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Experimental Study of a Vacuumed Solar Still System

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ABSTRACT

This experimental study presents a thermal design of a passive solar water distillation system with vacuum. The designed model consists of a glass cover, basin water equipped with reflecting mirror and insulation, and controlled vacuum pump to create vacuum inside the still to decrease the saturation temperature of water and in order to increase the yield. Feed water in the basin is heated by solar energy, and the evaporated water is condensed by inner glass cover. The temperatures at different locations in the system, the received amount of solar radiation, and the distilled water produced were determined. The highest temperature developed inside the distilling device was 51˚ C at ambient temperature of 24˚ C, the daily water production was 1.2 L/m^2.day, and the efficiency of the solar still was 15%.

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1. INTRODUCTION

1.1. Pure water uses

Pure water is a vital substance and it is used in many applications such as drinking and cooking needs, preparation of drugs, in chemical and biological Laboratories, and in many industries. Pure water can be produced by different methods such as filtration, reverse osmosis, and distillation. Distillation of water can be achieved by using different sources of energy such as petroleum and gas, oil shale, nuclear, wind, and solar. Jordan, the resource-poor country, which has no oil reserves as well as the scarcity of water, depends completely on the imported fossil fuel and natural gas at a cost of about 20% of its Gross Domestic Product, has singled out renewable energy resources as key to its future development and security.

1.2. Solar energy

Solar energy is the most abundant and the cheapest energy source on the planet [1],[2]. The amount of energy that the sun provides to the earth in a single day can power the entire planet and all of its energy needs for a whole year. Solar energy is the most important and the deriving for all other renewable energy forms. It is the cleanest source of energy as well, due to the fact that it does not produce byproducts or pollutants that will harm the environment. As solar fuel technology is evolving sharply, solar energy is becoming more proficient as an energy source, and it is recognized as a feasible alternative to fossil fuels.

Solar fuel cells are called photovoltaic cells. Solar energy is classified as either active solar energy or passive solar energy. For passive solar energy, panels and solar cells are not used, but rather, structures or buildings are constructed in a way to capture the sun's power through the use of windows or tanks. Solar still is considered as one of the passive solar systems used to absorb the solar radiation for distillation purposes. While active solar energy, solar panels or solar cells are used to capture the sun's energy for direct utilization.

1.3. Solar energy in Jordan

Jordan has an abundance of solar energy. The average daily solar irradiation is 5-7 kWh/m^2. Solar energy is widely used for water heating especially in the domestic sector (25% of households), water distillation, and electricity generation. Figure 1 shows the average daily solar irradiation in different regions of Jordan [3],[4]

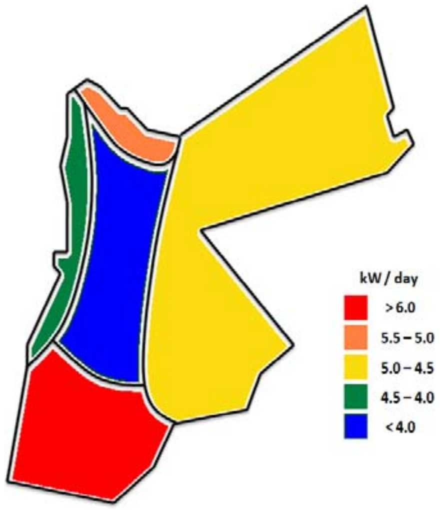

Figure 1. Distribution of solar radiation in Jordan

1.4. Solar still operation

The basic principle of solar water distillation is simple, as it resembles the natural rain process. The sun's rays (short-waves) pass through the glass cover of the still and heat the feed water inside. As water evaporates, water vapor rises, condenses on the inner surface of the glass cover. Condensed water flows down the inclined glass cover to an interior collection trough and then to an output collection port. The end product (distillate) is pure water; however, the remained water (residue) is concentrated with impurities such as salts, heavy metals, and microorganisms.

The factors that influence the rate of evaporation of water in the still are the system temperature and pressure. As the temperature increases in the still (this can be achieved by using high transparent glass cover, and installing outside and inside rays reflectors), more water molecules evaporate from the surface of the water basin. On the other hand, as the pressure of the system decreases (this can be achieved by using a vacuum pump to withdraw the air from the inside of the still), the saturation temperature decreases which causes water to vaporizes at relatively low temperature.

A solar still continues to produce distilled water until the water temperature in the still cools down. A typical still requires about three times as much make-up water as the distillate produced each day [5]-[8]. If the still produced 3 gallons of water, 9 gallons of make-up water should be added, of which 6 gallons leaves the still as excess. The excess water flushes the still basin through the overflow to prevent salt buildup.

The relation among the amount of energy utilized in vaporizing water in the still (Q_e in J/m^2.day), the daily distilled water production (M_e in Kg/m^2.day), and the latent heat of vaporization of water (H_{LV} in J/Kg) is expressed as:

$$Q_e = (M_e)(H_{LV}) \quad (1)$$

The solar still efficiency (η) is the ratio of the energy utilized in vaporizing water in the still to the total energy received by the still (Q_t in J/m^2.day). It can be expressed as:

$$\eta = Q_e/Q_t \quad (2)$$

1.5. Solar still design

A conventional solar still uses the greenhouse effect to evaporate brackish water. It consists of a basin in which constant amount of feed water is enclosed in a glass or plastic cover [9]. The cover must have a high degree of transparency in order to let the most incident rays to pass through into basin water. The transparent cover is made of glass or plastic such as polyvinyl chloride or polyvinyl fluoride. The basin is painted with a black paint film insulated against heat losses to the ground as shown in Figure 2.

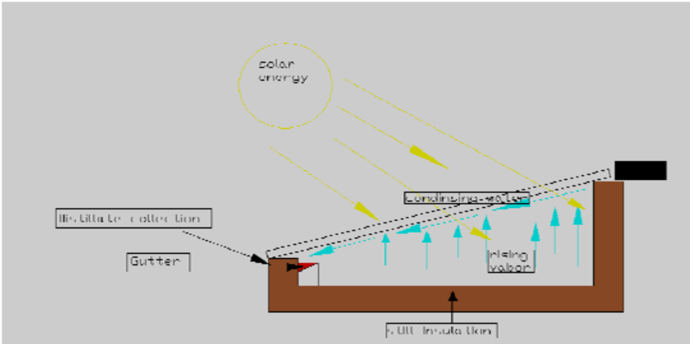

Figure 2. A schematic diagram of a solar still

The typical efficiency for a single basin solar still approaches 15 - 30%. The water production of a single solar still is 1-6 liter/m^2/day depending on the size of the basin and the intensity of sunshine [8]-[13]. This roughly corresponds to 3-7 kW/m^2/day.

2. EXPERIMENTAL SETUP

The solar system model used in this study was designed and constructed in the Engineering workshop facilities at Applied Science University (ASU) (Shafa Badran-Amman). The dimensions and parameters of the solar still components are shown in Table 1.

Table 1Dimensions and parameter values of the solar still components

Steel plate	inside (black sheet)	1.5 mm
	outside (silver sheet)	1 mm
Glass cover	Thickness	4 mm
	Length	78 cm
	Width	50 cm
	inclination angle	50 °
Reflecting mirror	Angle	10 °
	Area	43 X 45 cm
Basin water	50X50X60 cm	
Pure water tank	10X10X20 cm	
Compressor max power		120 W
Insulation thermal resistance (rock wool type)		0.7895 m .C /W

2.1. Controlled compressor

A reciprocating compressor was used to evacuate the air from the system and hence to enhance the evaporation process. The system pressure was preserved to a set value (40 kPa) during the distillation. This was achieved by connecting the compressor to a pressure controller. The controller receives electrical signals (corresponding to pressure values) from a Ranco vacuum sensor and then gives order to the compressor whether to continue or to stop.

2.2. Temperature sensors

K-type thermocouples were used to measure the temperatures at different locations within the system and they were as following:
T_1: the temperature of the mirror
T_2: the temperature of the inner surface of the glass cover
T_3: the temperature inside the system
T_4: the temperature of the top of the basin water
T_5: the temperature of the bottom of the basin water
T_6: the temperature of the outer surface of the glass cover
T_7: the temperature of the outside

2.3. Solar still setup

The experimental setup that was employed during this study is shown in Figure 3. It is composed of an inclined transparent glass cover (The glass must be set at an angle so that the water dose not drip off and fall back into the salt water basin, 50 ^{o} is the recommended angle), insulated water basin equipped with a reflecting mirror, a controlled vacuum compressor, and thermocouples.

Figure 3 Experimental setup of a vacuumed solar still

3. RESULTS AND DISCUSSION

The temperatures at seven locations within the system and the quantity of water production were measured and recorded at hourly intervals. However, the quantity of received radiation was calculated based on the temperature values and by using Stefan-Boltzmann equation and was checked by using a pyranometer installed in the testing area of the Renewable Energy Center at ASU were the experimental work conducted. These values are tabulated in Table 2

Table 2 Values of temperatures, radiation intensity, and water production

Time (hr)	T_1 (C°)	T_2 (C°)	T_3 (C°)	T_4 (C°)	T_5 (C°)	T_6 (C°)	T_7 (C°)	Radiation (W/m^2)	Distilled water (L/m^2)
9:00	19	17	24	11	12	18	17	468	0.0
10:00	27	26	36	20	21	24	19	487	0.116
11:00	35	36	44	28	28	28	22	505	0.178
12:00	46	48	51	36	40	32	24	542	0.251
13:00	41	37	46	31	35	30	24	511	0.239
14:00	37	34	44	27	32	28	22	490	0.221
15:00	30	30	34	24	30	24	20	482	0.189

It is clear from the above table (Table 2) that during a daily distillation operation the temperature at any location within the system increases until it reaches the peak (maximum) value at 12;00 noon, then it decreases (cools down) at the afternoon. Therefore, the relationship between the temperature values and time has a parabolic curve. The temperature inside the system (T_3) has the highest value during the distillation operation; however, the temperature of the outside (ambient) (T_7) has the lowest value. Figure 4 shows the relation between the temperature values and time

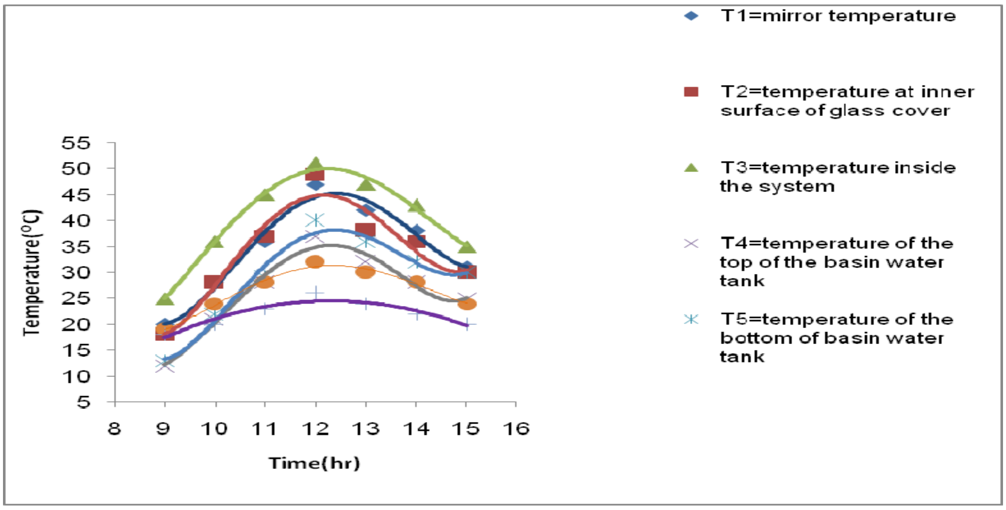

Figure 4 Plot of temperature versus time for different locations in the system

Furthermore, Figure 5 shows the received radiation throughout the sun shining period with the maximum value noticed to be at 12:00. Finally, the quantity of produced distilled water is plotted against the time in Figure 6. From the figure, and as expected, it may be noticed that the maximum amount of distilled water was achieved at the mid of the day.

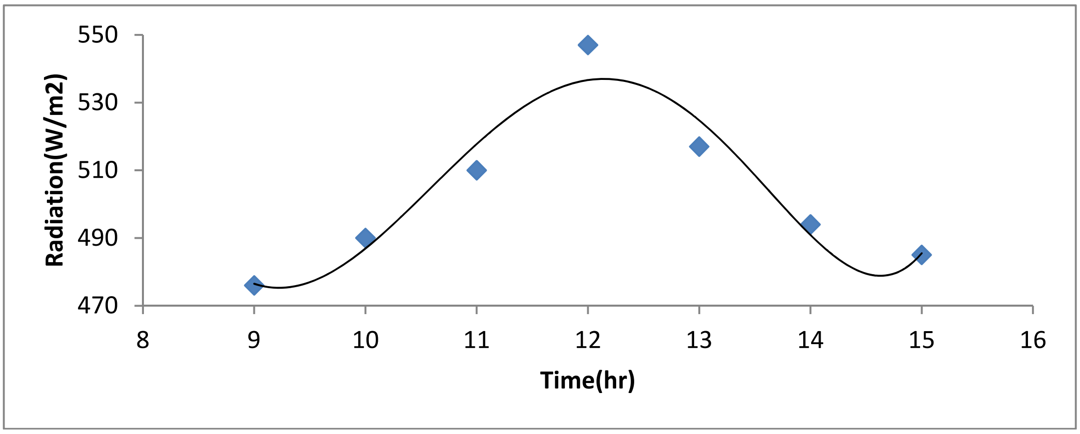

Figure 5 Plot of received radiation versus time

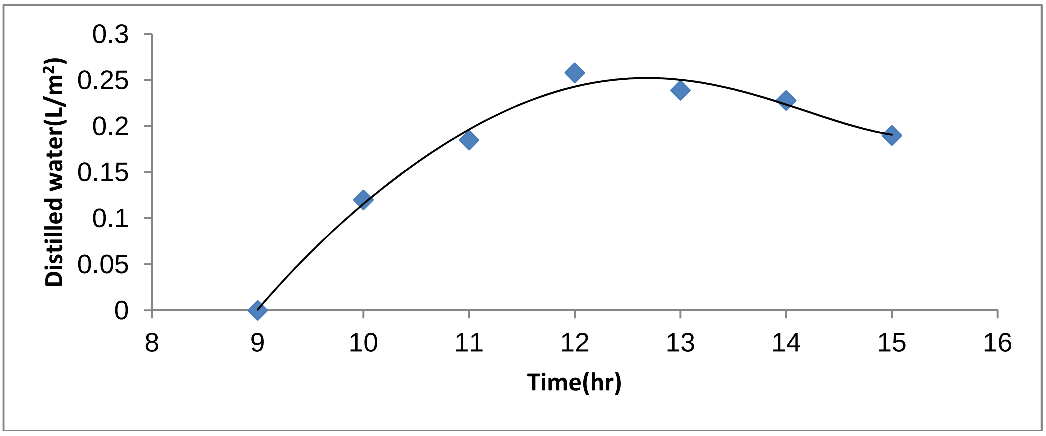

Figure 6 Plot of pure water production versus time

The daily received radiation during distillation was calculated (based on temperature values) and checked by pyranometer readings to be 3.5 kW/m^2.day. The daily distillation yield was measured to be 1.2 L/m^2.day. Thus, the efficiency of this experimental solar still was calculated (based on equation 2) and found to be 15%.

4. CONCLUSION

From the experimental data obtained during this work, the following can be concluded:

1) The produced amount of distilled water is directly proportional to solar radiation intensity
2) Creation of vacuum (sub atmospheric pressure) in the solar still leads to the possibility of vaporization of water at relatively low temperatures which in its role causes an increase in the amount of distilled water produced at low solar radiation intensities.
3) The efficiency of the solar still device can be enhanced by selecting better dimensions, Configurations and better quality of materials and components

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