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The use of a solar chimney and condensers to enhance the productivity of a solar still

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ABSTRACT

This paper analyses the effect of a solar chimney used to enhance the convective currents within a solar still. Moreover, a condenser was also installed to improve the condensation process. Condensers in solar stills typically consist of fresh seawater flowing through a bank of tubes. However, in the configuration presented, water vapour was passed through a number of ducts immersed in seawater. This solar still was constructed and tested under natural weather conditions using a typical simple solar still as a benchmark. When comparing the efficiency based on the actual evaporator (basin) area, one notes that the solar still with the solar chimney and condensers performed 8.8% better. The simple still produced 4.7 L/m^2 d, while the modified still generated 5.1 L/m^2 d with the majority of the yield (59%) condensing in the condensers of the still. This clearly shows that enhanced convection and condensation increases the evaporation efficiency and hence the distillation process of a solar still.

Keywords: Solar distillation; Solar still; Solar chimney; Convection; Condensation

1. Introduction

Water is a primary vital resource. Whereas freshwater availability is decreasing due to widespread droughts around the world, its demand is on the increase. It is estimated that by 2025, two-thirds of the world's population will be living under water-stressed conditions and around 1.8 billion people will face absolute water scarcity [1].

In regions where the supply of freshwater from natural resources is scarce, desalination or water treatment is required. Desalination uses energy to purify sea or brackish water and make it potable. In remote areas where the energy supply is not reliable and/or there is a lack of the required infrastructure, a conventionally powered desalination plant would not be an option. One of the possible solutions is renewable energy-powered desalination. One of the most promising renewable desalination couplings is solar desalination due to the fact that regions which are arid and lack freshwater supplies often have an abundant supply of solar energy. Solar desalination uses solar radiation as the primary source of energy to produce potable water. Remote villages often lack the required expertise and resources required to operate and maintain complex engineering systems. The simplest solar

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desalination configuration is a single-effect solar still in which the natural water cycle is replicated in miniature. Solar energy as a source of thermal energy is used in solar stills to evaporate water and produce freshwater by distillation [2].

1.1. Solar stills

Solar stills, which make passive use of solar energy, are the main constituents of direct solar desalination plants. Solar irradiation is used to generate the necessary heat transfer mechanisms in order to replicate the greenhouse effect and set up the natural water cycle within an enclosed volume [3].

The basic solar still comprises a black basin of water in a transparent enclosure, generally made of glass. The basin is filled with raw water up to around 20–30 mm depth. As the desalination unit is exposed to solar radiation, the water in the basin absorbs some of this radiation and the rest is transmitted through and absorbed and reflected by the black basin. The latter transfers heat from its surface to the water by convection and conduction. This results in an increase in water temperature and an increase in water vapour partial pressure in the chamber. The evaporative heat transfer mechanism is driven by the water vapour partial pressure difference between the water surface and the glass cover. Naturally induced convection currents carry the water vapour to the underside of the glass. Since the temperature of the covering glass would be lower than the dew point of the saturated air trapped in the enclosure, condensation takes place. The latent heat of condensation is released to the glass and distilled water droplets are formed. Water trickles down to the sides from where the product is collected [2].

This desalination mechanism is based on phase change. Solar irradiation supplies the latent heat of vaporisation to the water in the basin. The latent heat of condensation is extracted and dissipated into the glass cover. In the case of simple solar stills, this energy is lost by convection to ambient. The high latent heat of condensation of water limits the production capacity of single-effect solar distillation. Single-effect solar stills reach a low thermal efficiency of around 35–40% with a production rate of around 3–4 l/m^2 d [4].

1.2. Separate condensers in solar stills

In conventional solar stills, the covering glass serves two purposes: a transmitter of solar radiation and a condenser. However, since it is exposed to radiation and because it relies on passive cooling by natural air convection, its condensation capacity is limited [2]. Moreover, solar radiation might re-evaporate some of the condensate formed. One of the possible ways to increase the capacity and thus the productivity of a solar still is to include a separate condenser.

A possible configuration of using a separate condenser is shown in Fig. 1. In this case, the solar still is conventional however the evaporation chamber is connected to a shaded condensation chamber. This chamber is shaded from direct solar radiation and thus the temperature of the air inside it is lower than that of the evaporation chamber. This temperature difference creates a pressure difference which purges water vapour from the evaporation chamber to the condensation chamber. The latent heat of condensation is conducted through the material of the condenser and is dissipated to ambient by natural air cooling. The condensation capacity of such a condenser depends amongst others on its volume with respect to the volume of the evaporation chamber and on the thermal conductivity of its walls. Since the temperature of the covering glass in the evaporating chamber would be lower than that of the water in the basin, it would still act as a site for condensation. However, since the bulk of the water vapour would condense in the condensation chamber, the temperature of the glass would be kept low and the higher water-to-glass temperature difference would increase the evaporation rate. When water vapour condenses against the main covering glass, its transmissivity is reduced. Hence, when the condensation rate against the underside of the glass is reduced, the overall transmissivity of the fogged glass is improved and so the evaporation rate is increased. A study carried out by Fath in Egypt showed that such a condenser increased the solar still productivity by 45% [2,5].

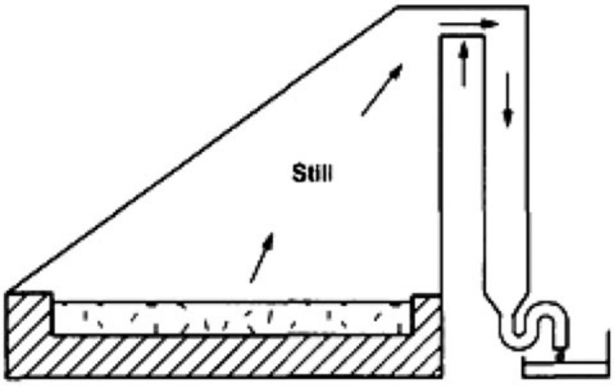


Fig. 1. Solar still with passive condenser [5].

Another similar configuration is shown in Fig. 2. Two galvanised steel cylinders are connected to the evaporation chamber of the solar still. H. Ahmed reports that the daily productivity increased by around 15% in summer and 17% in winter [6]. The amount of condensate collected from the external condensers amounts to 38% of the total.

The use of a typical condenser added to a solar still was analysed by S. Ahmed [7]. In this case, the condenser is active which means that cold water is pumped through a number of tubes. The latent heat of condensation is dissipated to the water flowing through and hence the temperature of the latter increases. This could be used as a pre-heater. However, in the case shown in Fig. 3, the water in the condenser was circulated in a once-through circuit. Two stills, one with and one without the condenser were tested in spring in Baghdad with 10 mm of freshwater in the basin. The separate condenser resulted in a productivity increase of around 7%, from 5.5 to 5.9 l/m^2 d. The very high productivity is attributed to the low amount of water in the basin. Had the stills been tested with seawater, the dissolved minerals would have precipitated and crystallised, covering the absorber of the basin with white salts.

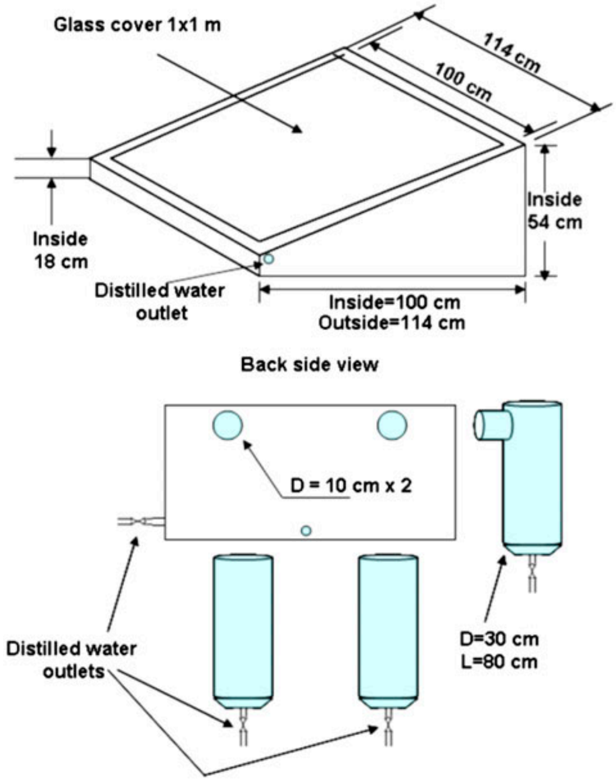


Fig. 2. Solar still with passive condenser [6].

In a paper published recently, Bhardwaj et al. [8] presented a solar still with additional surfaces for condensation as shown in Fig. 4. A unit without the added condensation chambers was tested in parallel as a benchmark. The author measured an improvement of 50% from the solar still with the additional surface area. The additional chambers increased the area available for condensation and hence the area available for latent heat dissipation to air. The prototype was also tested with forced convection generated by a fan installed between the evaporation and condensation chambers as shown in Fig. 4. The productivity improvement increased to 70% when compared to the benchmark. This occurred because of the higher convective heat transfer mechanisms in both chambers.

1.3. Natural and forced convection in solar distillers

The main driving force behind distillation is the evaporation process which is governed by the partial pressure difference created between the water surface and the glass, which in turn is generated by a temperature difference. The evaporative mass transfer is driven by convection. This fact inspired researchers to analyse the effect of naturally induced or forced convection currents on the evaporation and condensation processes in solar distillers.

One of the typical methods used to increase the convective currents is by creating an air-cycle. In doing so, a chamber where condensation is enhanced would have also been created as shown in Fig. 5. The main evaporation chamber is covered with double glazing and exposed to solar radiation. Double glazing increases the temperature of the innermost surface of the covering glass. This increases the temperature of the evaporation chamber, which in turn increases the humidity capacity of air. It also increases the pressure in the chamber. A duct/chamber around the basin is created by elevating the water basin. Since this duct is shaded from solar radiation, the temperature and hence the pressure are both low. This difference in pressure purges water vapour from the evaporation chamber to the condensation chamber. Since the chambers are connected at two points, the air purged to the back chamber is replaced by air from the duct beneath the water basin. This creates a convective loop carrying hot water vapour from the evaporation chamber to the condensation chamber and back. Aggarwal and Tiwari report that natural convection increased the productivity by 39% when compared to a conventional solar still without convection [9]. Around half of the distillate was collected from the main chamber and the other half from the condensation chamber.

Table 1
Average solar still water production results

Measurand	Units	Simple solar still	Solar still with solar chimney and condenser
Insolation	MJ/m^2 d	24.7	
Ambient temperature (Ta)	℃	27.9	
Wind speed	m/s	2.8	
Evaporator area	m^2	0.897	0.772
Product from sides	ml/d	1,116	645
Product from top	ml/d	3,205	1,041
Product from top + sides	ml/d	4,321	1,686
Total product	ml/d	4,321	4,084
Productivity (total area)	ml/m^2 d	3,830	3,591
Productivity (basin area)	ml/m^2 d	4,655	5,070
Daily efficiency (total area)	%	37.2	34.9
Daily efficiency (basin area)	%	45.2	49.2
% from sides	%	26.2	15.8
% from top	%	73.8	25.5
% from condensers	%	–	58.7

Table 2
Daily average temperatures and temperature differences—simple solar still

Measurand		Temp. (℃)
*T*1	Top glass	40.9
*T*4, 5	Air in evaporation chamber	48.1
*T*6	Seawater	48.2
*T*7	Basin surface	48.3
	*T*6–*T*1	7.3
	*T*7–*T*6	0.1

In a set-up very similar to that shown in Fig. 2, where purging of water vapour into an external condenser was used, the effect of creating a naturally induced air cycle was studied using a configuration as shown in Fig. 6.

When the external steel condenser was connected at two points to the solar still, a natural convection cycle was created. The productivity increased by 31% in summer and by 36% in winter, when compared to a conventional solar still. The amount of distillate collected from the condenser increased from 38% (by water vapour purging) to over 43% (by convective circulation). Since more water condensed in the condensers, the glass cover was less fogged and thus the solar radiation transmitted was increased. This resulted in a slightly higher water temperature but since the evaporation rate varies exponentially with temperature, a small increase in temperature has a greater end result. A higher evaporation drive and a faster circulation rate had a combined positive effect on the distillation rate [6].

Table 3
Daily average temperatures and temperature differences—chimney solar still

Measurand		Temp. (℃)
*T*1	Top glass	41.0
*T*4, 5	Air in chamber	46.6
*T*6	Seawater	46.7
*T*26	Basin surface	47.9
*T*8	Air in plenum chamber	42.4
*T*10, 17	Air in copper pipe, upstream	36.0
*T*13, 20	Air in copper pipe, downstream	34.1
*T*15, 22	Air upstream of chimney	34.8
*T*23	Solar chimney glass	43.3
*T*24	Solar chimney absorber	63.3
*T*25	Air downstream of chimney	48.0
	*T*6–*T*1	5.7
	*T*26–*T*6	1.1
	*T*8–*T*10, 17	10.1
	*T*10, 17–*T*13, 20	1.9
	*T*25–*T*15, 22	13.2

1.4. *Enhanced convection and condensation in solar distillation*

As discussed above, when the air flow in a solar distiller is invigorated, the condensation process is enhanced.

Moreover, if the condensation chamber is water cooled, the distillation rate is further increased. This lowers the temperature of the chamber and so its condensation capacity is increased. The latent heat of condensation of the water vapour is dissipated as sensible heat in the water flowing in the condenser. The low

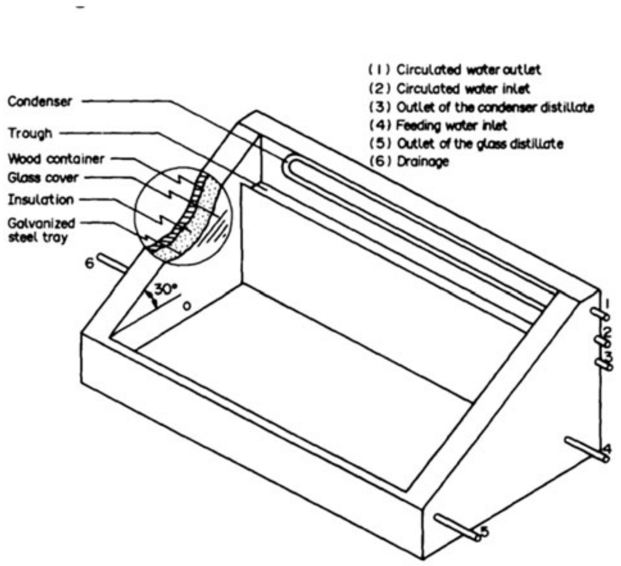


Fig. 3. Solar still with internal condenser [7].

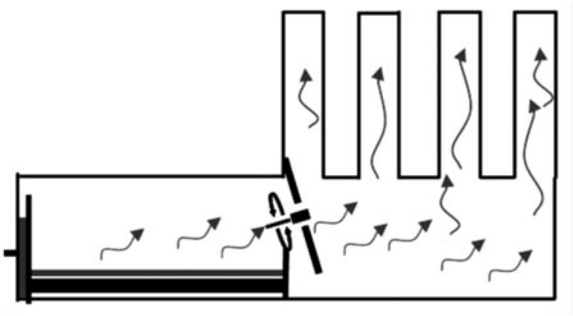


Fig. 4. Solar still with additional surfaces for condensation [8].

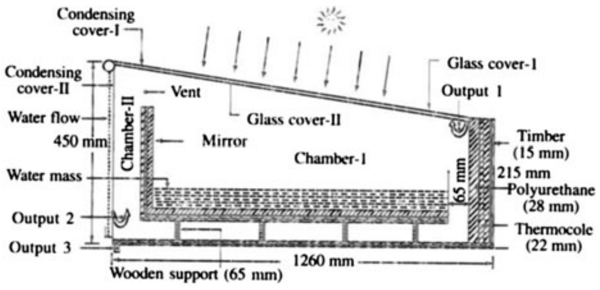


Fig. 5. Solar still with passive condensation chamber and natural convection [9].

temperature also lowers the pressure in the condensation chamber, which in turns creates a greater pressure difference. Due to this, the air flow is amplified and the productivity is further improved. Aggarwal et al. state that the amount of distilled water produced increased by 11% when comparing the water-cooled system with the passive system. When the water-cooled double-chamber system is compared to a simple solar still, the former produces 49% more water. In the water-cooled configuration, 80% of the distillate is condensed in the condensation chamber leaving only 20% condensing against the underside of the covering glass of the evaporation chamber [10]. This augments the productivity as described previously.

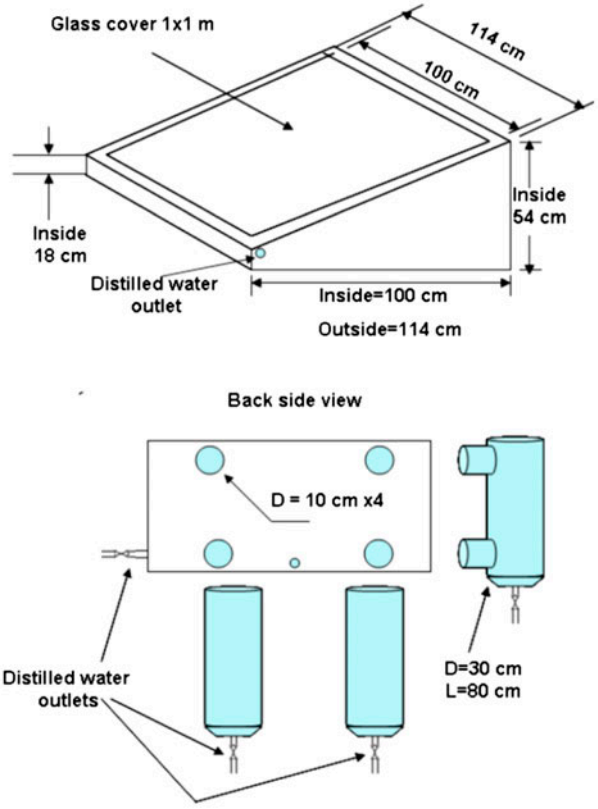


Fig. 6. Solar still with external condenser and natural convection [6].

1.5. Solar chimneys as convection generators

Solar chimneys are used to generate passive ventilation in systems. They are used for example in buildings, greenhouses and solar dryers. In the latter, the chimney effect is used to generate an air flow to increase the convective heat transfer mechanisms in an enclosed chamber and to expel the water vapour from the crops to ambient [11,12]. This is shown in Fig. 7.

A literature search on the use of solar chimneys in solar still configurations yielded very limited results.

A configuration published in a patent application by Coots in 2012 is shown in Fig. 8 [14]. The solar chimney (164) is used to generate a flow of air from the evaporation chamber of the solar still (130) to a water-cooled condenser (162). An open loop was proposed whereby fresh air is introduced to the system through a duct (166) and hot air is expelled to atmosphere through the chimney (164). Although such a system would increase the convective currents, it has two main drawbacks. The evaporation chamber of the solar still is continuously supplied with cool ambient air and the hot air generated by the chimney is not used but expelled directly to ambient.

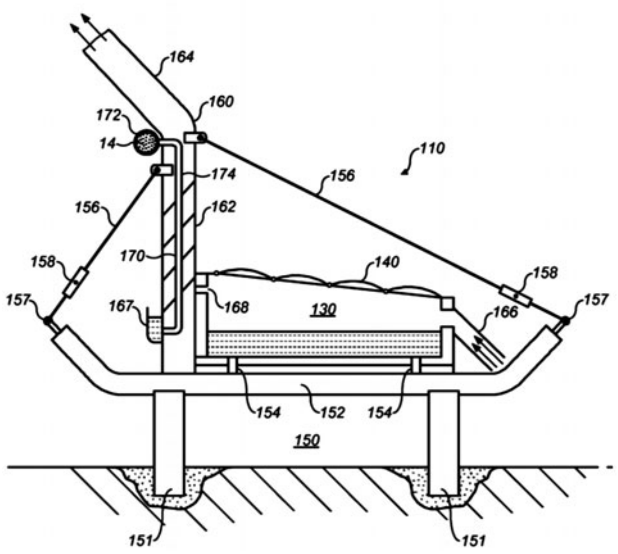


Fig. 8. Solar chimney combined to solar still [14].

2. Methodology

Two solar stills were constructed and tested simultaneously under natural weather conditions. A simple solar still was used as a benchmark. Another solar still comprising a solar chimney and a condenser was designed and tested. The footprint of both stills was fixed at 1 m^2. The prototypes are described in the following sections.

2.1. Simple solar still

A simple solar still with a footprint area of 1 m^2 was constructed using fibreglass-reinforced plastic (FGRP) as shown in Fig. 9. Low-iron glass, which has a higher solar transmittance than typical soda lime glass, was used for the transparent panes. The back vertical wall was gel-coated white to reflect solar radiation to the basin which was coated black to increase the solar absorptance. The condensate formed, which was collected from two side channels and one front channel, was measured using a tipping bucket. A silicone ridge was fixed to the underside of the inclined covering glass to drip the trickling condensate to the front channel. The floor area of the still occupied by the back insulation and by the side and front distillate collecting channels limits the effective basin area to

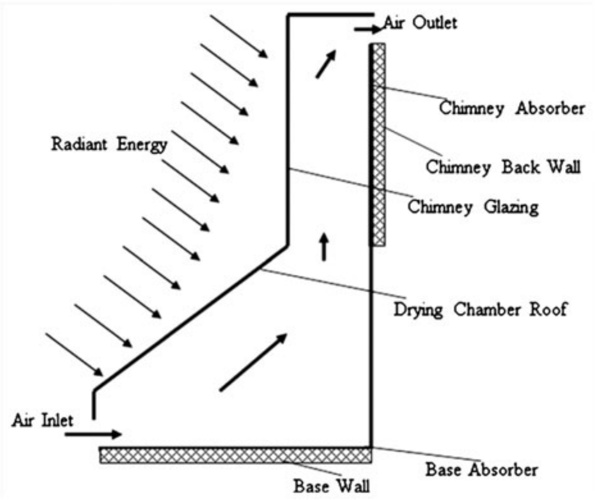


Fig. 7. Solar chimney use in dryer [13].

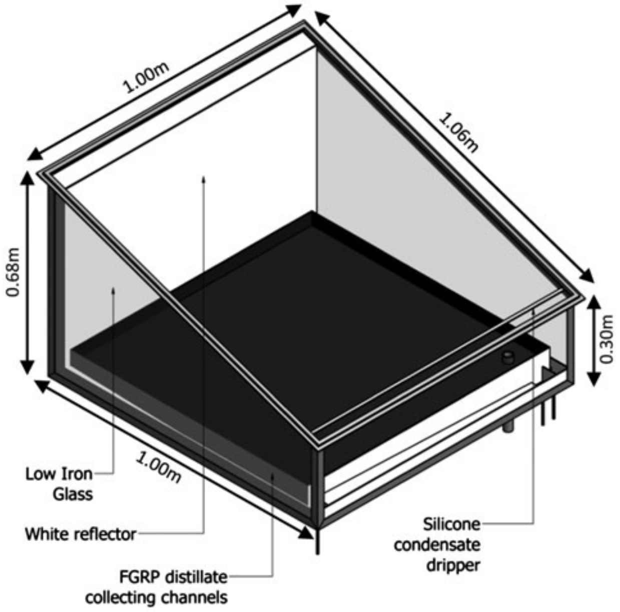


Fig. 9. Simple solar still.

0.897 m^2. The basin of the solar still serves as a solar absorber and as a water evaporator.

2.2. Solar still with solar chimney and condenser

The scope behind a solar still with a solar chimney and condensers is to improve the distillation process by enhancing the convection and condensation processes in a passive way. The design of a prototype (with a footprint area of 1 m^2) is shown in Figs. 10 and 11. It consists of three sections connected together:

(1) Glazed solar air heater (installed at 60° to the horizontal).
(2) Evaporation chamber.
(3) Copper condensers immersed in seawater reservoir.

The mode of operation is as follows. The fibreglass reservoir and the basin are filled with seawater in the morning. As the solar intensity increases, the temperature of the water in the basin increases and water starts to evaporate. At the same time, as the temperature of the black absorber (exposed area: 0.5 m^2, insulated with 50 mm expanded polystyrene) of the solar air heater increases, the density of the air inside the glazed collector decreases and the warm air rises into the space beneath the seawater basin. It then flows through to the evaporation chamber through ventilation gaps in the base of the basin as shown in Figs. 10 and 11. This air flow would increase the convection current and carry the evaporated water molecules to the inclined glass and the condensers.

The glazed solar air heater is covered with low-iron glass and is installed at an angle of inclination of 60° to the horizontal. The insolation at this angle varies the least throughout the year in Malta [15]. As the air flows upwards across the solar chimney, it is replaced with air from four pipes connected to the collector. The latter are connected to the evaporation chamber through an inlet to a plenum chamber. This creates a convection cycle which as shown in Fig. 10 flows in a clockwise direction.

Water vapour from the topmost section of the evaporation chamber flows through the rectangular inlet into the plenum chamber. The plenum chamber is connected to four fibreglass pipes (Fig. 11) which in turn are connected to four copper pipes (108 mm diameter, 1.5 mm wall thickness) immersed in a reservoir filled with seawater. This reservoir is insulated with expanded polystyrene and painted white to reduce the heat gain from solar radiation. The copper pipes are immersed in relatively cool seawater, and so as the water vapour flows through the pipes, its temperature is reduced and it condenses against the inner surfaces. The condensate trickles down the inclined pipes by gravity and is collected. The air then flows back from the condensers to the solar chimney to be reheated. The distillate produced against the surfaces

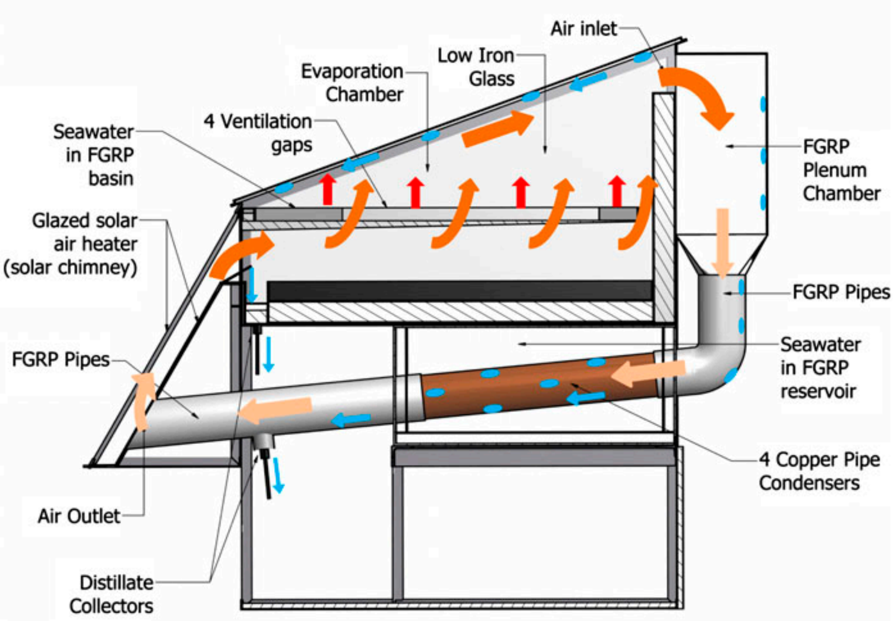


Fig. 10. Section through solar still with solar chimney and condenser.

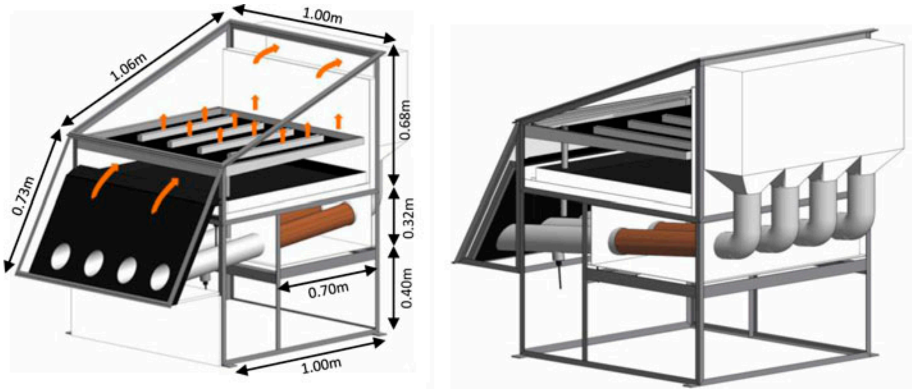


Fig. 11. Front and rear views of the solar still with solar chimney and condenser (shown with open seawater reservoir).

of the top evaporation chamber is collected and measured separately.

When water vapour flowing through the copper pipes condenses, the latent heat of condensation is conducted across the copper pipe walls and is dissipated to the seawater mass stored in the reservoir. The reservoir stores around 120 L of seawater and is capable to absorb the latent heat of condensation of around 4 kg of condensate with a temperature rise of around 20˚C. As the temperature of the water increases with time, the condensation drive decreases. Similarly, as the temperature rise across the solar chimney decreases, the buoyant pressure difference decreases and the air circulation rate decreases. This slows down the condensation process taking place inside the condensers and so more water vapour condenses against the inner surface of the main covering glass of the evaporation chamber. As more water vapour generated in the evaporation chamber condenses in the condensers and not against the inner surface of the glass, the temperature of the latter is maintained low and its solar transmissivity is not impaired by the condensate formed. Moreover, since the temperature of the covering glass would be relatively lower, the evaporation drive increases and the heat lost by convection from it decreases.

The space used for the four ventilation gaps, reduces the surface area of the basin of the still with enhanced convection. The area of the basin of the simple solar still is 0.897 m^2, while that of the still with the solar chimney is 14% less at 0.772 m^2. The specific evaporation performance (per unit area) was analysed.

2.3. Experimental set-up

The solar stills were constructed and tested under natural weather conditions (Fig. 12) for 20 consecutive days in August 2014 in Malta (Europe). A weather station was used to measure the weather variables affecting the distillation performance such as insolation, ambient temperature and wind speed.

Type-*T* class 1 thermocouples (±0.5˚C) were installed to monitor the temperatures in the solar stills as shown in Figs. 13 and 14. The beads of the

Fig. 12. Solar still set-up on roof (only two out of the three units shown are described in this paper).

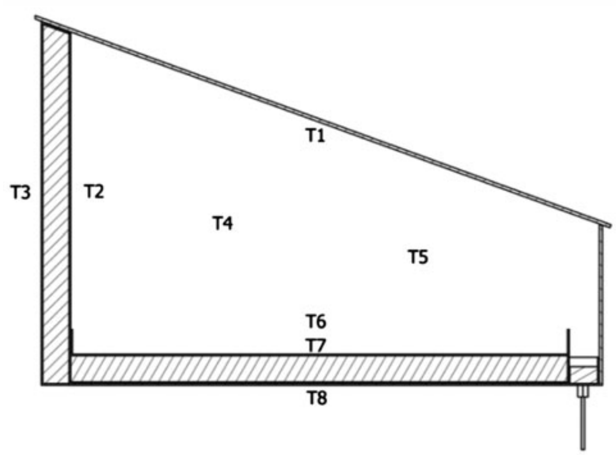


Fig. 13. Thermocouples in simple solar still.

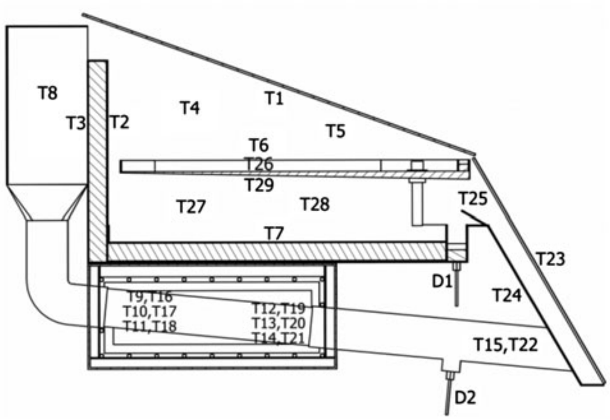


Fig. 14. Thermocouples in solar still with solar chimney.

thermocouples measuring fluid temperatures were shaded from direct solar irradiance using radiation shields. The air temperature measuring thermocouples were shielded using vertical shields made out of white PVC channels. Seawater thermocouples were shielded using white sockets to shade the beads from solar irradiance and to isolate the sensors from galvanic corrosion (which could interfere with the microvoltage reading generated by the dissimilar metals of the thermocouple). More details about the shields were published by the authors in [16]. The surface temperature measuring thermocouples were fixed to the surface depending on the substrate material. Epoxy resin was used for FGRP surfaces. The thermocouples measuring the copper pipe surface temperatures were soldered directly. Thermocouples measuring the temperatures of surfaces exposed to solar irradiance were coated using the same finishing of the exposed surface so that the thermocouple bead would have the same solar absorptivity as the surface.

Tipping buckets were used to measure the distillation rates. The dataloggers were programmed to take a reading every second and record the average once a minute. The basins were flushed and filled with 20 mm of seawater automatically at 01:00 every day during the testing period. The diurnal average values of each measurand were found and are discussed in the following section.

3. Results and discussion

The key results are shown in the Tables 1–3. If not otherwise stated, the values shown are the daily average or total from sunrise to sunset for the whole testing period. Where two thermocouple numbers are shown, the average value of both is tabulated.

The overall daily efficiency of the solar still, based on the area of the basin (which also serves as the evaporator) is given by:

$$\eta_{\text{day,bsn}} = \frac{M_{\text{e}}\, h_{\text{fg,sw}}}{H_{\text{hor}}\, A_{\text{bsn}}}$$

On the other hand, the overall daily efficiency of the solar still, based on the whole footprint area of the solar still is given by:

$$\eta_{\text{day,tot}} = \frac{M_{\text{e}}\, h_{\text{fg,sw}}}{H_{\text{hor}}\, A_{\text{tot}}}$$

where M_{e} is the total mass of distillate collected, $h_{\text{fg,sw}}$ is the latent heat of evaporation of seawater, H_{hor} is the daily insolation on a horizontal surface, A_{bsn} is the surface area of the basin (evaporator) and A_{tot} is the total footprint area of the still.

The simple solar still with an evaporator of 0.897 m^2 produced 4.32 L/d. The majority (73.8%) of the water vapour was condensed against the top inclined glass. On the other hand, the solar still with chimney and condensers, produced 4.08 L from an evaporator with an area of 0.772 m^2. The condensers were the most effective producing 59% of the condensate. When the area of the evaporator is taken into account, one notes that the productivity of the chimney solar still was 8.8% higher than that of the simple solar still.

The temperature profiles (Graphs 1 to 4) and the air circulation rate in the solar still with chimney generated the distillation rates shown in Graph 5. The area of the evaporator (0.772 m^2) was used for the calculation of the normalised production rate.

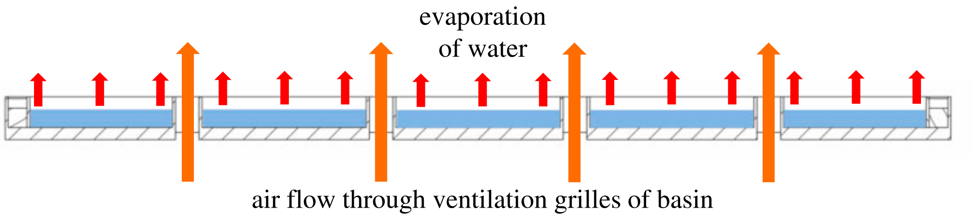
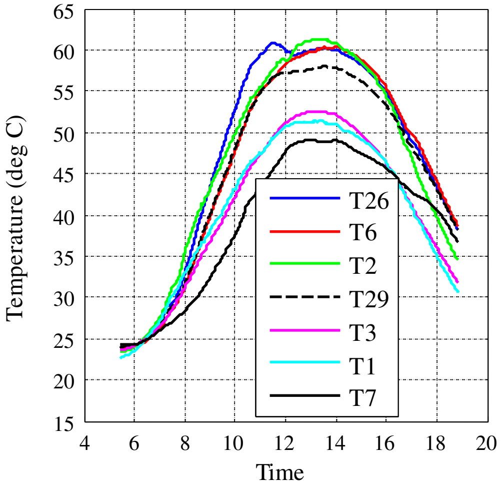
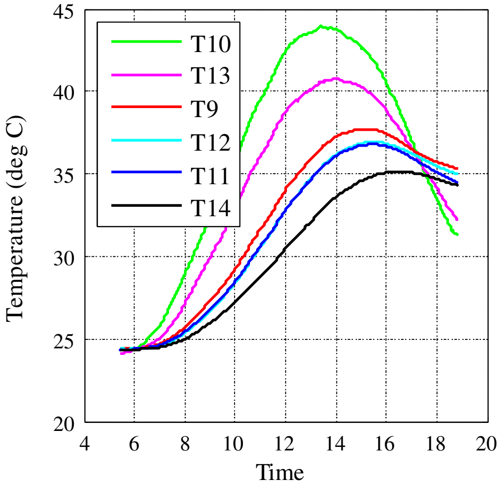


Fig. 15. Thermocouples in solar still with solar chimney and condenser.



Graph 1. Temperatures in evaporation chamber (solar still with chimney).



Graph 2. Temperatures in condensers (solar still with chimney).

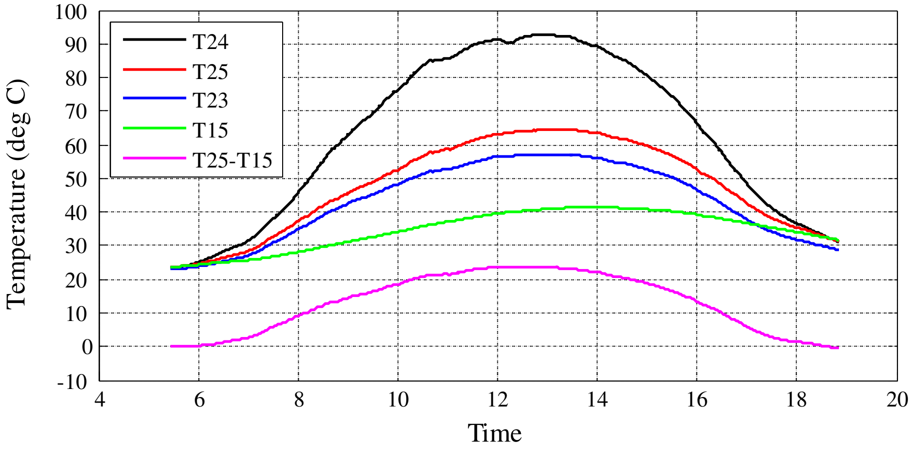
The seawater in the elevated basin reached a temperature of 60˚C (*T*6, Graph 1) at around 13:00. The black absorber of the solar chimney exceeded 90˚C (*T*24, Graph 3) and generated a maximum air temperature rise across the chimney (*T*25–*T*15) of around 24˚C. The buoyant pressure difference across the solar chimney generated an airflow and shifted the water vapour produced in the evaporation chamber to the plenum chamber and condensers. The temperature of the air dropped from *T*8 in the plenum chamber to *T*10 and *T*13 across the water-cooled condensers as shown in Graphs 2 and 4. The temperatures of the copper walls (*T*9, 11, 12, 14) are plotted in Graph 2.

As expected, the plenum chamber and copper condensers generated the majority of the distilled water (red curve of Graph 5). Moreover, the majority of the water which condensed in the evaporation chamber was collected from the top inclined glass (magenta curve). At around 17:00, the condensation rate from the condensers was lower than that from the evaporation chamber. This is due to the warming up of the water stored in the reservoir.

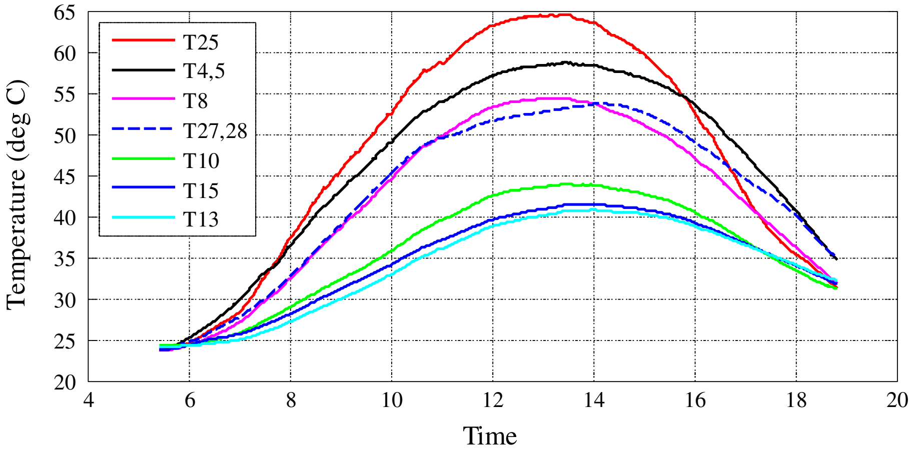
The scope of having a solar chimney coupled to condensers is twofold: to create a flow of air which carries water vapour from the evaporation surface and to shift the condensation process from the evaporation chamber to the condensers.

Graph 6 shows that the temperature rise across the chimney varies directly with the solar irradiance. The temperature rise governs the buoyant pressure difference generated which in turn results in air circulation.

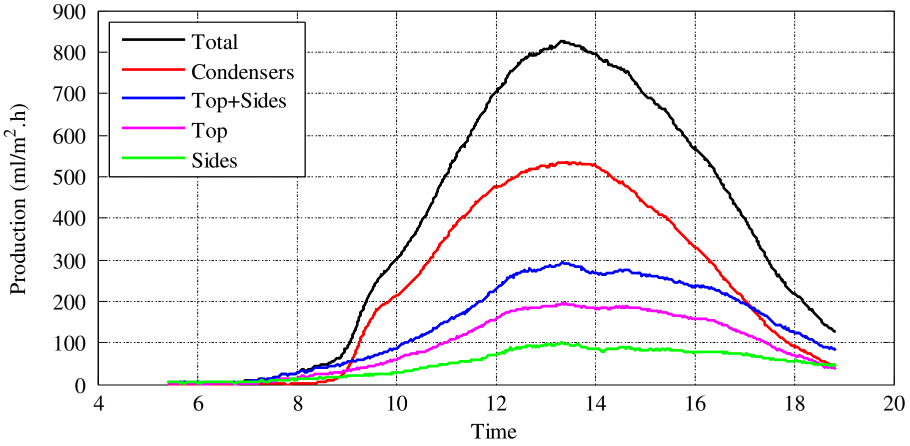
The circulating mass flow rate, the temperature and temperature differences reached govern the resulting condensation rates across the plenum chamber and condensers. The key temperature differences along the condensing path are plotted against the temperature rise across the chimney (*T*25–*T*15) in Graph 7. It is interesting to note that the temperature drop across the plenum chamber and condensers together (*T*8–*T*13) is proportional to the chimney temperature rise. The majority of the temperature drop, and hence also the specific humidity drop, occurs in the plenum chamber as shown by the blue curve. The rest of the drop which takes place along the copper condensers is



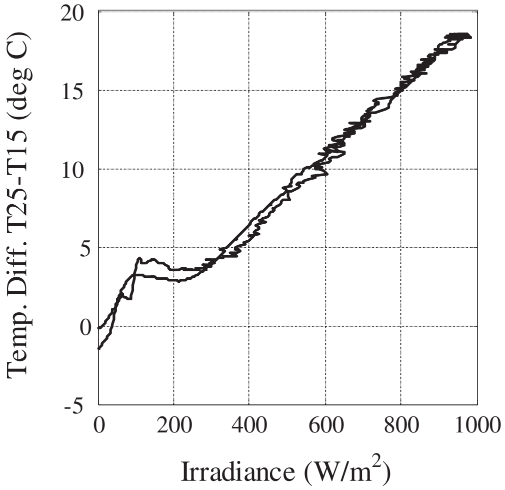
Graph 3. Solar chimney temperatures (solar still with chimney).



Graph 4. Air temperatures (solar still with chimney).



Graph 5. Distillate production rates (solar still with chimney).



Graph 6. Temperature difference across chimney with Irradiance.

represented by the red curve. The arrows on the curves show how the parameter varies from sunrise to sunset. For a given chimney temperature rise, the temperature drop in the plenum chamber in the afternoon was higher than that in the morning. This occurs due to the higher air temperature (*T*8) in the plenum chamber. Although the ambient temperature would also be slightly higher in the afternoon, the resulting temperature difference (*T*8–*T*a) would be higher, resulting in a higher temperature drop as the air flows across the ambient air-cooled plenum chamber (*T*8–*T*10).

The temperature of the water in the reservoir is also higher in the afternoon and this reduces the difference between the temperature of the air flowing through the pipes and the copper walls (*T*10–*T*9, 11—black curve). This in turn reduces the temperature drop across the copper condensers (*T*10–*T*13—red curve).

The air flowing from the chamber beneath the basin flows through the ventilation grilles to the evaporation chamber above it. The temperature increase (from ambient) of the air in the evaporation chamber in the chimney still was around 8% less than that of the simple still. The cooling effect across the plenum chamber and condensers was higher than the heat gain across the chimney and so the resulting temperature was lower. This also reduced the water vapour carrying capacity of the air.

The area used for the ventilation grilles reduced the area of the absorber and evaporator of the basin in the chimney still by 14%, when compared to the basin area of the simple solar still. Hence, the water surface area which is exposed to irradiance and from which water molecules are able to evaporate was reduced by 14%. Hence, one expects the chimney still to underperform by the same factor. However, even though it did not exceed the yield of the simple still, it produced only 6.3% less distillate as shown in Table 4.

When comparing the efficiency based on the actual evaporator (basin) area one notes that the difference is positive by 8.8%. This clearly shows that air flowing through the evaporator increases the evaporation efficiency and hence the distillation process.

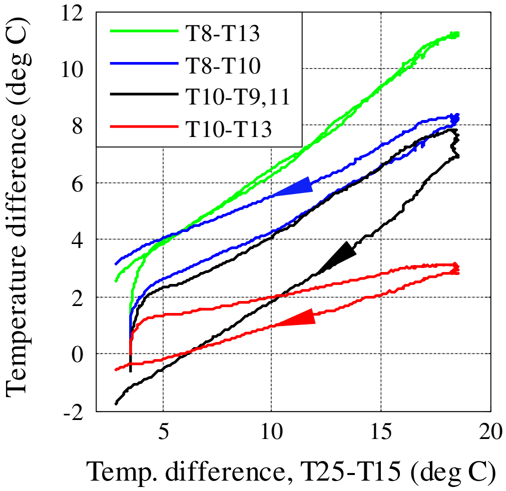
The water evaporation process is driven by the water vapour partial pressure difference between the region above the water surface and the air stream. The evaporative heat transfer is also directly related to the convective heat transfer. As the air flows through the grilled evaporator, this convective heat transfer is improved as shown in Fig. 15. Hence, the evaporation process is enhanced. This means that more water molecules were being carried away from the volume just above the water surface. In other words, the partial pressure due to water vapour was constantly being kept low. This in turn improves the evaporation mechanism.

For a water molecule to evaporate, it extracts the energy required from the water mass. Since the evaporation process was being augmented by the convection currents, more latent heat of evaporation was required. Hence, a higher portion of the irradiance absorbed by the water mass in the basin was being used to supply the latent heat. As the name of this type of energy implies, this heat supply was not recorded by the temperature readings. Since less thermal energy was stored as sensible heat, the temperature (*T*6) reached by the seawater in the basin of the chimney still was lower than that in the simple still. In fact the seawater temperature (relative to ambient) was around 8% lower in the chimney still when compared to that of the simple still. This does not mean that the water in the basin was absorbing or receiving less energy but the energy it was receiving was being used where it was actually needed, i.e. for evaporation.

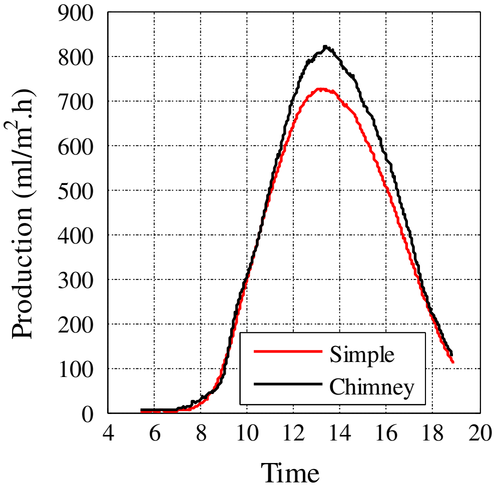
Some of the irradiance which is not absorbed by the water mass is transmitted and absorbed by the basin surface. In turn, as the temperature of the basin increases, the majority of the heat is transferred by conduction and convection to the water mass. Since the temperature of the water was kept low by more evaporation, the basin to water temperature difference was maintained high. In fact, there was a high improvement recorded when comparing the difference of the chimney still (*T*26–*T*6) with that of the simple still (*T*7–*T*6). Wherein the simple still, the basin to water temperature difference was of around 0.1℃,

Table 4
Comparisons of efficiency results

Distiller	Daily efficiency–total area $\eta_{\mathrm{day,tot}}$ (%)	Daily efficiency–basin area $\eta_{\mathrm{day,bsn}}$ (%)
Simple solar still	37.2	45.2
Still with solar chimney	34.9	49.2
Difference	−6.3%	+8.8%



Graph 7. Temperature differences with temperature rise across solar chimney.



Graph 8. Water production comparison with time.

that recorded in the chimney still averaged 1.1℃. This further reduced the heat lost through the basin and increased the heat supplied to the water mass. This further increased the thermal efficiency.

Graph 8 illustrates the water production rates from the simple solar still and from the still with chimney and condensers. It shows that the evaporator of the solar still with chimney exceeds the evaporation rate of the evaporator of the simple still from around 11 am onwards. This occurs due to the higher water and air temperatures in the afternoon. For the same temperature differences reached across the plenum chamber and condensers, the drop in humidity would be higher. Moreover, since the air volume of the solar still with chimney is higher, it takes more time to saturate it with water vapour. In the afternoon, the chimney still would be saturated and the condensation rates would be higher.

4. Conclusion

This study showed that a ventilated basin had a positive effect on the efficiency of the evaporator of a solar still. A solar chimney which was used to generate air circulation increased the convective heat transfer. This increased the evaporation rate and hence lowered the temperature of the water to be evaporated. This in turn increased the temperature difference between the basin surface and the water stored in it. As a result, the solar irradiance absorbed by the basin surface was used more efficiently by supplying more energy to be used as latent heat of evaporation. The conventional still produced 4.7 L/m^2 d, while the chimney still generated 5.1 L/m^2 d.

The externally water-cooled condensers coupled to the solar chimney improved condensation by separating and shifting the condensation process from the evaporation chamber to the condensers. The majority (59%) of the distilled water produced condensed in the plenum chamber and condensers. The water vapour temperature drop measurements revealed that the air-cooled plenum chamber was the most effective condenser. A 120-L seawater reservoir was used to externally cool the immersed copper condensers. This gained heat and resulted to be an ineffective cooler in the afternoons.

Some of the area of the basin of the solar still with chimney was used for the ventilation grilles. The effective evaporator area of the grilled basin was 14% smaller than that of the simple still. The 14% smaller evaporator generated 6.3% less water vapour than the simple still at an 8.8% higher efficiency.

This study shows how a solar chimney and externally water-cooled condensers could be coupled to solar stills. The proposed still uses a passive airflow generator (the solar chimney) which is powered using solar energy. This paper could serve as a basis for future research projects attempting to use a solar chimney in solar distillation.

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