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Performance Evaluation of a Conventional Solar Still with Different Types and layouts of Wick Materials

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Abstract
Solar distillation is regarded by many investigators as one of the important methods of utilizing solar energy to solve water scarcity problems. A solar still is a simple device which can be effectively used to convert saline water into fresh water. The enhancement of solar stills performance and improving their production capacity of distilled water are the main goals of the investigators in recent years. In this research, three identical conventional basin type solar stills were designed and constructed in order to experimentally investigate the affect of using different wick materials in two different layout arrangements. The first solar still was used as a reference still for comparison. The second solar still was used for uniformly spreading the wick material sheets in the saline water. In this case, the wick materials sheets were completely immersed in the saline water covering the total still basin area. The third solar still had a specially designed set up of steel mesh wires. In this case, the wick materials were partially immersed in the saline. The net basin horizontal effective area of each solar still was 1 m², and the glass cover's tilted angle was fixed at 32.5º. Five types of wick materials in the form of material sheets were used. They were light black cotton fabric, light jute fabric, black velvet fabric, black sheer mesh fabric, and a 4 mm thick sponge sheet. Spreading the wick material sheet to cover the basin area had the effect of preventing the sunrays from reaching the still basin and consequently absorbed by the saline water and the wick material resulting in enhancing the yields of solar stills. The aim of adding mesh wire layout arrangement is to have the additional effect of increase the surface area of evaporation relaying on capillary effect to raise the saline water to the non-immersed part of the materials. It has been found that the solar still with only wick materials and no special arrangement performed much better than the other two solar stills. In both layout arrangements, it has been found that the light black cotton fabric was the most effective material in enhancing the still productivity in with 36.9% and 26.3% respectively. The sponge sheet was found the less effective material in enhancing the still productivity with 11.5% and 9.9% respectively.
Keywords: Productivity; Solar stills; Water desalination; Wick materials; Wire mesh

1. Introduction

Water is a precious natural gift and is the essential source for all life forms on earth. It is a basic human necessity in domestic life and in agriculture as well as in industry. The availability of clean and pure drinking water is the most urgent need for human community in many countries [1]. The available amount of fresh water on earth is limited and almost fixed, but the demand of fresh water significantly increased all over the world due to the rapid population growth and considerable increasing trends of agricultural and industrial requirements. Unfortunately we are continuously losing fresh water reserves mainly due to industrialization. Industrial wastes and sewage discharges have polluted reveres and underground water. The polluted water is not only devastating people life but also to all living creatures in this world. Worldwide drought and desertification are increasing and further complicating the fresh water scarcity problem [2, 3].

The world is currently facing severe water related problems, and fresh water availability has become an increasingly significant worldwide issue. It is considered as one of the most important threats to human societies and a major obstacle for sustainable development [4]. This problem is much more serious in arid regions which will continue to worsen if no radical and effective solutions are found. In light of climate change, a growing population, an increasing demands for food and water and rising fuel prices [5].

Desalination is an effective way to partially satisfy the increasing demand of fresh drinking water. Still more than 768 million people in underdeveloped and developing countries drink water from unreliable sources. Many remote and coastal areas do not have resources of electric power for producing potable water using conventional desalination techniques [6]. The desalination and other purification methods use fossil fuels and electrical energy. The usage of fossil fuel increases the atmospheric pollution and global warming. In addition, fossil fuels are slowly declining with time because of the rapid consumption used in technology development [7]. Depletion of natural fuel resources from the earth increases the need and applicability of renewable energy sources [8]. Therefore it is not only necessary to preserve freshwater but also to develop clean and environmentally friendly technology to get the distilled water from brackish, saline, and contaminated water. Solar distillation technique has the advantage of being eco-friendly, zero fuel cost and low maintenance cost. But on the other hand, it has the disadvantage of occupying a large space and being a slow process leading to less distillate output per unit time. For so many years, efforts are continuously being made to make this technology more efficient, economical and faster [9, 10]. Therefore solar energy is regarded by many investigators as the best alternative heating energy source. This is not only because it is clean and environmental friendly, but also because it is available in huge quantities in the areas that suffer most from severs fresh water scarcity such as the Middle East and North Africa [11].

Solar desalination represents the most prominent and economical method especially when used in arid areas where sunshine is abundant and fresh water is scarce. Conventional solar still is one of the main solar desalination devices used for fresh water production [12].

The Conventional Solar Stills are selected due to their simplicity and passive nature. They are cheap to manufacture and do not need hard maintenance or skilled persons to operate. However, the Conventional Solar Stills suffer from some drawbacks, which sometimes limit the use of this system for large-scale production [13]. A solar still is a simple device which can be used to convert saline, brackish water into potable water. The basic principles of solar water distillation are simple, yet effective, as it exactly replicates the heating, evaporation and condensation processes occurring in nature to purify water. It represents a direct simulation process of the green house effect. The sun's rays penetrate the transparent inclined cover to heat up the water. The heated water evaporates and condenses on the inner side of the transparent surface. The condensate which is distilled water runs down the inner side into troughs from where it can be collected in storage containers [14. 15]

The main drawback of the solar desalination using solar stills is its low efficiency and production rate. Normally, a solar still can yield 2.5–5 l/m2/day of distillate. Though solar distillation is a simple method, productivity seems to be low due to the large thermal capacity and consumption of time. Researchers have been focusing on means and ways to enhance the productivity of the solar stills. One of the methods is the use of wick materials [16, 17].

Hansen et al. [18] conducted experimental test on three different wick materials for three different conventional solar still basin conditions using different absorber plates. The result indicates that the total production rate was increased by 71.2% and 48.9%, when water coral fleece with stepped wire mesh absorber was used and stepped absorber respectively.

Murugavel and Srithar [19] Conducted experiments in basin type double slope solar still, using six different wick materials. Block cotton cloth, Jute cloth, Sponge sheet, Coir mate, Waste cotton piece. They found that the Block cotton cloth yield the most effective wick material which yielded higher production rate per day. Mahdi et al. [20] designed and fabricated a tilted wick type still. Charcoal cloth was used as the wick material. It has been concluded that, the charcoal cloth is a good material for use as an absorber/evaporator and also as a water transport medium. The representative daily efficiency of the still was about 53% on clear days in summer. Kabeel [21] conducted experimental tests in pyramid shaped still. A concave wick surface was used for evaporation and the four sides of the pyramid shaped still were used for condensation of the distillate. The wick material placed on the concave surface had a thickness of 5 cm. The productivity of the still for 24 hours is $4l/m^2$ and its efficiency was 45%. Sakthivel et al. [22] introduced a medium of jute cloth into the conventional single slop solar still, in an effort to increase the evaporation surface and to utilize the latent heat of condensation. They found that still productivity increased by 8%. Arjunan et al. [23] found that using blue metal as a storage medium in a conventional solar still improved its productivity by 5%. Sakthivel and Shanmugasundaram [24] found that using a black granite gravel material as a thermal energy storage medium improved its productivity by about 17 to 20%.

The present research work aims to design and construct three identical conventional single slope solar stills and experimentally assess the effect of using different wick material in two layout arrangements. This may help in selecting a suitable wick material and design configuration for the solar desalination application.

2. Methodology

In this research, three identical conventional single slope basin type solar stills has been designed and constructed from 1.4 mm thickness galvanized steel. The net basin horizontal effective area of each solar still was 1 m^2 (1m x 1m). A 4 mm thickness glass cover was used for each solar still. The glass cover slope angle for all solar stills was set up at 32.5° with respect to the horizontal. The schematic diagram of the conventional single slope basin type solar still is shown in figures (1). In order to keep the whole system of each solar still vapor tight, the glass cover was rubber lined and was rested on the basin structure and completely sealed by using superior silicon sealants. The inside of the three solar stills were painted black using Black Epoxy in order to increase the suns rays' absorptions efficiency and also to eliminate any possible corrosion to the metal surfaces. The galvanized body of the solar still is shown in figure (2). To prevent any heat loses, the bottom and sides of each solar still was insulated with a sheet of glass wool 50 mm thick. Each solar still construction is contained in a wooden frame of a trapezoidal shape.

A feed water tank was fixed at the same level as the three solar stills with a float to keep the saline water level inside the solar stills at constant value of 1 cm. An L shaped trough of 4 cm x 4 cm was made to collect the condensate water running down the inner surface of the inclined glass cover of each of the solar stills.

The troughs will be fixed at slight slope to ensure that the flow of condensate water is towards the outlet pipe. A half inch diameter pipe and valve were fitted and connected to the lower end of each of the trough channels to control the collection of the condensate water. Flexible hoses leading to graduated flask were used to collect the distilled water of each solar still on hourly intervals.

All three stills had drainage pipes and valves fitted to the bottoms of the stills. Other sets of half inch pipes and valves were fixed at the lower end of the back of the still and were connected to the feeding tank through the main pipe. A detailed cross sectional view of the solar still is shown in figure (3).

The first solar still was used as a reference still for comparison. The second solar still was used with uniformly spread and completely immersed wick material sheets in the saline water. The third solar still will have a specially designed set up of steel mesh wires.

The mesh wires were made from twelve 5 mm diameter and 1 m long steel wires. A one square meter, 1.4 mm thickness galvanized steel plate and two 1 meter long, 10 mm thickness and 50 mm high wooden boards will be used to fix the wires in parallel rows horizontally across the solar still width. The wires will be 60 mm apart and 50 mm above the solar still basin. This design ensured that the wick materials sheets were partially immersed in the saline water. The schematic arrangement of the mesh wires is shown in figure (4). Figures (5 and 6) show photos of the mesh wires arrangement. A suitable frame was built and the three stills were mounted adjacent to each other as shown in Figure (7).

Five types of wick materials in form of cloth sheets were used. They were light black cotton fabric, black sheer mesh fabric, black velvet fabric, light jute fabric and a 4 mm sponge sheet. The dimensions of the sheets used in the second solar still were one square meter, which is the same area of the solar still basin. The sheets in this situation will be completely immersed in the saline water. In the third solar still that contain the mesh wires, the dimensions of the sheets used were 1 m x 1.25 m. The extra length of 0.25 m in sheet length was used to cover the extra length of the sheet folding over the mesh wires. The wick material sheets in this situation were partially immersed in the saline water. Figure (8) shows the five wick materials used in the experiments.

For each solar still, three calibrated Cr–Ni thermocouples will be used to measure the inside and outside temperatures of the glass cover, and the still basin. Another three calibrated RTD type thermometer will be sued to measure the ambient temperature, the basin saline water temperature, and the space (air–vapor mixture) temperature inside the solar still. Care must be taken to ensure that the thermocouples and thermometers are not affected by direct sun rays, so they will be fixed in ways or in positions to ensure that no direct sun rays could reach their sensing parts. All thermocouples will be connected to multichannel digital temperature indicators.

The global solar radiation on the inclined glass cover surfaces will be measured using a Daystar type solar meter. This instrument is analog type and can measure solar intensity in the range of 1–1999 W/m² with an accuracy of ±1 W/m². A digital wind anemometer Type LM-8010, with a range of 0-15 m/s and an accuracy of ±0.2 m/s, will be used to measure the wind speed at the solar stills height.

The data of the solar still with different wick materials (production rate, solar intensity, water temperatures, vapor temperatures, hemispherical cover inside and outside temperatures, and ambient temperatures) in all sets will be collected and will be studied, plotted, analyzed and compared with each other and with other type of solar stills. The results, conclusions and recommendations will be made on the effectiveness of using such wick materials.

The three solar stills will be kept in an open area and the experiments will be conducted on clear days. Preliminary tests will be conducted for two days in order to make sure that the system is ready. The experiments will be then conducted for another two days for each set of data, and then the average recorded values will be taken. All tests will be started around 6:00 am and carried out for 12 hours till 6:00 pm local time. The first collections taken at 6:00 am represent the overnight condensation. Measurements of all parameters will be recorded at two hours intervals."

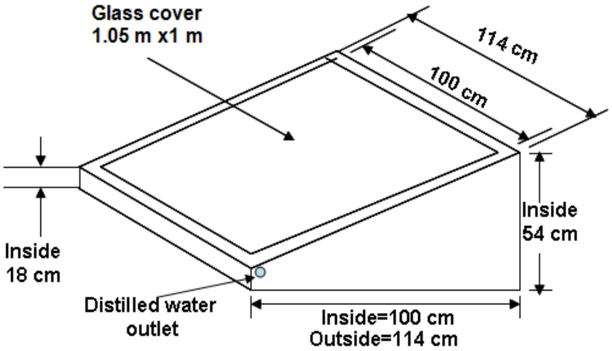


Figure (1) Schematic diagram of the solar still

Figure (2) the galvanized body of the conventional solar still

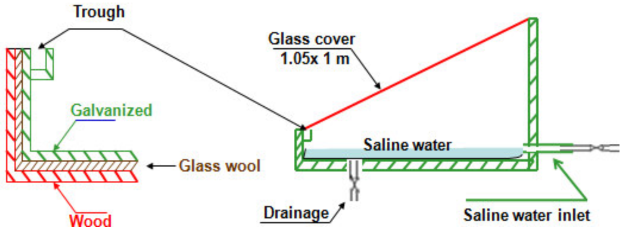


Figure (3) Sectional view of the conventional solar still

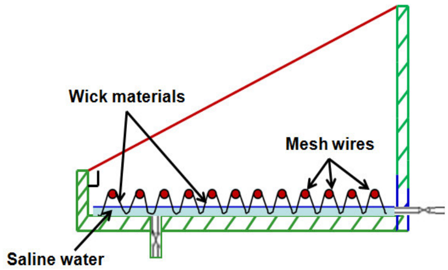


Figure (4) Sectional view of the conventional solar still with mesh arrangements.

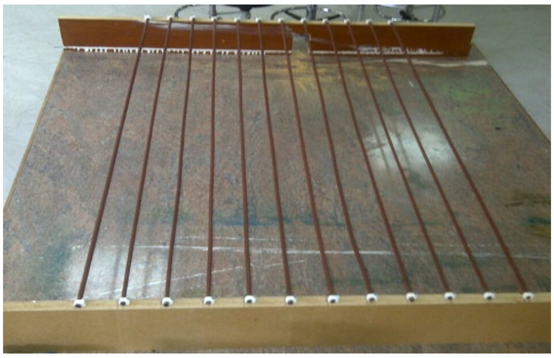


Figure (5) Mesh wires arrangements

Figure (6) Mesh wires arrangements inside the solar still

Figure (7) the three solar stills in situ

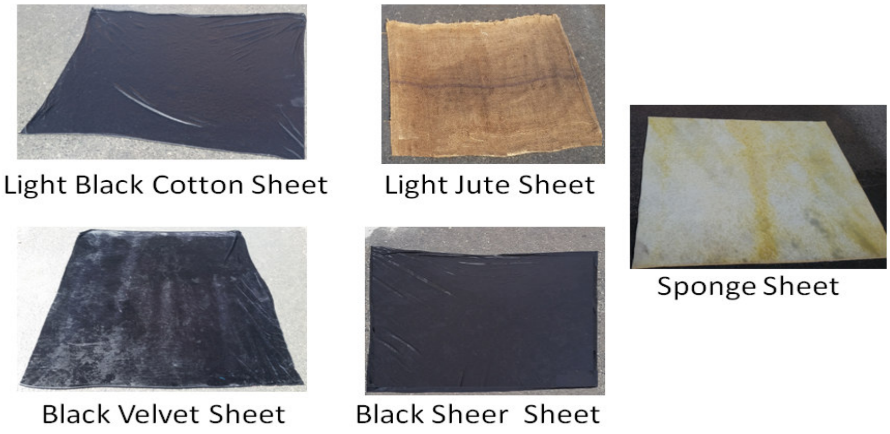


Figure 8 the five wick materials used in solar stills

3. Results and Discussions

In this research, the performance of the conventional solar still was experimentally investigated using five different wick materials in two different layout arrangements. The five wick materials were light black cotton fabric, light jute fabric, black velvet fabric, black sheer mesh fabric, and a 4 mm thick sponge sheet. Therefore three identical single slope basin Type solar stills were designed and constructed. The first solar still was used as a reference still for comparison. The second solar still was used to uniformly spread the wick material sheets in the saline water covering the total still basin area. In this case the wick materials sheets were completely immersed in the saline water. Spreading wick material sheets to cover the basin area should have the effect of preventing the sunrays from reaching the still basin and consequently be absorbed directly by the saline water and the wick materials. The third solar still had a specially designed set up of mesh wires. In this case the wick materials were also covering the total still basin surface area but the wick materials were partially immersed in the saline water. The aim of this layout arrangement is to have the additional effect of increasing the surface area of evaporation relaying on capillary action to raise saline water to the non-immersed part of the materials. The mesh wires set up was made from twelve 5 mm diameter and 1 m long steel wire. Two wooden boards were used to fix the wires 60 mm apart and 50 mm above the solar still basin.

Experiments were carried out in clear sky days during the month of July in the Kingdom of Bahrain. Preliminary tests were conducted to make sure that the stills and the systems were ready. The actual experiments were then performed for two consecutive days and the average values were taken for each set of data.

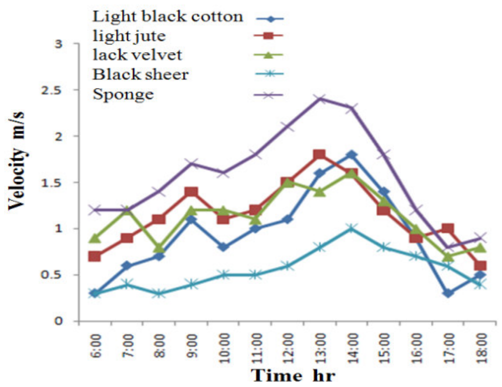
Figure 9 shows the wind speed variation for the five sets of tests. Figure (10) shows the solar intensity W/m^2 variations for the five sets of data. The profile of the solar radiation incident had the typical trend of increasing in the morning hours reaching its maximum values around midday and then decreasing in the afternoon. The maximum intensity was recorded at noon with the average total of 8360 Watts/day. Accordingly the productivity of the stills has been gradually increasing from 8:00 am and reached the maximum value at 2:00 pm. This is due to the accumulated heat being absorbed by the saline water and wick materials. Then it gradually decreases.

The first solar still (reference conventional bare still without wick materials) found to produce an average value of 3.261 Litter/day. The second solar still with wick materials found to enhance the still productivity by 36.9%, 23%, 20%, 16.8%, and 11.5% for the light black cotton fabric, light jute fabric, black velvet fabric, black sheer mesh fabric, and a 4 mm thick sponge sheet respectively. The light black cotton fabric is the most effective and the sponge sheet is the least effective materials in enhancing the solar still productivity.

The third still with wick materials and mesh layout arrangements found also to enhance the productivity by 26.3%, 16.9%, 14.8%, 12.5%, and 9.9% respectively for the same sequence of materials. It can be seen that immersing the wick materials has more positive effect in enhancing the solar still productivity than the still with mesh arrangements and partially immersed wick materials. The comparison between the production rate of the conventional solar still and five set of data of the solar still with wick materials is shown in figures (11 and 12) for hourly basis and daily basis respectively. The comparison between the production rate of the conventional solar still and five sets of data of the solar still with wick materials and mesh arrangement is shown in figures (13 and 14) for hourly basis and daily basis respectively.

Figure (15 and 16) shows a comparison of hourly and accumulated production rate of conventional solar still, solar still with wick materials, and still with wick materials and mesh arrangements for Light Black Cotton fabric and for Sponge sheet respectively. Table 1 shows the productions rates of all tests.

It can be seen that the production of solar stills wick material- mesh wire arrangements enhance the productivity by less than the amount enhanced by the solar stills with wick materials only. Fixing the mesh wire at a height of 50 mm above the basin may be higher than capillary effect capability to sufficiently wet the non immersed part of the wick materials. Lower heights of about 10-20 mm are could be more efficient.



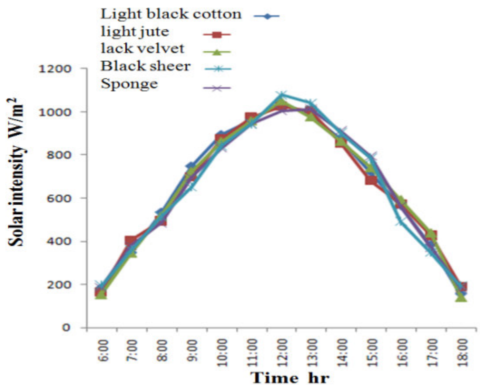


Figure (9) Wind speed variation m/s for the five sets of tests

Figure (10) Intensity of Solar radiation W/m^2 for the five sets of tests

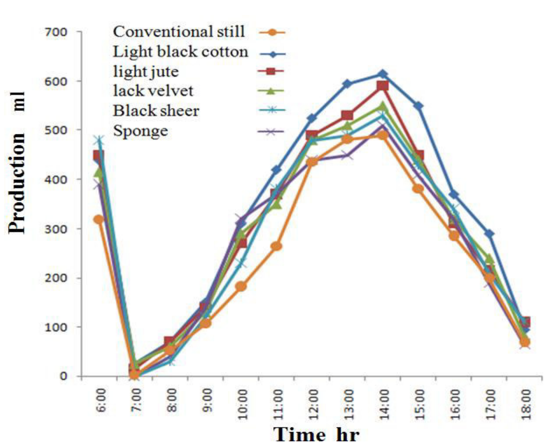


Figure (11) comparison of hourly production rate of conventional still and stills with wick materials

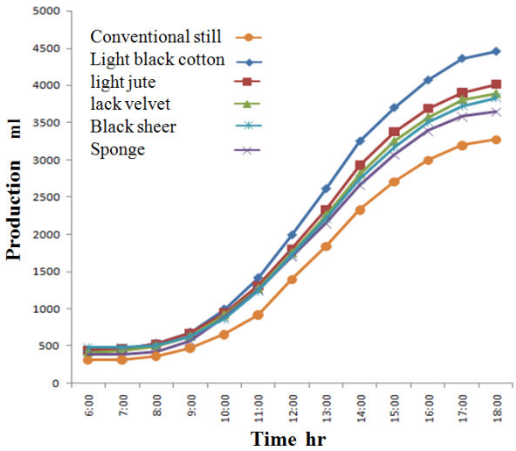


Figure (12) Comparison of accumulated productivity of conventional still and still with wick materials

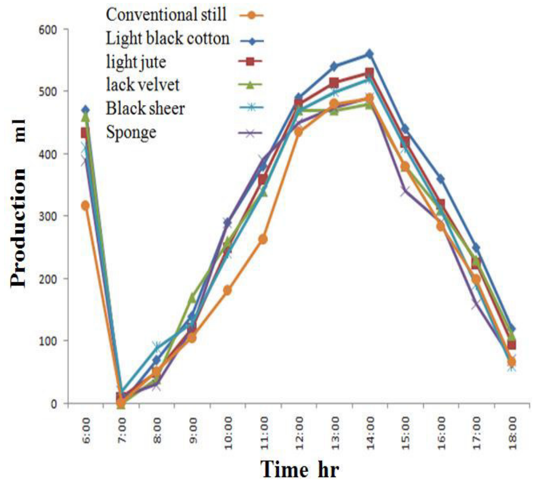


Figure (13) Comparison of hourly production rate of conventional still and stills with wick materials and mesh arrangements

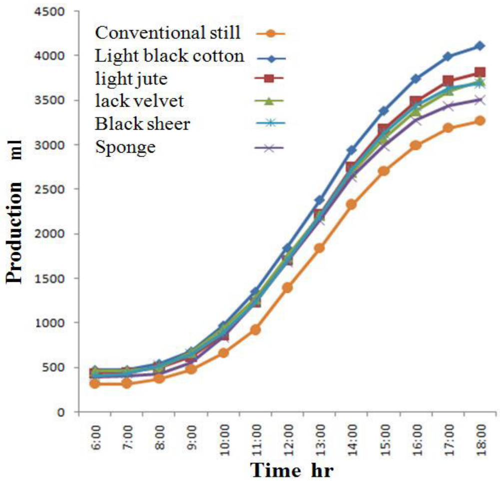


Figure (14) Comparison of accumulated production rate of conventional still and stills with wick materials and mesh arrangements

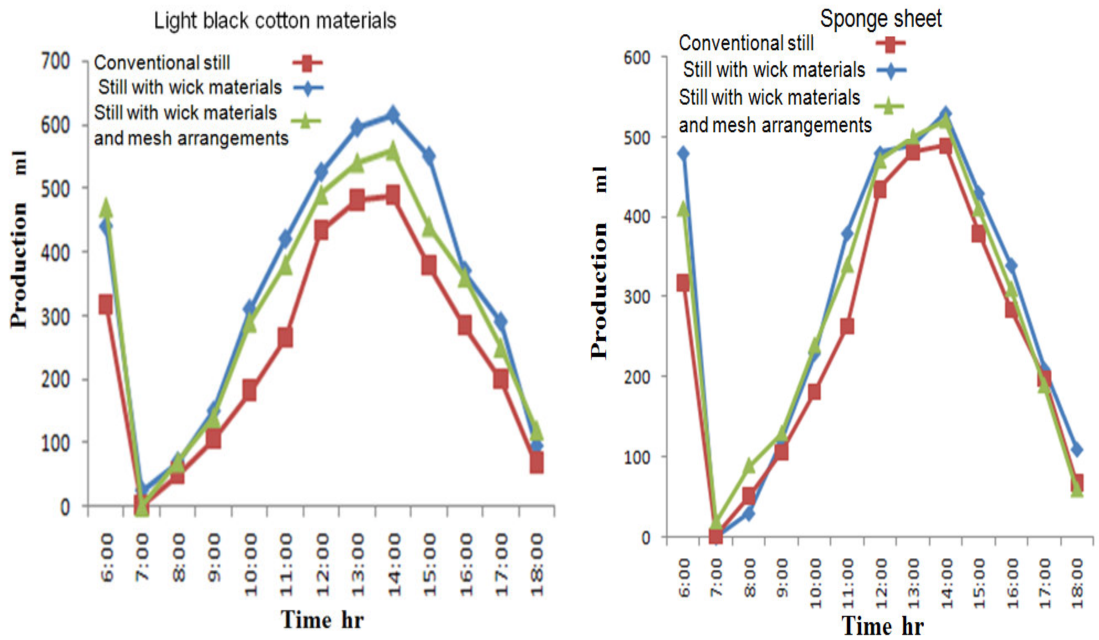
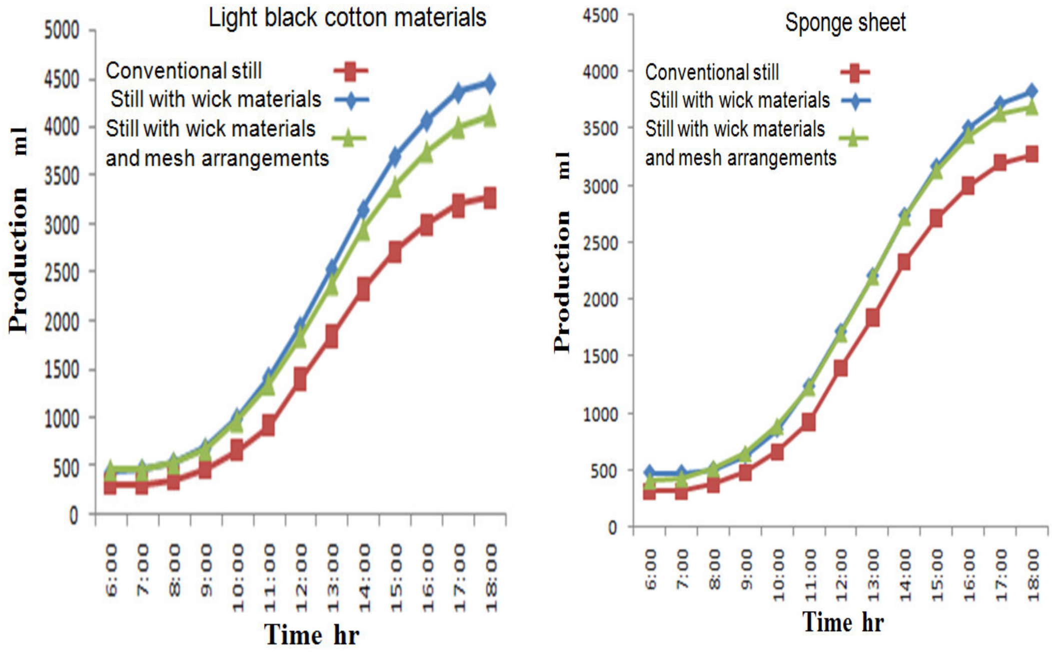


Fig. 15 Comparison of hourly production rate of conventional solar still, solar still with wick materials, and still with wick materials and mesh arrangements for light black cotton material and sponge sheet



(a) light black cotton material (b) sponge sheet

Figure 16 Comparison of accumulated production rate of conventional solar still, solar still with wick materials, and still with wick materials and mesh arrangements for light black cotton material and sponge sheet

Table 1 Production rates of all tests and percentage enhancements

	Wick Materials	Light Black Cotton	light Jute	Black velvet	black sheer mesh	sponge sheet
1-	Conventional solar still production rate ml/day	3255	3260	3240	3280	3270
2-	solar still with wick materials production rate ml/day	4455	4010	3890	3830	3645
3-	Percentage enhancements %	36.9%	23%	20%	16.8%	11.5%
4-	Solar still with wick materials and mesh wire arrangements production rate ml/day	4110	3810	3720	3690	3505
5-	Percentage enhancements %	26.3%	16.9%	14.8%	12.5%	9.9%

The higher production rate of solar stills with wick materials may be attributed to the fact that the wick materials increase absorption and the evaporation area and consequently increases the production rate. It may also be attributed to the fact that using wick materials enhanced the absorption of sunrays energy mainly by the saline water and less by the solar still tank basin. This is evident when comparing the saline water temperatures and basin tank temperatures of the solar stills. In bare basin solar stills (the reference solar still), the basin temperature was found on average about 2-4 degrees higher than the water temperature. This is because part of the sunrays passes through the transparent saline water hit and got absorbed directly by the still tank basin resulting in rising its temperature more than the temperature of the saline water. This can be seen in Figure (17) for light black cotton materials sets of data. On the contrary, the solar stills containing wick materials immersed in the water will cover the still basin area in both layouts. This resulted in no direct sunrays directly hitting the still tank basin and in consequence the saline water and basin temperatures are almost the same (the difference on average is about one degree centigrade). This can be seen in figures (18 and 19) for stills with wick materials and for the stills with wick materials and mesh wire arrangements respectively for light black cotton sets of data. Figure 20 shows comparison between basin temperatures of conventional still, still with wick materials and still-mesh wires arrangements for light black cotton material sets of data.

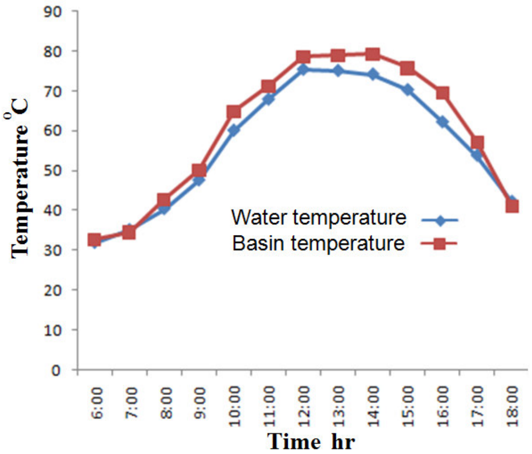
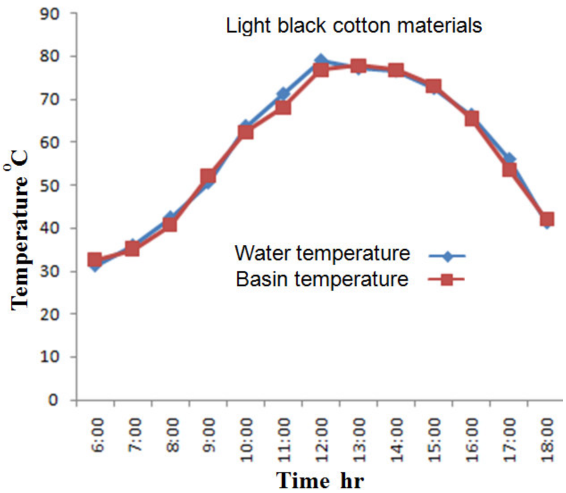


Figure (17) Comparison between saline water and basin temperatures of conventional solar still



Figure(18) Comparison between saline water and basin temperatures for still with wick materials and no mesh wires

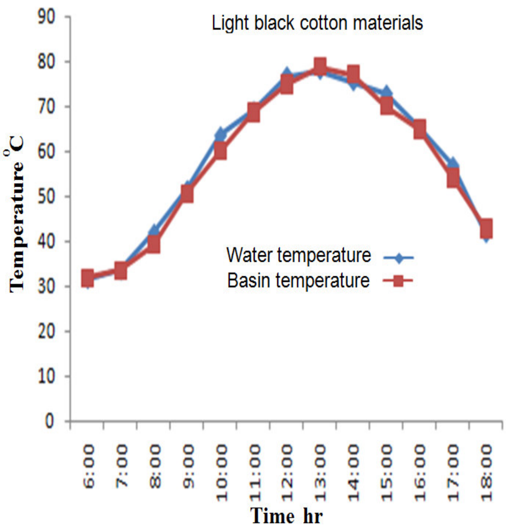


Figure (19) Comparison between saline water arrangements and basin temperatures for stills with wick materials- mesh wires arrangements

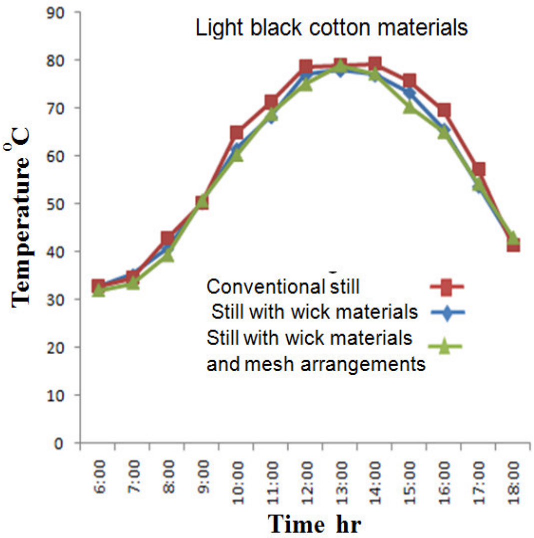


Figure.(20)Comparison between basin temperatures of conventional still, still with wick materials and still - mesh wires arrangements

4. Conclusions

Three identical conventional single slope basin types solar still were designed, fabricated and tested for five different wick materials and two different layout arrangements. From the five different wick materials, the light black cotton material was found to be the most effective which yielded higher production rate per day. The sponge sheet was found to be the lowest to effect the enhancement of the solar still production rate per day.

The layout arrangement of spreading and totally immersing the wick materials found to enhance the stills productivity more than the layout arrangement that use mesh wire and partially immersion of wick materials.

Layers of wick materials in the saline water have the effect of covering and preventing sunrays from hitting the still tank basin resulting in absorbing all the sunrays energy by the water and consequently increasing the saline water temperature and therefore increasing the evaporation rate and consequently enhancing productivity. In addition, layers of wick material in the saline water have the effect of increasing the absorption and evaporation area and enhance the production rate.

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