Experimental and Theoretical Study on the Productivity of a Single Slope Solar Still Coupled with Flat Plate Solar Collectors in Series

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Abstract: ***The availability of fresh drinking water is diminishing as the demand due to world population is increasing, thus, solar desalination of saline water is a great solution to this problem. The process usually uses solar stills of various designs, however, the productivity of these solar stills is limited and insufficient to use for mass production. Therefore, an enhancement is required to improve the productivity of the solar still. In this paper, a single slope solar still is coupled with two flat plate solar collectors in series connection to enhance the productivity of a conventional solar still. A theoretical and experimental analysis of the system is carried out, the theoretical model used MATLAB software and was validated with other researchers, while the experiment took place in the city of Basra, Iraq in February, 2020. A good agreement was found between the theoretical and experimental results. The study found that the productivity of the still increases with the increase of water temperature, which is increased using flat plate collectors, and the solar radiation intensity. Also, the thermal efficiency and productivity of the solar still is improved when using flat plate collectors in series connection in the system.***

Keywords: Renewable energy, Solar energy, Water still, Desalination, Flat plate collector

Nomenclature

h_{cw} -convective heat transfer coefficient from water surface to glass, W/m^2 ^{o}C
h_{ew} –Evaporative heat transfer coefficient from water surface to glass, W/m^2 ^{o}C
I(t) –solar intensity, W/m^2
P_{vg} –Partial vapor pressure (glass temperature), N/m^2
P_{vw} –Partial vapor pressure (water temperature), N/m^2
T_a –Air temperature, ^{o}C
T_w –Average water temperature, ^{o}C
T_g –Average glass temperature, ^{o}C
T_b –Basin liner temperature, ^{0}C
T_{sky} –Sky temperature, ^{0}C
A_b –Area of the basin, m^2
V_w –velocity of wind, m/s
K_i –Thermal conductivity of insulation, W/m^{0}C
L_i –Thickness of insulation, m
h_{cga} –Convective heat transfer coefficient (glass cover to air), W/m^{2}C^0
h_{rga} –Radiative heat transfer coefficient (glass cover to air), W/m^{2}C^0
h_{tga} –Total heat transfer coefficient (glass cover to air), W/m^{2}C^0
h_{tba} –Total heat transfer coefficient from basin linear to ambient, W/m^{2}C^0
q_{tba} –Total heat transferred (basin to air), W/m^2
q_{cga} –Convection heat transfer (glass to air), W/m^2

1. Introduction

Renewable energy or green energy is being sought after worldwide to be the main source of energy in the modern life. The reason why renewable energy is the next big thing is because it has many important advantages such as, securing national resources, being a clean and pollution-free energy and does not affect the climate change, and it provides a cost-effective service [1]. There are many definitions for renewable energy, but they all share the same principle, John Twidell and Tony Weir defined renewable energy in their textbook "Renewable Energy Resources" as the energy obtained from naturally repetitive and persistent flows of energy occurring in the local environment. One of the main sources of renewable energy is solar radiation, which is both continuous and available daily. Other examples include the energy stored in plants from solar energy in their growing season that can be used by combustion. Wind currents, rivers, sea waves, tides, geothermal heat are some other examples of renewable energy resources. Solar radiation can be turned into thermal energy by using a solar collector. There are three main types of solar collectors: flat plate collectors, evacuated collectors and parabolic trough collectors [2]. These are the most common type of solar collectors used in solar heating systems. They are made of a black painted metal plate insulated by all sides and covered in transparent glass by the top. The fluid runs through parallel tubes joined to a black metal plate, it is very important to have minimum thermal resistance between the tubes and the plate, and it must be air-tight and water-sealed to avoid any corrosion or heat loss. The flat-plate collector reaches the maximum efficiency within temperature range of 30-80 oC, but there are new types that use vacuum insolation and can reach temperatures up to 100 oC. The flat-plate collector is used for its many advantages, as it collects beam and diffuse radiation which makes them able to function even when beam radiation is blocked by clouds, relatively easy to manufacture with low cost, has a fixed position so there is no need for tracking system and requires very little maintenance [3]. Single slope solar still is the most common and the simplest design that can be fabricated easily using cheap and locally available materials like wood, aluminum etc. And it is also very easy to maintain. The tilt angle of the glass cover towards the south direction is usually chosen to be the same as the latitude of the test location since it averages the noontime insolation peaks over the year [4]. Rai and Tiwari (1983) [5], added a flat plate solar collector to the single slope solar still to enhance the productivity of the still. The water is circulated between the still and the collector using a pump, the heat added to the water by the collector increases the rate of evaporation in the still. Two solar stills were studied for comparison, one is coupled with solar collector and the other is uncoupled. The study showed that the productivity of the still increased by 24% when coupled with flat plate collector. Badran and Al-Tahaineh (2005) [6], also coupled a flat plate collector to single slope still with mirrors fixed inside its side walls. They studied the effect of water depth and solar intensity on the solar still production rate. The experiment took place under the climate conditions of Amman, Jordan. The study concluded that adding a collector to the still increased the production rate by 36%. Also, increasing the water depth decreased the productivity and it was found that the solar radiation intensity is proportional to the still's productivity. Dimri, et al (2008) [7], performed comparative study between a passive and active solar stills, which is coupled with two flat plate collectors. The experiment took place in New Delhi, India in December, 2005. The study found that the productivity of the still was increased in the active system compared to the passive still because of the higher operating temperatures. The study also included the effect of different parameters on the productivity of the still. These include the glass cover thickness, wind speed and water depth. The result shows that the daily productivity was decreased with the increase of glass cover thickness due to the reduction of top loss coefficient. Also, the increase of wind speed increases the daily productivity. The increase in water depth also decreases the still productivity. Raju and Narayana (2016) [8], studied the effect of flat plate collectors connected in series on the productivity and efficiency of single slope solar still. The solar still used in the study has basin area of 1 m2 and inclination angle of 30o. The flat plate collectors each has an area of 2 m2 and inclination angle of 5o, and are connected in series with the solar still. The test took place in the summer season in Kakinada, India. The study has shown that the still with two collectors in series increased the productivity by 41% and efficiency by 0.47% compared to the still with single collector. When three collectors connected in series are used, the productivity increased by 89% and still efficiency decreased by 0.48% compared to still with single collector. The decrease in still efficiency is due to larger collector area for radiation.

2. Governing equations and thermal model

The main cause of the convective heat transfer coefficient in solar still is the action of buoyancy force caused by density difference of the humid air due to the temperature difference. Natural convection takes place because of the temperature difference between the water and the inner surface of the glass. The convective heat transfer of the water surface to the condensing glass cover is given by the equation [9]:

$$q_{cw} = h_{cw}\left(T_w - T_g\right) \qquad (1)$$

h_{cw} Is the heat transfer coefficient, which can be calculated by:

$$h_{cw} = 0.884 \times \left[\frac{(T_w - T_g) + (P_w - P_g)(T_w + 273)}{(268.9 \times 10^3 - P_w)}\right]^{1/3} \qquad (2)$$

Where: T_w is basin water temperature, Partial vapor pressure Pg, water pressure Pw in the still, T_g is the glass cover temperature.

The distillate water from the solar still is formed by the act of solar energy. Radiation heat transfer is produced by the emission of internal energy between two bodies having different temperatures which are, in this case, water mass and inner glass surface. The radiative heat transfer from water surface to condensing glass cover is calculated by [9]:

$$q_{rw} = h_{rw}(T_w - T_g) \qquad (3)$$

h_{rw} Is the radiative heat transfer coefficient, which can be calculated by:

$$h_{rw} = \varepsilon_{effect}\,\sigma[(T_w + 273)^2 + \left(T_g + 273\right)^2] \qquad (4)$$

Where,

$$\sigma = 5.669 \times 10^{-8} W/m^2 K^4$$

$$\varepsilon_{effect} = \left(\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_w} - 1\right)^{-1} \qquad (5)$$

$$\varepsilon_g = \varepsilon_w = 0.9$$

The water inside the solar still is evaporated and turned to steam by the incident solar energy. Evaporation heat transfer occurs between water mass and the inner glass surface and is generated when vapor pressure is lower than the saturation pressure of the liquid. Therefore, the evaporative heat transfer is given by [9]:

$$q_{ew} = h_{ew}(T_w - T_g) \qquad (6)$$

h_{ew} Is the evaporative heat transfer coefficient, which is calculated by:

$$h_{ew} = 16.27 \times 10^{-3} \times h_{cw} \times \frac{(P_w - P_g)}{(T_w - T_g)} \qquad (7)$$

Where,

$$P_w = \exp\left[25.317 - \frac{5144}{(T_w + 273.15)}\right] \qquad (8)$$

$$P_g = \exp\left[25.317 - \frac{5144}{(T_g + 273.15)}\right] \qquad (9)$$

The total heat transfer coefficient from water surface to condensing glass cover is given by:

$$h_{1w} = h_{cw} + h_{rw} + h_{ew} \qquad (10)$$

The top heat loss is the heat loss from the outer glass cover to the atmosphere due to radiation and convection heat transfer. The convective and radiative losses from the glass cover to the ambient is given by [10]:

$$q_{tga} = q_{rga} + q_{cga} \qquad (11)$$

Where,

$$q_{rga} = h_{rga}(T_g - T_{sky}) \qquad (12)$$

$$q_{rga} = \varepsilon_g \sigma \left[(T_g + 273)^4 - (T_{sky} + 273)^4 \right] \quad (13)$$

$$h_{rga} = \frac{\varepsilon_g \sigma \left[(T_g+273)^4 - (T_{sky}+273)^4 \right]}{(T_g - T_{sky})} \quad (14)$$

$$T_{sky} = 0.0552 \times T_a^{1.5} \quad (15)$$

$$q_{cga} = h_{cga}(T_g - T_a) \quad (16)$$

Where,

$$h_{cga} = 2.8 + 3.0V_w \qquad if\ V_w \leq 5m/s \quad (17a)$$
$$h_{cga} = 5.7 + 3.8V_w \qquad if\ V_w > 5m/s \quad (17b)$$

The total heat loss coefficient from the glass cover to ambient:

$$h_{tgoa} = h_{rga} + h_{cga} \quad (18)$$

To estimate the basin and glass cover temperatures, an energy balance is carried out for glass cover and basin. For glass cover:

$$\alpha_g \times I_s \times A_g + h_{1w} \times (T_w - T_g) = h_{tga} \times (T_g - T_a) \quad (19)$$

$$T_g = \frac{\alpha_g \times I_s \times A_g + h_{1w} \times T_w + h_{tga} \times T_a}{h_{1w} + h_{tga}} \quad (20)$$

Where α_g is the glass absorptivity and A_g is the glass cover area.

For the basin surface:

$$I(t)\tau_g \tau_w \alpha_b = h_1(T_b - T_w) + h_b(T_b - T_a) \quad (21)$$

$$T_b = \frac{I(t)\tau_g \tau_w \alpha_b + h_1 T_w - h_b T_a}{h_1 + h_b} \quad (22)$$

Where τ_g and τ_w are the glass and water transmittance, α_b is the basin absorptivity and h_b is overall heat transfer coefficient from basin liner to ambient air through bottom and side insulation

The hourly distillate output of the still per basin area is given by:

$$m_{ew} = h_{ew} \times \frac{(T_w - T_g)}{L} \times 3600 \quad (23)$$

The accumulated productivity in the solar still can then be obtained as follows:

$$M_{ew} = \sum_{i=1}^{n} m_{ew} \quad (24)$$

Where *n* is the number of test hours.

And the thermal efficiency of the solar still can be defined as the ratio of the amount of the useful thermal energy to the incident solar radiation in certain period of time.
The thermal efficiency of the still is calculated by:

$$\eta_i = \frac{h_{ew}(T_w - T_g)}{I(t)} \times 100 \quad (25)$$

3. Experimental setup

The test rig consists of two main components: two flat plate collectors, and single slope solar still. Two flat plate collectors were constructed, both with identical dimensions and materials. The housing body of the collectors is made of wood. A cork sheet is placed on the bottom to enhance the insolation. On top of the cork sheet, a 1×1m metal plate is placed. A U-shaped copper pipe is fixed on the metal plate, one of the collectors is painted matt black, and the other is painted with a layer of tar. K-type thermocouples are fixed at the inlet and outlet of the collector to measure the change in water temperature. A transparent glass cover with 4mm thickness is placed on top. The construction is isolated and air tight from all sides. Both collectors are fixed on a metal body tilted at a 30° angle. The main part of the study is the single slope solar still, it is made of a wooden body, the bottom and all side walls are made of wood-cork-wood sandwich construction for enhanced isolation. A matt black metal plate 1m×1m×0.03m basin is placed in the bottom. The north wall height is 0.72m and the south wall height is 0.15m, which was calculated to get 30° tilt angle. A transparent glass cover with 4mm thickness is fixed on top. Inlet and outlet pipes are fixed at the bottom of both the north and south walls to allow for continuous water flow. A number of K-type thermocouples were fixed at the basin and glass cover to measure the basin water and glass cover temperatures. The solar collectors were connected together in series connection with the solar still. The setup is shown in Figure 1. The experiment took place under the climate conditions of Basrah, Iraq in February, 2020.

Figure 1: Photograph of the test rig.

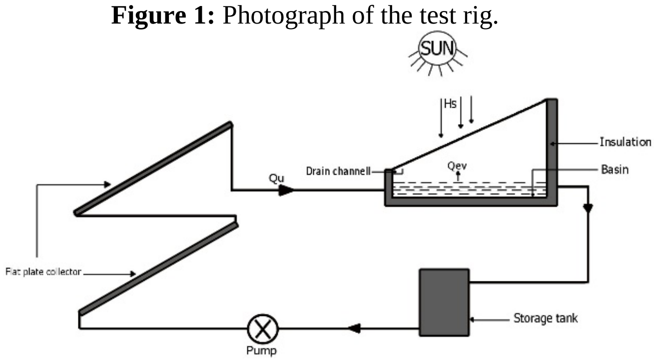

Figure 2: Block diagram of single slope solar still coupled with two flat plate collectors in series.

4. Error analysis

To evaluate the solar still performance, experimentally measured parameters are needed. These parameters are measured using measuring instruments, which have some degree of error or uncertainty, therefore affecting the accuracy of the results. These instruments include, thermometer, thermocouples, solar power meter and graduated jar were used to measure the air, water and glass cover temperatures, solar radiation intensity and the amount of distilled water. The range, accuracy and error percentage of these instruments are shown in Table 1.

Table 1: Range, accuracy and error of the instruments used in the test

#	Instrument	Readings Range	Accuracy	Error Percentage
1	Mercury Thermometer	0-100° C	±1° C	±0.5%
2	K-type Thermocouple	-100-200° C	±0.1° C	±0.25%
3	Solar Power Meter	0-2000 W/m^2	±10 W/m^2	±5%
4	Measuring beaker	0-1000 ml	±5 ml	±5%

5. Results and Discussion

The measured solar radiation intensity and ambient temperature during the test are shown in Figures 3 and 4, respectively. The numerical solutions of the equations shown in the theoretical analysis section were used to determine the results after taking hourly experimental measurements from 7 a.m. to 3 p.m. The measured and calculated temperatures of the basin water and glass cover versus the time of day are shown in Figure 5. As seen in the figure, the maximum theoretical water and glass cover temperatures were 55.65 and 43.41 °C, respectively. While the maximum measured water and glass cover temperatures were 54 and 42 °C, respectively. The water and glass cover maximum temperatures is because of the heat flow from the basin water to the condensing cover. The cumulative productivity comparison between experimental and theoretical results can be seen in Figure 6. The theoretical and experimental yield of the solar still was 2.255 and 1.7875 Kg/m^2, respectively. The hourly theoretical and experimental amount of distilled water from the solar still are shown in Figure 7. The experimental productivity of the still is in good agreement with the theoretical result. The maximum output occurred at 12:00 p.m., because of the maximum values of water temperature and solar radiation intensity, are 0.39 and 0.4282 Kg/m^2 h for experimental and theoretical values, respectively. The theoretical and experimental thermal efficiency of the solar still variation with time are shown in Figure 8.

To validate the software solver used in the theoretical analysis of this study, a comparison was made between the accumulated yield obtained by Ana Maria Johnson [11] and with the output obtained by the solver. A good agreement was found between the two, for the same given data, with an error of 4.26% as shown in Figure 9.

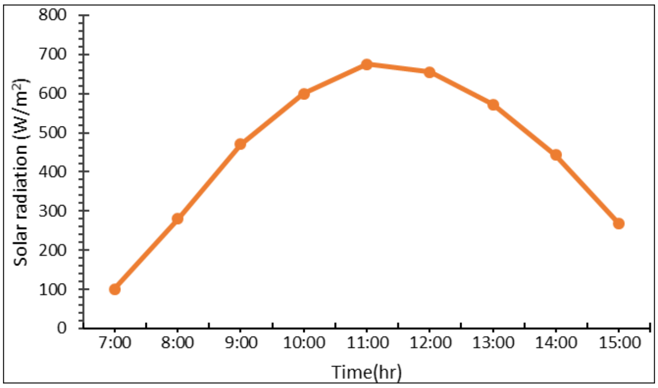

Figure 3: Hourly variation of solar radiation intensity.

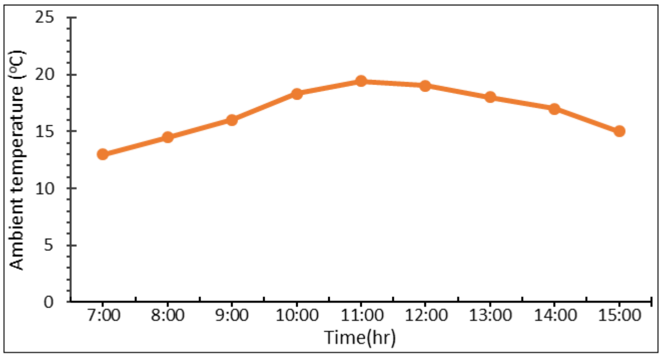

Figure 4: Hourly variation of measured ambient temperature.

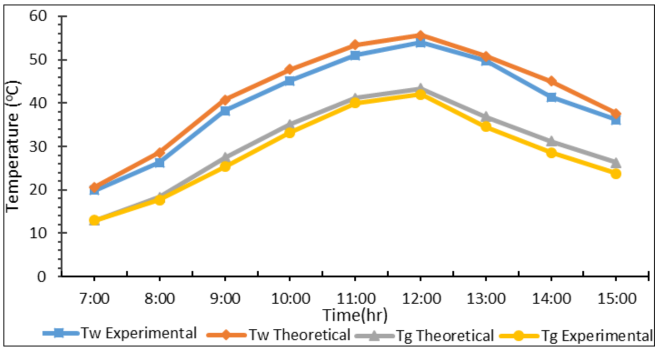

Figure 5: Hourly variation of experimental and theoretical basin water and glass temperatures.

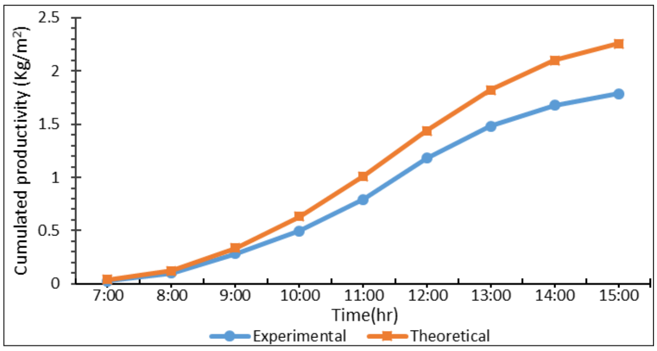

Figure 6: Cumulative productivity comparison between experimental and theoretical results.

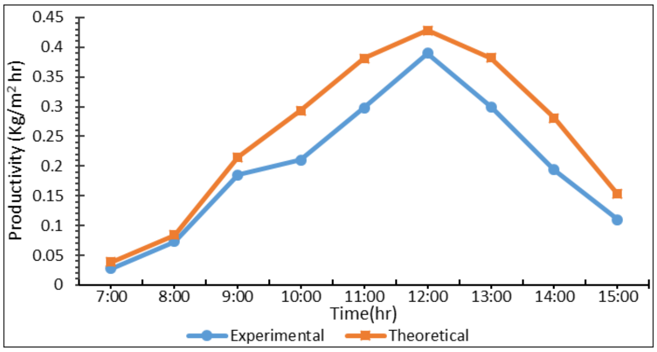

Figure 7: Experimental and theoretical hourly distilled water output

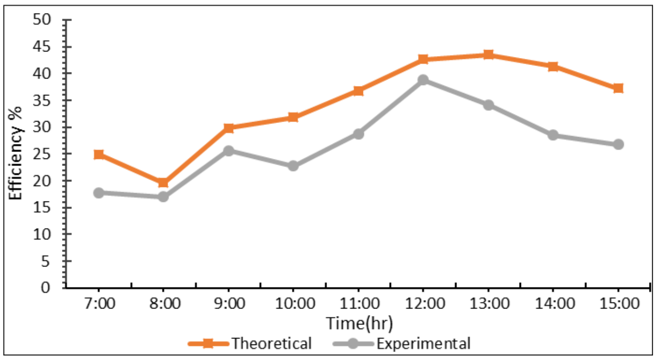

Figure 8: Experimental and theoretical instantaneous thermal efficiency of the solar still.

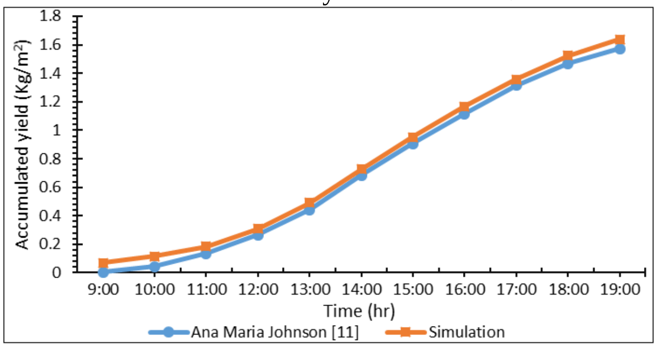

Figure 9: Comparison of accumulated yield between Ana Maria Johnson [11] and software used in the study.

6. Conclusion

A single slope solar still coupled with two flat plate solar collectors in series connection were fabricated and tested under the climate conditions of Basra, Iraq in February, 2020. Experimental study was performed on the active solar still to evaluate the performance and productivity of the system. A theoretical study was also developed to analyze the heat and mass transfer inside the still using MATLAB. A good agreement was found between the experimental and theoretical results of the productivity of the still which increases with the increase of water temperature, which is increased using flat plate collectors, and the solar radiation intensity. The study concluded that the thermal efficiency and productivity of the solar still is improved when using flat plate collectors in series connection in the system.

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