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# Enhancement of single slope solar still using sand: the effect of sand grain size distribution

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**Abstract**

One of the ways to improve the performance of simple solar stills is to use energy storage materials to store energy during the day and use it at night. Several energy storage materials have been studied by researchers, one of which is the use of sand. In this research, the improvement of a simple solar still performance has been studied using sand with different grain size distribution inside its basin. For this purpose, four solar still were made in Esfarayen (latitude 36.20 and longitude 57.67), Iran, and the effect of sand grain size distribution on its performance was studied in four treatments. The height of sand and water was 10 cm and the average grain size of treatments was considered 6.9, 2.8, 1.1 and 0.7 mm. The experiments were performed for 4 days in mid-August 2020. The results showed that the sand-containing treatment with an average grain size of 2.8 mm had better productivity and thermal efficiency than other cases where the average grain size of the used sand was larger or smaller. Therefore, grain size distribution of the sand seems to affect the performance of simple solar stills and there is an optimal amount for grain size.

**Keywords:** desalination, solar still, sand, grain size distribution

## Introduction

Population growth and increasing demand for water, along with the limited fresh water resources of the world, has led to the idea of using unconventional water as one of the complementary solutions for water supply. One of the most unconventional sources of water, which is also abundant on Earth and covers three quarters of the planet, is the saline waters of the seas and oceans. Due to the inability to use saline water directly for most human uses, desalination of it is inevitable. Therefore, saline water desalination is considered as one of the sustainable solutions for water supply (Miller et al. 2015). Conventional desalination technologies mainly consume high energy and have adverse environmental effects due to the major supply of this energy using fossil fuels (Manju and Sagar, 2017). Therefore, the use of renewable energy such as solar energy for this purpose can also reduce environmental concerns in addition to sustainable water supply.

So far, several types of solar water desalination devices have been developed and studied or operated. One of the first and most widely used solar

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desalination devices is the conventional solar stills (CSSs). CSSs that also called passive solar stills are stills that are not equipped with additional devices such as pumps and fans or additional components such as solar collectors for active heating. In these stills, the saline water is poured as a shallow layer into a black-painted chamber and the chamber is covered with a clear glass or plastic cover. Transient sun radiation from the glass cover is absorbed by the water and the black-painted pan and raises the water temperature and evaporates it. Evaporated water condenses on the underside of the glass cover. If the glass has a suitable slope, the condensed water flows downwards by gravity and is directed outwards through a inclned channel placed at the bottom of the glass cover and fresh water is obtained (Zheng, 2017).

CSSs are widely used for reasons such as simple design, cheap and available materials, and low operating costs. However, they have disadvantages such as low productivity (water production per unit sunlight area) and low thermal efficiency. On the other hand, in practical applications, due to the sunlight during the day, CSSs spend about half of the available time, i.e. night hours, without producing water (Zheng, 2017). Therefore, the main research related to the CSSs has mainly focused on methods of increasing productivity and efficiency along with improving the conditions for night water production. Although the methods used to improve performance are diverse, the methods of improving performance by producing water at night have relied mainly on energy storage. A major group of materials used to store energy are phase change materials (PCMs). These materials absorb the excess heat from the saline water during the day and change the phase from solid to liquid. They store the absorbed heat in the latent heat of melting and return it o to the water vernight and change back to the solid phase (Shukla et al. 2009).

Numerous studies have been conducted on the use of PCMs as energy storage in CSSs some of which can be listed as follows. Faegh and Shafii (2017) conducted an experimental study of a solar system with external heat and a energy storage system using PCMs and heat pipes and achieved 66% more production than the conventional one. Al-harahsheh et al. (2018) obtained 40% of the water produced by the still overnight using PCMs. Kabeel et al. (2018) theoretically compared the application of different PCMs in solar desalination plants. Mousa et al. (2019) experimentally studied the effect of PCMs on the performance of CSSs and observed an increase in water production at night and a decrease in water during the day. Using nanomaterials in the structure of PCM, Kabil et al. (2020) achieved a 67% improvement in performance compared to the use of conventional PCMs and 116% compared to the state without PCMs.

In addition to the use of PCMs, the use of simpler materials such as sand has also been used as an energy storage in some research. Sand absorbs and stores more solar energy and due to the abundance and cheapness of sand, its use can be considered a cheap way to improve efficiency. The use of a heat storage sand reservoir under a CSS has been studied by Tabrizi and Sharak (2010). This thermal reservoir increased the productivity by 75% compared to the case without heat storage reservoir. Madhu et al. (2018) achieved a 30% improvement in exergy efficiency using a sand energy storage system. Kabeel et al. (2018) reported an 18% improvement in water production using an energy storage system containing sand. Dumka et al. (2019) Using sand bags in a CSS achieved about 30% improvement in performance compared to the case without sandbags. Contrary to the above research, which has studied the use of sand as a heat storage material, separate from saline water, in some studies, sand has been used in contact with water. Mohamed et al. (2019) reported about 32% improvement in thermal efficiency using basalt rock materials and Gholizadeh and Farzi (2020) achieved 22% improvement in performance using sand. In this research, sand has been used inside and in contact with water in a CSS and the effect of sand grian size distibution on solar still (SS) performance has been studied.

## Materials and Methods

For this research, CSSs were constructed according to the schematic of Figure 1. The body of the chamber was made of composite sheets and after sealing the inside of it was painted with black color. The angle of the glass cover was considered to be 36 degrees equal to the latitude of Esfarayen city. The used glass was plain glass with a thickness of 4 mm. Despite the use of composite sheets in the wall of the pond, glass wool was used to further insulate the body of the chamber. For inlet water and outlet water, two valves were created in the body and floor of the device. The condenced water on the glass was collected by a Semi-cylindrical channel with a diameter of 3 cm and a slope angle of 20 degrees, which was installed at the lower end of the glass cover, and was transferred to a collection container outside the device.

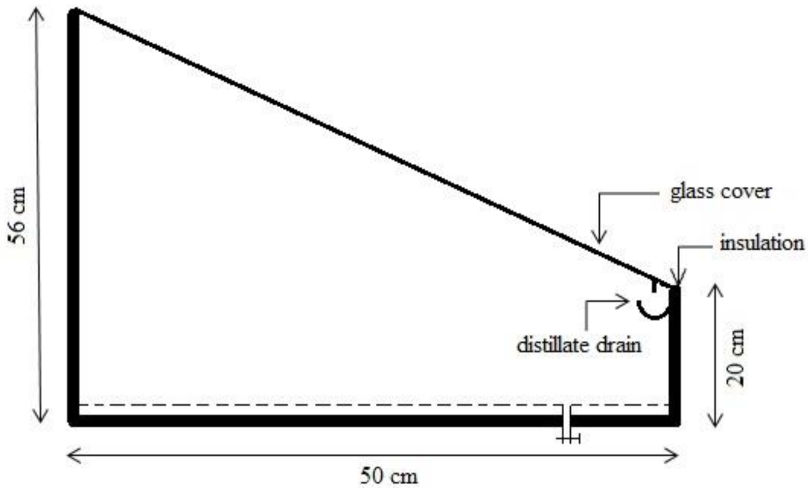


Figure 1. Schematic diagram of the fabricated solar stills

The experiments were performed in four different treatments (Figure 2). In all treatments, the sand has 10 cm height and water was added to the sand to match the surface of the sand and water. In other words, the relative height of water to sand was considered 1 in all treatments. The variable studied in this study was sand grain size distribution. For this purpose, standard grain sieves were used to prepare the treatments. In the first treatment, grains passing through the 3/8 inches sieve and remaining on the No. 6 sieve (average grain size (AGS), 6.9 mm), In the second treatment, grains passing through No. 6 sieve and remaining on the No. 18 sieve (AGS, 2.8 mm), in the third treatment , grains passing through No. 18 sieve and remaining on the No. 30 sieve (AGS, 1.1 mm) and in The fourth treatment, grains passing through s No. 30 sieve and remaining on the No. 50 sieve (AGS, 0.7 mm) were used. Four devices were operated and tested in batch mode. The concentration of used saline water was 15 g / l, which was artificially prepared by adding sea salt to drinking water.

After designing and manufacturing of four SSs, the experiments were performed during four summer days in late July 2020 in Esfarayen, Iran from 7 am to 10 pm. Ambient air temperature at the test site was measured using a TMP-10 digital thermometer. Data related to wind speed and solar radiation on test days were received from Esfarayen Meteorological Department. The glass temperature and water temperature inside the chamber were measured by TMP-10 digital thermometers. The volume of water produced by the SSs was also measured at one-hour intervals during the day from 7 am to 10 pm. The volume of water produced at night (from 10 pm to 7 am in the next day) was measured at 7am of the next day in order to study the storage of solar energy by sand and the production of water at night. During the experiment, in order to compensate for the evaporated water and to maintain the water level and to keep the relative height constant, the amount of fresh water produced per hour was returned to the device.

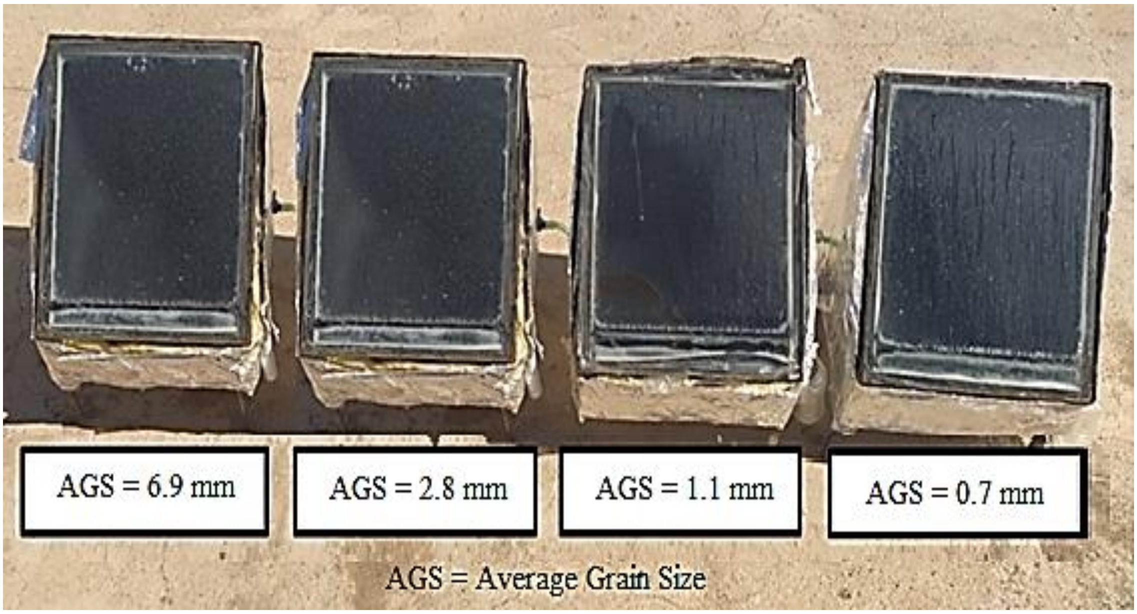


Figure 2. Image of the SSs used in the experiment

In order to calculate and compare the thermal efficiency of four devices, this parameter was calculated using the following equation for all four treatments, during sundials:

$$\eta_h = \frac{m_{dss} \times h_{fg}}{I \times t \times A} \qquad (1)$$

Also, the total thermal efficiency of each device during the day and night was calculated by the following equation:

$$\eta_d = \frac{\sum m_{dss} \times h_{fg}}{\sum I \times t \times A} \qquad (2)$$

Where $m_{dss}$ is the total mass of distilled water in grams, $h_{fg}$ is the latent heat of evaporation of water (2335 J/g), I is the intensity of solar radiation in $\frac{w}{m^2}$, t is the time in seconds, and A is the area of the system in $m^2$.

**Results & Discussion**

Experiments to investigate the effect of different sand grain size distribution on the performance of simple passive SS were performed in 3 summer days on 7, 8 and 13 August 1399 in Esfarayen, Iran (57.5533 longitude and 36.9203 latitude), and the necessary measurements were made. Wind speed is one of the parameters affecting the efficiency of a simple SS. Wind reduces the temperature of the glass cover and increases the condensate. Wind speed at the test site was received from Esfarayen meteorological station. Figure 3 shows a graph of the average wind speed over these three days. Accordingly, the average wind speed in these three days fluctuated between 1.58 km/h to 5.43 km/h and had a peak at 8 p.m.

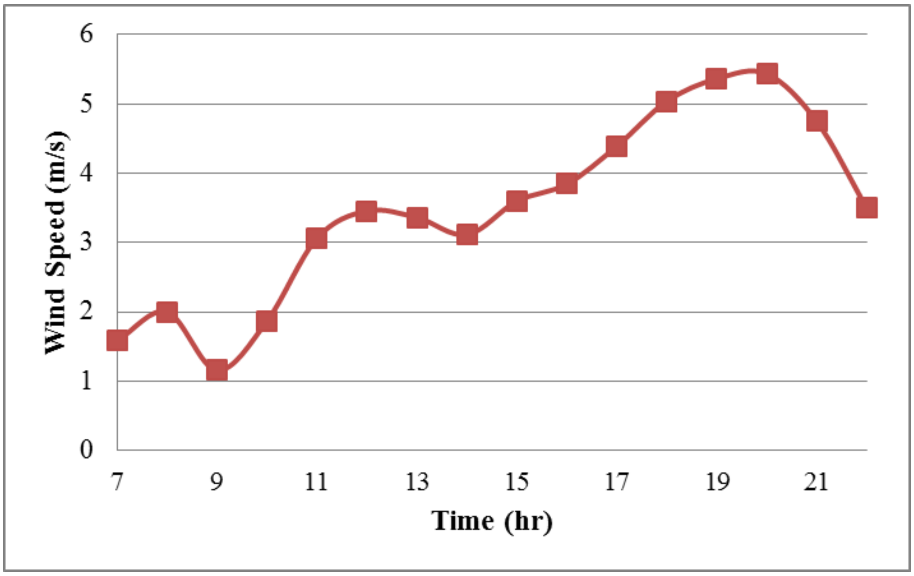

Figure 3. Wind speed at different hours of experiment days (average of three days)

Solar radiation is the main parameter affecting the performance of a SS. Values related to this parameter were also received from Esfarayen meteorological station. Figure 4 shows the variations of solar radiation intensity on average over three days of testing. This parameter directly affects the water, glass and ambient temperature. As can be seen in this figure, the maximum solar radiation occurred at 13 o'clock and its amount was measured at an average of 962.86 w/m2. In addition to the above two parameters, ambient temperature variations were also measured at the test site. The average measurements of the three days of the experiment are shown in Figure 5. The average daily temperature in these three days was 34, 35.54 and 32.7 ºC, respectively. The maximum daily temperatures for three days were 40.2, 40.9 and 38.8 ºC, respectively, and the minimum temperatures were 26.1, 27.6 and 22.3 ºC. Considering the solar radiation, wind and ambient temperature, it seems that in three days of testing, the weather conditions of the region were relatively stable.

In addition to measuring ambient temperature, indoor air temperature (under the glass cover) and saline water temperature were measured in all four treatments. Changes in glass temperature and saline water inside the SSs are shown in Figure 6. This chart shows the average hourly temperature in the three days of the experiment. Mean glass temperatures of SSs were between 25.3 to 75.27 °C in the treatment with AGS of 6.9 mm, between 26.37 to 77.4 °C in the treatment with AGS of 2.8 mm, between 25.67 to 84.9 °C in the treatment with AGS of 1.1 mm and between 25.04 to 81.34 °C in the treatment with AGS of 0.7 mm. For all four treatments, the highest temperature under glass occurred at 16 o'clock. Maximum and average temperature under glass did not show a significant difference between the four treatments.

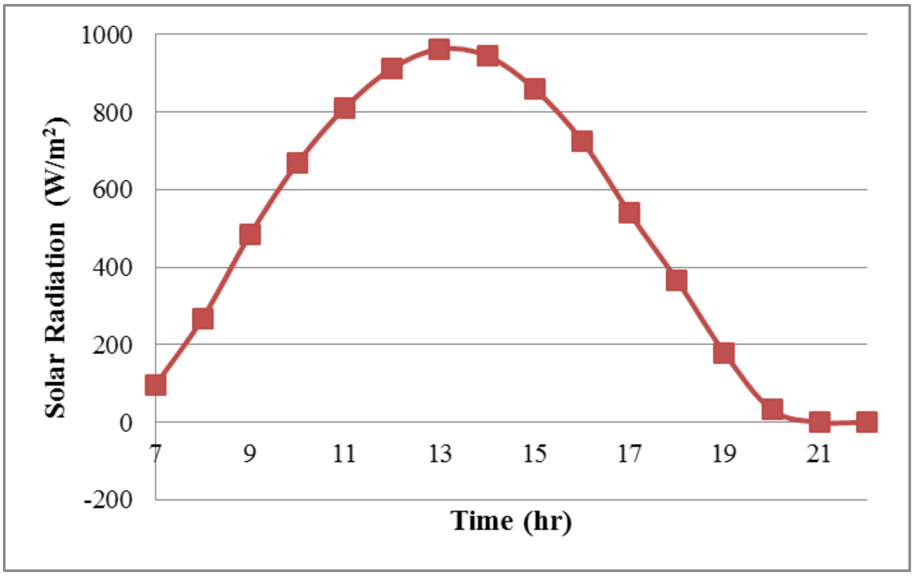


Figure 4. Changes in solar radiation during day (average of three days of experiment)

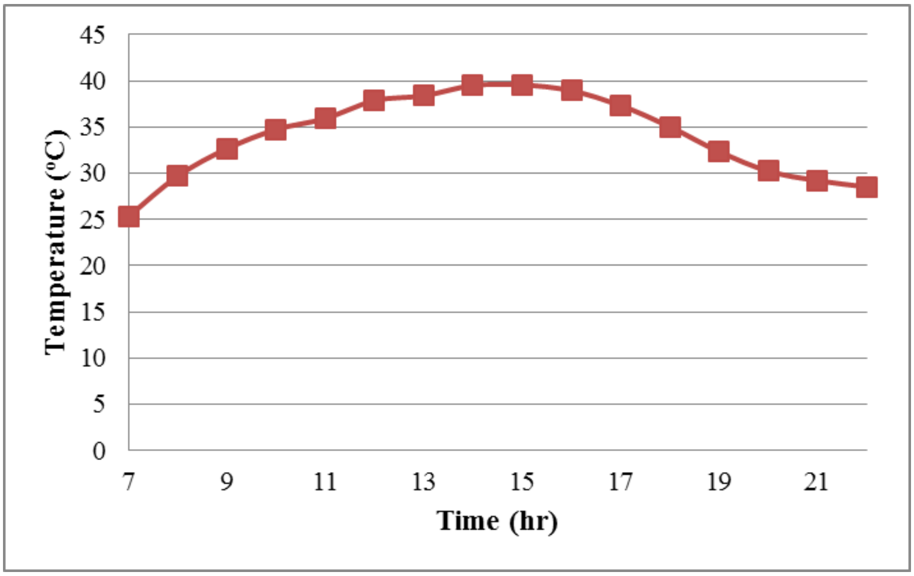


Figure 5. Changes in ambient temperature at the test site

Figure 6 also shows the average saline water temperatures inside the SSs. Average temperatures of saline water in SSs were between 29.34 to 57.74 °C, in the treatment with AGS of 6.9 mm, between 29.14 to 65 °C in the treatment with AGS of 2.8 mm, between 24.2 to 65.07 °C in the treatment with AGS of 1.1 mm and between 24.3 to 64.47 °C in the treatment with AGS of 0.7 mm. For all four treatments, the highest in-water temperature occurred between 15 and 18 o'clock. The water temperatures inside four different SSs also do not show a significant difference. As can be seen in Figure 6, the water temperature was lower than the glass temperature during the day, and from 7 pm onwards, at night, it was reversed and the water temperature was higher than the glass temperature, which seems it is related to the cooling of ambient air and storage of thermal energy in water and sand.

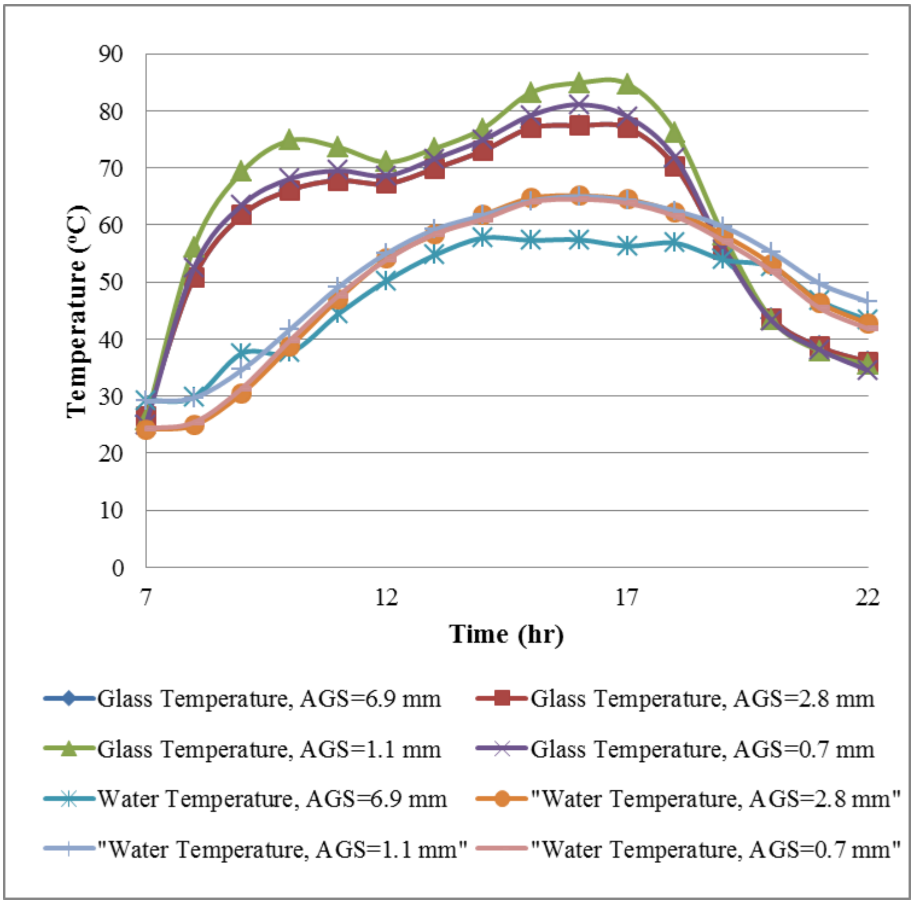


Figure 6. Changes in air temperature (under the glass cover) and water temperature inside the stills

The hourly water production was measured at during day between 7 and 22 o'clock and also at 7 o'clock in the morning of the next day. Figure 7 shows the hourly water production in four SSs. The values of this hourly average chart correspond to three days of testing. According to this figure, hourly production for all four treatments is upward in the morning and reaches its maximum at 4 pm and then decreases in the following hours. Maximum hourly production for the treatments with AGS of 6.9, 2.8, 1.1 and 0.7 mm were 97, 104.7, 105.3 and 87.3 ml, respectively. The average hourly production for the treatments with AGS of 6.9, 2.8, 1.1 and 0.7 mm were 41, 48, 44.4 and 19 ml, respectively.

Figure 8 shows the variations in the amount of water produced as a cumulative graph. According to this figure, the accumulated water produced until 10 pm, for the treatments with AGS of 6.9, 2.8, 1.1 and 0.7 mm were 655.3, 772.3, 710.3 and 549.7 ml, respectively. As mentioned earlier, the amount of water produced from 10 pm to 7 am in the next day was measured. These values were 165.34, 167, 124.34 and 15 ml for the treatments with AGS of 6.9, 2.8, 1.1 and 0.7 mm, respectively. By summing these two groups, the total amount of water produced by the SSs is obtained. Therefore, the total water production per day for the treatments with AGS of 6.9, 2.8, 1.1 and 0.7 mm was 820.7, 939.3, 834.7 and 564.7 ml, respectively.

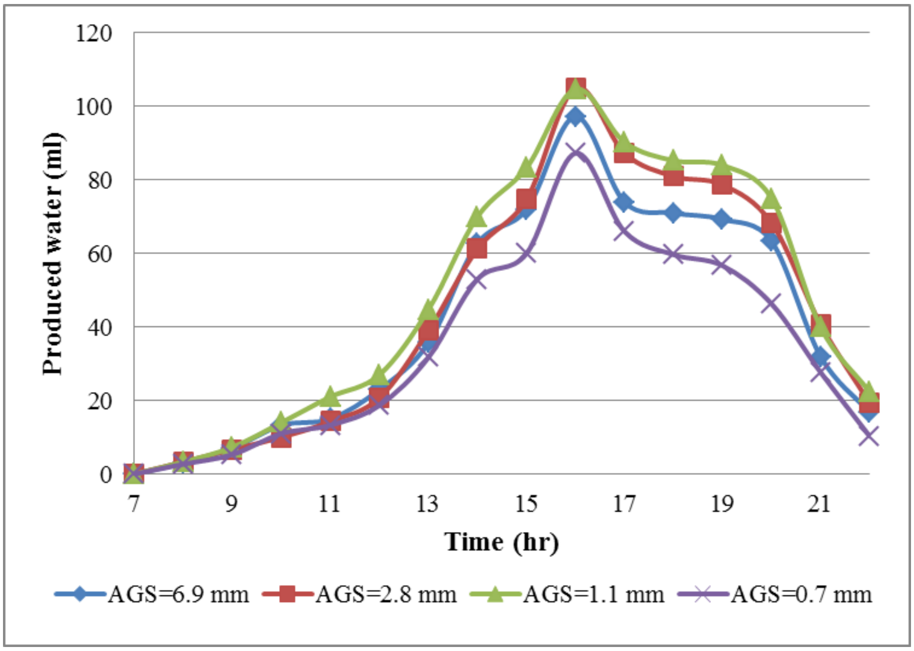


Figure 7. Water Production variations of four treatments

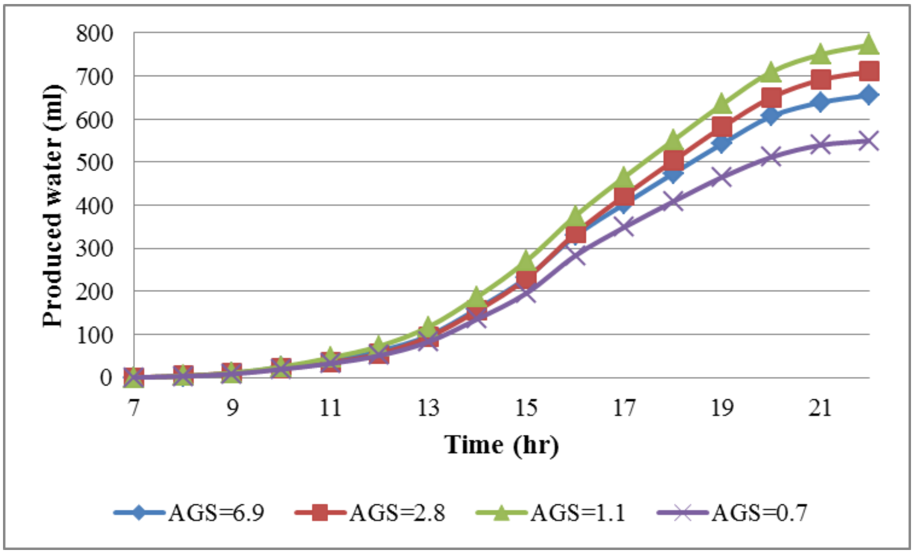


Figure 8. Cumulative water production of the stills

By dividing the total amount of water produced per day by the area of SSs (0.25 m2), the productivity of SSs containing sand is obtained 3282.8, 3757.2, 3338.8 and 2258.8 ml/m2 per day for the treatments with AGS of 6.9, 2.8, 1.1 and 0.7 mm, respectively. As can be seen from these results, the performance of sand desalination plants with different AGS has been different from each other. Therefor the productivity of the second treatment (AGS of 2.8 mm) was significantly higher than other treatments and was ranked first. The third treatment (AGS of 1.1 mm) is in the second place, the first treatment (AGS of 6.9 mm) is in the third place and the fourth treatment (AGS of 0.7 mm) is in the fourth place in terms of productivity.

Another noteworthy point about the water produced by the SSs tested in this study is the difference in the water produced during the day and night. The time of sunset in the three days of the experiment was about 20 o'clock. With this account, the hours of the day between 7 to 20 and the hours of the night between 20 and 7 in the morning of the next day are considered. In Figure 9, the amounts of water produced during the day and night hours and the total day and night are compared with each other. As can be seen in this figure, the amount of water produced during the night for the treatments with AGS of 6.9, 2.8, 1.1 and 0.7 mm, were 214, 229.3, 184.3 and 53 ml, respectively that were 26.07, 24.41, 22.08 and 9.38% of the total water production per day in these treatments. Therefore, it seems that the percentage of water produced at night in four different treatments decreases with decreasing grain size. Thus, coarser-grained sand appears to be more capable of storing energy in a SS to produce water at night.

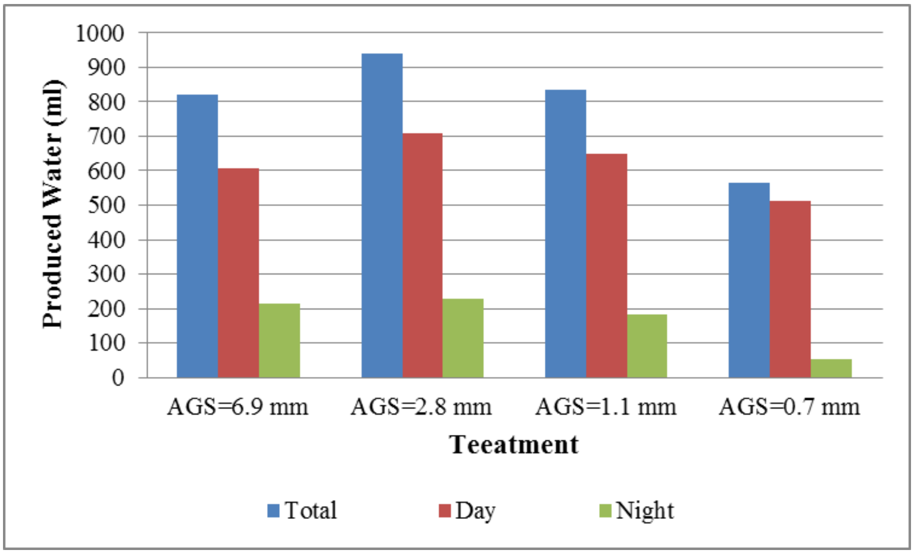


Figure 9. Thermal efficiency of the sand-containing still and the control still

The thermal efficiency of the four treatments was calculated based on the solar energy received and the cumulative water produced during the test hours. Figure 10 shows the calculated thermal efficiencies for the four treatments. According to this figure, the total thermal efficiency of the SSs were 28.15, 32.34, 28.72 and 19.37% for the treatments with with AGS of 6.9, 2.8, 1.1 and 0.7 mm, were 214, 229.3, 184.3 and 53 ml, respectively. These results show a significant difference between the thermal efficiency of the second treatment and other treatments so that the thermal efficiency of this treatment was significantly higher than the other treatments.

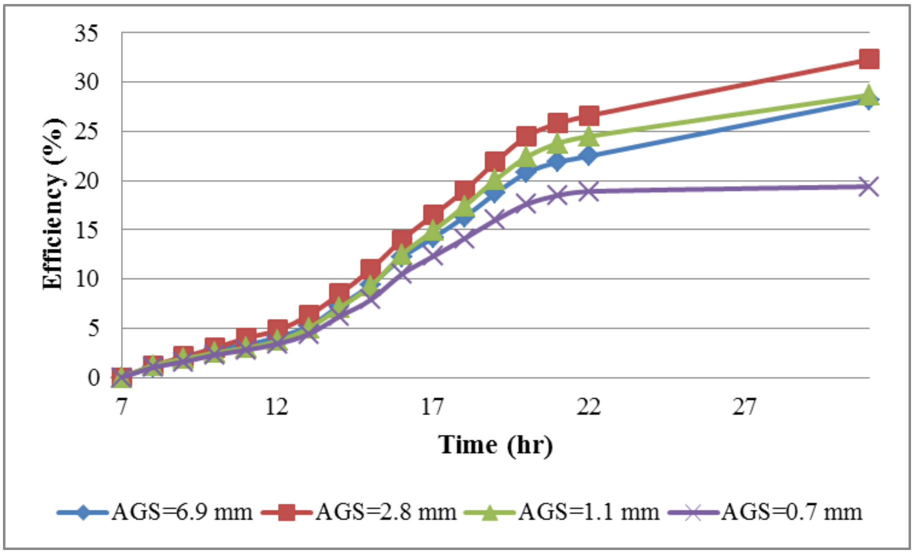


Figure 9. Thermal efficiency of the sand-containing still and the control still

In justifying the performance of the SSs used in this research, it seems that the behavior of simple SSs containing sand with different AGS affected by the porosity of the used porous media. We know that as the AGS decreases, the porosity increases. More porosity means more voids in the porous media. That is, in the sand used in SSs in this study, with decreasing the AGS, the amount of water in the porous media increased and on the other hand due to the smaller size of the average voids, the natural convection heat transfer in the water in these voids is reduced compared to the coarser-grained samples. Therefore, one of the reasons of the reduction of the SSs' performance with reducing the AGS is the reduction of the natural convection heat transfer properties of the saline water in the sand. In addition, due to the increase in the lateral surface in the finer sands and as a result of the increase in their contact area with the walls of the SS compared to the coarser grains, the rate of heat transfer from the sand to the walls (heat losses) increases. However, as seen in the results, there seems to be an optimal value for the AGS. In other words, in coarse grains, the behavior is reversed, which may be related to the size of the grains and most of their lateral surface and earlier heat transfer to water during the first hours of the night and no production of water in the later hours of the night.

The results of this study, compared to similar studies, seem to be in an acceptable state. Although, due to differences in the construction conditions of the devices and the way they are insulated, differences in how sand is used as an energy store, as well as differences in geographical location and climatic conditions of the test area, comparing the results of this research may not be very accurate. However, this comparison shows that the use of sand as an energy storage material in simple SSs in the case of AGS about 2.8 mm has better productivity and thermal efficiency than in the case of Tabrizi and Sharak (2010) and Dumka et al. (2019). This may be due to the complete contact of water with the sand in this study, that most of the heat stored in the sand is forcibly transferred to the surrounding saline water, which is a desirable phenomenon in order to improve the performance of the SSs but in similar studies where sand as an energy storage medium is not in contact with water, part of the heat stored in the sand is transferred to a non-water environment, which is not desirable in terms of device efficiency.

## Conclusions

The performance of a simple SS was studied experimentally by placing sand with different grain size distribution in it. To do this, four SSs were constructed and tested by placing sand media with an average grain size of 6.9, 2.8, 1.1 and 0.7 mm. The results showed that in the presence of sand with an average grain size of 2.8 mm inside the SS, compared to the other three cases, the yield and thermal efficiency were better. It seems that for the use of sand in the SS, there is an optimal grain size distribution that increases or decreases the grain size compared to this optimal state, the desalination performance decreases.

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