Enhancing Solar Still Distillation Efficiency through Integrated Solar Chimneys and Submerged Condenser Systems

[1*]*Balan* Varadhan, [2] *Chellathurai Amiirthabai* Subasini, [3]*Gopinath* Palani, [4]*Mayakannan* Selvaraju

[1*]Professor, Department of Mechanical Engineering, KSR College of Engineering, Tiruchengode, Namakkal, Tamilnadu -637215

[2]Associate Professor , Department of Computer Science and Engineering, St Joseph's Institute of Technology, Semmancheri, Chennai, Tamilnadu, India.

[3]Principal, KSR Institute of Technology, Tiruchengode, Namakkal, Tamilnadu -637215

[4]Assistant Professor, Department of Mechanical Engineering, Vidyaa Vikas College of Engineering and Technology, Tiruchengode, Namakkal, Tamilnadu -637214

Email : uvbalan@gmail.com, subasiniaji@gmail.com, kannanarchieves@gmail.com

Corresponding author : uvbalan@gmail.com

Abstract

A solar chimney has been studied in this research to increase the efficacy of still convection currents. The usage of a condenser also improved the condensation process. Solar still condensers are typically made up of tubes through which salt water is pumped. But in the setup shown, water vapour was channelled through a series of pipes submerged in the ocean. Solar still is built and tested in real-world situations with solar as a standard. Evaporator (basin) area-based efficiency comparisons reveal that the still-equipped solar chimneys and condensers yielded 9.1% superior results. The mainstream of the yielded (61%) condensed in the solar still condensers, resulting in a production rate of 5.3 L/m^2 d for the simple solar still and 6.2 L/m^2 d for the modified still. This demonstrates that the evaporation efficiency of solar still and, by extension, its distillation efficiency improved by increasing convection and condensation.

Keywords: Solar condenser, solar distillation, Solar chimney, Basin, Temperature, Single slope.

1. Introduction

One of the most important things is water and the global drought has led to declining freshwater supplies when demand rises [1]. Desalination plants and other water purification facilities are often needed when freshwater is in short supply due to a lack of local water sources [2]. Desalination is removing salt from saltwater or brine to make it drinkable. A traditional desalination plant cannot be built in a region where the energy source is unreliable and the necessary infrastructure does not exist [3], [4]. In desert regions where freshwater is scarce, solar desalination has the potential to be a highly effective renewable desalination solution because of the abundance of solar energy available in these areas [5]. To create drinkable water, solar desalination relies primarily on energy from the sun. The knowledge and equipment needed to keep complicated technical systems running well are often unavailable in outlying communities [6]. Single slope solar stills are the most basic solar desalination system design, as they are tiny versions of the natural water cycle. Solar stills utilize solar heat to distil salty water into drinkable water by evaporation [7].

Direct solar desalination plants rely mainly on solar stills, which harvest solar energy passively. Solar irradiation can replace the greenhouse effect and initiate a closed-volume natural water cycle to provide the required heat transfer mechanisms [8]. Typically, a solar still consists of a glass or transparent container with a black basin of water inside. Twenty to thirty millimetres of untreated water fills the basin [9]. The water in the basin grips a little sunlight that strikes the desalination unit, while the black basin itself takes in, transmits, and reflects the remainder [10]. The heat transferences from surface to below water by convectional and conduction rays. The temperature of the water and the relative humidity in the space both rise [11], [12], [13]. The partial pressure of water vapour gradient between surface of water and cover glass drives the evaporation process. Natural convection cause the vapour to descend to glass base [14]. When the glass covering is more relaxed than the precipitation points of the humid air inside, condensation clears the enclosure. Condensation's latent heat is transferred to the glass, forming tiny droplets of pure water. Water trickling down the walls collects the material [15]. Glass-top conventional solar stills transmit solar energy and act as condensers [16]. However, its condensation capability is restricted due to its exposure to radiation and reliance on passive cooling through natural air convection—some of the condensate that forms may also be re-evaporated by solar rays. Adding a condenser to a solar still is one approach to boost its capacity and by extension its output.

The evaporating slot is linked to a closed condensation, but the design is still similar to a standard solar. Since this area is shielded from direct sunlight, it is significantly more relaxed than the evaporation chamber. Due to the pressure difference created by the temperature difference, water vapour is forced from the evaporating chamber into the condensing section. The latent heat from condensation escapes into the atmosphere during the condenser operation [17]. The thermal conduction of the walls and the condenser's volume relative to the evaporation chamber's volume are two parameters that affect how well such a condenser collects condensation. The glass cover of the evaporating compartment may be used as a condensation location despite being more relaxed than the water in the basin[18]. More water evaporates when there is a more significant temperature variation between the water and the glass. The glass can be kept at a low temperature because most water vapour condenses in the condensation chamber [19]. Water vapour condenses on the primary covering glass, and visibility is impaired. Reducing the condensing rate, contrary to the lower side glass, increases the evaporation rate and improves the total transmissivity of fogged glass. According to experiments, using a condenser like this can increase solar still output by as much as 45%. The evaporation chamber is linked to two galvanized steel cylinders for the solar still. Daily output increases by about 16% in the summer and 18% in the winter, according to the author [20], [21]. The 38% of the total condensate is gathered from the outside condensers.

Solar systems can provide passive ventilation with the use of solar chimneys. Their applications range from construction to solar heating and drying to greenhouses. In the latter, water vapour is released from the crops into the ambient by boosting convectional heat transfer within an encircled chamber through the chimney effect. There is a lack of information in the literature about solar chimneys that use solar stills. The solar evaporation cavity is linked to the condenser, which is cooled by water through a solar chimney. It was suggested to run the system in an open loop, with cool air from the chimney and hot air escaping through the duct. Although this setup would boost convective currents, it does so at the expense of two other factors. Cool ambient air is continuously pumped into the evaporation chamber of the solar still, where the warm air from the chimney is not reused but released into the atmosphere.

This research needs a more comprehensive comparison with existing research, a deeper assessment of environmental impacts, consideration of scalability and practicality, investigation into long-term performance, analysis of energy efficiency, evaluation of water quality, and addressing integration with water distribution systems. Further research and detailed findings in these areas would enhance the overall understanding and applicability of the modified solar still system.

2. Methodology

The effectiveness of two still solar designs was evaluated simultaneously in real-time conditions. As a point of reference, basic solar still was employed. In second experiment, solar still using solar chimney with condenser was developed. Dual stills had a consistent $1m^2$ base size.

2.1. Simple solar still

FGRP is utilized to build the basic solar still with dimension of 1m2. The translucent panes were made of low-iron glass, allowing more sunlight than regular soda lime glass. The black coating on the basin absorbed more sunlight. Thus, the vertical back wall was gel-coated white to increase the reflectivity. The researchers measured the condensate produced by collecting it in a tipping bucket from three outlets (two on the sides and one in the front). Condensation drains into the front channel through a silicone ridge fastened to bottom of the glass. The actual basin area is only 0.912 m2 because of the space needed for the rear insulation of the solar still and the cross-view and front-view collection of distillation lines. The water is evaporated from the solar still basin, which also acts as a solar absorber for the system.

2.2. Standalone Solar still with chimney and condenser

The goal of condenser and chimney is to increase condensation efficiency through improved convection and condensation passively. Figures 1 and 2 demonstrate the prototype design. This structure has three interconnected parts:

(1) Solar-powered, glazed air heater (at 60^ohorizontal axis).

(2) Evaporating chamber.

(3) Submerged copper condenser in a saltwater reservoir.

Seawater is pumped into the basin and the fibreglass reservoir in the morning. Evaporation begins as the water in the basin heats up due to the increasing intensity of the sun. The solar rays warm the black absorber, which in turn causes the air inside the glassy collector to expand, lifting the hot air to the area below the saltwater basin. As can be seen in Figures 1 and 2, water flows through the ventilation holes in the base basin and into the evaporation chamber. Elevated molecules of water would be carried by the augmented convection current to the slanted glass and condensers as they evaporate.

This glazed solar air heater is fitted at an inclination of 60º to the horizontal and coated with low iron glass. In Malta, the insolation at this angle fluctuates the least from season to season [22]. The air in the collector is exchanged with air from four pipes as it rises across the solar chimney. The evaporation cavity is linked to the plenum chamber through an inlet. As shown in Fig. 1, this sets off a convection cycle with a clockwise motion. A clockwise convection cycle can occur when warmer fluid rises and moves clockwise while cooler fluid sinks to replace it.

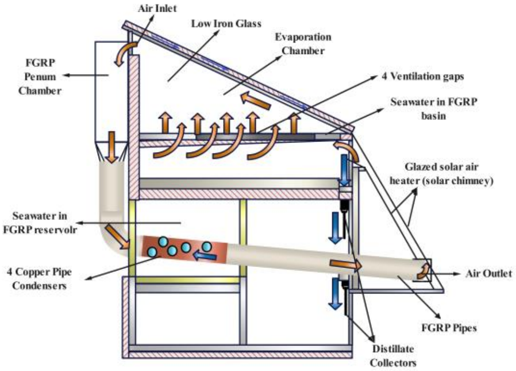

Fig. 1. Diagrammatic cross-section of a solar still with chimney and solar still with the condenser.

The saltwater mass in the reservoir receives the latent heat of condensation from the water vapour as it moves through the copper pipes. The pool can absorb about 4 kg of condensate, providing enough latent condensing heat to raise the temperature by 20ºC. Condensational force declines with increasing water temperature. Air circulation and the buoyant pressure differential are slowed when the temperature increase at the top of the solar chimney is reduced. Inside the evaporation chamber, the rate of condensation slows down as more water vapour condenses on the inner surface of the primary covering glass. This phenomenon is known as a condensation effect. As condensation on the inside of the glass would reduce its ability to transmit sunlight, it is diverted to condensers instead. The evaporation drive increases, while convective heat loss from the covering glass reduces because the glass will be at a lower temperature. The still's basin has less surface area because of the four ventilation gaps. This increases the still's convection. The simple solar still has a basin with an area of 0.912 m2, whereas the still with the solar chimney has a basin area of 0.772 m2. This difference amounts to a reduction of 15%. The efficiency of evaporation was evaluated on a per-area basis.

2.3. Experimental arrangement

Temperatures in the solar stills are tracked with Type-T class 1 thermocouples (±0.6 ºC), as indicated in Figs. 2 (a) and (b). Radiation shields block the solar rays from heating the thermocouple beads that record fluid temperatures. White PVC pipes were arranged vertically to form guards for the thermocouples to measure air temperature. White sockets protect seawater thermocouple beads from direct sunlight and galvanic corrosion. White sockets serve a dual purpose: to protect the seawater thermocouple beads from the heating effects of direct sunlight by reflecting solar radiation and to prevent galvanic corrosion by isolating the thermocouple beads from direct contact with the seawater. This ensures the accuracy and longevity of temperature measurements in the solar still system. In their work, the authors expanded on the shields' design and implementation. Thermocouple sensors were adhered to the surface depending on the substrate material to measure the surface temperature. The FGRP (Fiber Glass Reinforced Plastic) surfaces were coated with epoxy resin. Direct soldering was used to attach thermocouples that read the temperatures of the copper pipes. Thermocouple beads were finished to look like the surface being measured to accurately monitor the temperatures of surfaces in direct sunlight.

The rates of distillation were determined using tipping buckets. Each data (Temperature, Rate of Distillation and time) logger was set to record a new reading every second and then calculate an average every minute. Each day at midnight during the trial period, the basins were mechanically blushing and filled with 25mm of saline water.

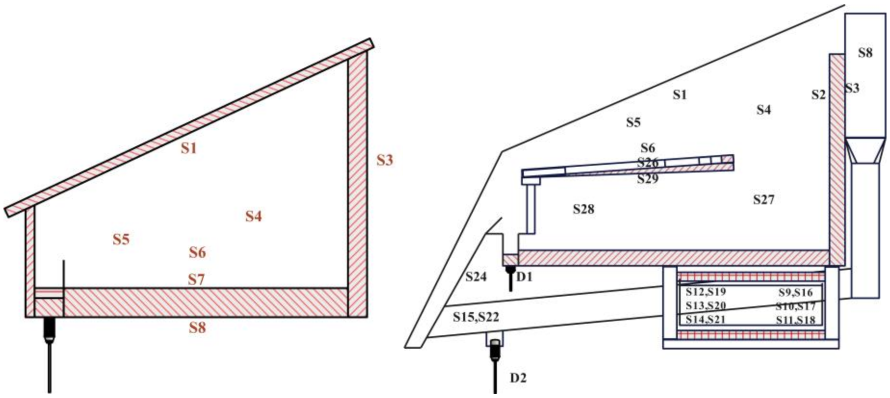

Fig. 2. Comparison of Standalone solar still Thermo-couples (a) without, (b) with chimney.

3. Results and discussion

Table 1 Comparison of Water productivity outcome of Standalone solar still and with chimney and condenser.

Parameters	**Standalone Solar still**	**Standalone Solar still with condenser and chimney**
Wind speediness (m/s)	2.9	-
Evaporation area (m^2)	0.912	0.823
Insolation (MJ/m^2 d)	25.3	-
Production from sides (ml/d)	1,204	683
Ambient temperature (Ta) (C)	28.1	-
Production from top + sides (ml/d)	4,408	1,712
Production from upward (ml/d)	3,323	1,114
Whole production (ml/d)	4,451	4,093
Production (entire area) (ml/m^2 d)	3,856	3,592
A percentage from condensers (%)	–	59.2
Production (basin area) (ml/m^2 d)	4,661	5,083
Everyday efficacy (basin area) (%)	46.7	49.8
Percentage from sides (%)	26.7	16.3
Daily efficiency (total area) (%)	38.1	35.6
A percentage from the top (%)	74.2	26.1

Table 2 Day-by-day mean temperatures and temperature variation —Standalone solar still and Solar still with chimney

Temperature Code	Factors	Temperature (◦C)
Standalone Solar Still		
S1	Upward glass	42.5
S4-S5	Air in the evaporating zone	49.3
S6	Saltwater	49.8
S7	Basin surface	49.9
S6-S1		8.1
S7-S6		0.2

Solar still with chimney		
S1	Upward glass	42.2
S4, S5	Air in the evaporating zone	49.3
S6	Saltwater	49.8
S8	Air in the plenum zone	43.2
S10, 17	Air in Cu pipe, upward stream	37.1
S13,S20	Air in Cu pipe, downward stream	35.3
S15,22	Air upward stream of chimney	35.9
S26	Basin surface	48.1
S10, 17	Air in Cu pipe, upstream	37.1
S23	Solar chimney glass	44.2
S24	Solar chimney absorber	64.7
S25	Air downstream of the chimney	49.2
	S6-S1	5.8
	S26- S6	1.2
	S8- S10, 17	11.3
	S10,17- S13,20	2.1
	S25- S15,22	14.3

Tables 1 and 2 shows the most important findings. Unless otherwise specified, the presented data represent an average or sum during the testing time, from dawn to sunset. Every instance of a pair of thermocouple readings is followed by a table displaying their average. The 0.912 sq-m solar still evaporator was able to generate 4.32 litres per day. The top slanted glass surface was the primary catalyst for the condensation of the water vapour. Instead, 4.09 L were collected from the evaporator's 0.781 m^2 surface area by chimney and condensers. Most of the condensation, 61% to be exact, occurred in condensers. When the surface area of the evaporator was considered, the solar chimney was still 9.1% more efficient than the simple solar system. Distillation rates (Figure 3) were calculated using the temperature outlines and air circulating in the solar chimney. The normalized output rate was determined using the evaporator area.

At roughly 13:00, the water temperature in the elevated basin had risen to 60ºC. The solar chimney's black absorber got hotter than 90ºC, whereas the maximum temperature increase in the surrounding air was only about 24ºC. Water vapour was transferred from the evaporating zone to the plenum zone and condensers by airflow generated by the buoyant pressure differential over the solar chimney. Solar energy is harnessed to heat the water in the evaporating zone, causing it to reach the boiling point and transform it into vapour. This warm and moisture-laden air naturally ascends into the plenum zone. Above, the solar chimney, which absorbs heat from the sun, plays a pivotal role by generating an upward draft through buoyancy. This buoyant airflow draws warm, moist air from the plenum zone into the solar chimney. As the air moves upward within the solar still, it encounters specially designed condensers that are cooler in temperature than the ascending air. This temperature difference prompts the water vapour within the air to condense onto the condenser surfaces. These condensed water droplets are collected systematically and stored as freshwater in the solar still. Finally, the now-dry air exits the top of the solar still, completing the cycle that efficiently distils freshwater from saline water using solar energy and natural buoyancy.

The air temperature declined from S8 in the plenum chamber to S10 and S13 in the area above the water-cooled condensers. The recorded temperatures of the copper walls, the plenum chamber and copper condensers was to be expected were responsible for the bulk of the distillation process. Water was collected mainly from the sloped top glass of the evaporation chamber. There was a period at about 17:00 when the condensation rate in the evaporation chamber was greater than that of the condensers. This impact is the result of the reservoir's water temperature rising. Using a solar chimney with condensers can move the condensing process from the evaporating zone to the condenser and produce air flow that transports water vapour from evaporation surface.

Realized temperature difference, mass flow rate, and temperature in the plenum chamber affect condensation rates. Figure 4 shows how the temperature rise in the chimney relates to the substantial temperature shifts throughout the condensing course. For the same reason that the plenum chamber and condensers get colder, the chimney gets hotter. The line indicates the plenum chamber's cooling and a similar drop, extrapolated to its humidity. The red curve shows the steady decline of the copper condensers. Observe how the arrows on the curves represent the variation in the parameter from daylight to night. The plenum chamber cooled more rapidly in the afternoon than in the morning for increased chimney temperature. The temperature decline across the more significant ambient air-cooled plenum chamber occurs in the afternoon when the ambient temperature is slightly higher than in the morning. There is less of a temperature difference between air cycling through copper walls and pipes in the afternoon when the water in the reservoir is warmer. As a result, the temperature difference between the copper condensers is mitigated.

Ventilation grilles allow air to move from below the basin to the evaporation space above. Compared to a simple solar still, the increase in temperature (relative to room temperature) of the air in the chimney still's evaporating chamber was only about 8%. Lower temperatures resulted because the plenum chamber and condensers had a more significant cooling impact than the heat input from the chimney [11], [12].

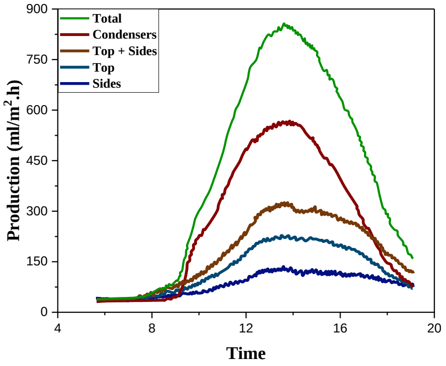

Fig. 3. Distillation productivity rate (solar still chimney).

The chimney's evaporator absorber basin is 14% smaller than its counterparts in a simple solar still due to the space needed for ventilation grilles. As a result, 14% less water surface area was available to absorb sunlight and allow water molecules to evaporate. So, it stands to reason that the chimney still will be similarly underwhelming. Table 3 demonstrates that while its yield was lower than the simple stills, the difference was just 6.3%. The positive difference of 9.1% efficiency is noted based on actual basin evaporator area. This indicates that evaporation efficiency was enhanced by airflow through the evaporator, and distillation produces purer liquids. Evaporation occurs when the partial pressure of water vapour in the air and the water is lower than the partial pressure in the air travelling through the atmosphere. Both sides hold when discussing the relationship between convective and evaporative heat transfer. The grilled evaporator improves convective heat transmission. Due to this, the rate of evaporation increases. This means that a greater number of water molecules were drawn out of the area just above the surface of the water. The partial pressure from water vapour is always artificially maintained at a minimum. Evaporation requires energy, which water molecules get by drawing hydrogen atoms out of the water molecules around them. Convection currents were increasing the evaporation rate, necessitating an increase in latent heat of evaporation. That meant most of the latent heat absorbed by water in basin was turned into proper heat. Since the chimney could not store as much heat as before sensible heat, the saltwater in its basin reached a lower temperature (S6) than in the basic still. The chimney still reduced the seawater's temperature by around 8% compared to the plain. This is because the solar rays hit the basin's water during evaporation.

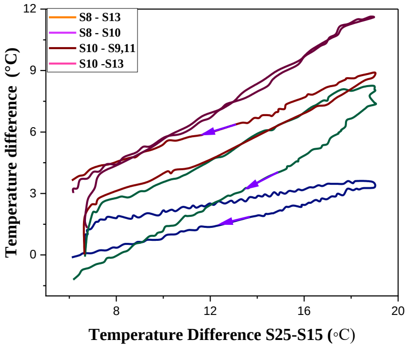

Fig. 4. Comparison of Temperature variation and rise over solar chimney temperature.

The water in the basin gradually warms as the air around it does via conduction and convection. Intense evaporation maintained a constant temperature gradient between the basin and the lake. The average difference between the basin and water temperature in the chimney still was 1.1ºC, while in the simple still, it was only 0.1ºC. As a result, less heat was lost through the basin, and more were delivered to the water. This resulted in a further improvement in thermal efficiency.

Table 3 Evaluations of outcome efficacy

Distiller	Everyday efficacy-total area η day, total (%)	Everyday efficacy-basin area η day,bsn (%)
Standalone solar still	38.1	46.3
Solar still chimney	35.2	49.7
Variation	-6.9%	+9.3%

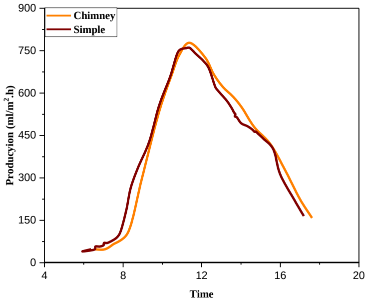

Fig. 5. Comparison of water productivity and time.

The water production rates of a conventional solar still and one with a chimney and condensers are compared in Figure 5. The solar still with chimney has a faster evaporation rate than the simple still by 11 a.m. Since air and water temperatures peak in the afternoon, this phenomenon occurs. Humidity drops faster than temperature gradient in plenum chamber and condensers. In a solar still equipped with a chimney, the air volume takes more time for the air to get saturated with water vapour. The chimney would still be moist in the afternoon, increasing condensation rates.

4. Conclusion

In this research, it was shown that a solar still's evaporator performed better in a basin that had enough ventilation. Utilizing a solar chimney to induce air movement increased the efficiency of the conventional heat transfer. This showed the decrease in water temperature as more of it evaporated. This process sharply increases the temperature variation among the stored water and basin's surface. The amount of energy released as latent heat of evaporation increased, meaning that the basin's surface made better use of the solar irradiance that reached it. There is no contest between the conventional still's output of 5.3 L/m^2 d and the chimney solar's production of 6.2 L/m^2 d. It conclude that the system is feasible, when combining solar stills with solar chimneys and external water-cooled condensers. Using a solar-powered passive airflow generator (the solar chimney), the suggested still would rely solely on renewable energy sources.

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