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Experimental investigation of a solar desalination with humidification-dehumidification using a rotating surface

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ABSTRACT

Water desalination by humidification-dehumidification (HDH) process powered by solar energy is a promising technique for small capacity production plants. This process has several advantages such as the use of separate components for the thermal processes (evaporation and condensation), allowing each component to be independently designed and allowing more flexibility in the design of the thermodynamic cycle. This use of a rotating black surface in an enclosed solar desalination unit to form a thin tab water film exposed to sun rays was investigated. Formation of thin film leads to rapid evaporation. A moving belt passing through water body was used for this purpose. External condenser was used to preheat the feed water and to improve fresh water productivity. The working principle of the setup was based on semi-closed water open-air flow. The effect of various parameters including the cooling water flow rate in the dehumidifier, the volumetric flow rate of air entering the unit, the rotating surface speed, and the weather conditions on the unit productivity was investigated. The average productivity obtained is 9 L/m^2·day during the hot months using cooling water at flow rate of 0.035 kg/s, air at volumetric flow rate of 30 m^3/hr and motor speed at 10 rpm. The results show that increasing cooling water flow rate and volumetric flow rate of air while slowing the moving surface speed increased the unit productivity.

Keywords: Desalination; Solar radiation; HDH process; Rotating surface; External condenser

1. Introduction

Water is one of the very important items in human life as a requirement for domestic, industrial and agricultural purposes. The continuous increase in the world's population and the expansion of industrial facilities around the world have resulted in increasing the demands on fresh water supply from natural resources (river, fresh water lakes, and brackish well) [1].

Solar desalination can be a suitable choice to solve the scarcity of fresh water, especially in the Middle East due to the abundance of solar energy coupled with the large amount of sea and underground saline water [2]. The solar still is the first desalination system appeared in which solar energy is utilized to desalinate water. In a solar still, various processes (solar absorption, evaporation and condensation) occur within a single compartment. The advantage of a solar still is the simplicity in design and the possibility to utilize simple locally available material to build a desalination system. However, the main disadvantage is the low efficiency and productivity. Thus there have been many initiatives to look for ways to improve its productivity and efficiency [3–7]. Among these modifications is the cycle by humidification-dehumidification (HDH). This cycle has

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several advantages; high efficiency compare to solar still, relatively simple, require inexpensive components and can operate over a high range of raw water quality without the need for complex pretreatment. Also, it has separate components for each of the thermal processes allowing each component to be independently designed and permitting more flexibility in the design of the thermodynamic cycle for vaporizing water into air and condensing the water vapor. Normally ambient air is employed as the medium to convert saline water to freshwater. In this cycle, water vapor is generated from saline water by evaporation into dry air in an evaporator (humidification). Then the water vapor is condensed out from the air in a condenser to produce freshwater (dehumidification) [8].

The HDH cycles are classified into three categories. One category is based on the form of energy used to power the cycle such as solar, waste-heat, geothermal, or hybrid system. The second classification is based on the cycle configuration; closed air open water (CAOW), closed water open air (CWOA) or open water open air system (OWOA), is also possible, but it has a lower thermal efficiency than the other two cycles [9]. The air in these systems can be circulated by either natural convection or mechanical blower. The third classification is based on the fluid being heated: water or air.

Different studies have been carried out to investigate the characteristics and performance of HDH desalination process. Parekh et al. [10] made a comprehensive technical review on solar desalination techniques using HDH with a multi-effect cycle. They indicated that the introduction of horizontal falling film evaporator, horizontal falling film condenser and modification in the water distribution system at the top of the condenser in solar Multi- Effect HDH units, lead to improvement in system efficiency. Nafey et al [11,12] made theoretical and experimental investigation of solar desalination using HDH processes to study the different system configuration, operating and weather conditions on the productivity. The system was based on a closed cycle for the water stream and for the air stream. The system consisted of a solar water heater, flat plate solar air heater, and a humidifier in a form of packed bed type with canvas as the packing material. Air cooled dehumidifier was used and there was no latent heat recovery in the system. They reported that the maximum productivity of the unit was 9 L/m^2·day. The productivity was strongly affected by the saline water inlet temperature to the humidifier, dehumidifier cooling flow rate, air flow rate and solar intensity. The wind speed and ambient temperature variation were found to have a very small effect on the system productivity. Xiong et al [13] investigated a baffled shell and tube desalination column using HDH process. They showed that the thermal efficiency and productivity of the process increased with increasing inlet water temperature and that the suitable flow rates for both the carrier gas and the water 4–20 kg/h and 6–30 kg/h, respectively. The performance comparison with unbaffled unit indicated that the baffle plate significantly enhanced the productivity of the column, 3–6 times that of the unbaffled shell. Cemil et al. [14] experimentally studied the effect of different operating conditions on the performance of a solar desalination system using HDH process. The maximum productivity obtained was 4 L/m^2·d. The increase in mass flow of water increased the productivity, while the productivity of the system was approximately constant when the air mass flow rate was increased. Al-Enezi et al [15] investigated a solar desalination based on HDH process with closed water open air cycle. The experimental system consisted of a packed humidification column, a double pipe glass condenser, a constant temperature water circulation tank and a chiller for cooling water. They concluded that the productivity of the system depends on the hot water temperature. In addition, the productivity increased with increasing the air flow rate and decreasing the cooling water temperature. Amer et al. [16] investigated a solar desalination based on HDH process with CAOW cycle. The air was circulated either by natural or forced circulation. Their system consisted of humidifier of 200 cm height, 80 cm length, and 50 cm width. A packing material was fixed inside the humidifier to have a surface area of approximately 6 m^2. The condenser was a copper tube formed as a coil. Fins were used to increase the surface area of the condenser. They obtained 5.8 L/h as the maximum productivity when using wooden slates packing and with forced air circulation. El-Haroun [17] performed a mathematical modeling to study the effect of various parameters; condenser surface area of heat transfer, humidifier area, heating capacity, type of packing material and flow rate of water on the performance of a HDH desalination cycle. He found that the productivity of fresh water increased with increasing surface area of heat transfer in the humidifier while keeping other parameters constant. Increasing the flow rate of water, and the heater capacity or the condenser area while keeping the other parameters constant, decreased the productivity of the process.

The objectives of this work is to investigate the use of a rotating black surface enclosed in a solar still for desalination using the HDH cycle. This system provides the provision of cleaning the surface in each rotation thus avoiding scaling on the surface. External condenser is used to preheat the feed water and to improve the unit productivity of fresh water and produce hot water. The effect of various parameters such as water flow rate, airflow rate and weather conditions on the desalination unit are also investigated.

2. System description and operation

Figs. 1 and 2 show a photograph of the experimental set-up and a schematic diagram of the desalination unit used in this work, respectively. The system consists of a solar collector (1) which consists of a solar basin facing south at an inclination angle of 32.5°. The basin is made of stainless steel and painted black from inside to ensure maximum absorption of solar energy. The cover of the basin is made of glass, having an area of one square meter, to allow the solar rays to pass through which is then absorbed by water in the basin. Two circular windows are made on the glass cover. The bottom window is fitted with a suction fan having a diameter of 15 cm. The top window serves as an exit to the humidified air passing through the unit. The air along with water vapor generated in the unit is directed to an external condenser to prevent the condensation of water vapor on the glass cover. The humidifier (2) consists of the basin which has a black rubber belt (0.45 m width

Fig. 1. A photograph of the experimental HDH unit.

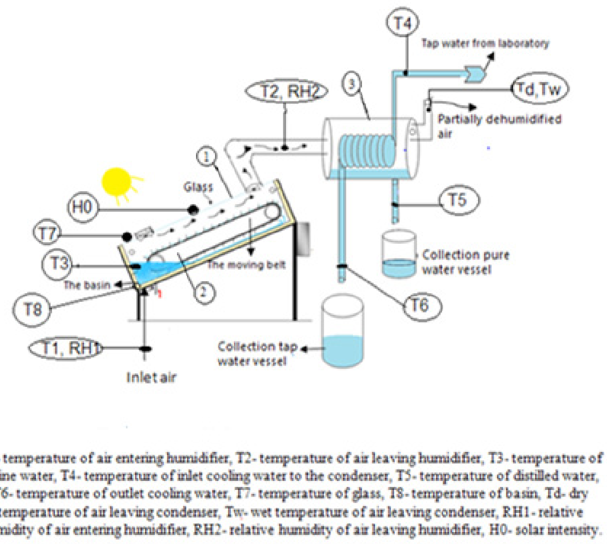

Fig. 2. Schematic sketch of the experimental set-up with measurements locations.

and 2.2 m length) attached to a rolling cylinder. The belt have aluminum blades (1 cm height) fixed in an upward direction. The rolling cylinder is slowly rotated in the basin. As it rotates passing through the saline water, a thin film of water is formed on its external surface thus, evaporation is made faster when exposed to the sun. Also as the belt passes through the saline water, its surface is cleaned from scaling, if any, formed in the previous rotation. The rotating belt movement is controlled by a variable speed motor. The dehumidifier (3) consists of an outside shell made from galvanized steel sheet (1 mm thickness) containing a spiral copper pipe fixed inside it by spot welding. The shell has a diameter of 35 cm and a length of 70 cm. The copper pipe has 6.0 m length and an outside diameter of 18 mm. The dehumidifier is insulated from the incoming solar radiation. Cooling water is flown inside the copper pipe to absorb the condensation latent heat and enhance the evaporation-condensation processes. The condensate is collected from the bottom of the condenser.

A number of thermometers (mercury thermometers) are used to measure the temperature in several locations including: the temperature of saline water in the basin, the temperature of air leaving the humidifier, dry and wet temperature of air leaving the dehumidifier (condenser). Chromel-Alumel thermocouples (type k) are used to measure the temperature of the air stream entering and leaving the humidifier, and the cooling water entering and leaving the condenser. Kestrel 3000 pocket weather meter is used to measure the ambient relative humidity, ambient temperature, wind and the velocity of air entering the unit. This meter has for the air velocity; a range of 0.4 to 60 m/s, a resolution of 0.1 and an accuracy of ±3%. A humidity/temperature converter and sensor kit (model EL026 made by Pico Technology) is used to measure the humidity and temperature of air at the entrance of the evaporator and at the outlet of the evaporator. The kit is connected to a data logger. The kit has the following features as provided by the manufacturer:

For temperature: it has a range from –20°C to 70°C, a resolution of 0.01°C, and an accuracy of ± 0.2% (0–70°C), ±0.3% (–20–0°C).

For humidity: it has a range from 0 to 95%, a resolution of 0.01% RH and an accuracy of ±2.5%.

In each experiment, the air stream entering the evaporator, the flow rate of the cooling water entering the condenser and the motor speed rotating the belt are adjusted to the desired values. During the experimental run, the data logger collect the relative humidity and the temperature data at 10 min time interval. Other data are taken manually every 30 min; the temperature of saline water in the basin, the temperature of air leaving the humidifier, dry and wet temperature of air leaving the dehumidifier, and the amount of fresh water produced.

3. Result and discussion

In this section, the effects of the various parameters such as solar intensity, cooling water flow rate, air velocity, and motor speed are presented and discussed. To study the effect of these parameters, experiments were conducted from 9 am to 4 pm. After finding the best operating parameters, the system was operated from sunrise to sunset to find its productivity and performance.

3.1 Effect of solar Intensity

Solar radiation that reaches the earth's surface at a certain location depends on many factors; among these factors, the time of the day and the season. Fig. 3 shows the solar irradiation and ambient temperature in two different seasons (Summer and winter seasons) in northern Jordan. Fig. 4 shows the variation of the productivity of fresh water through the day for two seasons of the year. The figure indicate that, the highest productivity is in the summer season, when high direct solar radiation occurs. While the lowest productivity is obtained in the winter season. This is mainly due to the low values of direct solar irradiation and the short duration time of solar irradiation. As shown from Fig. 4, the experimental accumulative productivity obtained is 8300 ml in the summer season and 5000 ml in the winter season.

3.2 Effect of operating parameters

Several operating parameters were investigated experimentally; cooling water flow rate, volumetric flow rate of air and motor speed. Fig. 5 shows the effect of cooling water flow rate on the system productivity. The same weather conditions (solar intensity, ambient temperature) of two consecutive days in September 2014 were used. The accumulative productivity increases from 7100 ml to 7600 ml when increasing cooling water flow rate from 0.01 to 0.035 kg/s. Increasing the cooling water flow rate decreases water vapor build up on the glass cover and lower the glass surface temperature thus increases the condensation rate and the system productivity.

The effect of air volumetric flow rate on the system productivity was studied, using the same weather conditions, at three different flow rates 0, 20, and 30 m^3/h. As shown in Fig. 6. It can be observed that the productivity of fresh water at air volumetric flow rate of 30 m^3/h is more than that at 20 m^3/h. The lowest productivity occurred at air flow rate of 0 m^3/h (natural draft). As would be expected, increasing the air volumetric flow rate increased the heat and mass transfer coefficients inside the humidifier, which increased the rate of vaporization of water, then subsequently increased the productivity of the unit. Increasing the air volumetric flow rate beyond 30 m^3/h did not improve the productivity of the system due to its cooling effect on the water body and decreasing the moisture content in the air leaving the humidifier.

The effect of motor speed on productivity is illustrated in Fig. 7. The speeds tested were 10, 15, and 20 rpm. Decreasing the motor speed increased the evaporation rate due to increasing the time of exposure of water film to the sun. The highest productivity occurred when the motor speed is 10 rpm, which reached nearly 8300 ml, while the productivity obtained at a motor speed of 20 rpm is 6400 ml. As clearly shown in Fig. 8, the saline water temperature is

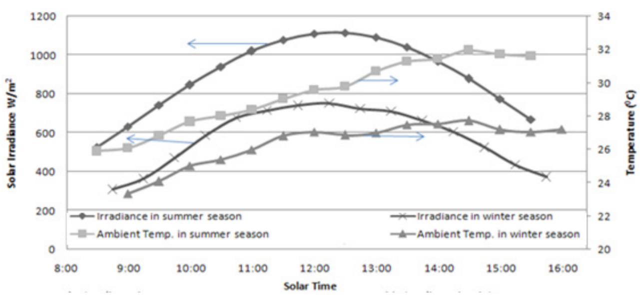

Fig. 3. Variation of solar intensity and ambient temperature.

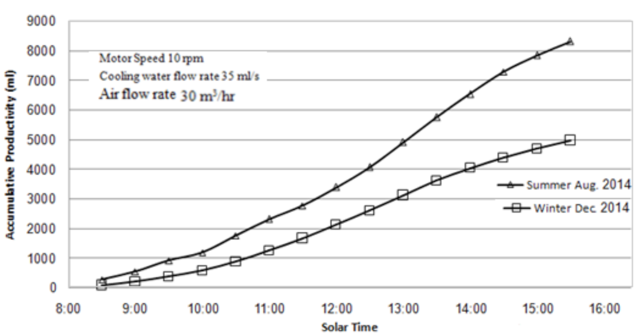

Fig. 4. Effect of weather conditions on unit productivity.

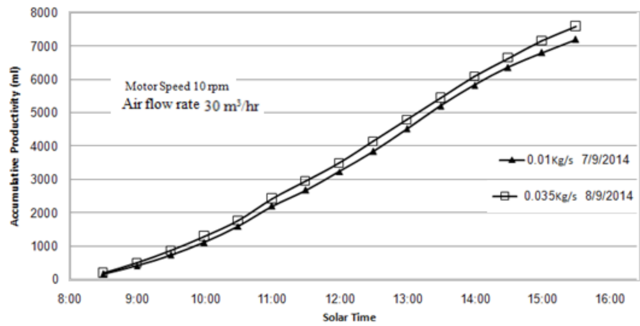

Fig. 5. Effect of cooling water flow rate on unit productivity.

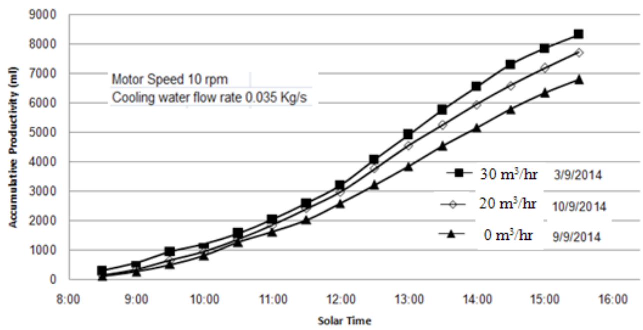

Fig. 6. Effect of air volumetric flow rate on productivity of fresh water.

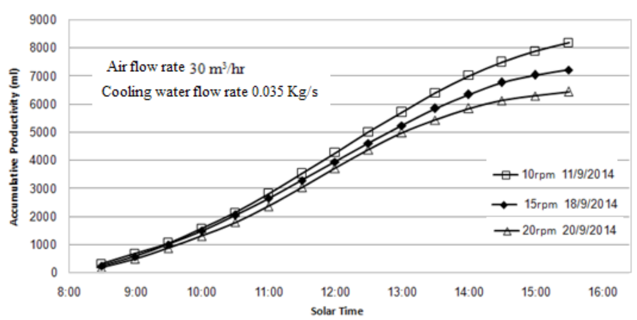

Fig. 7. Effect of motor speed on productivity of fresh water.

higher when the motor speed is 10 rpm since the exposure to the sun is long which resulted in giving high evaporation rate and increased productivity of the system.

3.3. Unit performance

The unit performance was investigated during the full sunshine hours under the best conditions found from the parametric study discussed in the previous section. Fig. 9 shows the hourly productivity. The productivity increases gradually to reach maximum value around mid-day and then decreases in the afternoon. The hourly productivity profiles follow similar trends as that of the solar radiation.

Fig. 10 presents the accumulative productivity found from sunrise to sunset at the same operating conditions for

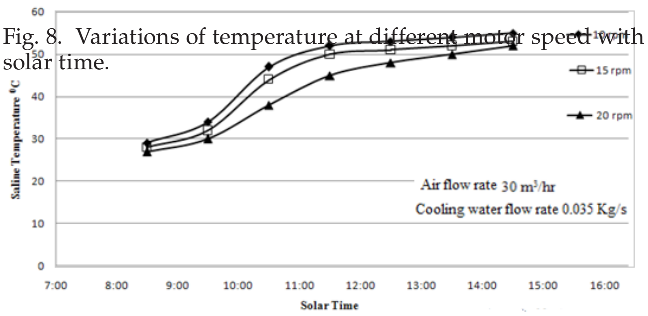

Fig. 8. Variations of temperature at different motor speed with solar time.

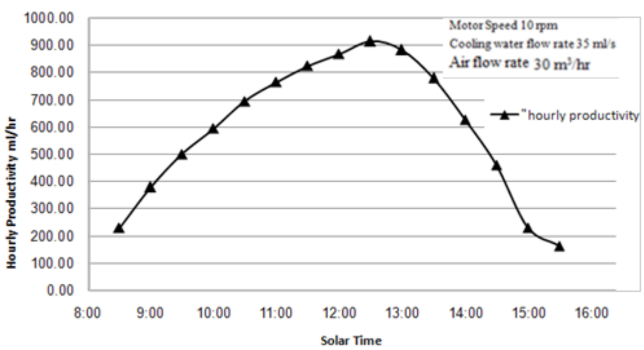

Fig. 9. Productivity variation throughout one day (18/8/2015).

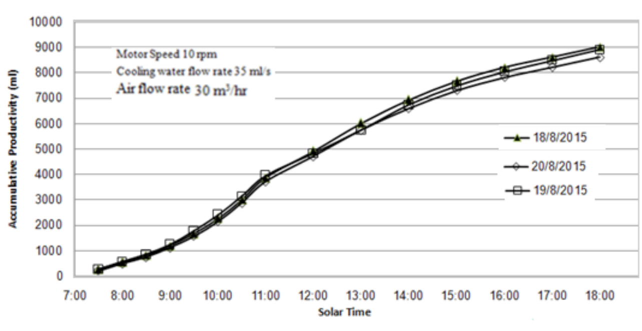

Fig. 10. Accumulative productivity on different days at the same operating conditions.

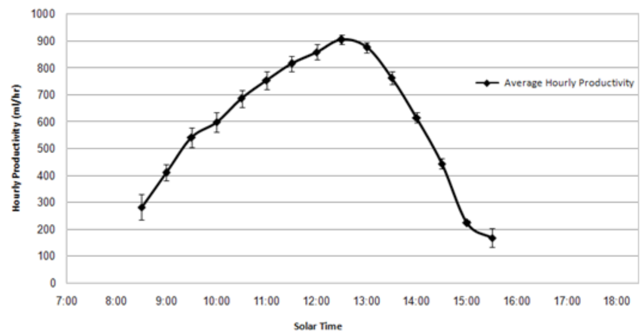

Fig. 11. Average hourly productivity on three different days.

three different days. The average accumulative productivity found experimentally for three days as shown in Fig. 10 reached 9000 ml.

Fig. 11, shows the average hourly productivity obtained in three days and error bars showing the variation, the maximum relative standard deviation reached 10%. The maximum average hourly productivity reached 900 ml/h, which occurred around solar noon.

4. Conclusions

- Incorporating a rotating surface to form thin water film improved the humidification process and the solar desalination unit productivity giving about 9 L/m²·d
- The solar irradiance has a strong effect on the productivity of the HDH unit as higher irradiance results in an increased basin temperature and consequently higher vapor generation.
- Increasing the air volumetric flow rate from zero up to 30 m³/h, increased the system productivity.
- The productivity increased as the rotating surface speed decreased due to causing higher exposure of the water film to the sun.
- The unit production rate depends strongly on the operating conditions. The highest measured daily production rate in this work reached 9 L/m² at the following conditions; cooling water flow rate of 35 ml/s, air volumetric flow rate 30 m³/h and motor speed of 10 rpm.

Symbols

A — The basin area (m²)
C_p — The heat capacity of water (kJ/kg·K)
DA — Dry air
h_{air} — Dry air enthalpy (kJ/kg)
h_{vapor} — Water vapor enthalpy (kJ/kg)
h — Total enthalpy of air (kJ/kg DA)
h_1 — Total enthalpy of air entering humidifier (kJ/kg DA)
h_2 — Total enthalpy of air leaving humidifier (kJ/kg DA)
h_3 — Total enthalpy of air leaving dehumidifier (kJ/kg DA)
h_a — Enthalpy of dry air (kJ/kg DA)
h_g — Enthalpy of water vapor (kJ/kg)

I_r — Solar irradiance (W/m^2)
K — Thermal conductivity of the material (W/m·K)
$\dot{m}_a$ — Mass flow rate of dry air (kg DA/s)
$\dot{m}_w$ — Mass flow rate of feed water through the condenser (kg/s)
$\dot{m}_d$ — Mass flow rate of distilled water (kg/s)
$\dot{m}_{evap}$ — Mass flow rate of water evaporated (kg/s)
T_1 — Dry temperature of air entering humidifier (K)
T_2 — Dry temperature of air leaving humidifier (K)
T_3 — Dry temperature of air leaving dehumidifier (K)
T_a — Ambient temperature (K)
T_{in} — Temperature of water entering the condenser (K)
T_{out} — Temperature of water leaving the condenser (K)
RH_1 — Relative humidity of air entering humidifier (%)
RH_2 — Relative humidity of air leaving humidifier (%)
RH_3 — Relative humidity of air leaving dehumidifier (%)
Q_{loss} — The heat losses from the unit to the surrounding (W/m^2)
w_1 — Absolute humidity of air entering humidifier ($Kg_{\text{water vapor}}$/kg DA)
w_2 — Absolute humidity of air leaving humidifier ($Kg_{\text{water vapor}}$/kg DA)
w_3 — Absolute humidity of air leaving dehumidifier ($Kg_{\text{water vapor}}$/kg DA)

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