

Experimental Study for a Solar Powered Desalination Unit using Humidification-Dehumidification Technique

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ABSTRACT

A solar powered desalination unit which working on a humidification –dehumidification technique (HDH) is one of the most important techniques used in seawater desalination in remote and rural areas. In this study, an experimental setup was designed and constructed for conducting a set of experiments on a solar assisted desalination unit working on a HDH principle under the prevailing conditions of Tajoura-Libya. Experiments were carried out on March, 2019 at the laboratories of Center for Solar Energy Research and Studies (CSERS) at Tajoura. The effect of different design and operating parameters that influence the performance of the unit and its productivity is closely investigated and interpreted. Results show that the productivity of HDH unit decreases by increasing the process air mass flow rate. A significant improvement in the productivity of the unit is noticed when the feed water mass flow rate to the humidifier is increased. Moreover, initial water temperature inside the tank has a remarked effect on the productivity of the unit. In order to obtain a reasonable amount of fresh water, the temperature of the water inside the tank should be increased. Increasing the cooling water mass flow rate to the dehumidifier leads to a corresponding decrease in the surface temperature of the cooling coil and hence the productivity of the unit is improved. The Productivity of HDH unit under investigation is varying from its lower value of (0.903 kg/m².day) to a higher value of (6.47 kg/m².day). These values are obtained for one meter square of solar air heater area. Gain Output Ratio (GOR) values range from a minimum of (0.082) to a maximum of (0.572). It is reasonable when compared to ones in literature for the water-heated HDH units.

Keywords: Solar, desalination, humidification, dehumidification, productivity.

1. Introduction

In recent years, solar thermal desalination systems have received a lot of attention because they are environmentally friendly and can be operated with low temperature sources such as solar energy, lost heat and geothermal energy. Conventional desalination processes consume a large amount of energy derived from oil and natural gas as heat and electricity, while emitting harmful CO₂ gas. They have many negative environmental impacts involves climate change, depletion of the ozone layer and pollution, in addition to its contribution to the increase in the demand for electricity and the consequent economic problems resulting in increasing the cost of supplying this power. Therefore, solar-powered desalination systems have the potential to reduce many of these problems [1]. Solar thermal desalination has emerged as a promising renewable energy-powered technology for producing fresh water. Combining the principle of humidification- dehumidification with solar

desalination results in an increase in the overall efficiency of the desalination plant, and therefore appears to be a promising method for water desalination with solar energy [2,3]. The solar powered humidification-dehumidification desalination process is a simple, economical and efficient method for small capacity of fresh water production. It has no parts which require extensive maintenance work like membranes or high temperature steam lines. There is also no bottle-neck in applying HDH for tough and varied water qualities. In view of above merits, HDH systems are convenient for application in arid and remote areas and limited applications. Moreover, no need for skilled or qualified people to operate and maintain such systems [3]. The aim of this experimental work is to study the effect of different design parameters and operating conditions on the thermal performance and the productivity of a solar assisted HDH desalination unit under the prevailing conditions of Tajoura-Libya and to compare the study results with the previous theoretical ones.

2. Experimental work

2.1 Description of the experimental set-up

An experimental set-up was designed and constructed at different private mechanical workshops at Al-khoms-Libya. It was assembled and started up at CSERS laboratories located at Tajoura-Libya as shown in Figure 1. The main components of the experimental set-up are as follows;

- Double-pass flat plate solar air heater
- Humidifier
- Water storage tank
- Dehumidifier
- Water circulating pump and Air blower
- Measurement system

Figure 2 shows the location of the measuring and testing points at the system.



Figure 1. General view of the experimental setup

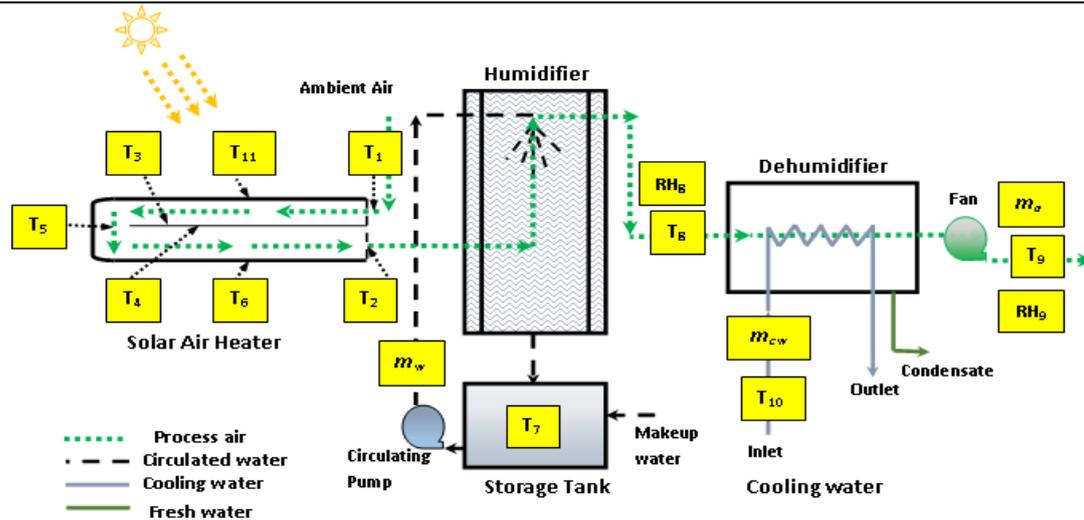


Figure 2. The location of the measuring and testing points at the system

2.2 Experimental Procedure

A set of experiments were planned and conducted. The main parameters studied are; (Process air mass flowrate, circulated water mass flow rate, cooling water mass flowrate, water temperature). Two settings were proposed for the studied parameters. Table 1 shows a summary of the setting values for the main parameters. Moreover, six experiments were planned and conducted based on the experimental work plan shown in Table 2 below.

Table 1: Setting values for the main parameters

Parameter	Symbol	Setting value No.1	Setting value No.2
Process air mass flowrate (kg/s)	\dot{m}_a	0.07	0.11
Feed water mass flowrate (kg/s)	\dot{m}_w	0.075	0.25
Cooling water mass flowrate (kg/s)	\dot{m}_{c_w}	0.013	0.036
Water temperature inside the tank ($^{\circ}\text{C}$)	T_w	30	45

Table 2: Experimental work plan

S.No.	Experiment No.	Experiment Code	Date of Experiment
1-	Exp.No. (1)	HD (1,1,1,1)	05.03.2019
2-	Exp.No. (2)	HD (2,1,1,1)	06.03.2019
3-	Exp.No. (3)	HD (1,2,1,1)	07.03.2019
4-	Exp.No. (4)	HD (1,1,2,1)	08.03.2019
5-	Exp.No. (5)	HD (1,1,1,2)	09.03.2019
6-	Exp.No. (6)	HD (2,2,2,2)	10.03.2019

It should be noted that the experimental code, HD (x,x,x,x) , is related to the setting values of the four parameters studied , ($\dot{m}_a, \dot{m}_w, \dot{m}_{c_w}$ & T_w), respectively. For example, experiment code, HD (1,1,1,1), means that the four parameters; process air mass flow rate, circulating water mass flowrate, cooling water mass flowrate and water temperature, are experimented at setting values no.1, respectively as shown in Table 2. The experimental code, HD (2,2,2,2), is proposed for the same parameters at their setting values no.2. whereas, a mix of experiments were carried out at both setting values no.1 and 2, namely, Exp. No.2, Exp.No.3, Exp. No.4 and Exp. No. 5. Prior to experimentation, the whole setup piping system, fittings, connections, tubes...etc, should be

checked against leakage. In addition, special attention should be taken into account for electric wiring, connections, grounding, and all safety measures to avoid undesirable electricity source accidents.

The experiments were started by switching on the power to the electric heaters at the water storage tank. When the water storage tank temperature reached its proposed value; (setting value no.1 or setting value no.2), the circulating water pump and air blower are switched on and adjusted according to their setting values for the experiment chosen. In addition, cooling water tap is opened and adjusted according to the mass flowrate proposed. Data acquisition system is also put in operation and configured to start data recording process. The product of fresh water is collected in a bottle. The measurements were taken every 10 minutes interval by data logger, starting from 9.00 O'Clock at morning until 17.00 O'Clock evening under the prevailing conditions of Tajoura-Libya. In order to record the experimental data, an experimental data recording sheet is designed and used. Finally, the recorded data was analyzed and interpreted by the help of Excel Sheets and graphical curves.

3. Results and discussion

3.1 The effect of process air mass flow rate

Figure 3 illustrates the effect of the process air mass flow rate on the productivity of the unit from 9.00 AM to 17.00 PM at 05th and 06th of March 2019. Two different flow rates were experimentally investigated, [$m_a = 0.07$ (kg/s) and $m_a = 0.11$ (kg/s)]. The value of the daily accumulated productivity is changing from 1.5 (kg/m².day) to about 0.905 (kg/m². day) corresponding to air mass flow rates of [$m_a = 0.07$ (kg/s) and $m_a = 0.11$ (kg/s)], respectively. In general, the productivity of the unit decreases by increasing the process air mass flow rate. This is attributed to the fact that increasing air mass flow rates results in decreasing the temperature of the air leaving the solar air heater and, hence, the moisture content of the air leaving the humidifier. Moreover, the humidifier effectiveness is also negatively affected. In other words, the dry-bulb temperature of the air leaving the humidifier decreases and gets closer to the wet-bulb temperature of the air at the inlet of the humidifier. As a result, the moisture content is decreased as well and the water temperature in the storage tank and the rate of vaporization in the humidifier are also decreased. Furthermore, at a constant cooling water mass flow rate and temperature, increasing air mass flow rate increases the absolute humidity of the air leaving the dehumidifier. For these reasons, the productivity of the unit is decreased. However, according to the theoretical study results [5], at a range of air mass flow rates of, [$m_a = 0.005$ (kg/s) to $m_a = 0.05$ (kg/s)], increasing inlet air mass flow rate, increases the productivity of the unit to a certain maximum value corresponding to air mass flow rate of [$m_a = 0.015$ (kg/s)] and then it decreases as inlet air mass flowrates become higher. This agrees with this study results since process air mass flow rates considered are higher than [$m_a = 0.015$ (kg/s)], namely, [$m_a = 0.07$ (kg/s) and $m_a = 0.11$ (kg/s)].

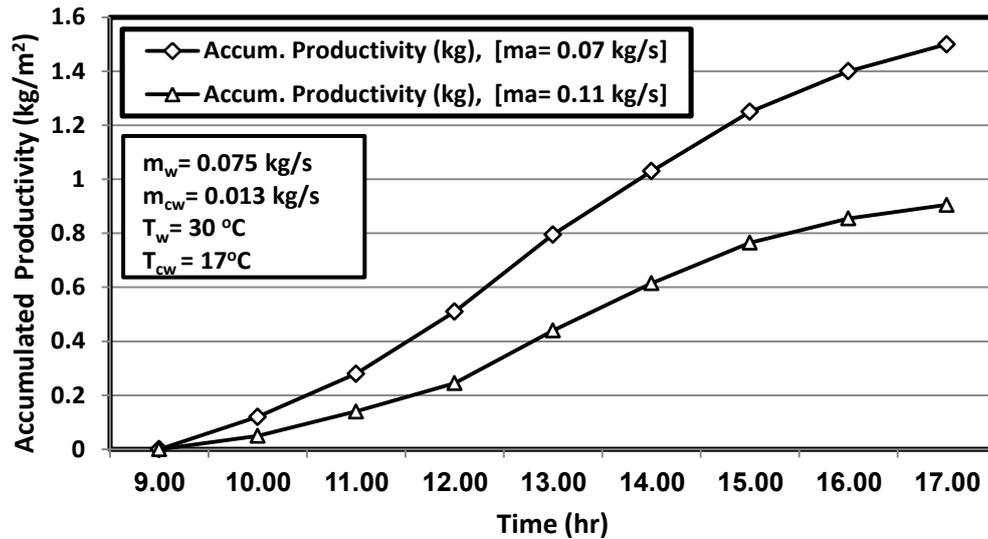


Figure 3. The effect of process air mass flow rate on the productivity of the unit on Daily Basis

3.2 The effect of humidifier feed water mass flow rate

The effect of the humidifier feed water mass flow rate on the unit productivity is shown in Figure 4. Experiments were carried out from 9.00 AM to 17.00 PM at 5th and 7th of March 2019. Two different flow rates were experimentally investigated, [$m_w = 0.075$ (kg/s) and $m_w = 0.25$ (kg/s)]. The value of the daily accumulated productivity is changing from 1.93 (kg/m².day) to 1.5 (kg/m².day) corresponding to water mass flow rates of [$m_w = 0.25$ (kg/s) and $m_w = 0.075$ (kg/s)], respectively. In general, the productivity of the unit increases by increasing the feed water mass flow rate. Since air is brought into contact with the water in the humidifier, the water temperature drops and wet-bulb temperature of the air leaving the humidifier at saturation state increases. For this reason, at a constant air mass flow rate, when the water mass flow rate increases, the wet-bulb temperature of the air leaving the humidifier increases and approaches to the temperature of the water at the inlet of the humidifier. As a result, the moisture content of the air leaving the humidifier increases and a significant improvement on the unit productivity is noticed.

3.3 The effect of dehumidifier cooling water mass flow rate

The effect of the dehumidifier cooling water mass flow rate on the system productivity is shown in Figure 5. Experiments were carried out from 9.00 AM to 17.00 PM at 5th and 8th of March 2019. Two different flow rates were experimentally investigated, [$m_{cw} = 0.013$ (kg/s) and $m_{cw} = 0.036$ (kg/s)]. The value of the daily accumulated productivity is changing from 1.79 (kg/m².day) to 1.5 (kg/m².day) corresponding to cooling water mass flow rates of [$m_{cw} = 0.036$ (kg/s) and $m_{cw} = 0.013$ (kg/s)], respectively. It can be deduced that the productivity of the unit increases by increasing the cooling water mass flow rate. By increasing the cooling water mass flow rate at a constant cooling water temperature, a significant drop in the surface temperature of the cooling coil can be achieved which results in an increase of the rate of the condensation of the water vapor on the cooling coil surface and ,thus, the unit gives higher yield. During preliminary testing and start up period (18-02-2019 to

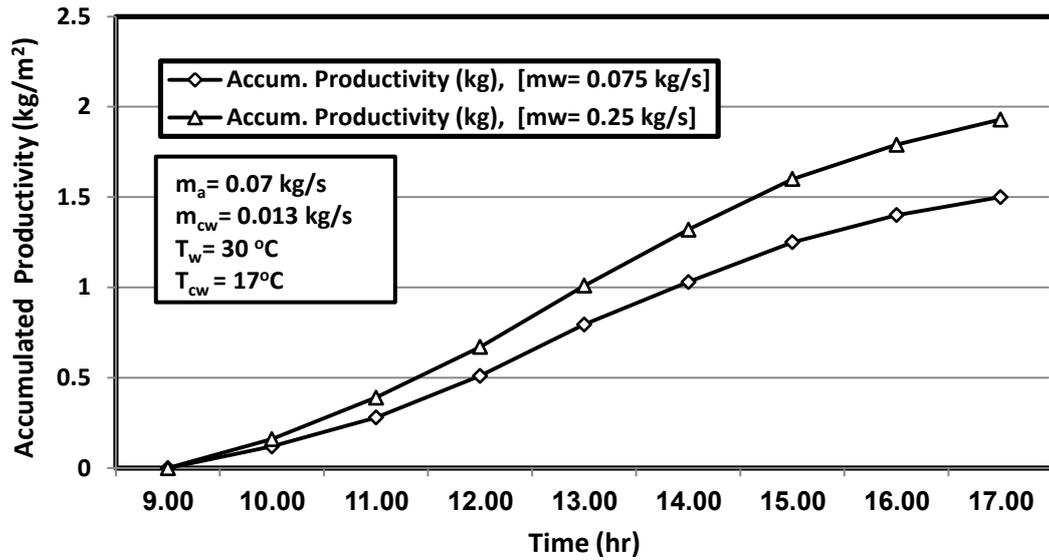


Figure 4. The effect of humidifier feed water mass flow rate on the productivity of the unit, on Daily Basis

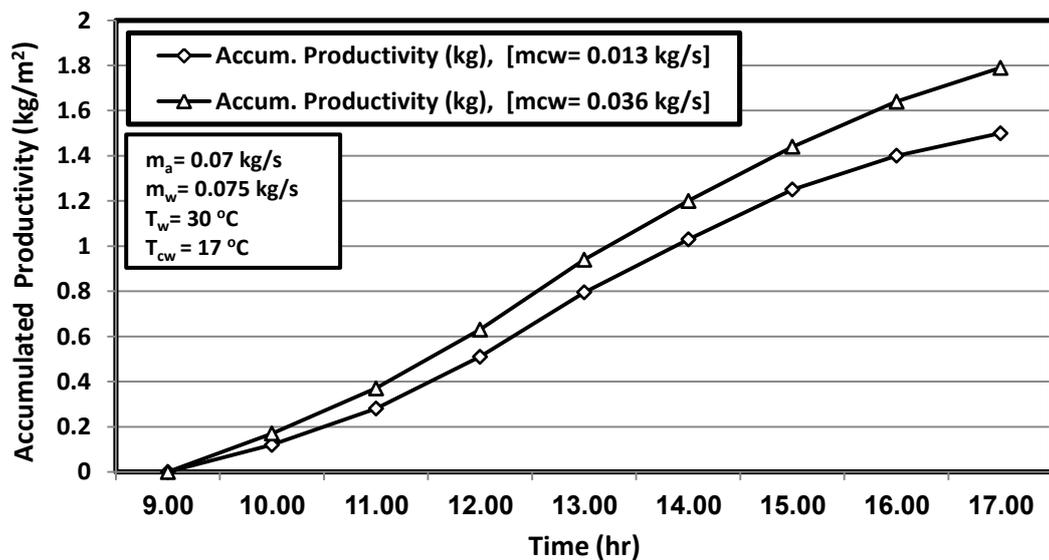


Figure 5. The effect of dehumidifier cooling water mass flow rate on the productivity of the unit, on Daily Basis.

28-02-2019), it is interesting to note that when changing the cooling water entrance connection from the lower part of the dehumidifier to the upper part, a remarkable decrease in the condensation rate of the fresh water was noticed. At the upper part of the dehumidifier, a dropwise condensation layer was noticed. In the other hand, at the lower part of the dehumidifier only filmwise condensation layer was the case. This is attributed to the fact that at a constant cooling water flow rate, the temperature of the cooling water inside the dehumidifier gets higher as cooling water passes through the dehumidifier tubes from top to bottom, results in decreasing of the condensation rate in general. In addition, at higher air flow rates, the velocity and momentum of the forced humid air that passes across the dehumidifier may be another reason that retards droplets of

condensate water from falling down. However, when cooling water entrance is located at the lower part of the dehumidifier, the situation is completely different and the condensation rate got higher and reasonable values.

3.4 The effect of initial water temperature in the storage tank

The effect of the initial water temperature in the storage tank on the unit productivity is illustrated in Figure 6. Experiments were carried out at 5th and 9th of March 2019, from 9.00 AM to 17.00 PM. Two different water temperatures were considered and experimentally investigated, [$T_w = 30\text{ }^\circ\text{C}$ and $T_w = 45\text{ }^\circ\text{C}$]. The value of the daily accumulated productivity is changing from 2.28 ($\text{kg}/\text{m}^2\cdot\text{day}$) to 1.5 ($\text{kg}/\text{m}^2\cdot\text{day}$) corresponding to initial water temperatures of [$T_w = 30\text{ }^\circ\text{C}$ and $T_w = 45\text{ }^\circ\text{C}$], respectively. In general, the productivity of the unit increases by increasing the initial water temperatures. Initial water temperatures in the storage tank have a considerable influence on the unit productivity. This is attributed to the fact that any increase in the initial water temperature in the storage tank leads to a corresponding increase in the feed water temperature to the humidifier. As a result, the moisture content of air leaving the humidifier increases and the quantity of the fresh water produced as well.

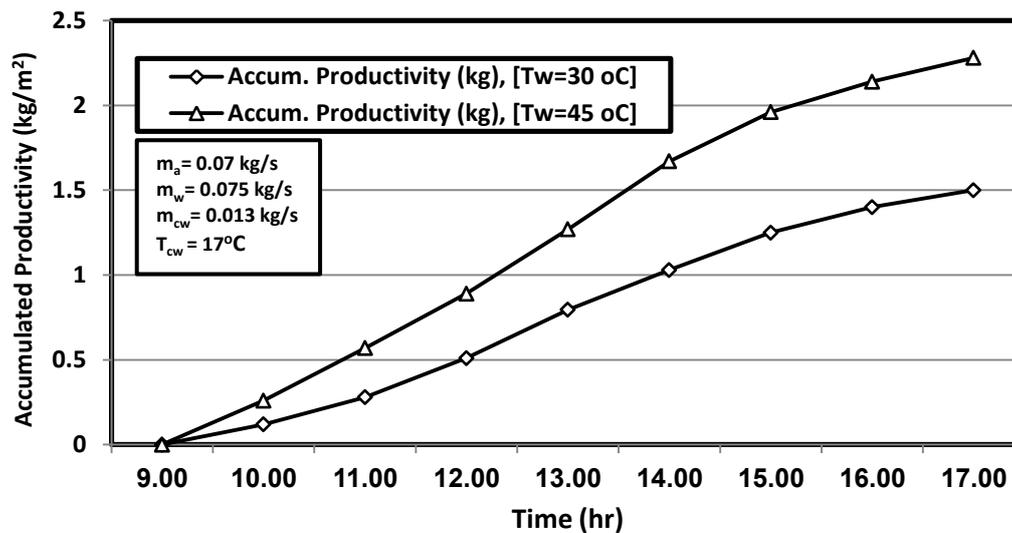


Figure 6. The effect of initial water temperature inside the water tank on the productivity of the unit, on Daily Basis.

3.5 The combined effect of all parameters

Referring to Table 1 and Table 2 that illustrate the setting values of the main experimental parameters, namely, process air mass flow rate, feed water mass flow rate to the humidifier, cooling water mass flow rate to the dehumidifier and initial water temperature inside the storage tank, there are two settings; HD (1,1,1,1) and HD (2,2,2,2) represent the minimum setting values and the maximum setting values for the experimental parameters studied, respectively.

Figure 7 shows the effect of the combined parameters on the productivity of the unit. Experiments were carried out at 5th and 10th of March 2019, from 9.00 AM to 17.00 PM. Two different settings

were considered and experimentally investigated, HD(1,1,1,1) with values of [$m_a = 0.07$ kg/s, $m_w = 0.075$ kg/s, $m_{cw} = 0.013$ kg/s, $T_w = 30$ °C] and HD (2,2,2,2) with values of [$m_a = 0.11$ kg/s, $m_w = 0.25$ kg/s, $m_{cw} = 0.036$ kg/s, $T_w = 45$ °C]. The value of the daily accumulated productivity is changing from 6.47 (kg/m².day) to 1.5 (kg/m².day). Corresponding to settings, HD (2,2,2,2) and HD (1,1,1,1), respectively. Consequently, a remarkable increase in the productivity of the unit is noticed when compared to other results. This is attributed to the combined effect of all mentioned parameters studied above.

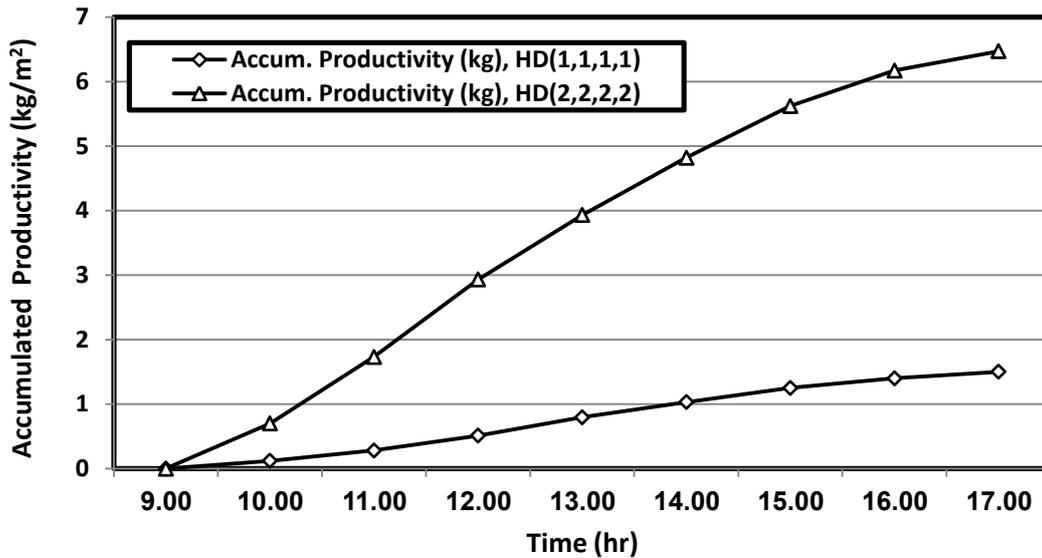


Figure 7. The effect of the combined parameters on the productivity of the unit, on Daily Basis.

3.6 Comparison of Results

A comparison of the experimental results for this study is illustrated in Table 3.

Table 3: Comparison of the experimental results for this study

S.No.	Experiment No.	Experiment Code	Date of Experiment	Accumulated Productivity (kg/m ² .day)
1-	Exp.No. (1)	HD (1,1,1,1)	05.03.2019	1.5
2-	Exp.No. (2)	HD (2,1,1,1)	06.03.2019	0.905
3-	Exp.No. (3)	HD (1,2,1,1)	07.03.2019	1.93
4-	Exp.No. (4)	HD (1,1,2,1)	08.03.2019	1.79
5-	Exp.No. (5)	HD (1,1,1,2)	09.03.2019	2.28
6-	Exp.No. (6)	HD (2,2,2,2)	10.03.2019	6.47

It can be deduced that the highest productivity value is (6.47 kg/m².day) corresponding to Experiment No. 6, Code HD (2,2,2,2), which studies the combined effect of all parameters on the unit productivity at their maximum values. However, the lowest productivity value is recorded for Experiment No. 2, code HD (2,1,1,1), where the effect of process air mass flow rate is investigated. It is 0.905 (kg/m².day). In order to improve the productivity, minimum value of air mass flow rate should be considered ($m_a = 0.07$ kg/s) in Experiment No.6 instead of the maximum value of ($m_a = 0.11$ kg/s) since increasing air mass flow rate will negatively affect the unit yield. In addition, the

effect of initial water temperature in the storage tank is more efficient than that of the feed water mass flow rate to the humidifier and cooling water mass flow rate to the dehumidifier respectively. It is worth to say that studying the effect of cooling water temperature is also very important, but due to some technical problems, the team couldn't manage that.

According to literature, a solar still has a GOR of about 0.5, air-heated HDH cycles have a GOR that ranges from 1.7 to 3, whereas the water-heated cycles have a GOR that ranges between 0.3 and 4.5. GOR values for conventional desalination systems such as RO (GOR = 35 - 45), MSF (GOR of about 8), and MED (GOR up to 12) [7]. In this study, GOR values for different experiments on March 2019, are evaluated and tabulated in Table 4. As expected, the maximum gain output ration, GOR, value is 0.572, attained from Exp. No.6 that represents the highest value of productivity, whereas, the lowest value of GOR is 0.082, the one related to Exp. No. 2 which represents the lowest productivity of the unit. These values are below the values mentioned in reference [7] for air heated HDH cycles but it reasonable when compared with the ones for water-heated cycles. This is attributed to the relatively low values of solar radiation intensity, ambient air temperatures and humidity ratio for cold season situation (winter season), when compared to hot season in summer where the HDH unit is expected to reach its maximum GOR values.

Table 4. Values of GOR for different experiments

S.No.	Experiment No.	Experiment Code	Date of Experiment	GOR
1-	Exp.No. (1)	HD (1,1,1,1)	05.03.2019	0.121
2-	Exp.No. (2)	HD (2,1,1,1)	06.03.2019	0.082
3-	Exp.No. (3)	HD (1,2,1,1)	07.03.2019	0.142
4-	Exp.No. (4)	HD (1,1,2,1)	08.03.2019	0.128
5-	Exp.No. (5)	HD (1,1,1,2)	09.03.2019	0.162
6-	Exp.No. (6)	HD (2,2,2,2)	10.03.2019	0.572

4. Conclusions

In this paper, an experimental study for a solar assisted desalination unit based on humidification – dehumidification principle was carried out at CSERS located at Tajour-Libya on the first ten days of March, 2019. The influence of different parameters and operating conditions were investigated under the prevailing weather conditions of Tajoura-Libya. The productivity of HDH unit decreases by increasing the process air mass flow rate. However, increasing feed water mass flow rate to the humidifier, initial water temperature inside the water tank and cooling water mass flow rate to the dehumidifier lead to a corresponding increase in the productivity of unit in general. The Productivity of the unit per one meter square of solar air heater area is changing from its lower value of (0.903 kg/m².day) to a higher value of (6.47 kg/m².day).. Finally, Gain Output Ratio, (GOR) values were ranging from a minimum of (0.082) to a maximum of (0.572). There is a good agreement with others in literature.

5. Acknowledgment

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