PERFORMANCE ANALYSIS OF SOLAR WATER DESALINATION SYSTEM USING HUMIDIFICATION AND DEHUMIDIFICATION CYCLE

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Abstract

The aim of this study is to investigate analytically and experimentally the effect of using an induced atmospheric air, ambient temperature and different mass flow rate of air on the performance augmentation of humidification–dehumidification (HDH) system. This system is designed to produce 5-6 L of water per day. This novel HDH system is a modified solar still with air blower and condenser used at humidification chamber inlet and outlet respectively and glass cover is positioned horizontally and solar energy is used to provide both thermal and electrical energy. This HDH system is composed of a 1.494 m2 solar air heater field, a 0.18 m2 solar water heater. The operational parameters include different air circulation flow rate, feed water flow rate and temperature. Energy analysis of the system has been done by experimental data. The results indicated performance of system increases with increase in mass flow rate of air. The maximum fresh water production rate is obtained as 480 g/h. Water production tests were performed out on several typical days when the average intensity of solar radiation got to 297.5 W/m2.

Keyword: Desalination, Humidification and Dehumidification, Solar Air Heater, Humidifier, Dehumidifier, Heat Exchanger.

1. Introduction

The system under consideration is proposed desalination system working on humidification and dehumidification using solar air heater. The effort is being made to investigate experimentally, the effect of different operating conditions, different design parameters and a weather condition on the performance of considered solar assisted water desalination system under an assumed climatic condition of India. Solar collectors can be over 40% of an air-heated HDH system's cost; thus, design optimization is crucial. Best design practices and sensitivity to material properties for solar air heaters are investigated and absorber solar absorptive and glazing transmissivity are found to have the strongest effect on performance. Wind speed is also found to have an impact on performance. In proposed arrangement, air is heated through solar air heater using various arrangements like Rough absorber plate, multiple passes of air through the collector, single glazing cover and their performances are evaluated and compared. Solar water desalination has a long history as being used for desalinating non drinkable water to produce potable water especially in remote areas with water shortages or scarcity. There are two types of solar desalination with two ways of using solar energy as directly or indirectly. Solar energy, collected from solar radiation, can be used directly to heat salty water in order to produce fresh water which is low cost and practical especially for small scale applications. They have low operation temperature and vapour pressure which make their production output less than their indirect counterparts. Two main types of direct desalination technique are HDH method and solar stills.

There are many technologies for desalination of water. But most using technologies are:

- *a) Multi stage flash*
- *b) Multi effect distillation*
- *c) Vapour compression*

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d) *Reverse osmosis*
e) *Electrodialysis*
f) *Humidification-dehumidification cycle*

The various important parameters that's having greatest impact on the system performance are absorber solar absorptive, glazing cover transmissivity, air flow rate, rough absorber material, number of passes in SAH, number of glazing covers used, temperature of ambient air and temperature of cooling water etc.

Emrah Deniz and sekan cinar[1] designed novel humidification-dehumidification (HDH) solar desalination system and tested with actual conditions and solar energy was used to provide both thermal and electrical energy. The maximum daily energy efficiency of the system was calculated as 31.54% and the maximum exergy efficiency was found as 1.87%. Jihane Moumouh et al.[2] proposed a study of desalination system based on air humidification-dehumidification is investigated theoretically and experimentally. The results obtained from the theoretical model are in very good agreement with those obtained experimentally. Guo-Pei Li & Li-Zhi Zhang[3] has given a model on a solar energy driven and membrane based air humidification–dehumidification desalination (MHDD) system is proposed. Juan-Jorge
EL-Shazly et al.[9] investigated the effects of using packed bed of screens with different width as humidifier in a solar HDH system on the system performance by testing the system under various real weather and operating conditions. Besides, they studied the main parameters affecting the solar collector efficiency and HDH unit productivity. System productivity value were measured as 9 L per m2 by increasing water flow rate up to 5 L/min and the bed thickness up to 40 cm. El-Shazly et al.[10] investigated the characteristic effects of pulsed water flow on solar HDH systems performance, and system productivity was measured as between1.3 and 1.9 L/m2h. Elminshawy et al.[11] investigated the effects of using the environmental conditions, external reflector and an induced atmospheric air in order to increase the HDH system's efficiency. They calculated the cost of fresh water produced a 0.035 USD/L and obtained system efficiency values up to 0.77.
Guofeng Yuan et al.[8] has done experimental investigation of a 1000 L/day solar HDH system. That system was composed of a 100 m2 solar air heater field, a 12 m2 solar water collector, a humidifier-dehumidifier unit, a pre-treatment and post-treatment system and the results showed that water production of the system could reach 1200 L/day when average intensity of solar radiation got to 550 W/m2.
In this paper, humidification-dehumidification solar desalination system is tested under the real weather operating conditions in Amravati, Maharashtra. Experimental system is designed to use only solar energy with collectors (for thermal energy) and photovoltaic (PV) panel system (for electric energy). This system is manufactured to produce 5-6 L/day of fresh water by using 1.494 m2 of SAH and 0.18 m2 of SWH and 1L/hr capacity condenser. As per calculation by Guofeng Yuan[8], if we increase the solar air heater area up to 100 m2 and solar water heater area up to 12m2 and condenser capacity 5 L/hr, we can achieve production of fresh water up to 300 L/day. The energy analysis of the system are done using data from experimental studies performed for 8 days under real and similar weather conditions. Besides economic analysis of the system are made to find out the economic effect of the system. The purpose this experimentation to develop self-sustainable solar desalination system to supply fresh water from saline water also to fabricate experimental set-up i.e. test rig, also to compare the quantity of fresh water outlet by varying flow rate of air in solar air heater and compare the gained output ratio and overall system efficiency for different flow rates.

1.6 Advantages of PV Systems

Photovoltaic modules can easily penetrate in remote areas since the electrical power that produce comes from a reliable, free from pollution and independent source, the sun. Photovoltaic systems can be economically feasible, since it can help in a large extent the viable growth of a region. Moreover they can produce electric current during cloudy days and the current that produced is a direct current (DC). Photovoltaic systems were manufactured in order to function in unfavourable conditions and it has a very small weight. It is possible

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installed on the ground, on the roofs of buildings or on any other location where sun light beams can reach on the photovoltaic cell surface easily.

The principal advantages of PV systems are:

i. A long life cycle since it can provide power for more than 20-25 years

ii. Zero operation cost, because it does not consume fuel or materials.

iii. Low variability of system efficiency and more reliable results.

iv. Maintenance cost is low.

v. No sound pollution in the period of operation.

vi. Energy conservation.

vii. Keep the environment clean and away from pollution of the CO2 emissions in atmosphere.

2. EXPERIMENTAL SETUP

The experiments with solar powered Humidification- dehumidification system are conducted in Amravati city (latitude: 20.95 N, longitude: 77.75 E) in April 2017 for eight days from 10:00 am to 4 pm and data for a day medium measurement data is used for the calculations. The HDH system consist of a blower, a solar air heater, a humidifier, a dehumidifier and two storage tanks. As the complete system is solar energy driven, only DC motors in blower and DC water pumps in humidifier and dehumidifier are used. Two number of DC motors of 100 rpm with steel gear boxes are used to rotate blade of blower. Two water pump of 12V are used to pump water in humidifier and dehumidifier. The design of solar air heater is as per conventional solar air heater consist of one glazing cover, one absorber plate, one back plate and base cover with insulation. Air heater also consist of 4 baffles and 5 number of passes having the same width as diameter of exit of blower. The SAH is followed by humidifier in which four number of nozzle sprays are used to spray saline water. Humidifier is followed by dehumidifier which consist of 24 number of copper tubes are used. Hot saturated air from humidifier is entered from top inlet of condenser having same width as diameter of outlet pipe of humidifier and this air passes through two number of baffles. Water produced is collected from the bottom of dehumidifier. The HDH system consist of eight thermocouples of K-type which is connected to temperature indicator for measuring the temperature distribution. The velocity of air and cooling water from storage tank is regulated by designing regulating circuit for DC current.

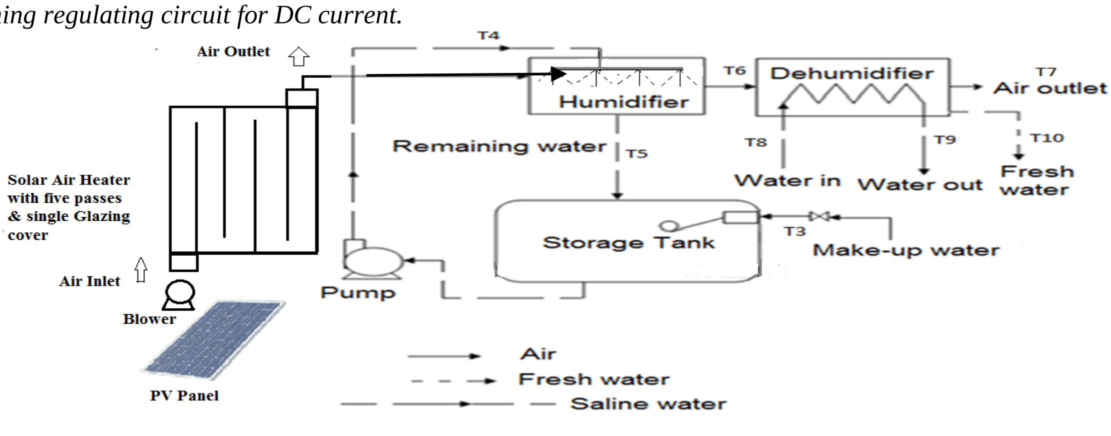

Fig. 1. Schematic diagram of experimental set-up

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Table 1 Components used in the experimental setup.

Component	Designed capacity
SAH area	1.494 m2
Dehumidifier	500×210×150 mm
Spray nozzle	0.5 mm
Number of nozzles	16
Hot saline water tank	100 L
Desalinated water tank	5 L
PV panel	100W(0.78m2)
Circulation pump	30W
Blower	30W

Table 2 Technical description of measurement devices

Measurement devices	range
Thermocouple (K type)	0-200oC
Pressure digital probe (testo510i)	-150 to +150 KPa
Air flow velocity (digital anemometer)	0.0 to 50 m/s

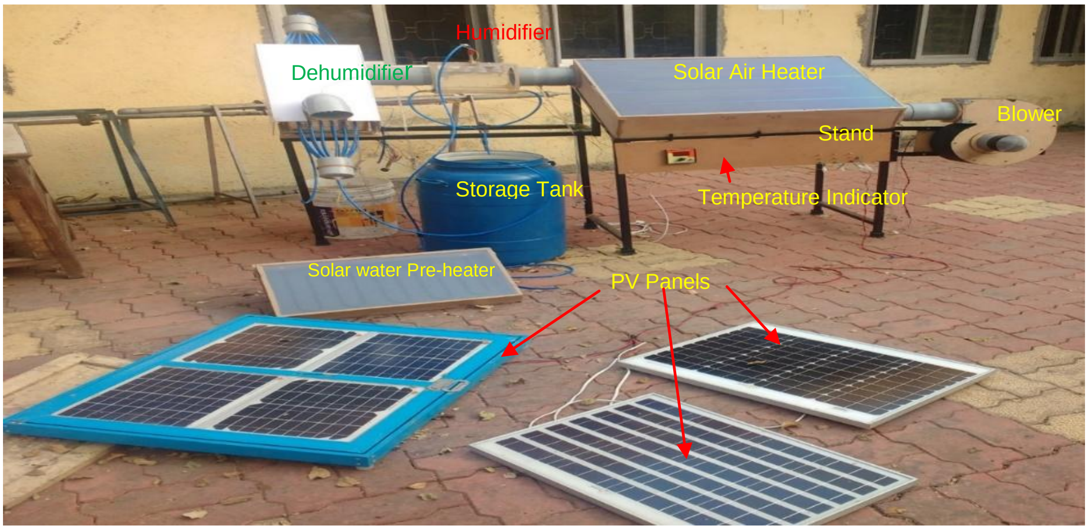


Fig. 2. Photograph of Experimental Set-Up

3. THEORETICAL ANALYSIS OF HDH SYSTEM

Ambient dry air which is heated by flat plate air collector taking into humidifier unit and then air gains vapour from spraying salt water. This hot saturated water vapours is now allowed to pass through condenser in which cooling water is used inside the copper tubes to condense the water vapours over the copper tubes. Two DC motors are used supply saline water to humidifier and cooling saline water to dehumidifier. The condensate forms over the tubes is then collected from the bottom of condenser. In the experimental study, solar radiation, ambient temperature and humidity and water and air temperature values will measure from different points of the system and all measurements will be recorded by a computer during the experiments. The fresh water is taken to the storage tanks and desalinated water mass per hour are measured.

3.1. Energy Analysis

Energy analysis done by yildrim and solmus[13] has made some following assumptions to simplify the calculations.

- *Solar radiation, wind speed and relative humidity & temperature of the ambient air are constant at each instant through an hour.*
- *There are no air leakage from the system, when air passes through the solar air heater, humidifier and dehumidifier.*
- *Cooling water temperature is constant throughout the operation.*

From Schematic Diagram of HDH system as shown in Figure 1.

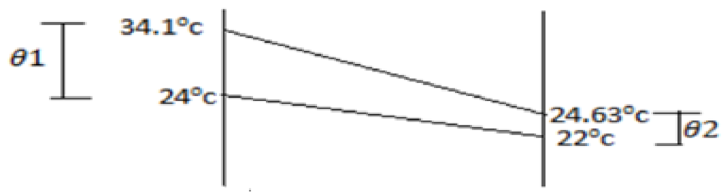
For Dehumidifier:

$$m_a\,(h_6 - h_7) = m_{cw} C_{pw}\,(T_9 - T_8) - m_{dw} C_{pw} T_{10} \quad (1)$$

Humidifier Energy balance is,

$$m_w C_{pw}\,(T_4 - T_5) = m_a\,(h_6 - h_2) \quad (2)$$

The moisture content of air at Solar Air Heater can be calculated as [1];



$$w1 = \frac{0.622\varphi Pg}{P - \varphi Pg} \quad (3)$$

where Pg is vapor saturation pressure and it is calculated as,

$$P_g = 2.7\times10^{-9}T^5 + 2.8\times10^{-7}T^4 + 2.7\times10^{-5}T^3 + 0.0014T^2 + 0.044T + 0.61 \quad (4)$$

where hfg is saturated water vapours enthalpy and can be given as;

$$h_{fg} = 2500.8 - 2.36T + 0.0016T^2 - 0.00006T^3 \quad (5)$$

The difference of moisture contents of dehumidifier unit inlet and outlet is used to calculate mass flow rate of produced clean water leaving dehumidifier.

$$m_c = m_a(w_3 - w_4) \quad (6)$$

3.2. System Performance

The most commonly used performance indicators for desalination systems are; the gained output ratio (GOR), performance ratio and system efficiency.

3.2.1. Gained Output Ratio

The gained output ratio is used for describing the effectiveness of water production of thermal desalination process which is also defined as an energy ratio or a mass ratio. GOR is calculated by an Eqn (7) [1];

$$GOR = m_{dw} L \,/\, Q_{in} \quad (7)$$

where "Qin" is the energy input to the desalination system from solar systems. Also "L" is the latent Heat of Vaporization (J/kg), "mdw" is hourly output of solar HDH system (Kg/h).

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3.2.2. Overall System Efficiency

The energy required for distilled water production depends on latent heat of vaporization and can be written as[1],

$$E_{dw} = m_{dw} L \tag{8}$$

The performance of HDH desalination system which also means the energy efficiency is calculated as latent heat of vaporization of distilled water divided by heat input to the system;

$$\eta = m_{ew} L / Q_T \tag{9}$$

where QT is the total energy input from PV panel, water & air heater [1].

3.3. DESIGN OF CONDENSER

First assume one tube pass and check to see if it satisfies the conditions of this problem. The exit temperature of the hot air calculated from,

$$Q = m_{cw} \times C_{pcw} \times \Delta T_c = m_h \times C_{ph} \times \Delta T_h \tag{10}$$

The mass flow rate, specific heat capacity and temperature difference of cooling water are known, so calculated total heat transfer. Also by knowing mass flow, specific heat capacity and air inlet temperature of hot saturated air, the air outlet temperature from condenser is calculated and obtained as 24.63oC.

For cross flow heat exchanger LMTD is given by

$$LMTD = \frac{\theta 1 - \theta 2}{ln \frac{\theta 1}{\theta 2}}$$

$$LMTD = 5.55^oC \tag{11}$$

Considered the overall Heat transfer coefficient in Heat exchangers from the table of typical overall heat transfer coefficient in heat exchanger for condensation type as,

$$U = 150\ W/m^2\ {}^oC \tag{12}$$

Heat transfer is also given by

$$Q = U \times As \times LMTD \tag{13}$$

The total surface area required for one tube pass exchanger is calculated as

$$As = 0.25\ m^2 \tag{14}$$

Using the average water velocity in the tubes and the flow rate, the total flow area with is calculated as,

$$m_c = \rho \times A \times V \qquad A = 7.364e^{-4}\ m^2 \tag{15}$$

Therefore, number tubes per pass is given by

$$A = n \times \frac{\pi d^2}{4} \qquad n = 23.25 \approx 24 \tag{16}$$

The surface area per tube per meter of length as,

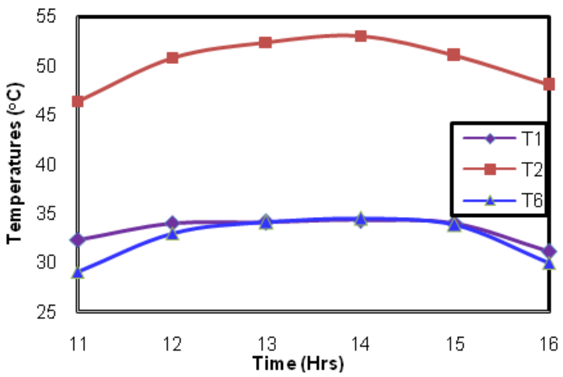
$$\pi d = \pi \times 0.00635 \qquad \pi d = 0.01994 \frac{m^2}{tube}.m \tag{17}$$

The total surface area required for a one-tube pass exchanger was calculated as 0.25 m2.

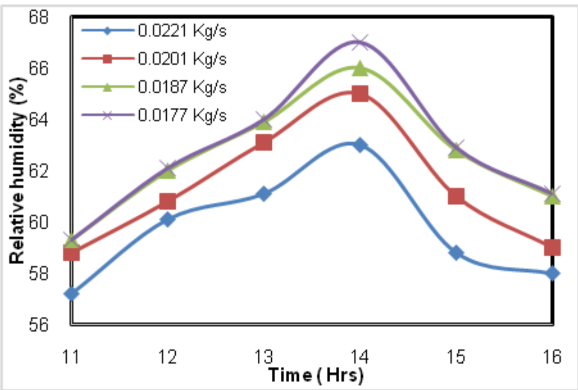
Computing the length of tube for this type of exchanger which is obtained as 52cm.

4. RESULTS AND DISCUSION

The behaviour of a one-stage HDH system is investigated experimentally and theoretically under real environmental conditions. There is no study in the literature that gives a complete analysis of a HDH system, using spray humidifying unit, including energy analysis. For these investigations, the tests are performed to determine the influence of the inlet and outlet temperatures of water and air, mass flow rates of the collectors, humidifier and dehumidifier, and the solar irradiation, relative humidity of the system air, and ambient air temperature and relative humidity on the HDH yield of the system. The tests are conducted for 6h for 8 days under very similar ambient conditions as ambient temperature and the solar radiation. Fig. 3(a) shows temperature variation of air at inlet and outlet of solar air heater and humidifier inlet verses time. Graph shows temperature becomes maximum at around 2 pm when solar irradiance is at its peak value. It shows temperature rise depends upon solar radiation intensity. As solar radiation decreases after 2 pm temperature also goes on decreases. It also gives the maximum temperature difference of air in solar air heater at inlet and outlet of about 20oc. The results of full day experiments from 11 am to 4 pm show that the water and air temperature inside the solar collectors does not exceed 35oC and 55oC respectively. Air entering the SAH is heated up to very high sensible temperatures and its relative humidity is decreased as much as possible in order to maximize the water vapour capacity. Fig. 3(b) shows relative humidity of air at dehumidifier inlet for different mass flow rate of air in increasing hours of a day. It shows the relative humidity of air increases as the temperature of air increases, it becomes maximum at around 2 pm. It also shows that relative humidity of air increases as flow rate decreases because for lower flow rate, we get higher outlet temperature of air.



(a)



(b)

Fig. 3. (a) Temperature Variations at Inlet and Outlet of SAH and Humidifier (b) Relative Humidity at DH Inlet for Different Mass Flow Rate

There is no study in the literature that gives a complete analysis of a HDH system, using spray humidifying unit, including energy analysis. For these investigations, the tests are performed to determine the influence of the inlet and outlet temperatures of water and air, mass flow rates of the collectors, humidifier and dehumidifier, and the solar irradiation, relative humidity of the system air, and ambient air temperature and relative humidity on the HDH yield of the system.

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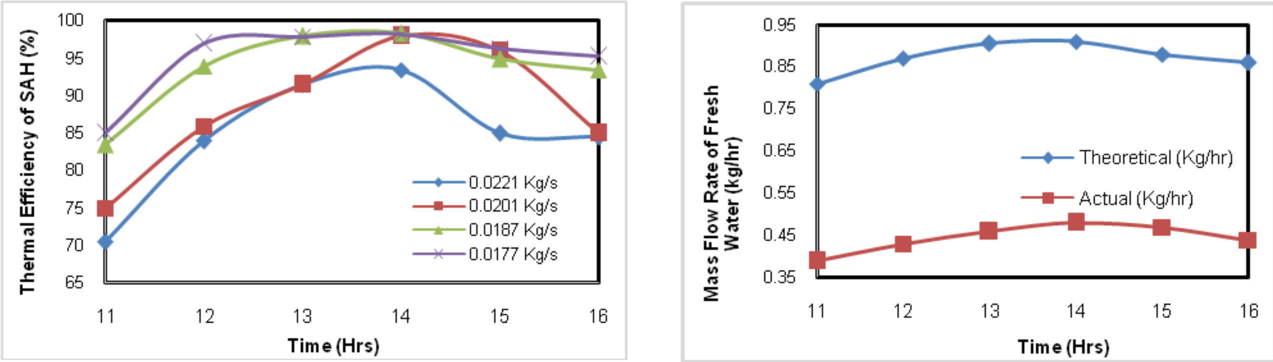
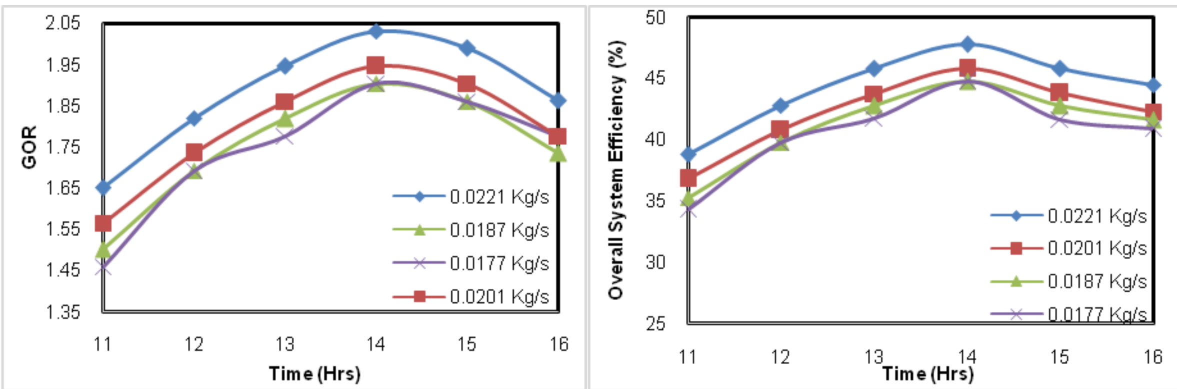


(a) (b)

Fig. 4.(a) Thermal Efficiency of SAH for Different Mass Flow Rate (b) Comparison Actual rate of water outcome with Theoretical

Fig.4(a) shows the thermal efficiency of solar air heater for different mass flow rate of air at increasing hours of a day. It shows thermal efficiency increases as the day progresses and becomes maximum at 2 pm. It also shows thermal efficiency is maximum at 2 pm for all flow rates having small variations and then decreases. Fig.4(b) shows the comparison of actual mass flow rate of fresh water with theoretical mass flow rate versus time. When the amount of solar energy falling onto the system decreases after 2 pm, distillation process doesn't affect much because it uses the energy stored before in solar air heater. The difference in actual and theoretical water rate is because of less effectiveness of condenser and different losses in the system. The maximum amount of distilled water is produced while the water temperature was maximum during the operation of the system. Fig. 5(a) shows gain output ratio for different mass flow rate of air in increasing hours of day. It shows, as the mass flow rate of air increases, the gain output ratio of system increases.



(a) (b)

Fig. 5(a) GOR for Different Mass Flow Rate (b) Overall System Efficiency at Different Mass Flow Rate

Fig. 5(b) shows the variation of the system efficiency by the time for different mass flow rate of air. This shows the overall system efficiency increases with the increase in mass flow rate of air. Because of system limitation mass flow rate of air is limited up to 0.0221 Kg/s. The system efficiency is significantly increases up to 2 pm and then decreases because of lesser production rate of water. The rate of fresh water production significantly increases up to 2 pm and becomes maxi-mum of 450 g/h. As the ambient temperature and solar radiation decreases after 2 pm, the rate of fresh water production decreases with lesser rate as heat was accumulated in solar air heater. HDH system gives the best production rate from 12 am to 3 pm. GOR value of the HDH system is obtained between 1.5 to 2.03. Low GOR value can be explained by inadequate recovery of the condensation *heat from the drainage system. Temperature and humidity of air exhausted from dehumidifier effect the overall system efficiency. Therefore, the most critical component of the desalination system is condenser which decreases the temperature of humid air as much as possible to condense the moisture in the air and increases the productivity.*

5. CONCLUSION

The thermal study of a desalination system based on humidification and dehumidification of air were presented. The mathematical model also predicted very well the heat exchangers and to calculate the inlet and outlet temperatures of each individual apparatus of the desalination system. The model has also been able to predict with very reasonable precision the rate of production of distilled water. Following conclusions are made:

1. *The overall energy efficiency of HDH are in the range of 34.32 – 47.77% and it goes on decreasing with decrease in mass flow rate of air.*
2. *The GOR of HDH system is obtained between 1.5 – 2.03 and it decreases with decrease in mass flow rate of air. Low GOR value can explain the inadequate recovery of the condensation heat from the drainage water.*
3. *The most efficient time period of HDH system is from 12:00 noon to 3pm.*
4. *The mean production rate of HDH system is 2.405 to 2.61 L/day and it goes on increasing with increase in mass flow rate of air.*
5. *The unit productivity increases with the temperatures of water and air entering the humidifier.*

6. CONCLUSION

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