Thermal Performance of a Tubular Solar Still

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Abstract - *This paper presents a new form of solar stills, the oval tube solar still (OTSS). It aims to increase the daily; production rate of freshwater by using some improvements such as covering cooling water, OTSS is characterized by its simple design. The OTSS is used with and without cooling water. Experiments have been carried out in Cairo, Egypt climatic conditions. Different design parameters are investigated; depth of saltwater in the basin of (2, 1.5, 1, and 0.5 cm). It is found that, without cooling water, the production rate decreases with increasing the water depth in the basin, and the maximum production rate reached 5.11 L/m^2/day at 0.5 cm water depth, with the highest efficiency of about 43.35 %.*

Key Words: Solar desalination; oval tubular solar still; cover cooling; Productivity enhancement.

1. INTRODUCTION

Water is one of the most important elements of human and animal life. Thus, the supply of potable water has always been a major concern in humanitarian affairs. It is very difficult for human life to find a source of drinking water, especially in remote areas. Water covers almost two-thirds of the Earth's surface, more than 97% of which is in the oceans, 2% is frozen as icebergs and glaciers, and only 1% is available as potable water. Thus, most water on Earth is not suitable or safe to drink [1]. Nowadays, many different methods are used to produce potable water from polluted or saline water. The oldest method of purification is called desalination which uses energy to remove impurities from the water. Considering the availability of renewable energies such as wind and solar energy in remote areas, these are the best options for making polluted and saline water safe to drink. Solar distillation uses solar energy to produce freshwater. Thus they are more economical than other distillation systems [2, 3].

Many researchers have made many different experiments to improve the performance of solar stills to increase the daily rate produced from desalinated water [4], such as using hot water heated by solar radiation [5-7], the use of nanofluids, which achieved a 38% increase in productivity [8, 9], use an air compressor to pump hot air into the saltwater basin[10], the use of phase change materials [11] , the use of a solar chimney, which led to an increase in productivity by 46.3% [12], Installing internal and external condensers [13, 14], paint the basin in black with the use of nanomaterial[15], combined wick and cover cooling [16], the integration of phase change material and nanoparticles, where an experimental study of the solar still using paraffin wax was carried out, with the performance enhanced by adding nanoparticles (Al_2O_3), and the improvement percentage was 45% after adding (Al_2O_3) [7].

In the year 2020, [17] experimental study was presented for circular tubular solar still. The study was conducted under the weather conditions of Tanta city - Egypt. Two cases were worked on the first case, which is the traditional circular solar still without additives, and the second case is the use of paraffin wax as a heat storage method in order to increase productivity and achieve the best performance of the solar still, where paraffin wax was shipped inside 10 copper tubes, was placed under the saltwater basin. The system productivity and efficiency reached 4.31 L/m^2/day and 33.8% without paraffin wax, respectively, but after adding paraffin wax, the productivity and efficiency increased to 9.05 L/m^2/day and 72.7%, respectively and the improvement rate in productivity was 115% [17]. Also, in the year 2020, an experimental study of circular tubular solar still was carried out, and three cases were worked. The first case was the traditional circular tubular solar still, the second case was the use of phase change material, which is paraffin wax, and the third case was the merging of paraffin wax with nanoparticles, which is graphene, and the productivity was in the three Cases of 4.3, 6, and 7.9 L/m^2 respectively, and efficiency 31, 46, and 59%, respectively [18].

2. EXPERIMENTAL SETUP AND PROCEDURES

Figures 1and 2, the new shape of solar stills, which is (OTSS), which is a new and simple design for solar stills, as it is a transparent oval cylinder made of polycarbonate or the so-called acrylic and is characterized by being transparent and permeable to sunlight from all directions, which increases the surface of heat transfer, increases the surface area of condensation, and the oval shape and also helps the water to descend faster to the bottom. The oval tube is 100 cm in length, the major diameter of 60 cm, minor diameter of 42 cm, and the thickness of a polycarbonate sheet is 5 mm. A rectangular saltwater basin of 80 cm length, 30 cm width, and height 5 cm is put inside the oval tube Table 1 shows the still design parameters used.

Table (1) still design parameters

Property	Value	Unit
Still length	100	cm
Major diameter	60	cm
Minor diameter	42	cm
Acrylic thickness	5	mm
Basin water dimensions	80 x 30 x5	cm
Basin water and paraffin dimensions	80 x 30 x5.6	cm
The distance between each two adjacent sprinklers	10	cm

The following equation is used in finding total uncertainty of any function *y* [19-22].

$$u(y) = \sqrt{\left(\frac{\partial y}{\partial x_1}\right)^2 u^2(x_1) + \left(\frac{\partial y}{\partial x_2}\right)^2 u^2(x_2) + \cdots + \left(\frac{\partial y}{\partial x_n}\right)^2 u^2(x_n)} \qquad (1)$$

Where $u(y)$ the uncertainty of the variable *x*, $\mathbf{u}_{xn}$ is the uncertainty of parameter and *xn* is the parameter of interest.
It is estimated that, uncertainties of thermocouples, solar power meter, calibrated flask and hot wire anemometer are ±0.10, ±2.88, ±2.88, and ±0.06, respectively.

3. RESULTS AND DISCUSSION

3.1. Weather condition through the experimental work

The climatic conditions in this experimental work are represented by the ambient temperature. The intensity of solar radiation and the wind speed variables affected the performance of the OTSS. The experimental work carried out during August and September of 2020 during the summer season in Cairo (latitude. 30.10º N, longitude. 31.29º E), Egypt.

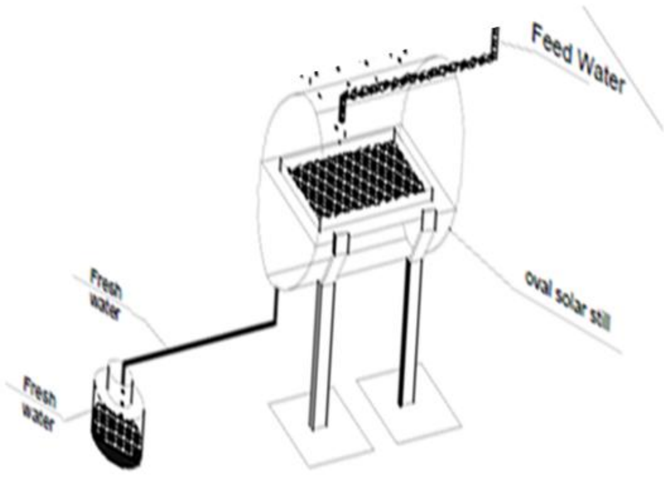


Fig.1. Schematic diagram of the experimental setup

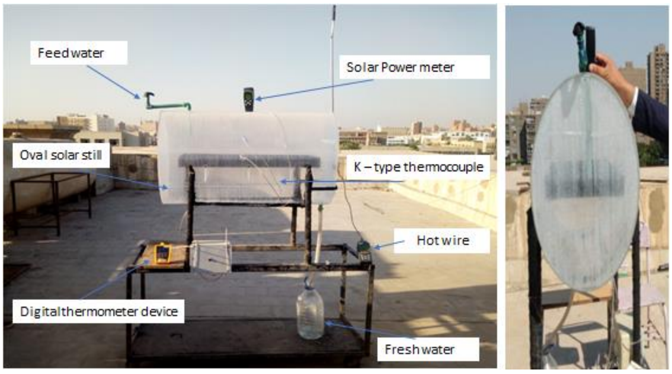


Fig. 2 Photograph of the experimental setup of oval tubular solar still.

A sample figure Fig. 3 is presented for the first case without cooling. It is found that the ambient temperature ranges between 31˚C at the beginning of the experiment till reaching its highest value 38.8˚C at 13:00 noon and then gradually decreases to 30˚C after sunset, as shown in Fig. 3(a). Also, Fig. 3(b) shows the intensity of solar is recorded through the days of the experiment, ranging from the minimum 550w/m^2 at 9am and its maximum value 1058w/m^2, and gradually decreasing to 400w/m^2 at the end of the experiment at 6pm at noontime. The wind speed during the days of the experiment at different depths of the saltwater in the basin is shown in Fig. 3(c), as the values range between 1.14 - 3.25 m/s.

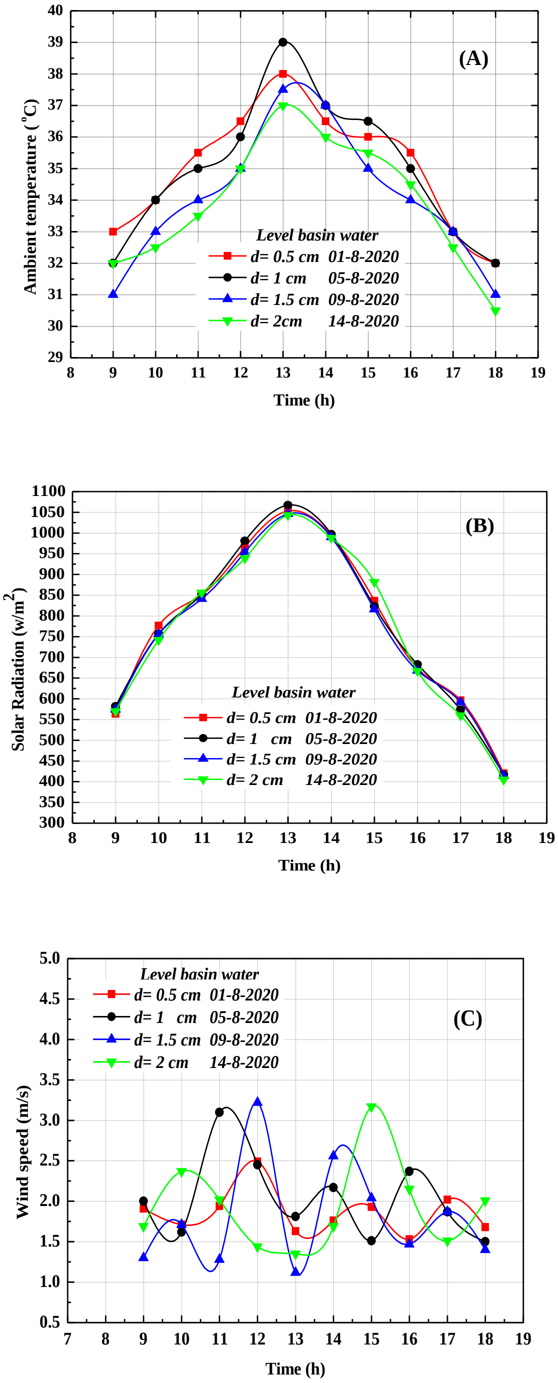


Fig.3 Climatic condition (A) ambient temperature, (B) solar radiation, and (C) wind speed.

3.2 The effect of different saltwater depths in the basin on OTSS performance.

Four different depths of saltwater inside the basin were investigated, namely 0.5, 1, 1.5, and 2 cm, in order to determine the best depth of saltwater inside the basin. Figure 4 (a) shows the relation between saltwater depth and its temperature with time. It is clear that the lowest temperature of the water inside the basin is at the beginning and the end of the day, namely at 9:00 and 18:00, while its maximum value is at noon (13:00) and the maximum value obtained is 65 ˚C, as this degree was achieved at the lowest water depth, which is 0.5 cm at 1 PM, while the maximum temperature was obtained at the largest depth of the saltwater, which is 2 cm, the temperature was 52 ˚C and the water temperature reached 57 and 62 ˚C at depth 1.5 and 1cm, respectively. It is clear that the lower the depth of the water inside the basin, the faster the water temperature increases, and this leads to a higher evaporation rate. On the contrary, the large depth of water takes a long time to heat up and evaporate. Figure 4(b) shows the surface temperature of the solar distiller (polycarbonate) during the study days with different depths of water, where the lowest temperature of the oval tube surface reached 32 ˚C and the maximum temperature 50 ˚C. As seen the temperature among the four cases is relatively small compared to the difference in water temperatures. It is clear that the lower depth of the basin-water increases rapidly the water temperature and leads to a higher evaporation rate and hence a higher cover temperature and vice versa. It is noted that the highest temperatures of the cover occurred at the lowest depth of the water.

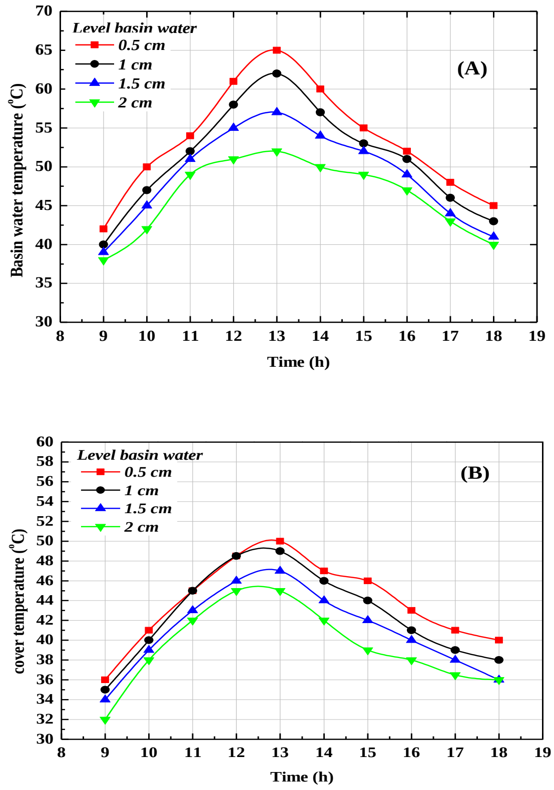
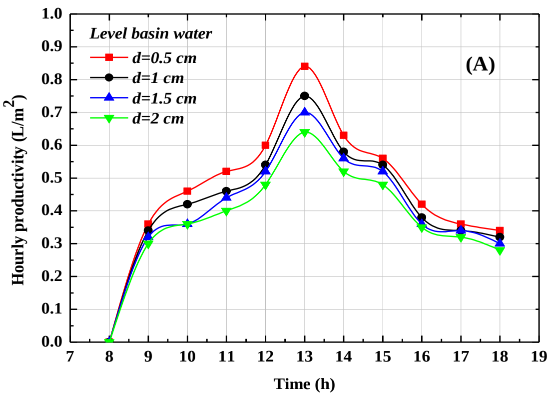


Fig.4 Effect of various saltwater depths in the basin on OTSS performance (A) basin water temperature, and (B) cover surface temperature

Figure 5(A) illustrates the production of desalinated water every hour at different depths, where the production of water increases every hour starting from the morning until it reaches its maximum production at noontime, then returns to gradually decrease after sunset. The highest production of desalinated water every hour at various saltwater depths 2, 1.5, 1, and 0.5 cm is 0.64, 0.70, 0.75, and 0.84 L/h, respectively. It is clear that the smaller the depth of the water, the higher the rate of desalinated water production because the lower depth of the water needs a small amount of heat and less time to heat up and evaporate. Moreover, the temperature variation between the tube surface and the saltwater reaches its maximum value as the depth of the water decreases [23].

Figure 5 (B) illustrates the rate of the total production of freshwater at various depths, which are 4.14, 4.42, 4.67, and 5.11 L/m²/day at depths of 2, 1.5, 1, and 0.5cm, respectively. As seen, the accumulated production of desalinated water at the depth of 0.5cm is higher than the depths of 2, 1.5, and 1cm by 23.42%, 15.61%, and 9.42%, respectively.



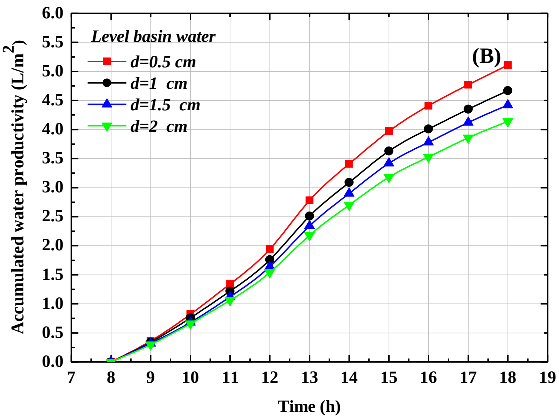


Fig.5 Effect of various saltwater depths on OTSS performance (a) hourly productivity (b) accumulated water productivity

Normally, heat is transferred from the vapor as a result of its condensation to the inner surface of the distiller cover, and then this heat is lost to the ambient by two methods of heat transfer, which are convection and radiation relatively and it increases when the wind speed is low [24]. Accordingly, the temperature of the inner and outer surface of the cover is high, close to the vapor temperature, which reduces the thermal performance, and to increase the temperature difference between them, water is used for cooling. Air cooling can also be used, and air and water can be used together to increase thermal performance [25].

4. Thermal efficiency of OTSS

Thermal efficiency (η_d) is calculated through Eq. (2). It is defined as the ratio between the products of the total freshwater produced per hour multiplied by the latent heat of vaporization of water and divided by the product of the sum of the total solar radiation intensity per day multiplied by the total absorption area [26-29].

$$\eta_d = \frac{\sum m_{dis} \times h_{fg}}{\sum I(t) \times A_{abs} \times 3600}$$

Knowing that (m_{dis}) total freshwater produced per hour Kg/h, ($I(t)$) total solar irradiance per day W/m², (A_{abs}) total absorption area m², and (h_{fg}) water latent heat of vaporization J/kg.

Through the results and compensation in Eq. (2) it is clear that the efficiency of the OTSS reached 43.35% at the lowest depth of the saltwater, which is 0.5cm, and this percentage in without any improvement or additions to the system.

Table (2) presents a comprehensive comparison from literature for the cost analysis of OTSS, TSS, and CSS. It is clear that the cost of one liter of desalinated water using the OTSS is lower than the cost of using the TSS and conventional stills CSS, as it is clear that it achieves the highest results in terms of efficiency and productivity.

Table (2) Comparison of present OTSS performance and different CSS and TSS

Reference	Total freshwater (L/m²/day)	η_d,(%)
[24]	2.8	29.98
[25]	3.5	Not given
[14]	2.14	31.99
[30]	2.1	29.20
[31]	2.9	29.98
[23]	5.45	41.4
Present study (OTSS)	5.11	43.35

5. Conclusions

1. The depth of salty water significantly affects productivity, for the case of without additions, the production rate decreases with increasing the water depth in the basin, and the maximum production rate reached was 5.11 L/m²/day at water depth of 0.5 cm.

2. at the lowest saltwater depth of 0.5 cm, the daily efficiency without and with cooling water was 43.35% and 58.44 respectively.

Nomenclature

A_{abs}	total absorption area, m²
h_{fg}	water latent heat of vaporization, J/kg
I_d	total daily value of solar radiation, W/m²
$I(t)$	total solar irradiance, W/m²
m_{dis}	total freshwater produced, kg/h
Greek Letters	
η_d	Thermal efficiency
⍰	uncertainty
Scripts	
P_d	daily productivity, L/m²/ day
a	Ambient
bw	basin water
w	Wind
x	Variable
xn	Parameter of interest
t	temperature, ˚C
T_a	ambient temperature, ˚C
Acronyms and Abbreviations	
OTSS	oval tubular solar still,
PSS	pyramid solar still,
TSS	tubular solar still

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