by almost 27 °C over the heating time, showing the smallest gain in metabolism among all experiments.

Compared to Day 2, there are no differences between Day 1 and Day 2. The variation in saline water temperature during heating at 60 W for 1 h 15 min is an indicator of the frequency of warming under the two operational conditions. The increase on Day 2 is very dramatic and rapid, reaching some 25 °C to some 60 °C in just over 45 minutes, indicating a greater transfer of warmth to the sedimentary layer, in this case presumably due to a combination of a greater radiance of the sun and an increased transfer of warmth between the sedimentary layer and the briny water.

In turn, Day 1 shows a more stable increase, with temperatures rising between approximately 34 °C and 48 °C, suggesting a slightly smaller heating stimulus and, in general, higher energy loss. The 1-hour condition shows a higher thermodynamic rise than the 3-hour condition during the heating phase, with the water temperature increasing during the first hour. Temperature increases by about 29 °C to about 41 °C, showing a more favorable heat-transfer condition and decreases reluctance to heat. The 3 h curve, on the other hand, begins at lower temperatures around 26°C and has a slower heating rate, so it takes around 2.5 h to reach the same temperatures. For 60W heating, the time to reach was 1 hour to reach a maximum temperature of 35 °C; for 80W heating, the time to reach was 45 minutes; and for 100W heating, the time to reach was 43 minutes to reach a maximum temperature of 70 °C.

Hence, for the 100 W heating, the heating temperature is 70 °C, which is 21.5 per cent higher than for 80 W heating and 50 per cent higher than for 60 W heating.

8. Future works

Future studies will involve brackish and seawater feedwater to study the impact of feedwater salinity on productivity, recovery ratio and specific energy consumption. Further development in future work is necessary to include more sophisticated thermal storage materials like phase change materials or nanofluids to provide even greater heat storage and system output. It is also possible to automate the steam flow and temperature control to perfect the experimental setup and to regulate the performance in real-time. Moreover, extensive field testing in various climatic conditions is suggested to test long-term feasibility and commercial applicability.

Authors contribution

Conceptualization, method, experimentation: Raja Kannan. Data analysis; D. Samundeeswari. Review and supervision: J. Jeha. Manuscript preparation: K. Sunil Kumar. Validation: S. Sudha.

Data availability statement

The datasets used and or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors would like to thank AI-powered writing tools, such as Grammarly, for their aid in enhancing the linguistic precision, correctness of grammatical structures, and the overall coherence of this article. All content, analysis and conclusions contained in this work are the author's own and are not in any way the work of AI. All content, analytical discussion and conclusions presented in this work are the sole work of the author and have not been generated using AI tools for any purpose other than to enhance the presentation and clarity of the text. The use of AI is aligned with the journal's standards of transparency and ethical guidelines in the authoring process.

Appendices

A	Amperes
Cm	Centimetres
CSSS	Conventional Spherical Solar Still
CSP	Concentrating Solar Power
C	Celsius
Ml	Millilitres
M	Metres
MSSS	Modified Spherical Solar Still
Mm	millimetres
PPM	Parts Per million
TSS	Tubular solar still
Pcm	Phase change material
TIG	Tungsten Inert gas welding
W	Watts

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