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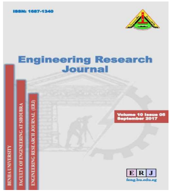

Enhancement of the Performance of a Solar Still Desalination Unit

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Abstract:
This work examines the influence of integrating a sponge layer of several densities on the performance of a solar still desalination unit (SSDU). Two identical SSDUs are constructed and tested simultaneously; one of them is used as a reference while a sponge layer is floated in the basin of the second unit. The results report that applying the sponge to the SSDU changes its operational principles and consequently changes the temperatures profiles inside the still and its corresponding performance. The maximum freshwater production and the thermal efficiency are recorded with using a floating sponge of density of 16 kg/m^3, with corresponding percentage increase of +58.1% and +55.4%, respectively, when compared with the reference unit. While the freshwater productivity and the SSDUs thermal efficiency are reduced with increasing the sponge density between 16 to 35 kg/m^3.

Keywords: Solar still, Productivity, Thermal efficiency, Sponge, Desalination.

1. Introduction

There is nothing more crucial to life on Earth than water. As well, supplying a freshwater alters everything; it is a bridge to progress. Regrettably, there is currently a water deficit in most districts of the world. Therefore, people spend a lot of expenses and make a lot of effort to provide the amount and quality of water they require to drink and use it in all aspects of life [1]. Unfortunately, the desalination of the sea water is a highly energy consumption process. There are at least three essential methods of desalination; thermal, pressure, and electrical. The solar still is an artificial water purifier that imitates the natural mechanism used by nature to purify the salty or brackish water; the sun drives the process of distillation. The solar still removes the impurities from sea or contaminated water by extracting pure water without using an external source of power. Stills leverage energy from the sun as opposed to fossil fuels by retaining enough heat from sunlight to form pure water vapour. The pure water vapour is then collected and condensed to liquid form as it cools.

Numerous researches were conducted on various designs of the SSDUs to improve their thermal performance, and consequently intents in cost and material. Higazy [2] tested the performance of a SSDU with incorporating four different sponge thicknesses of fixed density. Badran et al. [3] experimentally reported the effect of employing a solar collector with a SSDU on its yield. Eldalil [4, 5] theoretically and experimentally presented a new concept of active vibratory solar still beside passive helical wires in the still basin. The results reported that the excitation of the helical wires boosted the performance of the modified solar still; the productivity and efficiency were increased to be 3.8 L/m^2.day and 35%, respectively, and were augmented with vibration to be 5.8 L/m^2.day and 60%, respectively. Srithar [6] augmented experimentally the productivity of the SSDU by integrating a mini solar pond to preheat the saline water. Abdel-Rehim and Lashine [7] examined experimentally the operation of a combined SSDU with air-conditioning system. Kabeel and Abdelgaied [8] examined the combination of a phase change material and single-slope SSDU. El-Sebaii and El-Naggar [9] presented the performance of a finned single basin SSDU using finned basin. The results indicated that the measured yield of the reference and finned SSDUs were 4.235 and 5.065 kg/m^2.day, respectively, with a relative percentage augmentation of 16.4%.

Panchala and Patelb [10] reported that the orientation of the glass sheet hinges on the location latitude. Gnanaraj et al. [11] practically examined the combination of membrane and a solar pond with a single slope single basin SSDU with reflecting mirror. A significant enhancement in the SSDU yield was presented. Sharshir et al. [12] studied the effect of employing graphite and/or copper oxide micro-flakes in addition to the influence of basin water depth and glass cover cooling on the performance of SSDU. Kabeel et al. [13] tested practically the performance of a single slope SSDU with employing a sensible heat energy storage medium. Ni et al. [14] practically examined the SSDU performance with synchronized salt rejection. The authors employed a wick which delivered water for evaporation and rejected extra salt. Zanganeh et al. [15] tested practically the enhancement of SSDU productivity by applying nano-coating for the glass cover as an enhancement for the condensation process. Kabeel et al. [16] carried out experiments on a single slope SSDU combined with solar dishes. Significant augmentations are recorded in the SSDU yield and efficiency. In the present investigation, the influence of integrating a floating layer of a commercial sponge of several densities (16 to 35 kg/m^3) on the performance of a SSDU. The experiments are performed at Faculty of Engineering at Shoubra, Cairo, Egypt (30.1° N Latitude).

2. Experimental setup

Two identical double slope single basin-type SSDUs are fabricated with the same design parameters. Each SSDU consists of basin, glazing, insulation, support structure and distillate trough. In addition, valves, feed water system and measuring devices are also conducted to judge the performance of the SSUs. A schematic diagram of the SSDU is publicized in Fig. 1.

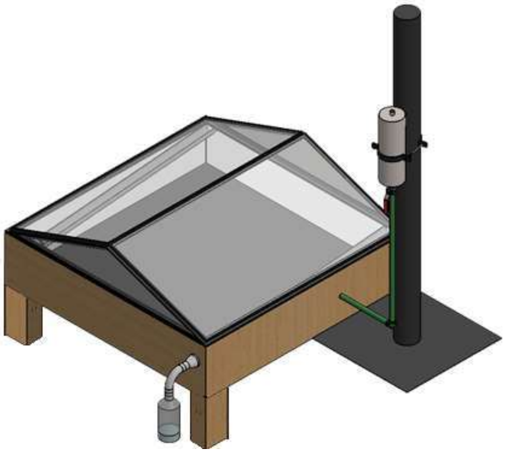


Fig. 1: A schematic diagram of the SSDU.

The basin of each unit is formed from a black steel sheet, 1 x 1 m^2 absorbing base and four sides of 20 cm height. The base is pained black to augment its absorptivity while the basin internal sides are coated with white paint to enhance their reflectivity. The basin is thermally insulated using a wooden box of internal dimensions of 1.04 m x 1.04 m x 0.22 m. The gap between the metallic basin and the wooden box is injected by polyurethane spray foam insulation. Four wooden legs are conducted to each SSDU to lift them to a height of 50 cm. Six holes of 0.5-inch diameter are drilled in the metallic basin and wooden box surfaces to allow attaching the thermocouples at their locations inside the SSDU, beside draining the washing water and salts, and a hole is connected to the feed water tank as demonstrated in Fig. 1. Additionally, a 1.5-inch diameter hole is drilled in the corner of the basin side to connect the distillate collection tray with the distilled water tank. It should be noticed that care is considered to seal off the gap that might be between the thermocouples and the holes in the basin walls. To keep a steady level of the saline water in the basin all the time of day, a feed water system is prepared for each SSDU. The tank is supported at a stand at a height of 1.5 m. An electric heater (1.5 kW) is fixed at the bottom of the tank to heat the brackish water to the required temperature; equals to the temperature of the saline water in the basin. The operation of the electric heater is according to a pre-adjusted digital thermostat. The temperature of the saline water in the basin is measured every 15 minutes and this value is set as a set point of the thermostat. It should be noticed that during the experiments, after 1 or 1:30 PM, there is no need to heat the feed water. On contrary, the temperature of the feed water in the tank requires to be reduced. Therefore, an amount of the water is drained from the feed tank, and at the same time, and the tank is partially filled with another cold amount with manual manner until reaching the basin water temperature.

For the glass cover, this part comprises four glass pieces of 4 mm thickness and transmissivity of 91%. Two of them are inclined rectangular plates (angle of 30° with horizontal), while the others are vertical triangular plates of 1000 mm base. Steel sheets of L-shape are utilized to construct a holder for the glass plates of each SSDU. Additionally, a rubber gasket is placed between the glass holder and the metallic basin to prevent any leakage. Then, the holder is bolted to the top surface of the metallic basin. A collection tray is incorporated in each SSDU to gather the condensed water tricking on the bottom side of the inclined glass plates and get it outside the still to be the output distilled water. The distillated water is collected outside the unit using a graduated transparent glass cylindrical vessel.

Five pieces of a commercial sponge are used in the present study. All of them have net dimensions of 980 mm x 980 mm, and 30 mm thickness while these pieces are of five different densities (from 16 to 35 kg/m^3). The top surface of the incorporated sponge pieces is sprayed with a black paint, and then they are floated in the SSDU basin over the saline water. A brine water of salinity of 32000 ppm is incorporated in all tests. Twenty-seven K-type thermocouples are incorporated to measure the temperatures at various locations of the two SSDUs; twelve thermocouples are used in the reference unit, while other fifteen thermocouples are used in the modified SSDU; three thermocouples are to estimate the basin base temperature, three thermocouples are to measure the water temperature in the basin, three thermocouples are to know the sponge temperature, a thermocouple is to measure the temperature of the water vapour in the unit, a thermocouple is to measure the temperature of the fresh water in the collecting vessel, and four thermocouples are to estimate the temperature of the two inclined glass plates. All thermocouples are connected through switching box to a digital thermometer indicator with a resolution of 0.1°C to display the thermocouples outputs. A digital solar power meter is incorporated to measure the incident solar radiation intensity. A digital environmental meter is utilized for measuring the weather conditions; wind speed, ambient temperature and humidity. The salinity of both the brackish water in the SSDU basin and the distilled water is estimated using the multiparameter meter.

3. Experimental procedures

The first step to recording the data from the SSDUs is to wash and clean the glass plates, the unit basin and the sponge from any formation of dust and salts deposited during the previous day. Then, the basin is partially filled with the saline water through the feed water tank until reaching the predesigned level. Thereafter, the thermocouples junctions used to estimate the water and sponge are attached at their locations, and the glass holder is then fixed tightly to the still basin using the rubber gasket and bolts in addition to the adhesive silicone. The next step is checking that the thermocouples are attached to their locations in the selector switch channels. These procedures are started daily at 7:30 AM before collecting the first reading at 9 AM. At this time, the incident radiation, the system temperatures (base, saline water, sponge, water vapour and glass temperatures), the ambient dry bulb temperature, and the wind speed are recorded. These measurements are repeated every 30 minutes till sunset. Furthermore, the temperature of the saline water in the basin is measured every 15 minutes and this value is set as a set point of the thermostat. A Microsoft Excel sheet is prepared to process the SSDUs productivity and thermal efficiency. Care is considered to positioning the SSDUs so that the tilted glass panels are oriented south and north directions.

4. Data reduction

After recording the system temperatures and the half-hourly distilled water produced by the two units, the average temperatures of the base (T_b), saline water in the basin (T_{sw}), sponge (T_{sp}), and glass (T_g) are estimated using the recoded values and number of their readings. The daily accumulative productivity ($V_{dis,d}$) can be obtained by adding instantaneous distilled water ($V_{dis,I}$) over the operating time (OT), and can be estimated as follows;

$$V_{dis,d} = \sum_{1}^{OT} V_{dis,I}$$

The instantaneous thermal efficiency of the SSDU ($\eta_{th,I}$) is estimated as the ratio of energy consumed for producing the fresh water to the total input energy [17];

$$\eta_{th,I} = \frac{\left[\frac{\rho_{dis,I}\, V_{dis,I}\, h_{fg,I}}{t_c}\right]}{G_{S,I}\, A_b} = \frac{\rho_{dis,I}\, V_{dis,I}\, h_{fg,I}}{G_{S,I}\, A_b\, (0.5 * 3600)} \qquad (2)$$

Where $h_{fg,I}$ is the instantaneous latent heat of vaporization of fresh water, J/kg, obtained at the saline water temperature, T_{sw}, using Eq. (3) [18].

$$h_{fg} = 1000[2501.9 - 2.40706\, T_{sw} + (1.192217 * 10^{-3}\, T_{sw}^2) - (1.5863 * 10^{-5}\, T_{sw}^3)] \qquad (3)$$

The daily thermal efficiency of the SSDU ($\eta_{th,d}$) is estimated follows [18];

$$\eta_{th,d} = \frac{\sum_{1}^{OT}\left[\frac{\rho_{dis,I}\, V_{dis,I}\, h_{fg,I}}{t_c}\right]}{\sum_{1}^{OT}[G_{S,I}\, A_b]}$$

The percentage change ratio in the freshwater production of the SSDU is estimated as follows;

$$\Delta V_{dis}\,(\%) = \left[\frac{V_{dis,d,mod} - V_{dis,d,ref}}{V_{dis,d,ref}}\right] x100$$

5. Verification of the SSDUs output similarity

Because the reference and un-modified SSDUs are tested in parallel, their distilled water productivities are compared under the same operating conditions for non-incorporating the sponge layer to examine their similarity. The results of the comparison are illustrated in Fig. 2. It is seen that there are tiny deviations between the fresh water produced by the two units (average deviation of ±1.6%), which state that they are identical and can be compared at dissimilar operating conditions.

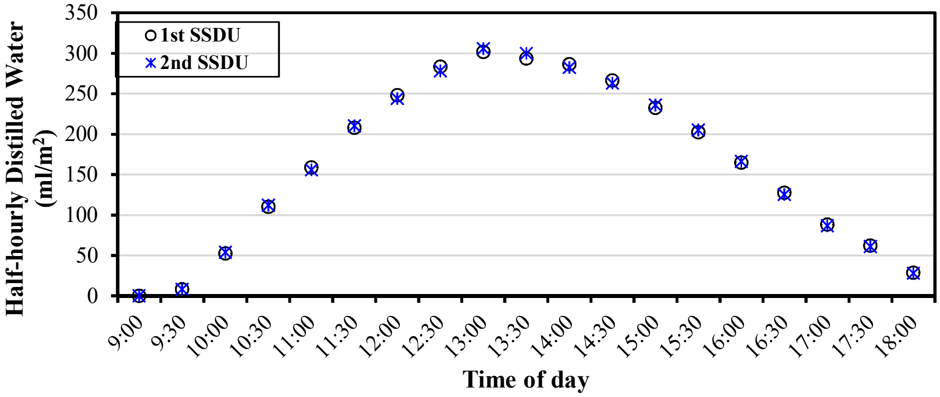
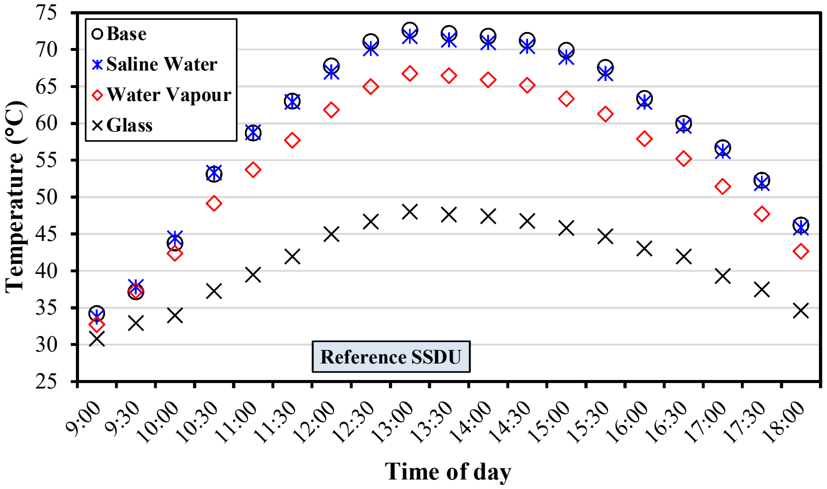


Fig. 2: Comparison between the two SSDUs under the same conditions.

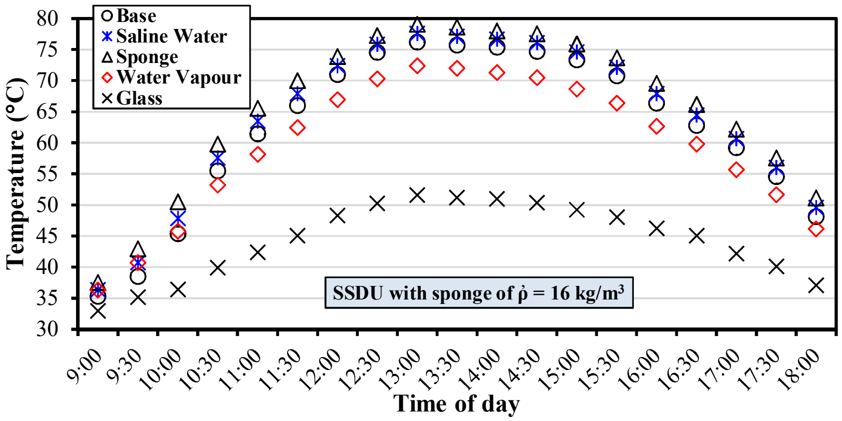
6. Results and discussion

6.1 Operational principle of the SSDUs

In this section, the operational principle of the SSDU due to using/non using the floating sponge is illustrated. Fig. 3 states the recorded average temperatures at various times of the day for the two tested SSDUs; reference and modified unit for sponge density of 16 kg/m^3.



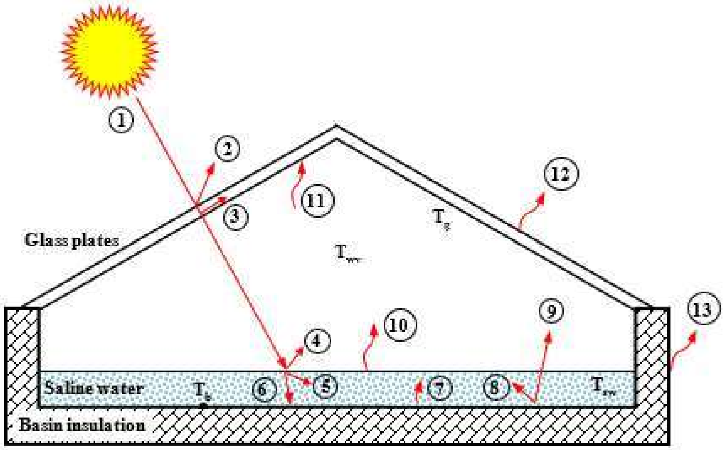
a)



b)

Fig. 3: The instantaneous temperatures at different locations in the modified SSDU.

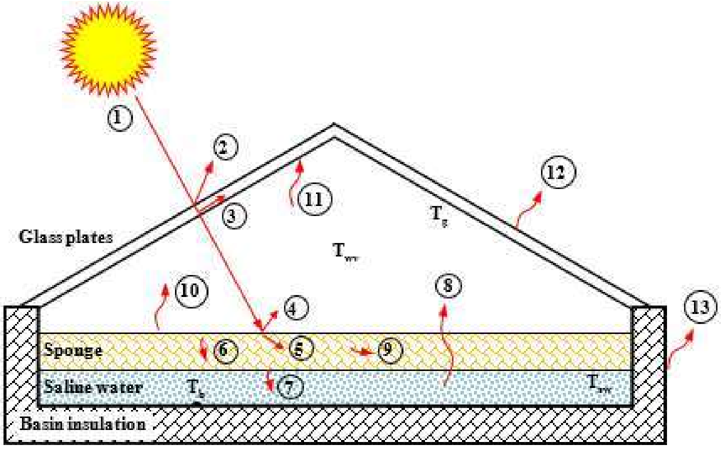
It is very clear that the temperatures profiles in both units are different, which state that their operational principles are different. In the reference unit, the maximum temperature is of the basin base, which absorbs the solar radiation and then heats the adjacent saline water by natural convection in addition to the thermal radiation absorbed by the slid particles in the saline water. This leads the water to evaporates. The water vapour is formed at a lower temperature than the saline water in the basin. Furthermore, this water vapour is condensed on the inner surface of the glass plates which have lower temperatures. The other heat transfer mechanisms in the reference SSDU are schematically illustrated in Fig. 4.



1- The incidental solar radiation.
2- Part of the incident solar radiation that is reflected by the glass plates.
3- Part of the incident solar radiation that is absorbed by the glass plates.
4- Part of the incident solar radiation that is reflected by the saline water surface.
5- Part of the incident solar radiation that is absorbed by the saline water.
6- Part of the incident solar radiation that is absorbed by the basin base.
7- Convection heat transfer from the base to the saline water.
8- Part of the emitted radiation by the basin base, which is absorbed by the solid particles in saline water
9- Part of the emitted radiation by the basin base, which is directed to all other surfaces in the basin.
10- Summation of evaporation, convection and radiation heat transfer transferred from the saline water surface.
11- Condensation heat transfer from the water vapour in the still to the inner surface of the glass plates.
12- Convection and radiation heat losses from the outer surface of the glass plates.
13- Convection and radiation heat losses from the outer surface of the basin.

Fig. 4: Operational principles of the reference SSDU.

For the modified unit, the incident solar radiation is absorbed by the black surface of the sponge, which rises its temperature to be the maximum value in the system. A part of the absorbed heat energy is conducted through the sponge thickness and then by conduction to the adjacent saltwater in the basin to evaporates (the average temperature of the saline water is higher than that of the base). The water vapour moves through the sponge layer, which is heated simultaneously, during the movement through the sponge. This drives the vapour to moves to the top to be condensed on the inner surface of the glass plates. The other heat transfer mechanisms in the modified SSDU are schematically illustrated in Fig. 5.



1- The incidental solar radiation.
2- Part of the incident solar radiation that is reflected by the glass plates.
3- Part of the incident solar radiation that is absorbed by the glass plates.
4- Part of the incident solar radiation that is reflected by the sponge outer surface.
5- Part of the incident solar radiation that is absorbed by the sponge.
6- Conduction heat transfer from the sponge outer surface to the sponge inner surface.
7- Heat transfer from the sponge inner surface to the adjacent saline water.
8- Evaporation heat transfer from the saline water.
9- Convection heat transfer from the sponge to the water vapour (in the sponge layer).
10- Summation of convection and radiation heat transfer transferred from the sponge outer surface.
11- Condensation heat transfer from the water vapour in the still to the inner surface of the glass plates.
12- Convection and radiation heat losses from the outer surface of the glass plates.
13- Convection and radiation heat losses from the outer surface of the basin.

Fig. 5: Operational principles of the modified SSDU.

6.2 Effect of sponge density

In this analysis, five different sponge densities (ρ̇ = 16, 20, 25, 30 and 35 kg/m^3) are tested at the same sponge thickness; 30 mm, and the same saline water level in the SSDU basin, 10 mm. Fig. 6 illustrates a sample of the recorded temperatures of the saline water at various times of the day for the two tested SSDUs; reference and modified unit at different densities of the tested sponge. In addition, Figs. 7 and 8 present the corresponding SSDUs productivities and thermal efficiencies, respectively.

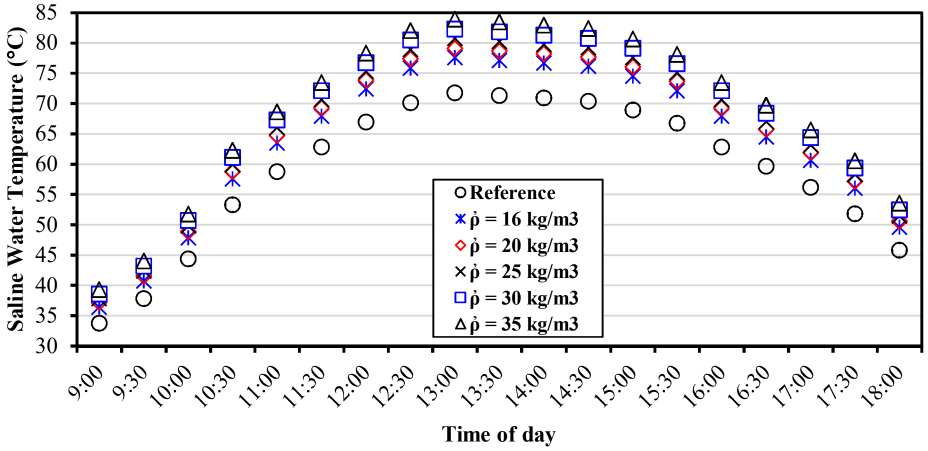


Fig. 6: Effect of sponge density on the instantaneous saline water temperatures in the SSDU.

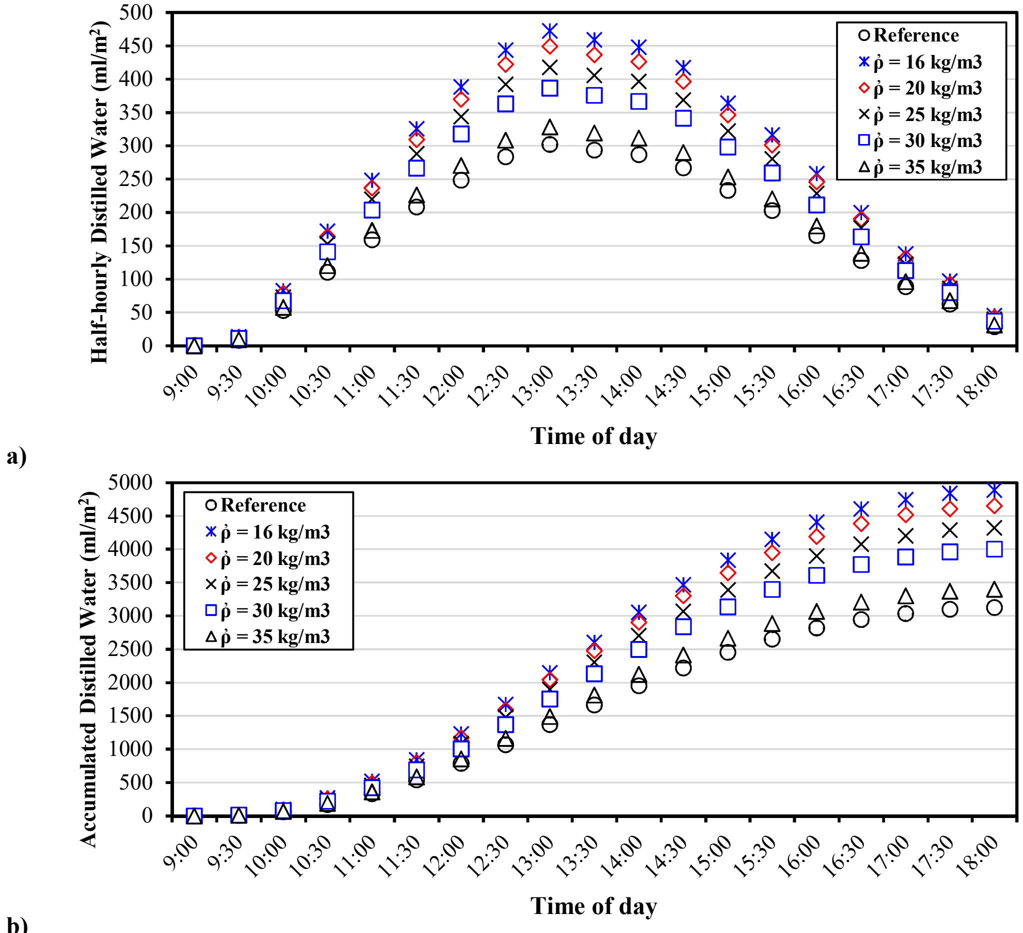


Fig. 7: Effect of sponge density on the SSDU productivity.

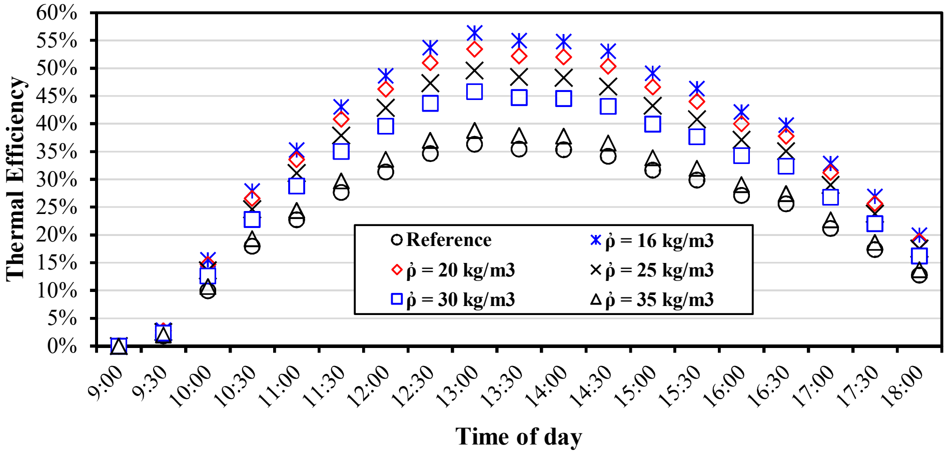


Fig. 8: Effect of sponge density on the SSDU thermal efficiency.

It is evident in Figs. 6 to 8 that the instantaneous temperatures at various locations in the SSDUs in addition to the instantaneous freshwater production and the thermal efficiency of the units exhibit the same trend of the solar radiation intensity that increases at first until reaching its maximum values at about 1 PM, and then falls down gradually as the time moves towards the sunset. Obviously, once the sponge is incorporated in the SSDU, the freshwater productivity and the still thermal efficiency in addition to the temperatures at different locations in the unit are meaningfully influenced. It is clearly shown in Fig. 6 that the temperatures in the modified still are higher than that in the reference unit, and their increasing growths with increasing the sponge density. This may be due to increasing the heat capacity of the sponge with increasing its density, which allows the more storage of the absorbed solar radiation. Furthermore, in contrary, it is clear in Figs. 7 and 8 that the freshwater productivity and the SSDUs thermal efficiency are reduced with increasing the sponge density although the saline water temperature is increased. This may be due to increasing the sponge density reduces its porosity, which blocks the water vapour and throttles its paths through the sponge layer. This is also another reason for increasing the system temperatures due to reducing the heat energy transmitted from the still with the reduction in the freshwater production for the same incident solar radiation.

The results reveal that incorporating a floating sponge, the freshwater production varies from 3.1 L/day.m^2 for the reference unit to be 4.9 and 3.4 L/day.m^2 at sponge density of 16 and 35 kg/m^3, respectively. The corresponding variation percentages are +58.1% and +9.7%, respectively. The same trend is appeared for the thermal efficiency of the SSDU. It is shown that applying the floating sponge, the daily thermal efficiency varies from 23.8% for the reference unit to be 37% and 25.6% at sponge density of 16 and 35 kg/m^3, respectively. The corresponding variation percentages are +55.4% and +7.6%, respectively.

7. Conclusions

According to the experimental results, the following conclusions can be expressed:

- Applying a floating sponge to the SSDU changes its operational principles and consequently changes the temperatures profiles inside the still and its corresponding performance.
- The instantaneous temperature at various locations in the SSDUs in addition to the instantaneous freshwater production and the thermal efficiency of the units exhibit the same trend of the solar radiation intensity.
- The temperatures in the modified still are higher than that in the reference unit, and their increasing growths with increasing the sponge density.
- The freshwater productivity and the SSDUs thermal efficiency are reduced with increasing the sponge density.
- The maximum SSDU freshwater production and the thermal efficiency are recorded as 4.9 L/day.m^2 and 37%, respectively, with using a floating sponge of density of 16 kg/m^3, with corresponding variation percentages of +58.1% and +55.4%, respectively, when compared with the reference unit (3.1

L/day.m^2 fresh water productivity and 23.8% thermal efficiency).

Nomenclature and abbreviations			
A	Area, m^2	SSDU	Solar still desalination unit
η	Efficiency	T	Temperature, °C
G	Incident solar radiation, W/m^2	t	Time, s
h_{fg}	Latent heat of vaporization, J/kg	V	Volume, m^3
ρ	Density, kg/m^3		

Superscripts and subscripts			
b	base	ref	Reference
c	Collecting	sp	Sponge
d	Daily	sw	Saline water
dis	Distillate	th	Thermal
I	Instantaneous	w	Water
OT	Operating time		

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