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Evaluating Potable Water Production of a Single Slope Solar Still for Waste Water under Jordan Climate Conditions

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Abstract
The scarcity of potable water constitutes a major problem in underdeveloped and also some developing countries. Economical and applicable water desalination solar still coupled with a solar collector was designed and investigated experimentally. Solar still can be considered an appropriate solution for solving the water scarcity in remote and semi-arid areas. The aim of this work is to determine the performance and productivity of a single slope solar still system using different operational parameters such as ambient temperature and solar intensity. The experimental results showed that water production is significantly affected by the solar radiation intensity during the day and the instantaneous productivity of distilled water increases gradually during the experiment. The water production reaches its maximum value of 0.13 L/m² at 13:00 pm were the solar radiation is higher.
Keywords: Feed water, Instantaneous productivity, solar still, solar radiation intensity, Potable water.

1. Introduction

A scarcity of clean and pure drinking water, potable water, is considered a major problem that face underdeveloped and also some developing countries. Despite 75% of the earth is covered with water, 97% of the earth's water is brackish, only one-third is accessible at the lakes and rivers, and 3% of earth's water is fresh (Bowers, 2006). One of the main responsible reasons for 90% of the health problems in rural area is contaminated water. The contaminated water which comes from various sources such as oceans is often brackish which contains dissolved salts and sometimes harmful bacteria. Thus, brackish water attracted many researchers such as Putohit*et al.,* (2006) and Klausner*et al.,* (2004) for developing water desalination technologies. The newest one of water desalination technologies is solar distillation. Solar distillation is used the heat of sun directly in simple equipment called solar still to purify water as listed by Tiwari and Tiwari (2007). Argaw (2003) illustrated solar still is useful in hot climate area and having limited resources of fresh water. Solar still consists of a basin, support structures, glazing, distillate trough, and insulation, reflector to concentrate sunlight, tank for storage, sealants, piping, and valves as cleared by Gordes (1985). In this method, the basin of the still is filled with contaminated water. The incident solar radiation is transmitted through the glass cover and thenit is absorbed as heat by a black surface of the basin which contains the contaminated water until evaporation occurs. The moisture rises and condenses on the cover, which is at a lower temperature due to contact with ambient air, and then it runs down into a collection trough. Meukam*et al.,* (2004) observed experimentally that the inclination of the glass cover of 150 ensures a very good transmission of solar radiation within the still while preventing the drops of the distillate to fall into the basin. The productivity of fresh water by solar distillation using five different shapes of still under the climate conditions of Iraq at Basra city is investigated by Hashim*et al .,* (2010) in order to select the best shape. Four solar stills with the same shape and different glass cover inclination are also tested to select best inclination angle. It was found that symmetric double slope with inclination angle 450 gave the best productivity. Badran (2011) studied theoretically the performance of active single slope solar still using different operational parameters and to find out best factors enhancing still productivity. Different insulation thickness, solar intensity, overall heat loss coefficient, effective absorptivity and transmissivity, temperature differences between the still cover and water, and wind speed are parameters implemented in the experiment. He found that wind speed and insulation thickness contributed to the enhancement of the overall yield. Badran*et al.,* (2007) conducted an experimental work on a single slope solar still in order to examined and evaluated thermal performance. The implementing parameter which is taken in this study were different insulation thickness (1, 205, and 5 cm), water depth of (2 and 3.5 cm), solar intensity, overall heat transfer coefficient, effective absorptivity and transmissivity, and ambient, water and vapor temperatures. Also a mathematical model was presented and compared with the experimental results. It was found a good match with the experimental values. Theoretical analysis of water distillation using solar still was conducted by Medugu and Ndatuwong (2009). They designed and tested solar still in Mun, adamawa state of Nigeria. Theoretical analysis of heat and mass transfer mechanism inside the still has been developed. The measured data and theoretical analysis showed the efficiency increases with the increase of solar radiation and with the increase of feed water temperature. Double basin solar still coupled with evacuated tubes was fabricated and tested in climate conditions of Mehsane, Gujarat by Hitesh (2013). The results indicated that the distillate output was increased to 50% with adding vacuum tubes and 65% of adding vacuum tubes and black granite gravel in double basin solar still. The effect of varying glass cover thickness on performance of solar still was investigated in a winter climate conditions by Hitesh *et al.,* (2011). They found that the lower glass cover thickness increases the distillate water output, water temperature, evaporation heat transfer coefficient, convective heat transfer coefficient as well as efficiency of solar still. Kalidasa and Srithar (2014) studied theatrically and experimentally single basin double slope solar still for local climate conditions at southern India. They concluded that the overall production of the still was higher during March, April, August, November, and December, and it is around 4L/day. Also, the average production of the still was 2.1L/day/m^2. Experimental and theoretical analysis of a modified solar distillation system was carried out by Zeinabeand Lasheen (2007). Improvement of the productivity and the performances of the system were achieved by introducing a solar parabolic trough with focal pipe and simple heat exchanger. A new approach to store excess heat energy in horizontal solar distillation still during day time for the continuation of the process at night was suggested by Rahim (2003). The proposed system divided the horizontal still into evaporation and heat storing zones. An improvement in the suggested system was evaluated. The purpose of this study is to determine the performance and productivity of a single slope solar still system using different operational parameters such as ambient temperature and solar intensity under Amman-Jordan climate conditions (longitude 35o 56' 0"N, Latitude 31o 56' 0" E).

2. Theoretical Analysis

The absorbed solar energy by the glass cover,q_g, is given as:

$$q_g = \alpha_g I_g + q_{cg} \quad (1)$$

Where I_g is the solar insulation for the selected site, α_g is the absorptivity fraction of energy absorbed by the glass cover and equal to 0.04, and q_{cg} is the external heat transfer convection losses from the glass cover to the outside atmosphere.

The external heat transfer, radiation and convection losses from the glass cover to the outside atmosphere,q_{lg}, can be expressed as

$$q_{lg} = q_{cg} + q_{rg} \quad (2)$$

Where;

$$q_{cg} = h_{cg}(T_g - T_a) \quad (3)$$

And

$$q_{rg} = \varepsilon_g \sigma (T_g^4 - T_a^4) \quad (4)$$

Where h_{cg} is the glass cover convection heat transfer coefficient from the glass to the ambient air,T_g (T_6) is the temperature of the glass cover,T_a (T_7) is the outside ambient temperature,ε_g is the emissivity for the inner glass surface which is equal 0.89, σ is the Stefan-Boltzmann constant which is equal 5.669×10^{-8} W/m^2.K^4 .

For the effect of free convection and radiation from the glass cover,h_{cg} is given by Watmuff *et al.,* (1977) as:

$$h_{cg} = 5.7 + 3.8 w_s \quad (5)$$

Where w_s is the wind speed and equal to 3m/s.

The absorbed heat by basin water surface area (0.25m^2) is expressed as:

$$q_w = \tau_w \alpha_w I_s - q_{lw} \quad (6)$$

Where τ_w is the transmissivity of the basin water which equals 0.8, α_w is the absorptivity fraction of energy absorbed by of the basin water which equals 0.7, I_s is the solar radiation intensity.

The total heat losses of the basin water is

$$q_{Lw} = q_{Ew} + q_{Rw} + q_{Cw} + q_{Lb} \quad (7)$$

Where,

$$q_{cw} = h_{cw}(T_w - T_g) \quad (8)$$

Where q_{Cw} is the convection heat transfer rate radiation between the saline water and the inner glass cover surface,q_{Rw} is the radiation heat transfer rate between the saline water and the inner glass cover surface, q_{Ew} is the evaporated heat transfer rate of saline water and is a function of the distillate production of fresh water, Wp (L/m^2.h) which is given as:

$$q_{Ew} = \frac{W_p \times 10^{-6} \rho_w L_w}{3600} \quad (9)$$

Where ρ_w is the density of basin water which equals 1000 kg/m^3,L_w is water latent heat which equals to 2.355×10^6 J/kg.

$$q_{RW} = F_{w-g}\sigma(\varepsilon_w T_w^4 - \varepsilon_g T_g^4) \quad (10)$$

Where F_{w-g} is the shape factor which depends upon the geometry of the still and nature of radiation. The geometry can be approximated by two parallel planes. It is usually taken as 0.9 for the condition inside the solar still as mentioned by Kalogirou (1997), ε_w is the emissivity of saline water surface and equal to 0.96, and ε_g is the

emissivity of the inner glass surface and equal 0.85.
The convective heat transfer coefficient between the saline water and the inner glass cover surface (h_{cw}) is cleared by Delyannis and Belssiotis (2001), which is calculated with the following relation:

$$h_{cw} = 0.884\left[T_w - T_g + \frac{(P_w - P_g)T_w}{268.9\times10^3 - P_w}\right]^{\frac{1}{3}} \quad (11)$$

Where P_w, P_g are the saturation partial pressures of water at water temperature and glass temperature respectively.
The heat loss by convection,q_{Lb}, through the basin base and sides to the ground and surrounding is given as
$q_{Lb} = h_{Lb}(T_w - T_a)$ (12)
$h_{Lb}$is the equivalent heat transfer coefficient by convection from the basin to the surrounding.

$$h_{Lb} = \frac{K_{in}}{X_{in}} \quad (13)$$

Where $K_{in}$and X_{in} are thermal conductivity and equals to 0.038W/m.K and thickness of insulation and equals to 0.03m respectively.

3. Experimental Setup

The experiments were conducted using a solar desalination system design shown in Figure (1). 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, 50o is the recommended angle), insulated water basin equipped with a reflecting mirror, a controlled vacuum compressor, and thermocouples. The solar still model was used for the experimental task consists of a basin of salty water with a sloping glass cover and sealed within low walls like a house with a glass roof to analyse the solar desalination as shown in Figure (1) The physical dimensions of the designed system were sufficient to conduct the experimental matrix. The designed parameters and dimensions of the experimental model are shown in Table (1). The bottom of the basin is coloured black and is well insulated underside, so when the sun shines the heat is attracted by the black surface and heats up the water.
K-type thermocouples were used to measure the temperatures at different locations within the system and they were as following:
T1: the temperature of the mirror
T2: the temperature of the inner surface of the glass cover
T3: the temperature inside the system
T4: the temperature of the top of the basin water
T5: the temperature of the bottom of the basin water
T6: the temperature of the outer surface of the glass cover
T7: the temperature of the outside

Table 1. Dimensions and Parameter Values of the Solar Still Components

Steel Plate	Inside (Black Sheet) Outside (Silver Sheet)	1.5 mm 1.0 mm
Glass	Thickness length width	4.0 mm 780 mm 500 mm
Mirror	angle length	10^o 430x450 mm
Basin water tank		500x500x60 mm
Fresh Water Tank		100x100x200 mm
Compressor Max. Power		120 W
Insulation Resistance		0.7895 m^2 C^o /W

Figure 1.Experimental Setup for Desalination System.

A pyrometer was used for the measurement of solar radiation received from the whole hemisphere. It is suitable for the measurement of the global or sky radiation usually on a horizontal surface. A flow meter was used to measure linear, nonlinear, mass or volumetric flow rate of a liquid or a gas.

The system receives water through the treasury valve, and the water accumulates in the water base. When the compressor start working a vacuum pressure is created inside the device where the evaporation of the water is enhanced when the pressure inside the device reach the required value. A pressure sensor gives a signal to the compressor to stop evacuating the air from the water still and as the pressure increase over the set point the sensor gives signal to the compressor to repeat evacuating again to the required pressure. This pressure will be continued repeatedly until the fresh water tank reaches the upper level where the compressor reverse its process to compress air to the solenoid valve to open and left fresh water to out of the fresh water tank.

4. Results and Discussion

Water is one of the most important resources on earth. It is so essential to our life. Jordan has been dependent on rains, dams, shallow rivers and underground water reservoirs for fresh water requirements in domestic life, agriculture and industry. With its limited natural resources of fresh water, Jordan has local and global crises that resulted in a large increase of demand for fresh water. Added to this is the problem of high energy consumption. Therefore, it would be attractive to undertake the Jordan water-energy problems with desalination using solar energy.

Experimental investigations were conducted using the designed desalination system. The effect of various parameters governing the operation of solar still is also reviewed in a view to enhance operational efficiency as described previously in the test matrix. In this test matrix all measurements were taken under normal conditions and carried out during Dec 2013 from 9:00 AM to 15:00 PM. Equations presented in the theoretical analysis section were employed to find out the results shown in Figures (2 to 6). The exposed experimental results obtained show that the productivity of the solar still system increases with the intensity of solar radiation and the temperature of water.

Figure (2) shows the time variations of temperature - experimental data with the local time during the day. It shows the experimental results for the hourly variations of water temperature, glass temperature, and ambient temperature during the working hours of solar still testing with considerable spatial variations between these temperatures. As shown, the temperature of water, glass cover and the ambient are increasing in the morning hours to reach maximum values around midday at 13:00 pm before it start to decrease later in the afternoon. The temperatures go up slightly with the increase in the solar flux and match the variation of solar radiation incident. The temperatures of the glass covers compared with the water temperatures are significantly higher because the water has higher thermal heat capacity than that of glass cover. As Shown in Figure (2), the bottom of the basin water attains the maximum temperature faster than the top of the basin water. This virtually occurred due to the solar radiation absorbed by basin black plate at the bottom of the solar still system were the heat is transferred to water by natural convection from the heated plate. Also Figure (2) indicates the convention between the ambient temperature and solar still output temperatures. Hence the ambient temperature has a very important effect on the incident radiation and so water temperature, which will affect the rate of evaporation process, so the productivity of the desalinated water in the solar still.

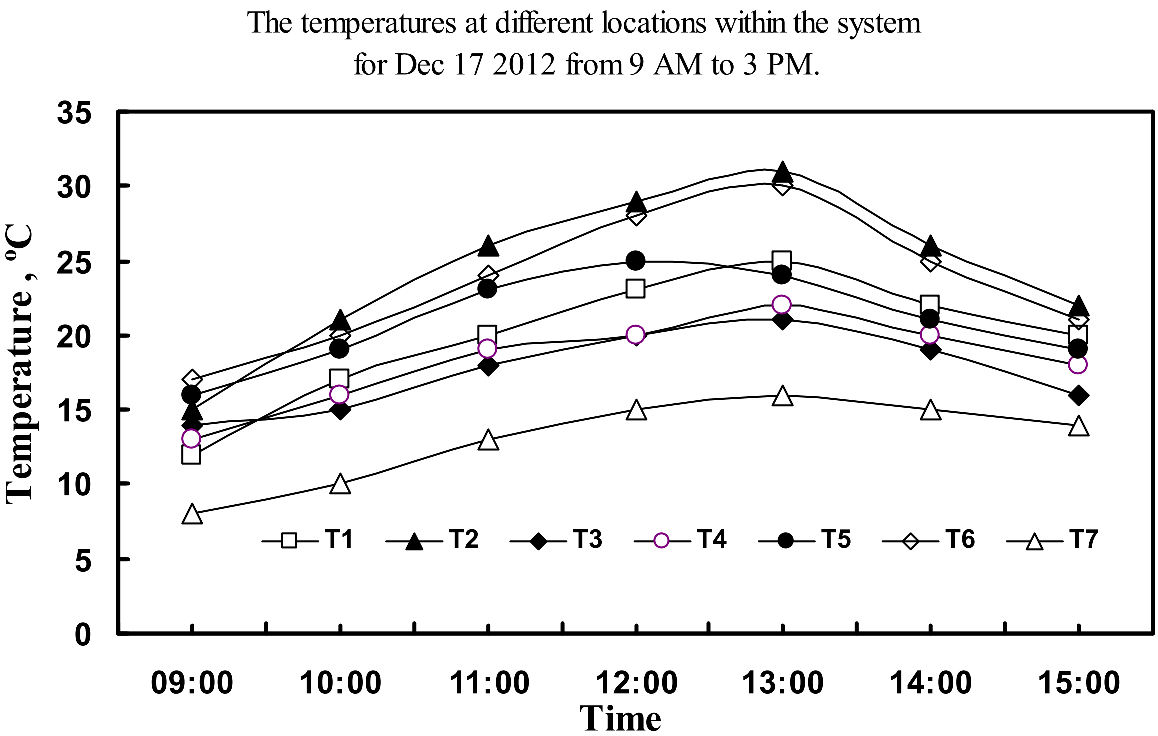

Figure 2.Time Variations of Experimental Temperature Measurements during the Day.

Figure (3) presents the time variations of solar radiation and the heat absorption by the glass inside the desalination system. The results show that the time variations of heat are of low values before and after the midday. The difference between the start and the end of desalination period is about 72 – 243 W/m^2, while it is about 165 W/m^2 at the mid of the day. It is actually due to the condensation of water that accumulated on the glass cover during the time of operation. The time variations of the experimental solar radiation absorbed by the glass compared with the amount of solar radiation during the day is shown in Figure (3). The curve is essentially quadratic with maximum values occurring at 13:00 pm. From the results shown in the figure, while the maximum solar radiation was 517 W/m^2, the maximum heat absorption was 281.5 W/m^2. The heat absorbed by basin water depends on solar radiation, transmissivity, absorptivity and heat losses from basin water tank. By the time the heat absorbed by basin water increases until 13:00 pm then it decreases according to the relation between heat absorbed and solar time as shown in Figure(3).

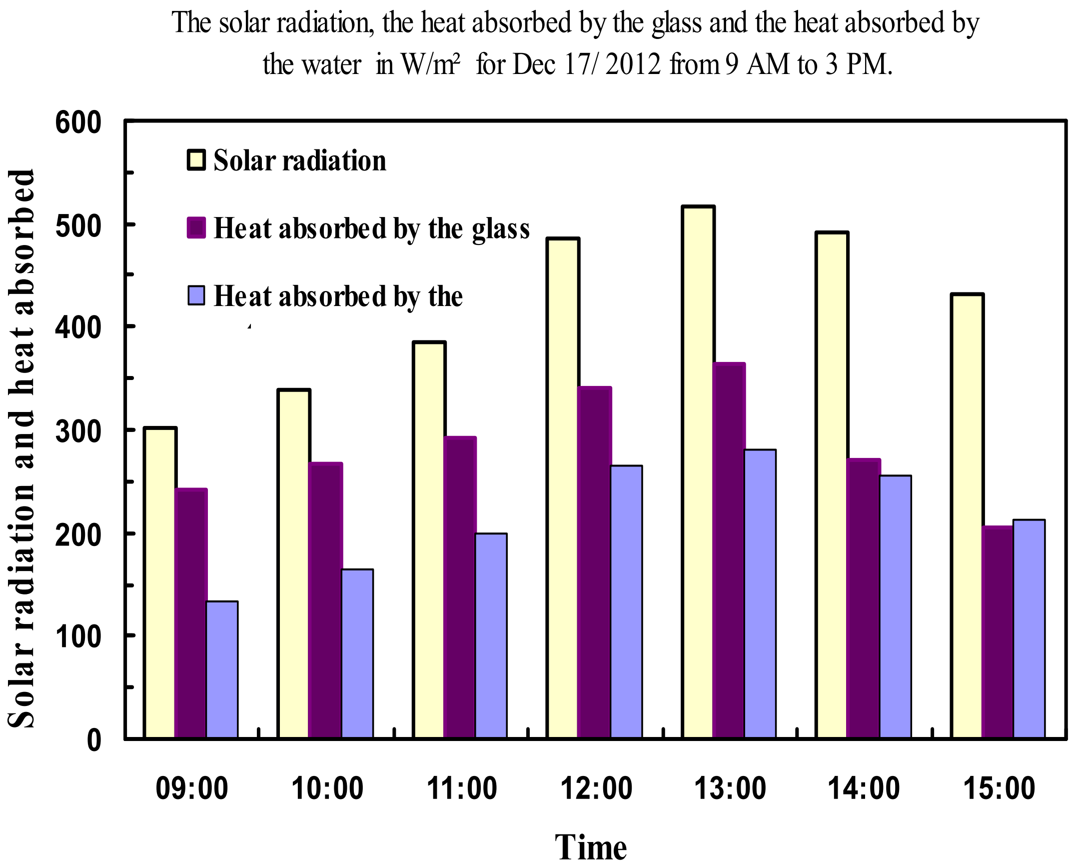

Figure 3. Time Variations of Experimental Solar Radiation Absorbed by the Glass Compared with the Solar Radiation during the Day.

The amount of distillated water during the day is due to evaporation of water at the surface of basin, which is caused mainly by condensation of evaporated water that takes place at the glass cover. The distillates yield around 870 mL/m²/day obtained for single slope solar still. This solar still receives radiation that is transmitted from the single slope-glass transparent surface. At the same time, the water vapor is condensed at the cover surface. Hence more water droplets are condensed on the surface.

Figure (4) shows the variation of water production rate as a function of time during the day. The desalinated water produced by this system is increased gradually during experiment, which is due to the increase of solar radiation. , the production rate starts very slowly due to warming of the still and the somewhat low solar energy during the morning hours. The amount of distillated water reached to a maximum within short intervals of time. The gradual increase in the water production reaches its higher value of 130 mL/m² at 13:00 pm were the solar radiation is higher.

Figure (4) shows the relation between the productivity of distillated water with the solar time. The results shows the amount of distillated water is increased during the period from 9:00am to 13:00 pm with a positive temperature gradient, this due to the increase in sun radiation and small amount of heat losses from the reservoir because of the small temperature difference between the temperature of the reservoir and the temperature of surrounding air, which increases the condensate of more droplets in the top cover and a rapid rate of water productivity. The results shows that the productivity of the still reached its peak value at 13:00 pm, were the total solar radiation is maximum this means that there is a contrast between the highest degree in the reservoir water and the highest productivity of the distiller which is three hours, then it reduced. This due to the decrease in sun radiation and increasing the heat losses from the reservoir because of the increase of its temperature to relatively high levels which makes the difference between its temperature and the temperature of surrounding air higher, this leads to a reduce in the quantity of absorbed energy by water in the reservoir, therefore, reduce its productivity.

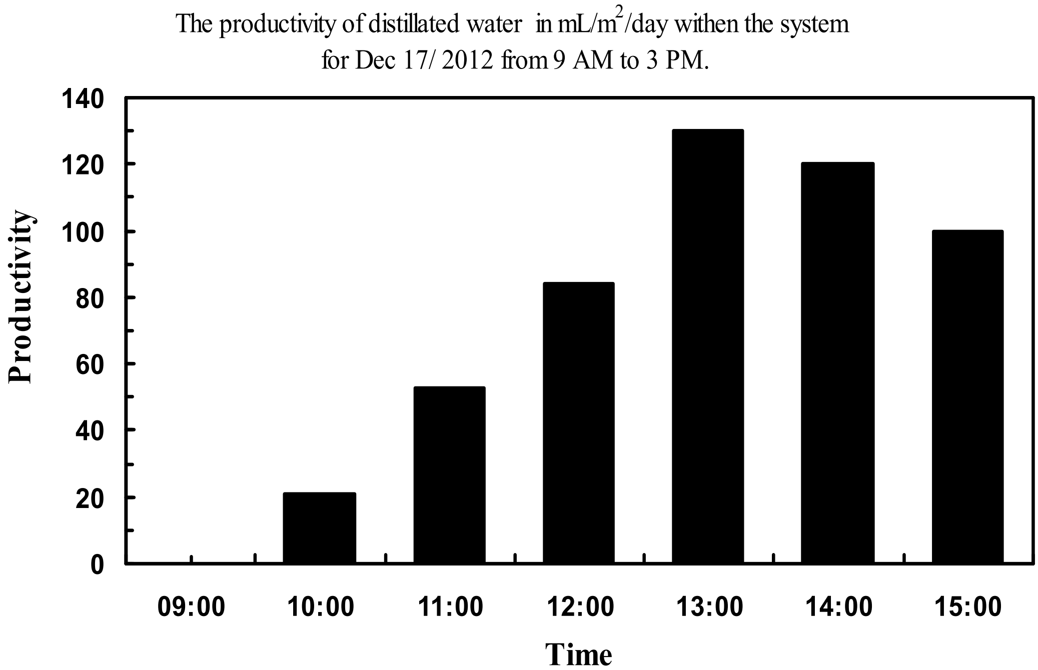

Figure 4. Time Variations of Experimental Desalinated Water during the Day.

The cost of water produced in solar distillation systems depends on the total capital cost, the maintenance requirements, and the amount of water produced. Thus, the major sharing factor of the total capital cost is the total accumulation of distillated water and the cost per unit of water produced. Figure 5 shows the total accumulation of distillated water collected from the system. The daily rate of accumulation increases gradually to reach maximum value around midday and then decreases in the afternoon according with the variation of solar radiation incident. The amount of water desalinated is gradually increased. It is the heat withdrawal of water in the solar still temperature which is further increased by the incoming solar radiation. So the gradual increase has been dependent of water temperature within time intervals and evaporative heat transfer in the solar still.

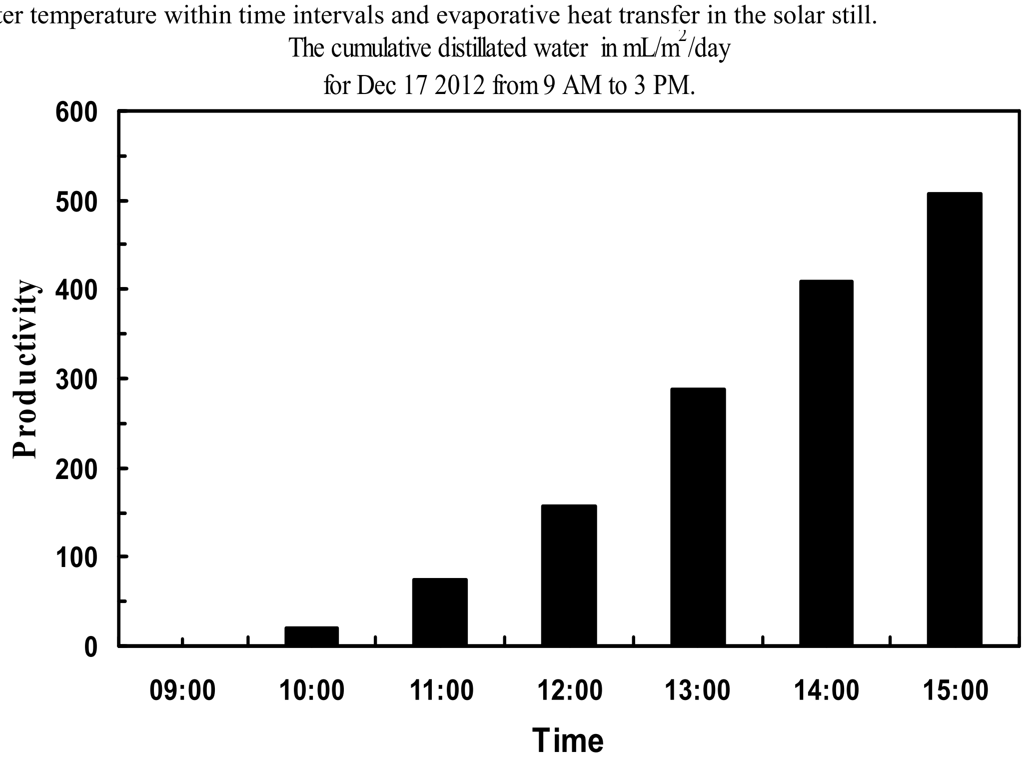

Figure 5.Cumulative Volumetric Productions as a Function of the Hour of the Day.

To present the economic analysis of a solar distillation plant in Jordan and while the production rate is proportional to the area of the solar still (the cost per unit of water produced) is nearly the same regardless of the size of the installation. The overall system efficiency in terms of daily distillate output is shown in figure 6. Results show the still performance defined by the amount of water collected per watt per meter square of incident radiation. It shows that the defined performance increases to reach the highest values at the midday at 13:00 pm and then decreases in the afternoon due to the declining rates of solar radiation and an increasing in heat losses. It is clear that the still defined performance distribution follow similar trends as of those for solar radiation and water production as shown in Figure(6) . The maximum value of solar still performance based on flow conditions reached approximately 0.25 mL/m²/W of incident radiations.

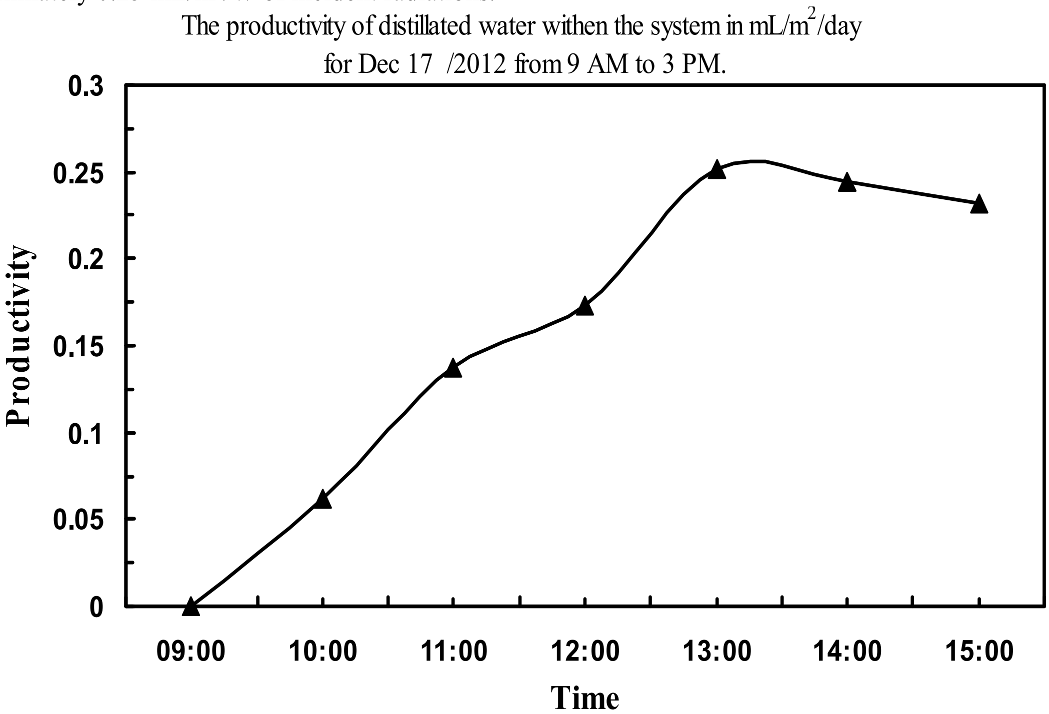

Figure 6. The Amount of Water Collected per watt per meter square of Incident Radiation during the Day.

5- Conclusions

Economical and applicable water desalination solar still coupled with a solar collector was designed and investigated, which can be considered an appropriate solution for solving the water scarcity in remote and semi-arid areas due to their simplicity. An experimental work is conducted to determine the performance and productivity of a single slope solar still system using different operational parameters. The ambient temperature and solar intensity are considered to have an effect on the overall still productivity. It has been evaluated that the water production is significantly affected by the solar radiation intensity during the day. The productivity of the solar still system and the overall system efficiency in terms of daily distillate output are significantly affected by the basin water temperature and the intensity of solar radiations.The productivity of the solar still system increases with theintensity of solar radiation and the temperature of water. The daily rate of accumulation increases gradually to reach maximum value around midday. The maximum value of solar still performance based on flow conditions reached approximately 0.25 Ml/m²/W of incident radiation. 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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