IoT-based performance analysis of hybrid solar heater-double slope solar still

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ABSTRACT

Remote monitoring of solar still systems is an interesting step for performance analysis and supervision. In this article, a monitoring system is developed and integrated to a solar still system. The parameters considered (such as air temperatures, relative humidity, etc) have been posted on a webpage via the Internet of Things (IoT) technique. For this, the ThingSpeak platform of the MathWorks is used. The results demonstrate that the ground water after desalination has practically the same chemical parameters values like mineral water (Nestle) and ordinary home drinking water. It has been also confirmed that by adding a solar preheater, the process of evaporation of saline water has been accelerated, which permits to improve efficiency the proposed prototype.

Key words: double slope, drinking water quality, IoT, monitoring, solar still, ThingSpeak

HIGHLIGHTS

- Investigating the use of renewable energy systems in water desalination plant.
- Design of a smart solar still water desalination prototype.
- Monitoring system for controlling online its performance.
- Collecting Data using Internet of Things technique (IoT) via a web page for users.
- Controlling the quality of the water.

1. INTRODUCTION

Water and energy are the first need for living in any locations in the world. The major quantities of water are available in ocean than in earth. So, only the little amount of fresh water is available in earth as lakes, rivers and ground water. Demands of water is increasing in the world due to the increase of population, agriculture production and industries sector. The impure water affects extremely the health of humanity. So, due to the small amount of fresh water availability, it is primordial to extract the fresh water from impure water to meet people’s needs in fresh water. For this reason, industrials focus to get fresh water from impure water using many industrial processes.

There are two process which are direct and indirect desalination process. In direct systems, solar energy produces thermal energy needed for water desalination process (Solar Still Systems) while in indirect systems, we produce the electricity which is needed to power the membrane processes. In indirect desalination systems, there are two units to produce distilled water which are desalination process and solar collector. A desalination of seawater has been done using an experimental solar still system in arid region. The Adaptive Neuro-Fuzzy Inference System (ANFIS) models have been generated using a hybrid learning algorithm with different functions where data has been distributed randomly (training, testing and validation) (Mashaly & Alazba 2018).

Another experimental work proposed the use of lenses and mirror attached to a basin of single slope solar still to enhance the concentration effect for solar radiation. The productivity of distilled water has been monitored (Fang et al. 2018).

A recent study has been done to improve the heat transfer inside evaporator which allow increasing the yield of distilled water. It has been found that using energy storage enhance considerably the average daily of distilled output water (Tigrine et al. 2021).

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Another recent study has been done and it has found that using hybrid solar distiller give a production of 6.5 l/day compared to the traditional solar production (3.4 l/day) in the same environment. This increase in productivity represents almost an increase of 91% compared to the classical system (Randha et al. 2021).

One of the low-cost processes is using solar still desalination system. In fact, the available of solar radiation over the year encourage to use of solar desalination system based on solar heat energy. The Principle of Solar water desalination system consist to take out dissolved salts from water. The different components of this type of solar still are as: Basin, Black Liner, Transparent Cover (glass in general), Output channels and Insulation.

Glass cover is an essential element in the still. It has been concluded (Panchal & Shah 2011, 2012) that to improve the performance of still, it is recommended to choose the lower glass cover thickness. An analysis of different kind of solar still has been done by Kaushal & Varun (2010). Different designs have been presented to show the impact of these parameters including the meteorological conditions, on the performance of solar still. Experimental and theoretical investigation has been done, by Badran & Abu-Khader (2007), to study the effect of water depth on a single slope solar still. The results showed that the yield in output water increase by almost 26% if water depth decrease from 3.5 to 2 cm. They observed also that maximum solar radiation intensity allows increasing in output of still.

The performance of double slope solar still has been done by Kandasamy et al. (2013), the authors made an experimental test on water depth. Another investigation about the effect of condensing cover material has been given by Dimri et al. (2008). Due to the high thermal conductivity of copper compared to plastic and glass, the copper gives high yield. Also, in this same study, it was found that the lowest thickness of glass cover gives the best yield for passive and active solar still. Another study has been investigated by Tiwari & Tiwari (2007) about the inclination angle of solar still slope. It was found that 15° is the best angle to give the best annual performance of solar still.

The study of the performance of single slope solar still has been experimented by Badran (2007) using asphalt basin liner and sprinkler. The effect of absorbing materials has been studied by Abdalla et al. (2009) on four solar still units with same size. Another experimental study was carried out, by El-Bialy (2014), for studying different floating absorber plate in a single slope solar still. Also, an experimental and theoretical results have been done for a double slope active still by Dwivedi & Tiwari (2010). Boukar & Harmin (2001) have investigated the effect of desert climatic condition in Algerian Sahara, on the efficiency of both a single solar still and a solar still attached to a flat plate collector.

An experimental and theoretical research have been done by Rajaseenivasan & Kalidasa Murugavel (2013), to study the different basin conditions on double basin double slope solar still.

The impact of depth under insulated and uninsulated conditions has also been investigated by Elango & Kalidasa Murugavel (2015) to study the performance of such solar still. Experimental results were done by Panchal (2015) to study the impact of connecting evacuated tubes to the basin of solar still using absorbing material such as black granite or without. Another investigation has been done by Khalifa & Ali (2015) to study the effect of wind speed on the performance of solar still. In addition, the impact of water salinity was studied by Akash et al. (2000). It was concluded that the yield of output water decreases with increasing salinity. The high solar irradiation gives the maximum yield in experimental results done by Safwat Nafey et al. (2000). A recent study has developed a new solar still device using a new design formed by a dome slope solar still which cover on the walls of the solar still. The goal of this work is to increase the area of the glass cover and due to this new geometry, more sunrays are concentrated inside the basin. It was found, that the yield of distilled water for this new design is 36% higher that four slope still (Sun et al. 2021).

Desalination and water recycle is consider one of the scientific research priorities in Saudi Arabia. We have designed an experimental solar still called two slopes solar still. A two slopes basin type solar still is fabricated with inner dimensions of 1 m \times 1 m (effective area is 1 m²) and the tilt of the glass cover is 25 °C and which correspond to the latitude of Madinah city location. A solar heater has also been added to the solar still designed, in order to preheat the salted water before entering the basin of solar still.

The objective of this research is to design a smart hybrid solar heater – solar still system. A monitoring system based on a low-cost microcontroller and Internet of Things (IoT) technique. The monitoring system permits to control and study the performance of the proposed hybrid solar still remotely. The system has been implemented and experimentally validated at Madinah city, Saudi Arabia (Benghanem et al. 2021a).

Numerous designs of solar still have been developed in different locations in the world to improve the water productivity per day (Watercone 2001; Nassar et al. 2007; Panchal & Shah 2012; Dsilva et al. 2014; Mamouri et al. 2014; Suneesh et al. 2014; Harris Samuel et al. 2016; Panchal & Patel 2016; Chandrashekara & Yadav 2017; Randha et al. 2021; Tigrine et al. 2021), (Manual of low-cost solar water purifier for rural households http://www.nariphaltan.org/swpmanual.pdf). Our
present work contributes in this field by presenting a new design based on monitoring of hybrid solar heater-solar still using IoT technique. A comparison between the outcome of present work with average daily production with others research works is given in this manuscript.

This paper is organized as follows: The principal of solar still is given by the next Section. The effect of some parameters on the performance of solar still are reported in Section 3. In Section 4 provides the discussion and performance analysis of the proposed solar still, while the final Section 5 gives some concluding remarks and perspectives about the designed prototype.

2. PRINCIPAL OF SOLAR STILL

The principal of simple solar still is presented in Figure 1. It is constituted by basin containing the salted water, a transparent cover which should be in general glass. Due to the incident solar radiation and due to the design of solar still which act like a greenhouse effect, the water is evaporated and condensed on the inner side of the glass cover and then cool down due to the tilt of the glass until the output channel. The black liner of basin absorbs more solar irradiation and then improve the heating of the solar still and allow more evaporation of salt water. There are two kinds of solar still: Active and Passive solar still. The active solar still needs external energy source in order to upgrade the heating inside the still by using collector to give distilled water while the passive solar still are based only on solar thermal and needs only suitable design and use thermal evaporation to get distilled water.

2.1. The proposed smart hybrid desalination system using IoT technique

The performance of solar stills system is affected by numerous operating factors and design configuration (Safwat Nafey et al. 2000). Thus, to get the best performances of the investigated solar still system some steps should be taken in consideration for

![Figure 1](https://example.com/solar still figure)

**Figure 1** | Principal of Solar Still: (a) Single slope solar still and (b) Double slope solar still.
This work, which can be summarized as follows: best absorption of solar radiation; great surface area; using a heat recovery system to increase the condensing surface temperature (Dimri et al. 2008). The two slopes solar still is designed with inner dimensions of 1 m x 1 m and the glass cover is tilted at 25° (latitude of the location). We have studied the effect of water capacity in the basin on the internal and external heat transfer. The average yield of distilled water produced by the proposed solar still is 9.75 L/m²/day. So, to get the best performances, we have combined between the two slopes still and solar heater in order to preheat the salted water before injecting it in basin as shown in Figure 2.

This proposed hybrid system (Solar Heater – Solar Still) allows the fast evaporation of water vapor. The average yield of distilled water produced is around 12 L/m²/day. In order to test and control the proposed prototype, we have designed a smart data acquisition system based on a microcontroller (Arduino Mega 2560). The different data are as follow: solar radiation, ambient temperature, relative humidity, input water temperature to the heater, Output water temperature from the heater, Temperature inside the heater, water temperature inside basin, relative humidity inside basin, the amount (liter/hours) of output distilled water, salinity of desalinated water and the daily average yield of distilled water (Liter/day).

Figure 3 illustrates the schematic diagram showing the viability of IoT technique in water desalination unit. In addition, the integration of small photovoltaic system has contributed to power the designed circuits corresponding to the different sensors. The salty water is introduced first in a solar heater designed also in this work. The heated water is introduced on a black plate of the solar still. The solar irradiance allows the fast evaporation of the heated water to produce distilled droplets of water. The droplets slide down, due to the gravity, until a special channel of collecting water (Benghanem et al. 2021a).

Figure 4 shows the photos of different experiments of the proposed prototype hybrid solar heater – solar still. During phase of test, we have done different measurement under different conditions to measure the hourly and daily output distilled water (Benghanem et al. 2021a).

A low-cost smart water desalination system powered by solar energy has been designed. The solar module inserted between solar heater and solar still in Figure 4(b) allows powering the designed data acquisition system-based Arduino mega board which collect different data described above.

The monitoring system has been integrated to the designed solar still using Internet of Things (IoT) in order to control the evolution of the system in real time. The main steps of the control process, implemented into the microcontroller, are summarized as follows:

1. Initially the tank (containing salt water) is considered full (L3=500 L) as well the basin (100 L).
2. Checking water position in the basin, which should be between two levels (L1=2 cm and L2=10 cm), if the position sensor indicates the measured level is less than L1, the microcontroller activates the reply and the valve will be opened till the water level L2 is reached, then the rely is set off automatically by sending a signal from the microcontroller.
3. Verification of the water level in the tank if the level is less than L3, the microcontroller sends a signal to start the water pump, till the L3 is reached.

As example the basic electronic circuit connection is shown in Figure 5.

Figure 2 | Hybrid Solar Heater-Solar Still Water Desalination System (Benghanem et al. 2021b).
The control process is presented in Figure 6.

The controller circuit is designed and simulated by using Proteus simulator. The corresponding developed circuit is shown in Figure 7. A basic Arduino code for measuring air temperature (T) and relative humidity (RH) is shown in the Appendix 1.

As example Figure 8 shows the collected RH and T on the webpage using ThingSpeak platform of MathWorks.

The detailed code which permits the connection to ThingSpeak platform via ESP8266 Wi-Fi module is given in the Appendix 2.
3. EFFECT OF SOME PARAMETERS ON THE PERFORMANCE OF SOLAR STILL

The performance of solar still depends on the choice of some parameters which can contribute to get the best amount of distilled water per day. The most influencing parameters are the meteorological factors and the design of different constituents of solar still. So, we can classify the factors affecting the performance of solar still in three categories:

- Environmental factors.
- Design factors.
- Operation factors.

The environmental factors influencing the performance of solar still are:

- Solar irradiation,
- Ambient temperature,
- Wind velocity.

Figure 4 | Experiments of the proposed prototype hybrid solar heater – solar still (a) Test on hourly and daily of outputs distilled water for different days (b) Front and back side of the desalination unit showing the integration of Arduino Mega board for controlling and collecting data.
The design factors influencing the productivity of solar still are:

✓ Cover material,
✓ Thickness and tilt of glass,
✓ Water depth,
✓ Evaporation area,
✓ Insulation and salinity of water.

The operation factors affecting the performance of solar still are:

1 Maintenance,
2 Dust Accumulation,
3 Water feeding,
4 Position of the solar still.

In this work, we have studied the performance of the proposed solar still and the effect of climatic factors such as *Air temperature* and *solar radiation*; and design factor such as *water depth*, on the daily output yield of distilled water.

### 3.1. Water depth

Some researches work (Safwat Nafey *et al.* 2000; Elango & Kalidasa Murugavel 2015) concluded that the maximum output yield of distilled water produced by different types of solar still corresponds to the minimum water depth. In fact, the rate of evaporation is affected by water depth. In this present work, we have chosen different depth of water at each experiment and we confirm also that minimum depth chosen of 2 cm give us the maximum output. *Figure 9* presents the hourly evolution of yield for different water depth. *Figure 10* indicates the amount evolution of output distilled water for different depth. From this curve, it can be concluded that maximum output water corresponds to a minimum water depth. This is due to fast evaporation of salted water.

So, it is found that the productivity of water increases with the decrease of basin water depth.
3.2. Air temperature

During our experimental work, it has been observed that the increase in air temperature, still productivity is increasing. Figure 11 presents the impact of ambient temperature on the output distilled water. 1.35 L/h has been obtained when the air temperature reaches the value of 51°C (Benghanem et al. 2021a).

3.2.1. Temperature difference of glass cover plate and water

The measured parameters are: Air temperature, Vapor Temperature, Glass Temperature and Water Temperature as shown in Figure 12. Temperature measurement of the hybrid system are given by Figure 13.
It has been concluded that the productivity of distilled water is improving when the temperature difference between the water and glass cover plate is high.

Figure 14 shows the amount of output water of double slope distiller connected with solar preheating water. The impact of a solar heater on the yield was carried out as indicated in Figure 14.
**Figure 9** | Hourly output water vs time of the day for different depth of water inside still.

**Figure 10** | Evolution of the output water for different water.

**Figure 11** | Solar still productivity and Air Temperature vs Time of the day.
Figure 12 | Evolution of different temperature collected on two slopes Solar Still.

Figure 13 | Evolution of different temperature collected on the Hybrid system: Solar Heater – Solar Still.
Figure 14 | Comparison of yield between double slope solar still and hybrid solar heater – solar still.

Figure 15 | Solar irradiation vs time of the day.
With reference to the experimental results, a higher amount of distilled output from the hybrid solar heater-solar still compared to the output of double solar still is obtained (Benghanem et al. 2021a).

It has been found that the efficiency of the hybrid solar heater-solar still is greater than the standard double slope solar still, for the same size of basin. The maximum daily yield produced by double slope solar still in this study is 9.75 L/m²/day while the hybrid solar heater-solar still produce the maximum yield of 12.165 L/m²/day.

3.3. Solar irradiation

Figure 15 represents the hourly solar irradiation recorded during a clear sky in 18 February 2021. We note that Madinah city has a great potential of solar energy (Benghanem & Joraid 2007) and almost all days are sunny and clear sky. This is an advantage to make different applications in solar energy such as solar desalination systems.

In this part, we have studied the influence of incident solar irradiation on the productivity of the proposed hybrid solar still. In fact, the evaporation of salted water inside the still is due to the incident solar irradiation which allow heating of water. So, distillation requires daily high intensity of solar irradiation to get best daily yield of distiller. Figure 16 shows that the maximum productivity is reached when maximum of incident solar irradiation is obtained in the time period of 12 to 2 pm.

Figure 16 shows that solar radiation intensity recorded daily at Madinah city during the period February–April 2021, is influencing on the distilled water productivity. It has been found that the maximum yield, in the day of 25 March 2021, is obtained during mid-day due to high solar intensity which was around 1,100 w/m². Thus, it can be concluded that the productivity of solar still increase with the increase of solar radiation intensity.

4. DISCUSSION AND PERFORMANCE ANALYSIS OF THE PROPOSED SOLAR STILL

The measurements have done during the period February–April 2021. After a large experimentation done, we got good results. In fact, the proposed solar still unit gives a good amount of distilled water production in comparison with the previous solar still systems. Table 1 shows the outcomes of researches work with average daily production. The proposed prototype allows fast evaporation of water inside the still and the average yield of water production is around 12 L/m²/day.

Figure 17 shows the average water production for different designs of solar still corresponding to hourly daylight in different countries including our present design (Type No. 9 in graph).

From Figure 17, it is shown that the best productivity of solar still design is given respectively by decreasing order: Elliptical solar still design (Nassar et al. 2007). Solar water purifier (Chandrashekara & Yadav 2017), (Manual of low-cost solar water purifier for rural households, http://www.nariphaltan.org/swpmanual.pdf), hybrid design (present work), Still coupled with ETC (Mamouri et al. 2014), Stepped type (Dsilva et al. 2014), Still in V type design (Suneesh et al. 2014), Pyramidal type (Panchal & Patel 2016), Cone type design (Watercone 2001) and triangular type (Harris Samuel et al. 2016).
We conclude the following outcomes:

- To increase the output distilled water, we should use minimum water depth.
- It is recommended to choose a glass cover with lower thickness.
- It is suggested a tilt angle of glass cover around the latitude angle of the site.
- Integrating the solar preheating with still, enhance the amount of output distilled water.
- Still productivity is increasing by 44% by decreasing water depth from 5 to 2 cm.
- In this work, we got the maximum productivity by using minimum water depth which is equal to 2 cm.
- It is recommended a low thickness of glass cover which is 2 cm in this work.
- It is observed that high intensity of solar irradiation gives greater yield.

Table 1 | Outcomes of researches work with average daily production

| Solar still designs                          | Country  | Daylight (h) | Average water production (l/day) |
|---------------------------------------------|----------|--------------|----------------------------------|
| Elliptical type (Nassar et al. 2007)        | Libya    | 8            | 20.11                            |
| Pyramidal type (Panchal & Patel 2016)       | Oman     | 7–8          | 4.15                             |
| Triangular Type (Harris Samuel et al. 2016) | Malaysia | 7–17         | 1.55                             |
| Still coupled with ETC (Mamouri et al. 2014)| Egypt    | 8            | 6.35                             |
| Solar still of type stepped (Dsilva et al. 2014) | Egypt | 8            | 6.35                             |
| Cone still (Watercone 2001)                 | Germany  | 7–8          | 1.6                              |
| Still in V type with water and airflow on CGTCC (Suneesh et al. 2014) | India | 9–17         | 4.6                              |
| Solar water purifier (Chandrashekara & Yadav 2017) | India | 7–10         | 15                               |
| Hybrid Solar Heater-two Slope Solar still (Present work) | Saudi Arabia | 10–12 | 12                             |

Table 2 shows the chemical parameters (Before and After desalination) of a ground water from a palm farm at Madinah city. A comparison has been done with mineral water (Nestle) and ordinary home drinking water. The results show that the Ground water after desalination has almost the same values of chemical parameters of mineral water (Nestle) and
ordinary home drinking water. The limit values (Benghanem & Joraid 2007) of Saudi Standard Organization (SASO) have been in good agreement with the produced water after desalination (Benghanem et al. 2021a).

In this study, the water sample analyzed has concentration of hydrogen ion (pH) within the recommended values of 6.5 to 8.5 standard values (Benghanem & Joraid 2007). Freshwater is usually between 0 and 1,500 μS/cm (Benghanem & Joraid 2007; Benghanem et al. 2021b). The electrical conductivity (EC) of the used Sample before desalination is 7,550 μS/cm which is higher than the standard value and after desalination, the electrical conductivity is 384 μS/cm which is considered as acceptable value. Before Treatment the Total Dissolved Solids (TDS) value is 3,770 (mg/L) and after desalination is 210 (mg/L). This TDS value of water after desalination is within permissible value (Benghanem & Joraid 2007). The salinity of the tested ground Water is 0.39% corresponding to 3.9 g/kg. After desalination the salinity is 0.01% corresponding to 0.1 g/kg which is lower than 0.5 g/kg (<0.5 ppt, where ppt is parts per thousand).

As scientific discussion about using IoT technique in solar desalination plants, we can say that the IoT technique allows to control easily the performance of solar desalinations units. The IoT-based performance analysis of solar still units will populate dedicated web server-based database with real time data that will improve the decision-making process of the considered solar desalination unit. The generation monitoring, fault detection of the solar desalination units in real time will be available on website and then the data such as hourly and daily productivity of distilled water, temperature inside and outside the still and relative humidity can be used for historical analysis. Thus, using IoT technique will enhance the decision-making process for large scale solar desalination units. In this present work, we proposed an IoT-based performance analysis of hybrid solar heater- double slope solar still. The realized prototype of solar desalination unit is studied, implemented and successfully achieved the online supervision of collected data which have been posted on a webpage via the Internet of Things (IoT) technique using the ThingSpeak platform of the MathWorks.

5. CONCLUSION

It has been shown that the proposed solar still preheated by a solar heater system gives a good amount of distilled water production, in comparison with the previous solar still systems. It allows fast evaporation of water inside the still and the average output distilled water is around 12 L/m²/day.

The physical-chemical parameters of the produced distilled water have been found in a good agreement with the limit values of Saudi Standard Organization (SASO). The monitoring and control of the proposed hybrid still has been done using a low-cost microcontroller (Arduino mega board).

Thanks to the IoT technique and ThingSpeak platform the user could monitor easily different parameters like temperature, relative humidity, daily yield of distilled water, pH, EC, TDS and salinity. In addition, based on the measured data the user can check if the system works correctly or not by analyzing the obtained data.

Further extension to this work is to design an application which permits to notify the user by an email about the status of the system, in this case other board such as Raspberry Pi is suitable.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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