Experimental investigations of single-slope solar still integrated with a hollow rotating cylinder

Naseer T Alwan 1,2, S E Shcheklein1, Obed M Ali 3

1Ural Federal University named after the first President of Russia B. N. Yeltsin
19 Mira St., Yekaterinburg 620002, Russia
2Kirkuk Technical College, Northern Technical University, 36001 Kirkuk, Iraq
3Renewable Energy Research Unit, Northern Technical University, 36001 Kirkuk, Iraq

E-mail: nassir.towfeek79@gmail.com

Abstract. The main objective of the current study is to increase the productivity rate of conventional solar still by increasing the surface area of heat transfer in the evaporation section within solar still. Lightweight rotating hollow metal cylinder made of galvanized iron layer (0.06 cm thickness and diameter of 32 cm) with a length of 90 cm was used as evaporation section within the improved single slope solar still. The tests were carried out for 3 months (Jun, July and August) at the Ural Federal University of Yekaterinburg/Russia, the experimental results taken for a perfect day on 12 Jun 2019. The impact of different parameters on the productivity of freshwater has been investigated using the new improved solar still. Study results reveal that environmental factors such as the intensity of solar radiation, ambient temperature, relative humidity and wind speed have the greatest impact on freshwater productivity. The analyses of results show that the ratio of water productivity enhancement found to be about 161% than that of the conventional solar still over the long day period.

1. Introduction
Recently the problem of water scarcity around the world is increasing day by day, and the availability of potable water requires a source of energy to desalinate saltwater, which covers about 71% of the earth's area. Solar energy is the best solution to the problem of water scarcity in areas where solar energy is abundant because it is a clean, sustainable and simple source to convert saltwater into drinking water. It is considered as one of the most suitable types of energy for utilization provides the intensity of radiation. The earth receives 174 beta watts of radiation, at the upper atmosphere, approximately 30% of this radiation is reflected back to the outer space, while the rest is absorbed by clouds, oceans, and the earth masses [1]. The water desalination techniques are classified into two groups, the first being called membrane techniques, which include reverse osmosis and electrolysis. The second group is called thermal processes, which include multi-effect distillation, multi-stage flashing, compression of vapor, dehumidification-humidification and solar still. Solar distillation is a thermal process that represents a sustainable solution to the world's water shortage, but the limited production is considered the main problem of conventional solar still. There are many different factors that affect the productivity of solar stills which have been reviewed in detail by various researchers [2-3]. Several studies have been conducted to improve the productivity of solar distillates in different
methods, for instance, enhance the heat transfer from the basin liner to the saltwater by increasing the surface area of the basin by placing fins with different configurations and forms [4-6]. Used different materials within solar stills to store thermal energy in the form of latent or sensible heat energy during sunrise hours and then release it during shadow and evening hours [7-8]. Increase the thermal conductivity value of water within the solar still basin by using nanoparticles and thus increase the rate of heat transfer [9-10]. Thermoelectric coolers were used to decrease the evaporation surface temperature and thereby increase the temperature difference between the condensation surface and evaporation thus increasing the condensation rate and productivity of distilled water [11-12]. Refrigeration system integrated with solar still [13-14]. Evacuated tube collector with solar still [15]. Estimate the economic feasibility for solar still with hollow rotating cylinder [16]. To increase the surface area of evaporation section within solar still, a hollow rotating cylinder has been used within solar still [17]. Study the effect of cylinder speed, saltwater depth, cooling glass cover, cylinder material and type cover of solar still [18]. Mathematical modelling to estimate the production of solar distillers with a hollow rotating cylinder [19]. From the above mentioned there is a challenge to produce drinking water at a lower cost and more efficiently. From the above literature it is noted that there are limitations to produce freshwater by using solar distillation technology which characterized by high-cost complex and difficulty of installation and maintenance. Accordingly, the main objective of current study is to design a simple solar distilled with a low-cost, high productivity that can be installed and maintained easily, especially in rural areas.

2. Description of the principle of improvement
The main objective of the present study is to increase the surface area of heat transfer in the evaporation part of the solar still. Lightweight rotating hollow metal cylinder made of galvanized iron sheet 0.06 cm thickness with a diameter of 32 cm and length of 90 cm was used as evaporation part within solar still A. It has been installed on a low carbon steel shaft, the inner and outer surface of the hollow cylinder coated with a black colour to gain the largest amount of solar radiation. The hollow cylinder partially immersed in the water basin. The most important feature of this type of improvement is that the energy required to rotate the electric motor (12 V) which is responsible to rotate the hollow cylinder is very low (0.1 Ampere), which can be supplied from any source of renewable energy. Therefore, a single photovoltaic cell (PV) with a capacity of 30 Watts was sufficient to rotate the hollow cylinder. A storage battery was used to ensure the motor continues to rotate in times of shadow and sunset. The amount of energy consumption is very small compared to the daily distillate water produced from modified solar still with a rotating hollow cylinder (RHC).

2.1. Experimental setup
Figures 1and 2 show a photograph and schematic diagram of the experimental setup of two solar stills. The first solar still (A) is a modification single slope solar still with a RHC while the second solar still (B) is a single slope solar still without a RHC. Type A with dimensiones of 100 x 50 x 60 x 24.8 cm consists of wooden frame of dimensiones 100 x 50 x 10 cm and thickness of 18 mm. A plexiglass cover (0.3cm) fixed on the wooden frame with single inclined to the horizontal (35 degrees). In order to form a transparent cover from all sides except the bottom and back the frame was opened in order to install thecover on both frame and MDF wooden board. The water basin with a dimension of 94 x 46 x 10cm has been coated with black colour to absorb maximum amount of solar radiation. The inner surface of still covered by Aluminum foil with 0.03cm thickness to reflect solar radiation to the hollow cylinder and water basin. Plexiglass is fixed on the wooden frame by using an Aluminum channel to collect condensed water droplets through the plexiglass. The condensed water passed through the Aluminum channel to a gradient plastic cylinder installed at the bottom of solar still. All parts are fixed by silicone glue to prevent air leakage. Galvanized iron plate (100 × 100 × 0.06 cm) was used to form the hollow cylinder (diameter 32 cm, length 90 cm), which was installed on the low carbon steel shaft (diameter 0.8 x length 95 cm) by using 0.8 cm ball bearings on the two ends. The hollow cylinder is rotated using a small DC electric motor (12 V) which used to lift car’s glass (0.1 Ampere)
by a rubber belt. An electric motor is powered by electric current from a small 30Watts photocell panel during the daytime is connected to a storage battery in order to operate the DC motor during off sunshine hours. A water tank is connected to the solar still via pipes to feed the solar still with seawater. The level of seawater inside the basin fixed at 5 cm by using a mechanical float, to clean basin liner a hole was made at the bottom of the water basin and a ball valve was installed to drain brackish water. The design and details of the solar still B is the same as the solar still A but without RHC.

Figure 1. Photographic view of the experimental setup (A: with HRC B: without HRC)

Figure 2. Schematic Figure of the experimental setup of the distillers. A. Modification solar still, B. Conventional solar still, 1- Plexiglass; 2- MDF wood; 3- RHC; 4- Water basin; 5- The base; 6- DC-Motor; 7- Tank; 8- Mechanical float; 9- Salt water outlet; 10- Flask Plastic with ruler

Thermocouples K-type 0.3 mm diameter has been used to measure the temperatures at different points of the solar still by using SD data logger 4 channel K-thermocouple device (model 88598). The thermocouples have been calibrated between 0-100 °C. These points include the temperature of saltwater basin, vapour temperature within solar still and inside and outside plexiglass cover
temperature and temperature of basin liner. To measure the temperature of the hollow drum surface a digital laser infrared thermometer temperature model (TEGMART TE-TEM-LS-PRB) has been used. Humidity and temperature meter (GM1362) has been used to measure the temperature and relative humidity of the ambient air which putted in the shade to protect it from the sun radiation at a height of 1 m from the surface ground. The values of the solar radiation intensity throughout the day were measured using a solar power meter device (TENMARS TM-207) in W/m² units. Anemometer device (ut363) has been used to measure the wind speed surrounded.

The error ratio is calculated, as shown in Table 1 which includes lists of transaction error measurements that verified for several experiments. Some attempts are repeated later to validate the results. Standard error calculation is very important in the field of analytical engineering which used to determine the error percentage.

| No | Device                                                                 | precision            |
|----|----------------------------------------------------------------------|----------------------|
| 1  | SD data logger 4 channel K thermocouple device (model 88598)         | ± 0.3{\%} rdg + 1{\degree}C |
| 2  | Digital laser infrared thermometer temperature model (TEGMART TE-TEM-LS-PRB) | ± 1.5{\%}            |
| 3  | Humidity and temperature meter (GM1362)                              | Humidity 3{\%}       |
|    |                                                                      | Temperature 0.5{\%}  |
| 4  | Solar power meter device (TENMARS TM-207)                            | ±10 W/m²             |
| 5  | Anemometer device (ut363)                                            | ±5{\%} rdg + 0.5{\degree}C |

The current study carried out according to Ekaterinburg/ Russia city climate (Latitude 56.84 °N, Longitude 60.58 °E), all testing days were started at 08:00 am and ended at 08:00 pm for different days. Before each test, the Plexiglas cover of the solar stills was cleaned, and the water level in the basin adjusted at 5 cm. The solar distilled directed to the south and the following measurements recorded per 30 minutes throughout the day:

a. Temperatures inside and outside plexiglass cover, vapour temperature within the solar still, the ambient temperature and relative humidity, temperature of water basin, temperature of basin liner and the temperature of the hollow drum.

b. Wind speed which has been measured every 30 minutes and the average calculated for one day.

c. Productivity per 30 minutes (mL) divided by the unit area of distilled.

2.2 Procedures of test

The tests were carried out for 3 months (Jun, July and August) at the Ural Federal University of Yekaterinburg/Russia. The measurements conducted in two stages, in the first stage, primer testing on the experimental station was conducted to evaluate the performance and possibility of the amendment in the designs to reach the best case. Tests were conducted in different days and an uneven environmental condition with 40 tests. Second stage included studying the amount of distilled water productivity in each 30 minutes for the two patterns (A & B) in a similar condition and then comparing the results obtained from those patterns (improved and conventional) with each other. All the readings were registered every 30 minutes for all variables, tests begin at 8:00 am and continue to 08:00 pm (12 hours).
3. Results and discussion
In the current experiments, weather data recorded continually at the Ural Federal University of Yekaterinburg/Russia. In order to know the effect of weather data on each other and on the performance and productivity of solar distillers, an analytical program (Origin pro-2018) was used to illustrate these effects. Experimental weather data has been studied in detail, which included solar radiation intensity, relative humidity, ambient temperature and wind speed. Figure 3 shows the experimental results taken for a perfect day on 12 June 2019. It is obvious that the intensity of solar radiation varies depending on the weather, in the Yekaterinburg city rarely the weather is clear and without clouds. The effect of solar radiation started after 8:00 am and the maximum intensity of the solar radiation is approximately at 02:00 pm, in which the intensity of radiation 942 W/m².

To investigate the performance of the enhanced single slope solar still, its relations with basic parameters are discussed in detail in this part to be able to draw valid conclusions about important factors influencing performance. Figure 4 illustrates the relation between the time for every 30 minutes and important parameters such as Plexiglass cover, vapour, basin liner and water temperatures for suggested solar still with HRC (A). Due to the lower thermal capacity of the plexiglass which is less than galvanized iron cylinder and water, the plexiglass was heated first by two effects, solar radiation and heat convection and radiation energy transferred from the hollow cylinder surface. On the other hand, basin water is heated by heat conducting from the hollow cylinder and solar radiation reaching the surface of the water through transparent Plexiglass. Therefore, plexiglass heated first and reach a maximum value of 45.3 °C at 12:30 pm, while the water temperature 40.9 °C. After 12:30 pm, Plexiglas temperature decreased to 42 °C at 01:30 pm, while the water temperature increased continuously to reaches its maximum value of 42.5 °C at 02:30 pm. All that due to the fact that the solar radiation absorbed by solar still exceeds the heat losses to the system surrounded. After about 02:30 pm, basin water temperature decreases because of the heat losses from solar still body to the ambient was larger than the solar radiation absorbed from solar still. Moreover, it can be seen that the basin liner temperature becomes closer to the basin water temperature due to the continuous contact between them, that leads to thermal equilibrium. It can be noted that the vapour temperature within solar still approximately maximum after 10 am within solar still, because of the particles in this temperature has enough energy to evaporate. Furthermore, the condensation process depends on several parameters such as the coefficient of heat transfer by evaporation, latent heat of vaporization of water and temperatures differences between basin water and inner surface of the plexiglass. Moreover, the vapour reached saturation state with high temperature before noon, while the saltwater did not reach the saturation degree until the afternoon, only surface water particles which was direct contact with the generated water vapor.

Figure 5 illustrates relation between the time for each 30 minutes and important parameters such as Plexiglass cover, vapour, basin liner and basin water temperatures for conventional solar still without HRC (B). Because of the thermal capacity of the plexiglass is less than water, the plexiglass was heated and reach maximum of 44.5 °C at 12:30 pm, while the water temperature 40.6 °C. After 12:30 pm, Plexiglass temperature decreased, while the water temperature increased to reaches its maximum value 43.6 at 02:30 pm because of the solar radiation absorbed by solar still exceeds the heat losses to the system surrounded. After about 02:30 pm, basin water temperature decreases because of the heat losses from solar still body to the ambient was larger than the solar radiation absorbed from solar still. Also, from Figure 5, it can be seen that the basin liner temperature becomes closer to the water temperature due to continuous contact between them, that leads to thermal equilibrium. It can be noted that the vapour temperature within conventional solar still has the largest temperature from 8:00 am to 02:00 pm, because of the particles during this period has enough energy to evaporate.

Figure 6 shows the comparison of still temperatures (Plexiglass cover, vapor, basin liner and water basin temperatures) between two the types (A&B), it can be seen that the Plexiglass cover temperature of the solar still A almost higher than solar still B along the day, due to the thermal effect of the hollow cylinder on the temperature of the plexiglass throughout the day. Also can be seen that the vapour temperature within solar still type B larger than vapour temperature within solar still type
A. because of the particles in this temperature has a higher enough energy to evaporate, moreover, in solar still type A part of this energy is lost by the rotation of the hollow cylinder, which works to move wet air within the solar still. From Figure 6 it can be noted that the basin liner temperature and basin water temperature for still A until 02:30 pm is higher than in still B. After 02:30 pm the opposite happens, because the solar intensity has an important effect on the hollow cylinder temperature. The increase in the solar intensity in the early morning until it reaches the maximum at around 02:00 pm, thus the cylinder temperature is high during this period which in turn effect on the water temperatures and the basin lining, then decreases in the late afternoon.

Figure 7 illustrates the productivity of distillate water in milli-litres which it is changed with time for both two stills because it depended on the intensity of solar radiation and ambient temperature during a typical day on 12 June 2019. Experimental data show a statistical significance improvement between the new suggested still A and traditional still B. The most important reason for this enhancement is the increase in the surface area of evaporation part (the area between the end of the black column and the red column), which is constantly renewed in comparison with the conventional solar still. This area represents the area of a rectangle and equal to the length of the rib of the basin multiplied by its width. In the hollow cylinder solar still, the surface area of evaporation part at any moment of time equal to the summation of the inner and outer cylinder circumference plus the surface area of the exposed horizontal water at the edges as follows [19].

\[ A = 2\pi r (h_1 + h_2) \]

Also can be seen from the figure that the productivity of the solar still A started early since the morning sunrise hours, to exceed the productivity of traditional still B about 8-14 times until 11:30 am and reduced approximately afternoon to reach to 1.61% at 08:00 pm.

**Figure 3.** Relation between the time for each 30 minutes and solar radiation intensity, temperature and relative humidity of ambient air
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Figure 4. Relation between the time for each 30 minutes and cover Plexiglas, vapor, basin liner and water basin temperatures for suggestion solar still with HRC (A)

Figure 5. Relation between the time for each 30 minutes and cover Plexiglas, vapor, basin liner and water basin temperatures for conventional solar still without HRC (B)

Figure 6. Relation between the time for each 30 minutes and Plexiglas cover, vapor, basin liner and water basin temperatures for types (A` & B) solar sills in one panel and 4 panels
4. Conclusion

The main objective of the current study is to increase the productivity rate of conventional solar still by increasing the surface area of heat transfer in the evaporation section within solar still. The following conclusion can be addressed from the obtained results:

1. The increased surface area of the evaporated part within the enhanced solar still has led to a significant improvement in daily freshwater productivity compared to conventional solar still.

2. Increasing the ambient temperature or/and solar radiation intensity with low relative humidity leads to an increase in the productivity of solar still.

3. The temperature of the glass was higher than others temperatures until 9:30 am for conventional solar still (B) because of heat capacity of the glass is less than water and basin lining, but in the improved distillate (A) the glass temperature was higher than others temperature until 01:00 pm, due to the influence of high temperature of the surface cylinder, which increases the temperature of the plexiglass when the intensity of solar radiation is greater than 600 W/m², therefore, the condensation is occurring due to the temperature’s differences between the water and glass cover (an increase of temperatures differences, that’s lead to increase of condensation process). This difference is a result of the variation in the thermal heat capacities between both materials (glass and water).

4. The ratio of freshwater productivity for enhanced solar still used a rotational hollow cylinder (A) improved by about 161% compared to that of the conventional solar still B, over the day period.

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