Performance Evaluation of a Solar Humidification – Dehumidification Desalination Unit

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Abstract — **This paper is to investigate the use of solar energy in desalination by humidification and dehumidification process (HD). Here, a proposal for the desalination unit has been come out with cylindrical shape containing the evaporator in the middle and surrounded by the condenser. The hot feed water coming from the solar thermal system is sprayed at the top of the evaporator where the air flows from the bottom. In the evaporator the air is humidified until it gets out saturated, then introduced to the condenser, where it is dehumidified to obtain the fresh water and circulated back to the evaporator. Practically there are many parameters influence on the performance of this desalination unit, which are environmental, design and operational. In the current study these parameters are taken in consideration to formulate mathematical models which govern the performance of the main components of this unit, which are the evaporator, the condenser and the solar thermal system. The deduced mathematical models have been interpreted in many programs in visual basic language as a computer software. This software contains many pages which help in introducing and analyzing the most influential parameters. In this case many operational parameters have been studied such as feed water temperature, mass flow rate and salinity, in addition to cooling water mass flow rate and inlet temperature, as well as quantity of solar irradiance with others. At these inputs many outputs have been obtained which are related to the performance of the desalination unit such as fresh water productivity, energy consumption, humidifier volume, recovery ratio and gain output ratio. The obtained results show a great influence of the input variables on the performance of the unit which help in selecting and preliminary design of the desalination unit in any region of study with known environmental conditions and at any certain specifications**

Index Terms – **Solar Energy, Desalination, Humidifier, Condenser, Operational, Parameters.**

I. INTRODUCTION

Water shortages affect many developing countries that are forming more than half of the world's population. The areas with the severest water shortages are the warm arid countries in the Middle East and North Africa (MENA) region. These areas are characterized by the increase in ground water salinity and infrequent rainfall. The increasing world population growth together with the increasing industrial and agricultural activities all over the world contribute to the depletion and pollution of freshwater resources. Desalination is one of mankind's earliest forms of water treatment, and it is still a popular treatment solution throughout the world today [1].

On the other hand, in these regions, abundant of solar energy is available with the large amount of sea or underground saline water. Therefore, it is possible to produce fresh water from sea or underground saline water using solar energy economically [2].

Solar desalination systems become a great challenge as important subject for research and study in the national and international scale. Solar energy as one of the renewable energy resources represent an alternative source of energy, which provide many advantages compared to fossil fuel. Thus solar energy provide a solution to cover the energy needed for desalination in rural dispersed communities, improving inhabitants' living conditions with no negative impact on the environment [3].

One of the solar desalination techniques is based on the humidification–dehumidification process and is considered as the most viable among the other methods, due to the following characteristics [4].

- Low specific process heat consumption of 100-140 kWh thermal per meter cube of fresh water.
- Low temperature process heat can be supplied by solar collectors, waste heat or other sources of low temperature heat, (e.g. geothermal).
- Raw water of any salinity can be used (brackish, sea, even brine of other processes).
- No chemical pre-treatment needed.
- Low auxiliary energy demand (pumps) can be provided by photovoltaics.
- Product water is distillate (best quality product water).
- Modular set up – Capacities of up to 5 m³ per day are considerable.
- Simple and robust construction, easy maintenance.

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- No corrosion because all components in contact with brine are made of plastic materials.

In the current study a mathematical model for the solar HD desalination process has been developed for the all components of the system, which is composed of two main units, the heating unit and the distillation unit. From this model the performance parameters are specified which include the operational, design and environmental conditions. The operational parameters include the inlet and outlet temperatures of the feeding water, air stream, and cooling water, while design parameters include the size of the evaporator and condenser as well as the type and size of the flat plate solar collector. The environmental parameters include the solar insolation, the ambient temperature and pressure, and the wind speed are taken according to the meteorology of Misurata city in Libya.

II. MATERIAL AND METHOD

A. Components of the solar HD system

Compared to previous studied HD desalination systems, which are almost composed of two different and separated humidifier and dehumidifier towers, the following system in this study is cylindrical with one tower, where the humidifier is in the middle of the dehumidifier for operational benefits, as shown in Fig. 1. In this system the feed water getting its heat from the heat storage unit through the heat exchanger.

The heating source is a solar collector. The hot feed water is sprayed through the evaporator which works as humidifier for the air coming down stream of the humidifier. The saturated air getting out from the humidifier is passed through the condenser to produce the fresh water and to preheat the cooling water which is working as the feed water.

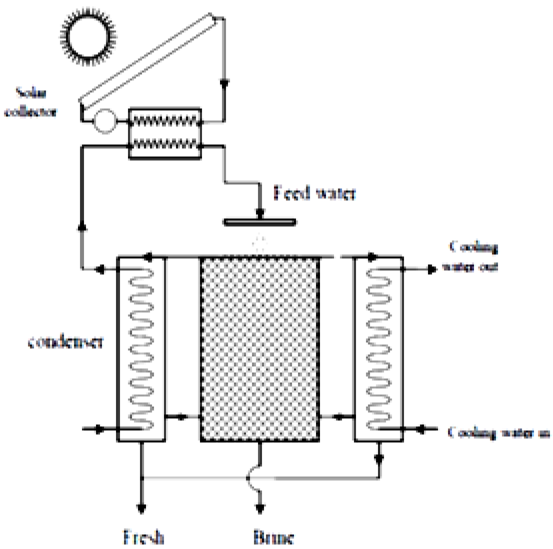

Figure 1. Schematic Representation of the Solar HD Cylindrical Desalination System

B. The Mathematical Model Of The Solar Collector

The useful energy output of the collector in steady state is the difference between the absorbed solar radiation and the thermal loss [5]:

$$Q_u = A_c F_R [S - U_L (T_i - T_a)] \tag{1}$$

Where

Q_u = useful energy output, A_c = collector area,
F_R = removal factor and S = solar radiation
U_L = overall loss coefficient, and is the sum of the top, bottom, and edge loss coefficients.
T_i = inlet temperature & T_a = ambient temperature.

C. Mathematical Model Of The Humidifier

The humidifier or the evaporator looks like cooling tower and it is functioning on heat and mass transfer between the hot falling water and upward air stream, as shown in Fig. 2. In performing the analysis of this unit the following assumptions have been made [6]:

1. The process operates at steady-state conditions,
2. There are no energy losses to the environment from the heat and mass transfer equipment,
3. Air and water vapor may be treated as a perfect gas,
4. Changes in kinetic and potential energy are relatively small,
5. The pumping power is neglected in the energy balance.

The air/vapor mixture leaving the evaporator is assumed to be fully saturated (relative humidity of unity), and due to heat transfer limitations, its maximum temperature will be taken to be that of the feed water entering the evaporator.

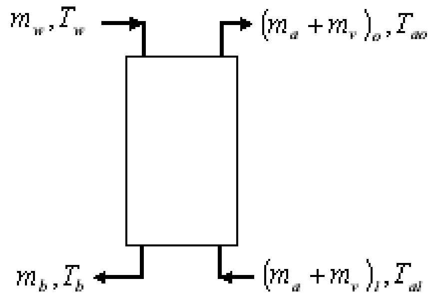

Figure 2. Schematic Diagram of the Evaporator

Conservation of mass through the evaporator dictates that,

$$\dot{m}_b = \dot{m}_w - (\dot{m}_{vo} - \dot{m}_{vi})$$
$$= \dot{m}_w - \dot{m}_a (w_o - w_i) \tag{2}$$

Where w_o and w_i are the humidity ratios at outlet and inlet of the evaporator. By dividing this equation by $\dot{m}_a$ we get,

$$\xi_b = \xi_w - \left(w_o - w_i\right) \tag{3}$$

Where,

$$\xi_b = \dot{m}_b / \dot{m}_a \ \& \ \xi_w = \dot{m}_w / \dot{m}_a$$

The control volume formulation of energy conservation applied to the adiabatic evaporator leads to,

$$\dot{m}_w h_w + \dot{m}_a h_{ai} + \dot{m}_{vi} h_{vi} - \dot{m}_b h_b - \dot{m}_a h_{ao} - \dot{m}_{vo} h_{vo} = 0 \tag{4}$$

With respect to air mass unit this equation becomes,

$$\xi_w h_w + h_{ai} + w_i h_{vi} - \xi_b h_b - h_{ao} - w_o h_{vo} = 0 \tag{5}$$

By substituting the enthalpy in terms of temperature the above equation becomes,

$$\xi_w h_w - C_{pa}\left(T_{ao} - T_{ai}\right) + w_i h_{vi} - \xi_b h_b - w_o h_{vo} = 0 \tag{6}$$

It is noticeable that this equation is function of feed water to air mass ratio (ξ_w), which can be considered as a controlling variable in addition to the values of the feeding water temperature and air temperature. However, the thermodynamic analysis is carried out at this variable and other pre-mentioned operational variables.

The humid air coming out of the evaporator is introduced to the condenser to produce the fresh water which has the amount given by:

$$\dot{m}_{fw} = \dot{m}_a\left(w_o - w_i\right) \tag{7}$$

Consequently, the production efficiency can be defined as the amount of fresh water produced with respect to the amount of feed water used in the evaporator, as follows:

$$\eta_p = \frac{\dot{m}_{fw}}{\dot{m}_w} = \frac{\dot{m}_{fw} / \dot{m}_a}{\dot{m}_w / \dot{m}_a} = \frac{w_o - w_i}{\xi_w} \tag{8}$$

The rate of energy consumed per unit fresh water produced can be determined from the amount of heat lost during adiabatic humidification process as follows:

$$\frac{Q_g}{\dot{m}_{fw}} = \xi_w \frac{\left(h_w - h_b\right)}{\left(w_o - w_i\right)} + h_b \tag{9}$$

D. Heat Transfer Analysis Of The Condenser

The heat from the humid air transfers to the cooling water through three thermal resistances, the first $R_{o,w}$ is between air and outer surface of tubes, the second $R_{f,w}$ is between the outer and inner surfaces of the tubes, and the third resistant $R_{i,w}$ is between the inner surface and the coolant. From these resistances one can find the overall heat transfer coefficient of the condenser (U_c), thus;

$$U_c = \frac{1}{R_{i,w} + R_{f,w} + R_{o,w}} \tag{10}$$

The amount of heat transferred through the condenser is given by:

$$Q_c = U_c A_c \left(LMTD\right)_c \tag{11}$$

Where A_c is the condenser area and $(LMTD)_c$ is the log mean temperature difference of the condenser [7]. The amount of heat of the condenser is the same amount of latent heat of condensation, which could be written as

$$Q_c = \dot{m}_{fw} h_{fg} \tag{12}$$

Equating equations (11) and (12) gives the specific heat transfer area in the condenser, as follows:

$$\frac{A_c}{\dot{m}_{fw}} = \frac{h_{fg}}{U_c\left(LMTD\right)_c} \tag{13}$$

From this equation we can find the surface area of the condenser required to produce a certain amount of fresh water.

III. RESULTS AND DISCUSSION

Due to the many variables can be taken in the analysis, a computer software using Visual Basic has been designed to obtain the performance of the HD unit. In this case the air to feed water mass ratio is considered the main variable with others, such as humid air inlet temperature, feed water temperature, and salinity of feed water. Here, the main outputs taken in consideration in this paper are the productivity, the recovery ratio, and the gain output ratio.

In Fig. 3 it is observed that the fresh water productivity increases with both mass ratio and air temperature. By increasing the mass ratio at constant feed water mass flow rate, the air mass flow rate increases, then the mass transfer between feed water and air increases, causing more vapor formation which increases the productivity. Also the higher the temperature of the exit air means more heat transfer and mass transfer between the two fluids too, thus will increase the productivity also.

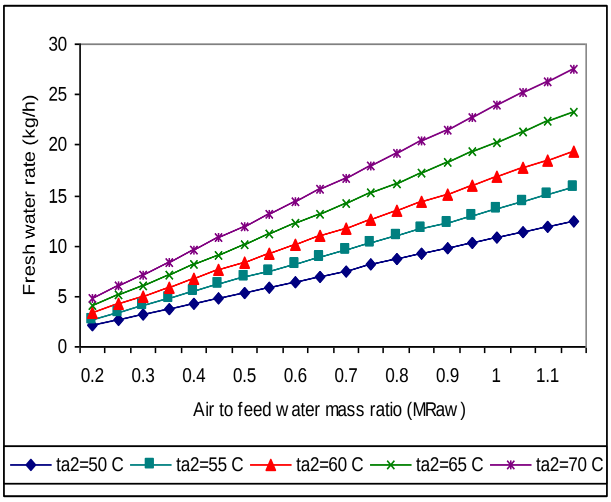

Figure 3. The Fresh Water Rate versus Mass Ratio and Exit Air Temperature

The recovery ratio in Fig. 4, which is the amount of produced water with respect to the amount of saline feed water, increases also with the mass ratio and the air temperature. This case is related to the previous one, in which the increase of the productivity is due to the higher recovery ratio caused by more heat and mass transfer.

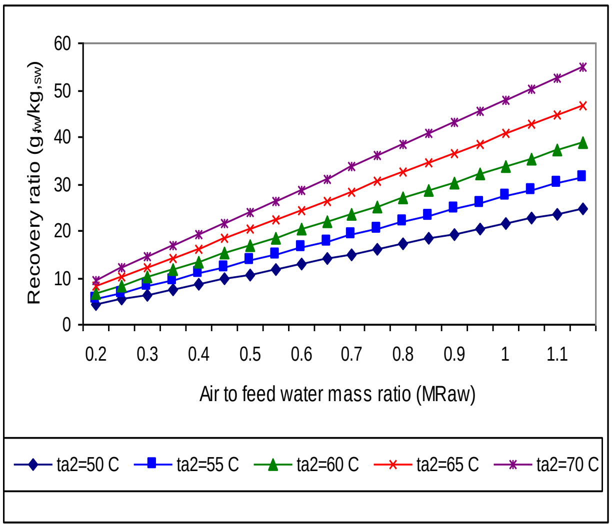

Figure 4. Recovery Ratio versus Mass Ratio and Air Temperature

The gain output ratio increases also with both mass ratio and air temperature as shown in Fig. 5. This ratio is related to energy and is defined here as the amount of latent heat lost during condensing of vapor to produce fresh water with respect to the amount of heat added to the feed water. By increasing the mass ratio, the humid air mass rate increases too, also the increase in air temperature means more heat is transferred to the air, thus giving higher gain output ratio.

The other variable taken with the mass ratio is the feed water flow rate which has shown a clear influence on the unit performance. By increasing the feed water mass flow rate and the mass ratio, the quantities of both fluids (the feed water and air) become higher, and the heat and mass transfer increase in this case, giving higher productivity as shown in Fig. 6.

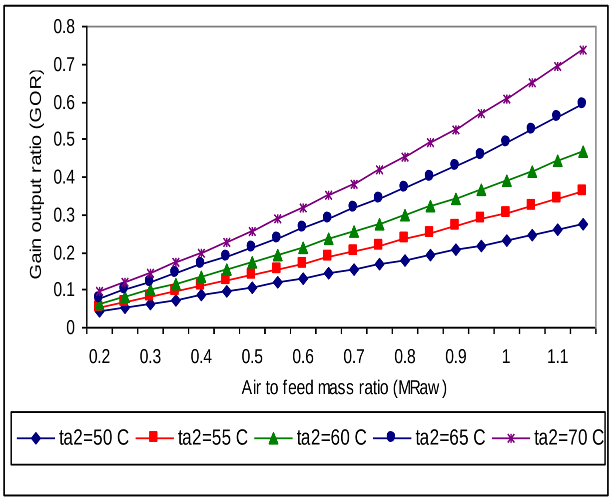

Figure 5. Gain Output Ratio versus Mass Ratio and Air Temperature

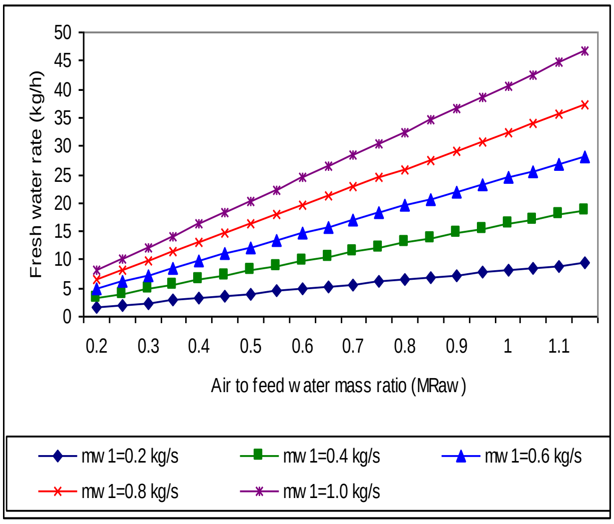

Figure 6. Fresh Water Rate versus Mass Ratio and Feed Water Rate

By increasing the feed water rate, the cooling temperature difference goes up, which means higher cooling water outlet temperature, then more amount of heat transfer. This increase in the amount of heat will reflect positively on the gain output ratio, making this parameter goes up as shown in Fig. 7.

The unit specific heat transfer area is related to the humidifier and condenser heat transfer areas. Here, in Fig. 8 we notice that this parameter goes down with the air to feed water mass ratio and with feed water rate. This means that at smaller areas we can get higher productivity of fresh water, by increasing these variables.

From practical point of view the salinity of feed water could be variable, from low values for brackish water to high values for sea water. Here, in the current study this parameter has been taken variable from 3000 ppm to 35000 ppm, with other variables such as feed water mass rate, and air to feed water mass ratio.

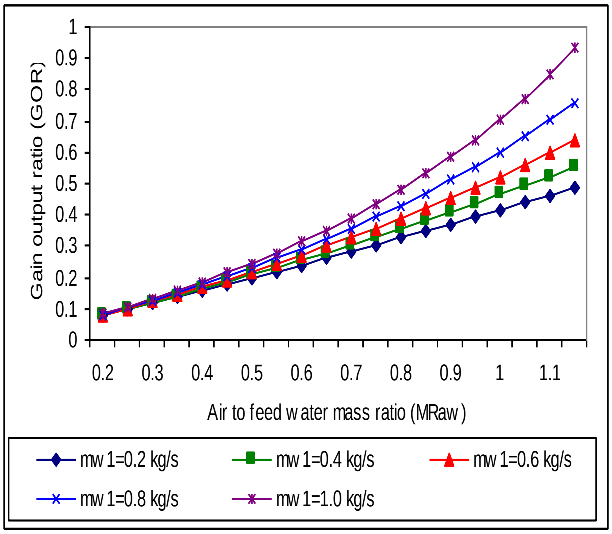

Figure 7. Gain Output Ratio versus Mass Ratio and Feed Water Rate

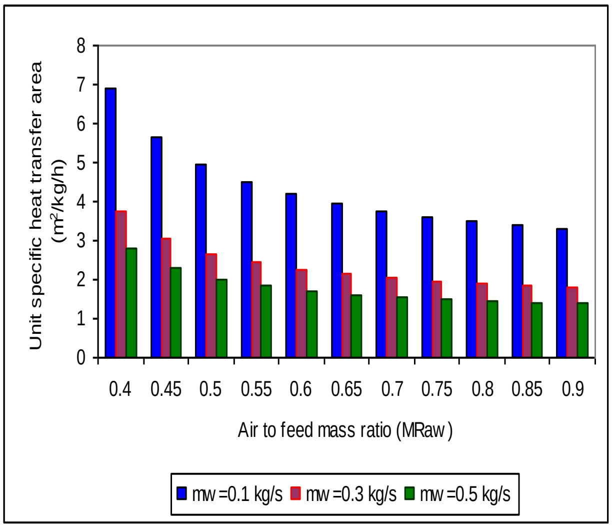

Figure 8. Unit Specific Heat Area versus Mass Ratio and Feed Water Mass Rate

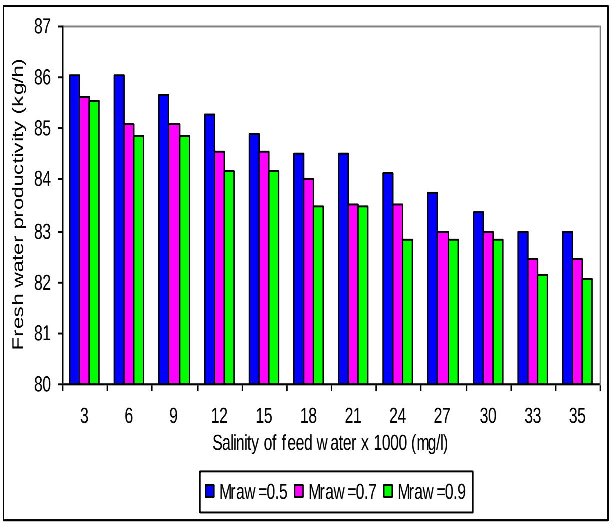

Figure 9. Fresh Water Productivity versus Salinity of Feed Water and Mass Ratio

From the output results we notice that the fresh water productivity goes down with the increase of the salinity of feed water and also with the increase of mass ratio as shown in Fig. 9, consequently the recovery ratio decreases too with salinity, as shown in Fig. 10. This drop is due to the decrease of the specific heat of the feed water with the increase of its salinity , which is reflected on the amount of heat transfer from the feed water to the humid air, then the evaporation will be less and producing less amounts of vapor.

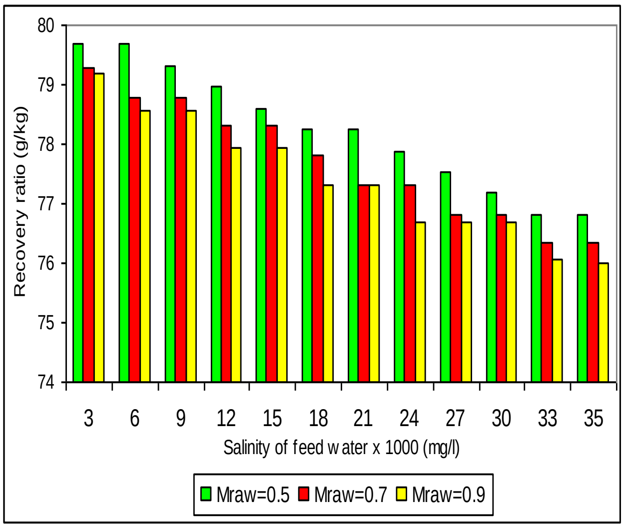

Figure 10. Recovery Ratio versus Salinity and Mass Ratio

Fig. 11 show that the productivity of the fresh water goes up with this variable, also with feed water rate. This is due to more heat and mass transfer, then more vapor formation. Feed water temperature plays an important role on the performance of the HD unit, in which it is noticeable in

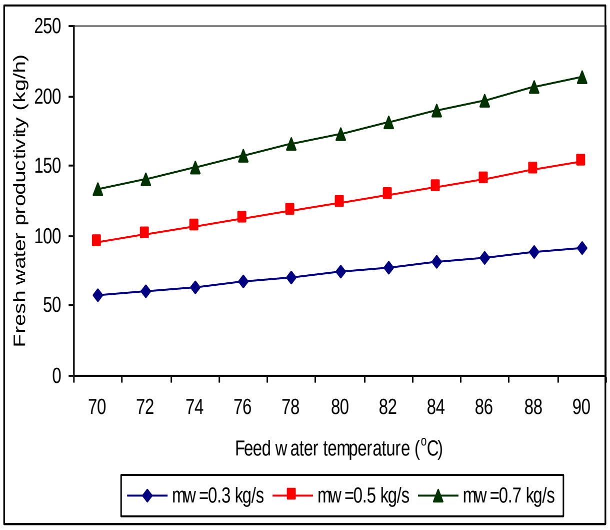

Figure 11. Fresh Water Productivity versus Feed Water Temperature and Mass Rate

One of the premium advantages of the HD desalination unit that it needs low energy heat source, as it has been mentioned before. However, in this paper, from design point of view the quantity of heat gained by humid air has been calculated as it is the same lost by feed water during heat transfer process between the two fluids. The heat of feed water is coming from a flat plate solar collector. Here, in this analysis the useful energy obtained from the solar collector is calculated per unit area, also the productivity has been determined per unit area too, and during one hour. Thus, according to the specifications and dimensions of the solar systems that could be logically accepted as input data, and according to the meteorology of Misurata city in Libya. Whence the thermal load of the desalination unit is determined, the useful energy of the solar system can be specified, then, the capacity and the productivity of the desalination unit can be obtained at any time in the day and at any month.

As a case of study these two variables are calculated every fifteen minutes during twenty first of three months of different solar intensity, during three sessions, which are March, July, and November, to find the influence of solar energy on the productivity of the HD unit.

From Fig. 12 we notice that the collector capacity, which is the productivity harvested per unit area of the solar collector is maximum at noon for the three months, and this is expected due to higher solar radiation at this time.

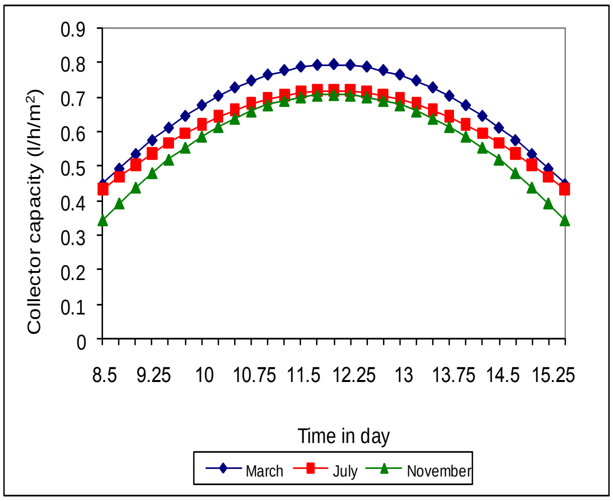

Figure 12. Distribution of the Collector Capacity during the Day

IV. CONCLUSIONS

From the outputs obtained at the input variables we can conclude the following:

1. The air to feed water mass ratio has shown a great influence on the performance of the desalination unit. At a certain water mass flow rate $(\dot{m}_w = 0.5 kg/s)$ and variable mass ratios, the fresh water productivity of the system increases, also the recovery ratio and gain output ratio go up.
2. In the thermodynamic analysis of the system, the analysis is carried out at variable values of humid air exit temperature, with a restriction that it must be always less than feed water inlet temperature by at least 10 degrees to guarantee heat transfer from water to air. The range of temperatures is taken from 50 to 70°C. In this case also the productivity, the recovery ratio and the gain output ratio increase.
3. The other important parameter which has shown influence on the productivity is the feed water mass flow rate. Here, at a certain mass ratio by increasing the feed water mass rate the air mass rate increases too, giving higher productivity. Also the cooling water outlet temperature increases, giving higher gain output ratio.
4. From practical point of view the salinity of feed water could be variable, here in this study it is taken variable from 3000 ppm to 38000 ppm. This means that the proposed desalination system could be used for brackish or seawater. From the results obtained we notice that the productivity goes down with the salinity, at the same time the recovery ratio decreases. In this case to obtain a certain productivity at any salinity the other operational parameters such as feed water temperature and mass rate must be changed to suit the productivity requirements.
5. The influence of feed water inlet temperature has been studied, in which the productivity of the desalination unit goes up as well as the gain output ratio, with the increase of this temperature.

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BIOGRAPHIES

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