THEORETICAL AND EXPERIMENTAL INVESTIGATION OF AN INNOVATIVE SOLAR AIR HEATED HDH SYSTEM

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

MECHANICAL ENGINEERING

DECEMBER 2017

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

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This work is dedicated to my family

ACKNOWLEDGMENTS

First of all, praise be to Allah almighty, most beneficent and merciful. I would like to thank King Fahd University of petroleum and minerals (KFUPM) for offering me this opportunity to accomplish my Master of Science in mechanical engineering and providing me the environment to achieve this level of study.

I would like to express my sincere gratitude to my advisor Dr. Mohammed Antar for his guidance, enthusiasm, encouragement and the imparting of his knowledge and expertise. He is not only helpful with deep vision and understanding but also most importantly a kind person. Beside him, I would like to express my appreciation to my committee members Dr. Atia E. Khalifa and Dr. Fahad Al-Sulaiman for their valuable assistance, guidance and constructive advice which really help me to successfully complete my thesis.

I would like to thank Mr. Mohammed Karam for his technical support in the experimental work.

I would equally like to thank all my friends and colleagues for their encouragement. Finally, I express my gratefulness to my parents, family and friends for endless love, supplication

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NOMENCLATURE

A	Surface area [m^2]
C	Minimum to maximum heat capacity ratio
C_{min}	Minimum heat capacity [$W\ K^{-1}$]
cp	Specific heat at constant pressure [$J\ kg^{-1}\ K^{-1}$]
h	Specific enthalpy [$J\ kg^{-1}$]
h_{fg}	Enthalpy of vaporization [$J\ kg^{-1}$]
h_d	Mass transfer coefficient [$kg\ m^{-2}\ s^{-1}$]
hg	Specific enthalpy of saturated water vapor [$J\ kg^{-1}$]
H	Height of humidifier/dehumidifier [m]
k	Thermal conductivity [$W\ m^{-1}\ K^{-1}$]
Me	Merkel number
$\dot{m}$	Mass flow rate [$kg\ s^{-1}$]
P	Pressure [kPa]
$\dot{Q}_{in}$	heat input [kW]
U	Overall heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
w	Salinity – grams of solutes per kg of solution [$g\ kg^{-1}$]
W	Width of humidifier/dehumidifier [m]

Greek symbols

ε	Effectiveness
ρ	Density [$kg\ m^{-3}$]
ω	Specific humidity [$kg_{vapor}\ kg^{-1}_{dry\ air}$]

Subscripts

a	Air
br	Brine
D	Dehumidifier
fw	Fresh water
H	Hight of humidifier packing material
ideal	Ideal condition
max	maximum system temperature

ma	Moist air
out	outlet
sw	Saline water (or seawater)
sat	Saturated
w	Water
W	Width of humidifier packing material

Acronyms

GOR	Gain-output-ratio
MR	Mass-flow-rate-ratio
NTU	Number-of-transfer units
RR	Recovery ratio

ABSTRACT

Full Name : [Khalid Makhlad Almutairi]

Thesis Title : [Theoretical and Experimental Investigation of An Innovative Solar Air Heated HDH System]

Major Field : [Mechanical Engineering]

Date of Degree : [December,2017]

Humidification dehumidification desalination (HDH) is one of the promising techniques for water desalination and treatment water. Due to availability of solar energy and low temperature demand of this method in areas that need drinking water, these systems are very compatible with solar energy and the solar radiation can be introduced as a driving thermal energy.

In this study, the Modified closed air open water solar air heated humidification and dehumidification desalination system is designed, built and investigated experimentally. The effect of different mass ratios of the HDH system in the performance is studied. A theoretical design for predicting the input heating energy, GOR, humidifier and dehumidifier area that is needed to produce 5 L/h of fresh water for a modified (CAOW) air heated HDH system is carried out. Moreover, different setups of the modified solar air heated HDH system were built and tested in the outdoor (uncontrolled) climate at KFUPM beach facilities.

Gained output ratio (GOR) increases with increasing inlet water temperature to humidifier, and with decreasing the inlet water temperature to dehumidifier system. However, it decreases with increasing mass ratio greater than 1.2 and input solar energy. The high mass ratio of system is found to produce higher production rate while it is associated with higher energy consumption. The combined evacuated tube solar collectors are able to provide air up to 130 ^{o}C for the HDH system while the maximum temperature of water inside system reaches almost 65^{o}C.

ملخص الرساله

الاسم الكامل:خالد مخلد عايض المطيري

عنوان الرسالة: التحليل النظري والتطبيقي لتحلية المياه المالحه بنظام HDH وإستخدام الطاقة الشمسيه كمصدر طاقة حراريه للنظام

التخصص: الهندسه الميكانيكيه

تاريخ الدرجة العلمية:ديسمبر 2017

تعتبر عملية إنتاج المياه الصالحة للشرب بنظام (HDH) إحدى التقنيات الواعدة لتحلية المياه ومعالجة المياه .ونظراً لتوافر الطاقة الشمسية في المناطق التي تحتاج إلى مياه الشرب والحاجة لدرجة حرارة منخفضة لتسخين المائع في هذه الطريقة ، فإن هذه الأنظمة متوافقة جداً مع الطاقة الشمسية ويمكن إدخال الإشعاع الشمسي كطاقة حرارية.
في هذه الدراسة ، تم إجراء اختبار لتسخين دائره المياه المفتوحه عن طريق دائره الهواء المفتوحه والتي يتم تسخينها بالأساس عن طريق الطاقه الشمسيه في نظام HDH وأيضا تم عمل عدة تجارب عمليه لتحسين النظام . تم دراسة تأثير نسب مختلفه لكتله المياه مع الهواء لنظام HDH في الأداء .أيضا نُفذ التصميم النظري للتنبؤ بالطاقة الحراريه المطلوبة، الأداء ، جهاز المبخر وجهاز المكثف وذلك لإنتاج 5 لترات / ساعة من المياه العذبة لنظام HDH المعدل (CAOW) المسخن بالهواء .علاوة على ذلك ، تم بناء واختبار أنظمة مختلفة من نظام HDH المعاد تسخين الهواء بالطاقة الشمسية في المناخ الخارجي في شاطئ جامعه الملك فهد للبترول والمعادن.

بعد دراسة نتائج الإخبارات تم ملاحظة أن أداء النظام يزيد مع زيادة درجة حرارة الماء الداخل إلى المبخر ، مع تقليل درجة حرارة الماء الداخل إلى نظام المكثف .لكنه لوحظ أنه ينخفض مع زيادة نسبة الكتلة بين الماء والهواء اذا كانت النسبه أكبر من 1.2 ومدخلات الطاقة الشمسية .في حال كانت نسبة كتلة الماء للهواء عالية في النظام فإن معدل إنتاج المياه العذبة تكون أعلى لكن النظام في حاجة إلى استهلاك أعلى للطاقة .تم الحصول على درجه حراره للهواء المسخنه عن طريق الطاقة الشمسية عند 130 درجة مئوية لنظام HDH بينما وصلت درجة الحرارة القصوى للمياه داخل النظام إلى 65 درجة مئوية في شهر مارس.

CHAPTER 1 INTRODUCTION

1.1 Background

Water is one of the few natural resources that is in abundance on earth but still many people face shortage due to the unequal distribution of potable water. Almost 70% of the earth is covered in water yet only 2% of that water is fresh water which is available in the form of glaciers, snow, rivers and underground water table.

Saudi Arabia is one of the driest regions in the world with only 59 mm average precipitation yearly. The largest consumption is for agricultural purposes followed by municipal and industrial usage. With a current population growth rate of 3%, it is assumed that the demand for water will increase by 4.3% per annum [1]. To cope with this, water desalination is the only viable solution to date.

Desalination or "Desalinization" refers to water treatment processes that remove salts and minerals from water. Currently, 50% of drinking water in Saudi Arabia is provided by desalination and this number is due to increase in future keeping in view the drop in the ground water table height. Many desalination plants have been built on different types of technologies mainly Multi Stage Flash Desalination (MSF), Multi Effect Distillation (MED), and Reverse Osmosis (RO).

1.2 Overview of Desalination Processes

The two most common conventional desalination technologies that rely on thermal energy are MSF and MED. The thermal energy can be obtained from either power plant in the form of steam, flue gases, or by using solar or geothermal energy.

MSF plants use flashing to form the vapor from sea water; flashing is a process whereby vapor is formed due to sudden pressure reduction. Each stage has less pressure than its preceding stage and the process is repeated in successive stages. The vapor is collected at the end and is passed through a condenser where regenerative heating of feed water provides the necessary condensation. The energy required during the process is catered by an external supply of steam at or around 100°C. The main disadvantage of this process is the scale formation due to high temperature within the stages, which limits the maximum operating temperature of the plant, thereby limiting the thermodynamic performance of the system.

For an MED system, the feed water is vaporized by using steam in the first stage and then the vapor that is formed in each “effect” is used as a heating medium for each consecutive stage at a lower pressure. The thermal performance of the system is directly proportional to the number of stages.

The next important type of desalination systems is reverse osmosis (RO) plants, which uses a membrane to separate the salts from saline water under high pressure. A high pressure is used to overcome the osmotic pressure of seawater that increases with the salinity pumps. Since concentration of salts is high on feed water side, high pressure forces the water molecules to leave the salts behind pass across the semi-permeable membrane. This process requires excessive pre-treatments and high electricity consumption besides the regular maintenance of membranes to avoid bio fouling and excess concentration of salts on the membrane which hinders the productivity.

1.3 Humidification Dehumidification (HDH) Desalination System

We know that the natural hydrologic cycle is under continuous operation. The thermal energy from sun falls upon the rivers, oceans and lakes and cause water to form vapors (evaporation) that rise into the atmosphere and cause air to “humidify”. As the vapors rise further into the atmosphere, they get cooled down due to low temperature in the upper atmosphere and form droplets; a process known as “condensation” or “de-humidification”. These droplets, then, fall back to the earth in the form of rain, snow or hail entering water bodies or seeping into the soil to be a part of the underground water. In this way the cycle repeats itself again and again.

HDH is a desalination technique developed by mimicking this cycle. The air is humidified usually at atmospheric pressure by brackish or saline water and then de-humidified in a separate chamber to condense the water droplets carried by it which are free of any salts, minerals or other impurities. The heating is done by either solar energy or any other low grade of energy. The efficiency of the system can be enhanced by using the energy of humid air to pre-heat the feed water. This technique is more suitable for de-centralized desalination at low to mid-scale because of less moving, easy to maintain and inexpensive parts such as solar collectors, humidifiers and pumps etc. which do not require sophisticated technical know-how. Besides these, HDH system boasts of other advantages such as: easy operation at ambient pressure, flexibility in operation and use of low grade energy which is otherwise useless. Considering these benefits, the coming years will see more advancements in this technology.

1.4 Categorizations of HDH Units

Depending on the way that is used to heat the system, humidification and dehumidification desalination can be categorized into air or water heated cycles. The efficiency or the gain output ratio of HDH system depends significantly on heating method. From the previous studies, there are a lot of experiences and knowledge on HDH heated by water solar collectors, comparatively there are a few of experiences on the air solar collectors considering their significance to the performance of HDH unit.

1.4.1 Open-Water Closed-Air (OWCA) HDH Water Heating System

In this system, the saline water flows into the dehumidifier of the unit to dehumidify and cool the inlet hot and humid air. Saline water is heated as the enthalpy of condensation/vaporization is transfer from humid air to saline water. After condensation of the humid air, condensed water is flows out as product water, while the preheated saline water leaving the dehumidifier is heated further in water solar collector. In the humidifier, the hot saline water moisturizes the inlet colder air that flow inside the humidifier, so heat and mass are transferred from the hot saline water to the humid air and again brine is rejected from the unit. Air moves continuously in a closed circle between the dehumidifier and humidifier. The process is shown in Figure 1.1.

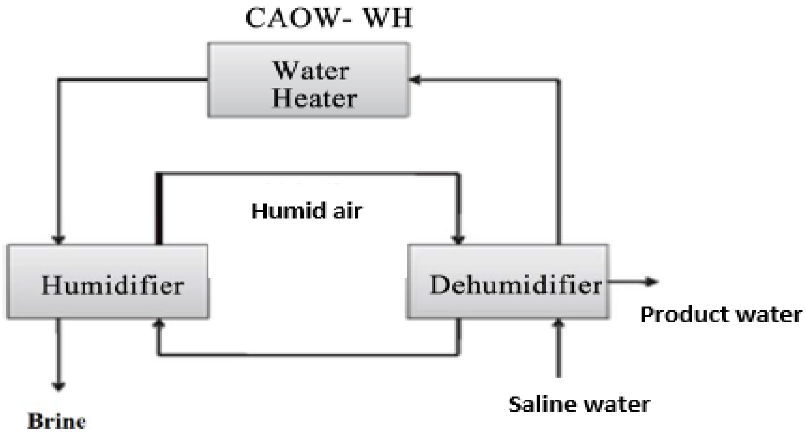

Figure 1. 1 Open-Water Closed-Air (OWCA) unit heated by Water.

1.4.2 Open Water Closed Air (OWCA) Unit Heated by water with mass extraction

To improve recovery of heat in the (OWCA) HDH heated by water, air is circulated from the humidifier to dehumidifier at different locations as displayed in Figure 1.2. This keeps the unit running with a small temperature difference which results a higher recovery of heat from the dehumidifier to increase the efficiency of the system.

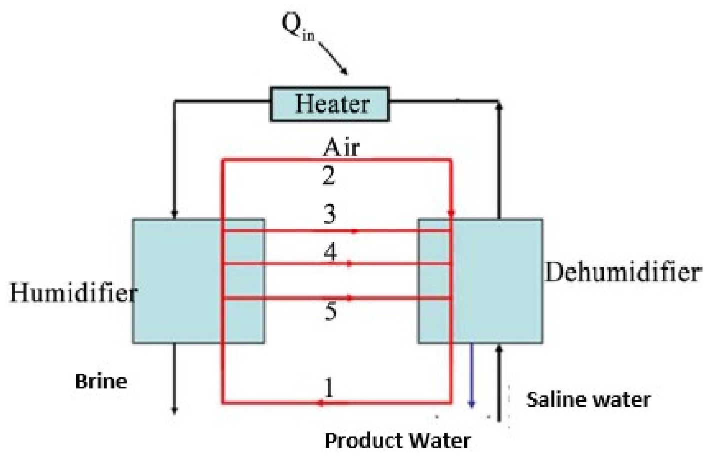

Figure 1. 2 Multi Effect Open Water Closed Air (OWCA) Unit Heated by water.

1.4.3 Open Air Closed Water Unit Heated by Water (OACW-WH)

In this system, the air is heated and humidified in the humidifier using the hot water from the heater. Then, air is dehumidified using outlet water from the humidifier. The water after being pre-heated in the dehumidifier, it enters the heater and it is working in a closed loop. The humid air is condensed at the dehumidifier. The humidification and dehumidification processes are shown in the figure 1.3 below.

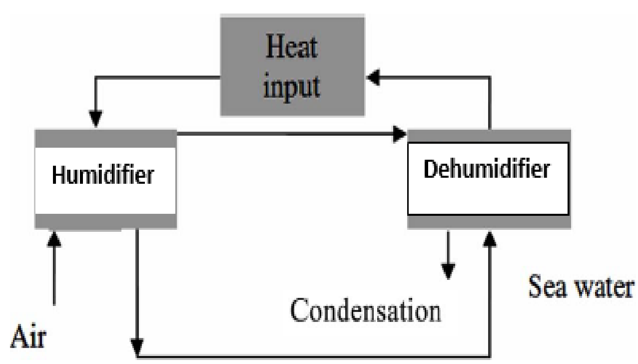

Figure 1. 3 Open Air Closed Water Unit Heated by Water (OACW-WH)).

1.4.4 Open Water Closed Air Unit Heated by Air (OWCA-AH)

In this configuration, a solar collector heats air to a maximum temperature, as seen in Figure 1.4. Then, it enters a humidifier where the air is saturated and cooled by a colder water. After that, the humid air is condensed to produce the fresh water in the dehumidifier. This air process is circulated in closed cycle to increase the humidity in the humid air to increase the product as well as the efficiency.

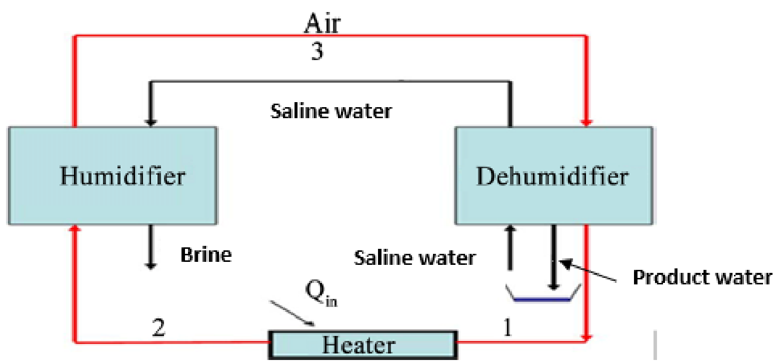

Figure 1. 4 Open Water Closed Air Unit heated by Air (OWCA-AH).

1.4.5 Open Water and Air Unit Heated by Air Heater (OWOA-AH)

A cycle of open air and water (OAOW) heated by air works like the closed air cycle as in figure 1.4. However, Air heater is located between the dehumidifier and humidifier in the air flow side and it is an open cycle as shown in Figure 1.5. This is also called a modified air heated system and the air heater needs less input power to operate the system because of its less heat capacity.

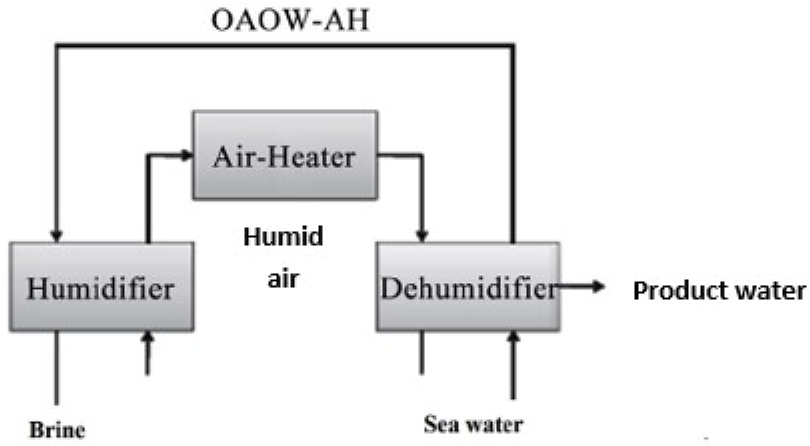

Figure 1. 5 Open Air and Water Unit heated by Air (OAOW-AH).

1.4.6 Water Heated Open Water and air System (OWOA-WH)

The cycle of open air and water (OAOW) that is heated by water heater works like the closed water cycle as it is discussed in section 1.1.3. However, water solar collector is located between the dehumidifier and humidifier in the open water cycle as shown in Figure 1.6.

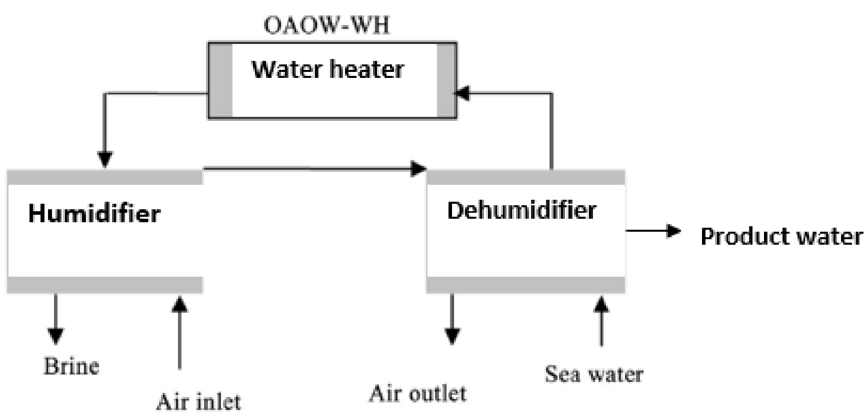

Figure 1. 6 Open Water and air Unit Heated by Water (OWOA-WH).

1.5 The Main Components of HDH System

The HDH units consist of four main parts namely; humidifier, dehumidifier, blowers and solar water or air heater. Theses component will be discussed in this section.

1.5.1 The Humidifier

Figure 1.7 shows that the Schematic diagram of humidifier. In the humidifier have two inlets and two exit each of water and air has one inlet and one exit. The main components inside the humidifier are nozzle spry of the water and packing material where the air carries most of water vapor from inlet heated water. For the humidification process, the driving force is that the difference of concentration between the boundary of air-water and the vapor of water in the air. This difference of concentration is influenced by partial pressure of water vapor in the air and the pressure of vapor at the water–air interface.

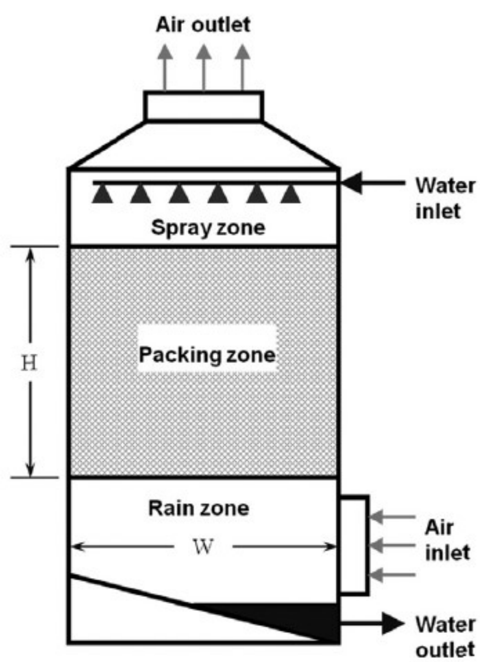

Figure 1. 7 Schematic diagram of humidifier.

1.5.2 The Dehumidifier

The dehumidifier is where the humid air condenses on the surface of cold water pipes to produce fresh water. There are two inlets and three exits in the dehumidifier. For saline water it has one inlet and one exit as well as the air. The bottom exit is for the collected fresh water from the condensation process. The only component that is available inside the dehumidifier is the condenser as it is shown in figure 1.8.

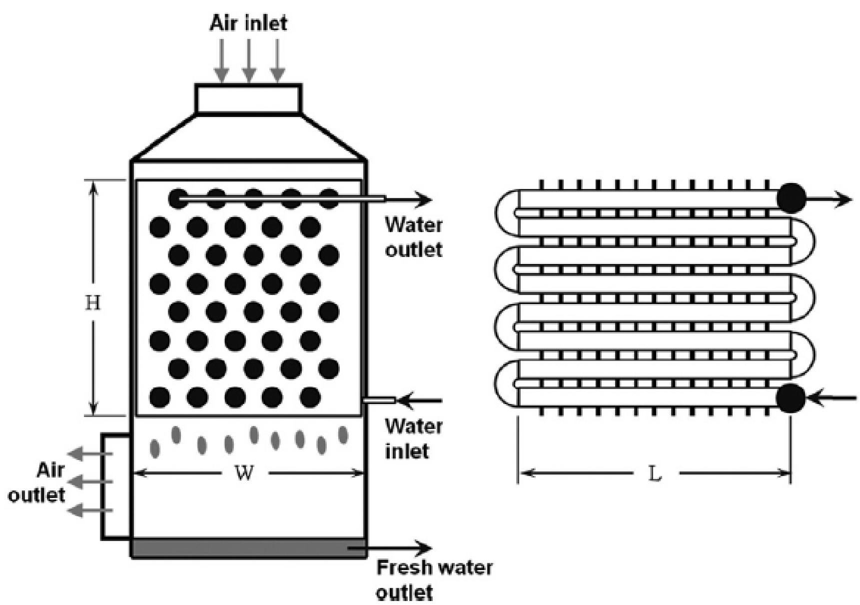

Figure 1. 8 Schematic diagram of dehumidifier.

1.5.3 Solar Air Heater Collector

Solar air collectors are used to transform solar energy radiated from the sun to internal energy to heat the air as shown in Figure 1.9. The main parts of the Evacuated tube air solar collector construction are

1.5.3.1 Evacuated Tube

Absorbs and converts the radiation of the sun to heat the air. There are two glass layers surrounded by vacuum to prevent heat loss. Also, it contains heat transfer fin that is used to transfer heat to the heat pipe.

1.5.3.2 Heat Pipe

Vacuum pipe that is made from copper used to transfers the heat from the evacuated tube to the header in the manifold.

1.5.3.3 Manifold

Insulated box containing the copper header pipe. The header are copper pipes that is connected to the heat pips by dry joint sockets.

1.5.3.4 Mounting Frame

A range of attachment options that need to fix or install the Evacuated tube air solar collector probably.

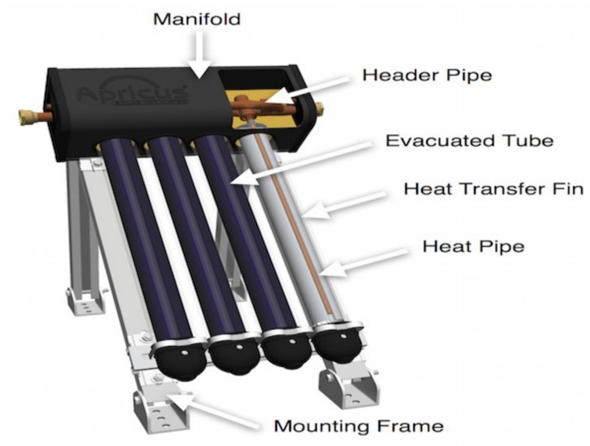

Figure 1. 9 Evacuated tube air solar collector.

1.5.4 Air Fan or Blower

Fans and blowers as shown in figure 1. 10 used to provide the energy of air flow that needed for air circulation. Air fans or blowers produce pressure to move air in contrast to a resistance produced by other part of HDH system. The energy of blower is received through a rotating shaft that conducts it to the air.

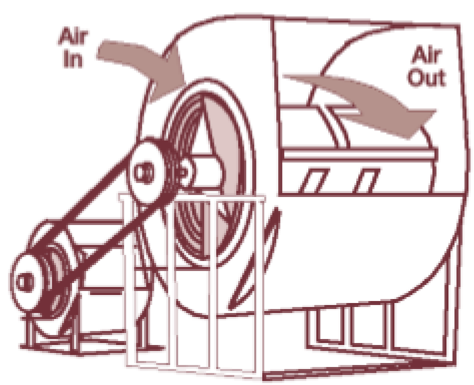

Figure 1. 10 Centrifugal Fan.

1.6 Research Objectives

The objective of this work is to investigate Theoretically and experimentally performance and productivity rate of a modified (CAOW) air heated HDH system. The specific objectives are as follows:

- To conduct a comprehensive literature review on humidification dehumidification systems developed by other researchers.
- To conduct a theoretical design for predicting the input heating energy, GOR, humidifier and dehumidifier area that is needed to produce 5 L/h of fresh water for a modified (CAOW) air heated HDH system.
- To study the effect of the main operating conditions such as feed flow rate, dehumidifier inlet water temperature, humidifier inlet water temperature and for modified (CAOW) air heated HDH system.
- To manufacture a counter flow packing bed humidifier and a cross flow fin coil dehumidifier for modified (CAOW) HDH system.
- To construct an outdoor solar system, with evacuated tube solar collector, for heating the air of a modified (CAOW) air heated HDH system.
- To perform energy and efficiency analyses for modified (CAOW) air heated HDH system.
- To investigate the performance of a modified (CAOW) air heated HDH system.
- To compare the productivity of modified (CAOW) air heated HDH system for different water flow rates.

1.7 Research Methodology

The above-mentioned objectives are achieved through the following steps:

- Collection of information about water scarcity problem worldwide, human consumption and the needs for fresh water, desalination role, desalination technologies, etc.
- A comprehensive literature review on humidification dehumidification desalination systems.
- Data Collection from different points of the system for water and humid air i.e. temperature, flow rate and relative humidity by prober measuring devices.
- A mathematical heat and mass transfer model using **E**ngineering **E**quation **S**olver (**EES**) program in order to perform a parametric study.
- A comprehensive investigation on the performance of a modified (CAOW) air heated HDH system at different operating parameters and experimental conditions.

CHAPTER 2 LITERATURE REVIEW

The experimental study of the main operative parameters of HDD unit heated by electric water heater is studied by El-Agouz[1]. El-Agouz studied experimentally impact of the operating conditions such as water temperature, saline water level and the rate of airflow on the performance of HDD unit heated by electric water heater. The outcomes of experimental work show that, the unit efficiency and productivity increase with the decrease of the rate of airflow and the increase of the water temperature while, a little influenced by sea water level. The efficiency of humidifier and the thermal efficiency the HDD system are higher for $\dot{m_a}$ = 14kg$_a$/h at different temperature and level of sea water. In addition, the study shows that, the maximum system productivity attained was 8.220 kg$_w$/h at water temperature of 86 ºC and $\dot{m}_a$ = 14kga/h.

Ben Bacha and Zhani [2] carried out an economic and an experimental investigation on a HDD system heated by both air and water solar heaters .The HDD system was installed in Tunisia. The humidifier used in the HDD system has an area of 0.6 m x 0.8 m and its height is 0.56 m. The area of air solar heater collectors is 16 m^2 and the water solar heaters used in the HDD system contain six collectors 1m in width and 2m in length. The isolated distillation component has a width of 0.88m length of 1.5m and 2.07m in height. The experimental outcomes demonstrate that the performance of thermal of the unit tend to reach its maximum performance in July. When the solar radiation increases, the amount of product water increases. In addition, the temperature of ambient air has a minor impact on unit thermal performance. The maximum production rate of this system is 21.75 L/day.

A numerical investigation of HDD desalination cycle heated by Solar water collector is studied by Farsad and Behzadmehr [3]. Design of Experiment method (DoE) is implemented to show the influences of the main factors on the produced water. The outcomes indicate that, the rate of mass flow and feed water temperature, inlet air, the design parameters of condenser, and the overall heat flux have major influences on the performance of system.

Nonlinear programming techniques have been applied by Mistry et al. [4] under various operating conditions to optimize the performance of humidification dehumidification (HDH) desalination systems. They considered four scenarios of cycles; each with either water heater or an air heater, which include open water-open air (OAOW) system and open water-closed air (OWCA) HDH unit. Finally, for a terminal temperature difference of 3 K, the CAOW-AH cycle can reach a GOR of 5 whereas the GOR of CAOW-WH set reaches 4.06.

An experimental study of solar HDH system heated by water solar collectors with production capacity of one thousand liters per day was investigated by Yuan et al. [5]. They constructed the designed system in Shandong Province of China. The components of the system include 10 solar heaters with total area of 112 m^2 and the dehumidifier –humidifier unit, which had a length of 1.6 width of 2.02 m and the height was 4.0 m. The experiment results demonstrate that when the radiation of solar achieves about 760 W/ m^2, the exit temperature from the solar collectors can reach 118 °C. The temperature of the outlet air from the humidifier is in the range of 40 to 55 °C, and the relative humidity is between 80 % and 90 %. The GOR of the HDH system is between 2.0 and 2.3. In addition, the results show that the product water increase to 1200 L/day as the solar radiation increases, when the radiation solar achieves 550 W/ m^2. Finally, the economic study illustrate that the price of product water is about 19.2 Yuan/m3.

A mathematical modeling validated to an experimental work for using solar collectors of air and water to operate the humidification and dehumidification solar desalination system

(HDH) in Tunisia is developed by bacha et al. [6]. To evaluate the experimental and the numerical data using an orthogonal collocation method (OCM). The outcomes presented that, the water solar collector behavior is described precisely with two-temperature model. The air and water solar collectors demonstrate the thermal characteristic can be accurately predicted by using the proposed model. Also, the mathematical models have an ability to test the behavior and size those types of water and air solar collectors.

A humidification–dehumidification (HDH) system driven by a photovoltaic (PV) panel has been proposed and studied by Wang et al. [7] under free or forced convection flow for salty water desalination. They evaluated the main parameters that affect condensation and evaporation rates. The result showed that upon increasing evaporative saline water temperature, the water mass flow rates of condensation and evaporation will be increased. Additionally, when the water condensation rate increased, the cooling water temperature decreased. According to these results, the free convection produced less fresh water than the forced convection flow. The highest freshwater production for forced convection was 0.873 $kg \cdot m^{-2} \cdot d^{-1}$.

A theoretical investigation of a solar operated HDH unit using parabolic trough concentrators is conducted by El-Minshawy [8] to calculate the productivity and performance. The investigation indicated that, the produced fresh water of the studied system has a maximum value at optimum value of daytime after which it showed a decrease. During summer, with long time of solar exposure and high thermal radiation of the sun, the highest productivity is recorded which is 0.095 distilled water per kg air at 1 PM. The time of production reaches 42% of the day, which is the maximum value.

The direct contact HDD desalination system was improved by Mehrgoo and Amidpour [9] using a set of linear and nonlinear equations to model the components performance of the HDD unit. The methods of Lagrange multiplier and genetic algorithm are used to improve two types of air circulating flow method of HDD systems. The results indicate that the rate of produced water is affected by the temperatures of hot and cooling water. Furthermore, if the temperature of the inlet water to the humidifier is high, the humidifier outlet recirculated water reduced the consumption of specific thermal energy about 15–25%.

An analytical analysis is proposed by Alnaimat and Klausner[10] to test the operation of humidification–dehumidification desalination unit in dynamic operational conditions. The HDH unit was built in Florida. The input heat of solar energy is reused to operate without external cooling to enhance the production of water and lower the consumption of specific energy. They concluded that delayed operating mode provides enhanced performance by reducing the specific energy consumption. In June, the rate of produced water for the delayed operating mode is 6.3 L/ m^2 collector per day with an average consumption of specific energy of 3.6 kWh/m^3.

A numerical investigation was carried out by El-Said and Kabeel [11] to study a hybrid desalination system consisting of air humidification and dehumidification–single stage flashing (HDH–SSF). They reported six main factors that have impact on the production of the system. They are the rate of mass flow of feed water of both units, the rate of mass flow rate of cooling water of SSF unit, the rate of mass flow of cooling water and air of HDH unit, the rate of mass flow of air and the inlet temperature of cooling water. The humidifier size is 0.45 × 0.8 m and the Packing bed (packing void) is 0.92 m. The dehumidifier size is186 ×

144 × 260 in mm. The Exchange surface area is 0.14 m^2 and the surface area of heat exchanger Exchange is 1.37 m^2.

Additionally, the condenser surface area is 0.2 m^2. The total area of water heater solar collectors is seven m^2 compared to total area of solar collector heated by air that is 1.415 m^2. The results illustrate that, hybridization have a major improvement of the productivity of SSF unit and HDH unit, the daily production of water is almost 11.14 kg/ m^2 /day. The productivity of SSF–HDH hybrid system is mainly affected by the heat regaining when a mixing tank was used to mix the desalinated water, feed water and brine water which results in GOR that almost reaches 4.5. When increasing the rate of mass flow of cooling water, an increase in the product water and the temperature of inlet cooling water decrease. When the inclination of the water solar heater collectors was changed, there was a noticeable decrease in the produced water rate compared to changes in the air solar heater collector's inclination.

Narayan et al.[12], demonstrated the impact of the improved heat capacity rate ratio (HCR) on thermal design of HDH units as heat and mass exchange devices (HME). A water heated (CAOW) HDH unit with capacity of production 700 l/day has been built. The humidifier cross section was 0.278 m^2 that is 3 m high and the dehumidifiers had an area of heat transfer of 2 m2 with total area of 8 m^2. The results showed that, when HCR equal to 1, the HME is under thermal stable state. To get highest GOR of the HDH systems without the extractions of mass, it required operating a high-top brine temperature. The extractions of Mass to the dehumidifier increase the GOR by over 55%. There is an improvement in GOR because of the extractions of mass is increased. Finally, the maximum GOR of proposed system constructed is 4.0 compared with 2.4 for similar HDH system without extractions and the maximum product water is 0.7 m^3/day.

Thiel et al. [13] had examined the effect of mass injections and extractions to increase the performance of HDD systems. The humidifier area is 455 m^2 and the dehumidifier area is 4.88 m^2. The cycle examined was an open water, closed air cycle. They found the increase in GOR that reaches up to 10 % for a single extraction of the water from the dehumidifier into the evaporator. They proved that this extraction to the evaporator is more effective compared with reverse direction. The highest GOR of the HDD system is 5.65 when the flow of Extraction was about 20 % of circuit at a temperature of extraction 53.1°C. The extraction of the system produced lower values of GOR at lower temperatures. They proved that the best stream rate of extraction was approximately 40% of the total stream of whole unit. Additionally, when the size of humidifier and dehumidifier are increased, the product water and GOR increase. In summary, there are several main factors that affect the HDH units with extractions. They include (1) the temperature of injection and extraction and the rate of mass flow (2) cycle temperature and concentration range (3) the size of system; and (4) the mass flow rate ratio.

A theoretical and experimental analysis of solar HDH unit heated by water solar collectors is studied and built by Zhani [14] in Tunisia. He developed a steady state mathematical method for each component for heat and mass transfer. This method is generated by C++ program to demonstrate the influence of operative conditions on the performance of unit. The area of solar collectors is 7.2 m^2, the size of humidifier is 1.20m x 0.50m x 2.55m and for the dehumidifier dimensions are is 1.2m x 0.36m x 3.0m. The results indicate that, at the inlet of humidifier as the rate of mass flow of water increases, the GOR of the unit increases. There is an optimum maximum GOR of about 2.75 when the rate of water mass at humidifier is about 0.4 kg/s.

However, The GOR of the unit drops with increasing rate of water mass flow in the dehumidifier after that it becomes stable. The thermal performance of the water solar heaters increases with the increase in rate of water mass flow or decreasing the inlet temperature of water. However, it decreases when the intensity of solar radiation decreases except if the inlet temperature of water is the same as the ambient temperature, then it will have no affect at the thermal performance. Finally, the results of experiments were related to the simulation results and a good agreement was reported.

The performance of humidification dehumidification desalination system (HDH) powered by solar energy is theoretically investigated by Yıldırım and Solmus [15] for different system operating and design factors. They developed mathematical model of HDH system and the governing conservation equations are solved by using the Fourth order Runge–Kutta method. They calculated yields for different setup of HDH system for example only heating by air, heating by water and heating by both water and air. Since the air heat capacity is less than that for water, heating water has a main significance on the amount of produced fresh water. The production of fresh water is increased by the increasing the rate of mass flow of air and feed water. Conversely, the product water decreases if the mass flow rate of air increases above a certain value. The production of daily fresh water can be improved by operating the system 24 hours and the annual fresh water that can be produced reaches approximately 12 tons.

A low temperature solar humidification dehumidification (HD) desalination system is simulated using a computer code developed by Franchini and Perdichizzi[16]. A single stage humidification dehumidification system integrated with closed air cycle are used to introduce the loop of the proposed system. The optimization of the water and air mass flow rates and the heat exchanger surfaces was conducted via computer code with regards to the heat source temperature levels and the sea water. A 200 l/day of fresh water production is used to analyze the proposed system at different solar driven configurations. The first configuration when the HD unit operates using the exploited heat of absorption chiller driven directly via the solar collectors, while the other one when the solar collectors heat the salty water before entering the HD unit. Additionally, an integration between the well-known software; Transys environment and the computer simulation code for all systems has been conducted for transient simulation purposes.

An analytical analysis of a new HDH unit heated by water heater was investigated by Ghalavand et al [17] to compare it with two conventional HDH processes. The analysis showed that, under the same operating conditions, the gain output ratio of the new HDH technology of water-heated process is 2.7 Compared with the GOR of conventional air heated process CAOW and water heated process CAOW; which are 0.33 and 0.4 respectively. Also, the proposed method has lower cost of product water and higher production rate than the two conventional methods.

Sharqawy et al [18] have investigated the performance factors for modified air as well as water heated HDH cycle. The humidifier has same width for both cycles which is 0.25. However, they have different heights; the humidifier height for HDH system heated by air is 0.16 m whereas the height for the humidifier in the water heated system is and 0.97 m. Furthermore, the dehumidifier surface area of the air heated HDH is 47.1 m^2 compared with 11.7 m^2 for water heated HDH cycle. The calculations of their analysis demonstrate that for the HDH cycle heated by water, the optimal flow rate of mass ratio is continuously having a value more than 1.

However, for the adjusted HDH cycle heated by air it is always less than 1. When increasing minimum temperature of water or decreasing the maximum temperature of water the GOR of water heated cycle increase up to 1.93. In addition, optimal mass ratios increase when the minimum or maximum temperature of water increases. For the modified HDH cycle heated by air, The GOR increases up to 2.19 for as the effectiveness of humidifier increases with a consequence of increasing the size of system, the original cost and the optimal mass flow rate ratios. Finally, upon increasing the maximum temperature, the GOR of cycle increases.

An experimental investigation of a new configuration of HDH heated by a new type of air solar collectors was tested by Xing Li et al. [19].They used mathematical methods to design both the dehumidifier and humidifier. The humidifier cross sectional area is 500 mm x 400 mm and 150 mm in thickness. The rate of flow of heated water sprayed inside the humidifier is 4 L/min. For the dehumidifier, the rate flow of the cooling water is 18.3 L/min and the power of cooling is 2.1 kW. The outcomes indicate that, when they vary the temperature of inlet water to humidifier between 9 °C and 27 °C, the relative humidity of exit humid air increase from 89% to 97% and the temperature of exit air increase from 35 °C to 42 °C.as result of that, the production fresh water is improved at similar conditions of the flow of air and cooling.

An experimental study of an open-water and closed-air HDH desalination system is investigated by Kabeel et al. [20]. The experiments were executed in Kafr Sheikh University, Egypt. The humidifier has a cross sectional area 50 x 80 c m^2 and the height is 200 cm and the dehumidifier have a 20-cm radius and its height is 200 cm.

when the ratio of hot water at humidifier inlet is half of the cold water at condenser inlet, the maximum production is achieved; that is about 23.6 kg/h. furthermore, the natural air, forced up-down, and forced up circulation provides less performance than Forced down air circulation. However, natural air circulation provides almost similar efficiency as Forced up-down air circulation. Finally, the performance of the HDH unit is mainly affected by the area of wet surface.

Chehayeb et al. [21] designed a transport HDH unit with a single air extraction to the dehumidifier from the humidifier. The impact of the rate of mass flow ratio on the efficiency, the generation of entropy and the driving forces of heat and transfer mass is studied. Furthermore, energy effectiveness for heat and mass exchangers is generalized. The humidifier has a height of 3 m with a cross sectional area 0.05 m^2. For the dehumidifier, the length of pipe per tray is 2.5 m with a total of 30 trays. The ratio of pipe outer to inner diameter is 9.5 mm/8.7 mm and the diameter of coil 0.4 m. The results show that, when HCRd (heat capacity ration in the dehumidifier) is equal to 1, the generation of entropy decreases. The entropy generation per unit product decreases by decreasing the differences in the driving forces to the transfer of mass and heat. The best GOR is 3.8 when the extraction takes place.

Muthusamy and Sridhar [22] made an enhancement of the performance of a HDH unit by is made by placing three types of inserts in the air heater, two types of packing materials in the humidifier which are gunny bag and saw dust and also coil insert in the dehumidifier. The maximum distillate water for the improved HDH system was 0.670 kg/h per 0.0597 m^2 area of air heater with 45% increase of productivity than the basic HDH system. In the improved HDH system, the efficiency of energy was 44% and the efficiency of exergy was 38%.

An experimental investigation of solar air bubbling HDH unit is investigated by Khalil et al. [23].The influences of the temperature and height of water, the rate of airflow and diameter of holes on the system performances are detected during these experiments. The humidifier of the system has a cross section of 580 mm x 580 mm with 10 mm thickness, and 900 mm height. The dehumidifier dimensions are 400 x 400 mm, and the height is 900 mm. The kind of solar water collectors is an evacuated tube unit. The outcomes showed that, the GOR, productivity and efficiency are affect potently by flow rate of air and the temperature of inlet water to the humidifier. At temperature of inlet water of 62 °C, the daily efficiency, productivity and GOR are, 63%, 21 kg and 0.53, respectively. For all measurements, the variation of the temperature difference is less than 2.5 °C along the column. The best performance is obtained at outlet air from the 1 mm hole diameter bubble columns which is saturated. The formal humidifier gives lower performance than air bubble column.

A Thermodynamic analysis to calculate the efficiency of two arrangements of the HDH units combined with PTSC (parabolic trough solar collector) was carried out by Al-Sulaiman et al.[24]. In the first arrangement, the humidifier was placed after solar air heating collectors while the second arrangement the solar air heating collectors was located between the dehumidifier and the humidifier of HDH system (modified air hating system). The HDH unit is an open air and water with a PTSC air heated system.

The study showed that PTSCs is situated for air heated HDH units for location that have high radiation, for example Dhahran in Saudi Arabia. Also, the study demonstrates that the GOR of the first arrangement is about 1.5 while the GOR of the second arrangement have a greater value with an average of 4.7. Finally, during daytime throughout the year, the collector efficiency for PTSC has an average value of 0.71.

Kabeel et al.[25] made a theoretical and experimental investigation to study the performance of a solar HDH unit. They developed a mathematical model to evaluate the productivity and performance of the HDH system working at different operating times during the day, (from 9 am to at 17 pm) and (from 13 pm to 17 pm) respectively. The results showed that, a 22 L/day (11 L/day· m^2 of collector) freshwater production is recorded when the system operates in the second period while 16 l/day is recorded when the system operates 8 hours in a day. The results also showed that the cost per 1 liter of fresh water produced from the proposed system is 0.0578$.

CHAPTER 3 THEORETICAL DESIGN

3.1 Mathematical Modeling

For remote areas, humidification and dehumidification desalination (HDH) process is designed to be a suitable choice to produce fresh water in a small scale using source of waste heat or solar energy.

Figure 3.1 shows a schematic diagram of modified air-heated HDH cycle. In air-heated HDH cycle, the exit moist air from the evaporator (humidifier) is heated by air solar collectors and then it enters the condenser or (dehumidifier). In the humidifier, the colder air interacts with hot water so that the water gives its latent heat to the air, so the air becomes hot and humid. After that, the humid air will be heated sensibly by air heated solar collectors until it reaches its maximum temperature before it enters to the dehumidifier. Then, condensation process takes place. Air leaves the dehumidifier at the bottom and then flows back to the humidifier by blowing fans. It is worth to mention that the air enters the humidifier at lower temperature than water. This promises that the process of humidification is further beneficial than the situation where cold water and hot air are admitted to the humidifier (in conventional air heated system). Furthermore, only one stream is required to be heated for humidification purposes. It is important to mention that the hot air that enters the dehumidifier transfers heat to the cold water flowing inside the tubes and accordingly heat water that is sprayed then in the humidifier).

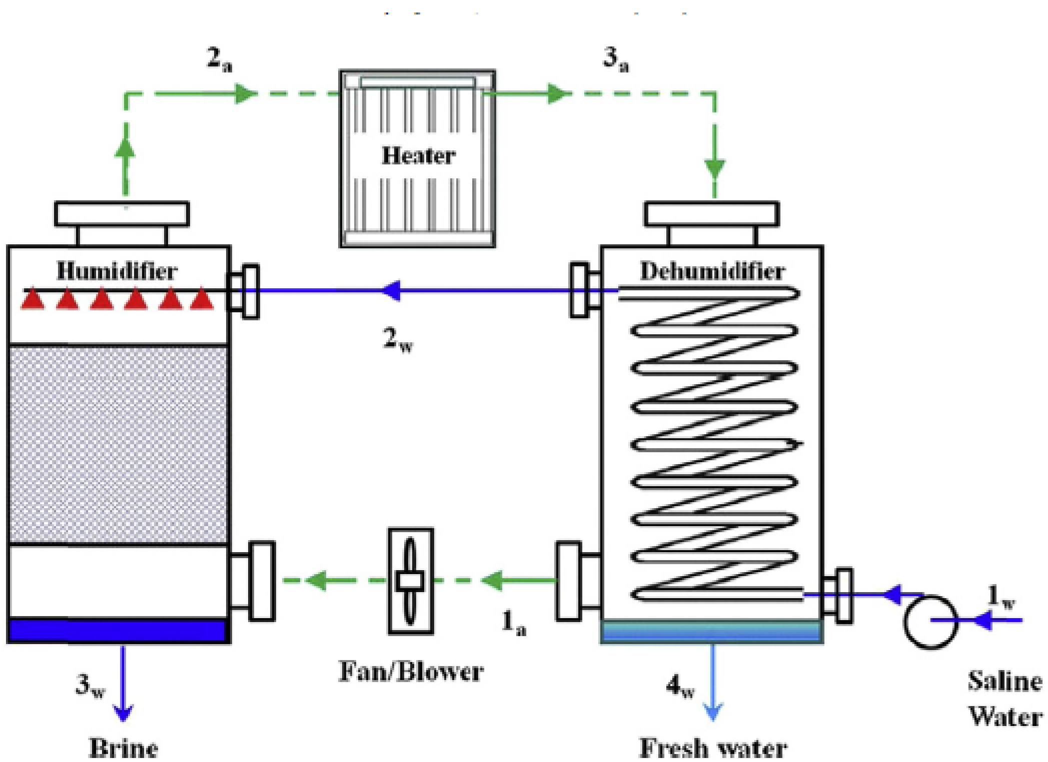

Figure 3. 1 Air-heated Humidification Dehumidification Cycle [18].

To design the air-heated HDH cycle shown in figure 3. 1, we need to consider the following assumptions that are used in design charts developed by Dr. Antar [18]:

- Steady-state operation.
- The heat losses from the components to the surrounding are neglected.
- The pumping power are negligible [1],[18].
- The thermal energy input should be calculated.
- Sea water with a salinity of 35 g/L is assumed for feed water.
- The relative humidity of moist air leaving the dehumidifier is assumed to be 90%.

The thermodynamic model for this model where energy and mass balances are applied on each components of the cycle following the first law of thermodynamics and mass conservation [27]. However, there are other variables that should be known to investigate the cycle and calculate its performance parameters.

These variables are the inlet water temperature at the dehumidifier (the minimum temperature), inlet water temperature at the humidifier. For the modified air heating system, the inlet air temperature to the dehumidifier is considered as the maximum temperature, in addition to the humidifier and dehumidifier effectiveness. The minimum temperature of water in the cycle at the inlet of dehumidifier may it vary between 10 – 30 °C because the temperature changes during the four seasons of the year [28]. The maximum water temperature in the cycle at the humidifier inlet is suggested to be between 50 and 70 °C to minimize the scale formation [28]. The humidifier and dehumidifier effectiveness are assumed to be between 65 and 95% [28].

This effectiveness is defined as the change of actual enthalpy to the maximum change of enthalpy for a simultaneous mass and heat exchanger [29]. The main model equations are summarized as:

Energy and mass balances of the dehumidifier give, respectively,

$$\dot{m}_a\left(h_{a,in} - h_{a,out}\right) = \dot{m}_w\left(h_{w,out} - h_{w,in}\right) + \dot{m}_{fw}h_{fw} \tag{3.1}$$

$$\dot{m}_{fw} = \dot{m}_a(\omega_{in} - \omega_{out}) \tag{3.2}$$

Effectiveness of the dehumidifier is expressed as [15],

$$\varepsilon_D = max\,\langle\frac{(h_{a,in}-h_{a,out})}{(h_{a,in}-h_{a,out,ideal})}, \frac{(h_{w,out}-h_{w,in})}{(h_{w,out,ideal}-h_{w,in})}\rangle \tag{3.3}$$

Where the ideal enthalpy of outlet air is calculated when the outlet air is fully saturated at the temperature of inlet water, while the ideal enthalpy of outlet seawater is when water temperature is equal to the inlet air dry-bulb temperature.

Energy and mass balances of the humidifier, respectively, are written as

$$\dot{m}_a\left(h_{a,out} - h_{a,in}\right) = \dot{m}_w h_{w,in} - \dot{m}_{br}h_{br} \tag{3.4}$$

$$\dot{m}_{br} = \dot{m}_w - \dot{m}_{fw} \tag{3.5}$$

Similar to the dehumidifier, the effectiveness of the humidifier is expressed as [15]:

$$\varepsilon_h = max \langle \frac{(h_{a,out} - h_{a,in})}{(h_{a,out,ideal} - h_{a,in})}, \frac{(h_{w,in} - h_{w,out})}{(h_{w,in} - h_{w,out,ideal})} \rangle \tag{3.6}$$

Energy balance of the air heater (for an air-heated cycle):

$$\dot{Q} = \dot{m}_a (h_{a,out} - h_{a,in}) \tag{3.7}$$

The following performance parameters are subsequently used to compare the HDH cycles:

1) Gain-Output- Ratio (GOR) which is the produced water multiplied by the latent heat of vaporization to the input of thermal energy which is the amount of input energy that is used to heat the air and water by solar collectors and heaters, as expressed by Eq. (3.8)

$$GOR = \frac{\dot{m}_{fw} \times h_{fg}}{\dot{Q}} \tag{3.8}$$

2) Recovery ratio (RR) which is the produced water to the seawater mass flow rate, as given by:

$$RR = \frac{\dot{m}_{fw}}{\dot{m}_{sw}} \tag{3.9}$$

3) Mass flow rate ratio (MR) which is the seawater mass flow rate to mass flow rate of dry air in the cycle, as given by:

$$MR = \frac{\dot{m}_{sw}}{\dot{m}_a} \tag{3.10}$$

3.2 System Design

The air-heated HDH cycle is designing to produce fresh water with average production rate of 5 L/hr. Based on that, we assumed some main parameters of HDH system to reach our target of the produced fresh water. One of these assumptions is the effectiveness of the humidifier which influences the amount of water vapor carried to the recycled air that leaves the humidifier. Another assumption is the effectiveness of the dehumidifier; which influences how much of the humid air will condense in the system. These assumption values of the humidifier and dehumidifier effectiveness are 80%. The other parameters are the maximum temperature of the sea water for the cycle which is about 60 °C and the minimum temperature which is 30 °C. The average latent heat of condensation and evaporation is taken at 45°C which would be 2345 kJ/kg.K. A summary of initial design parameters is shown in Table 3.1

Table 3. 1 The assumed design parameters of the air-heated HDH cycle.

Parameter	Value
Fresh water rate (m_{fw})	5 L/hr.
Humidifier effectiveness (ε_h)	80%
Dehumidifier effectiveness (ε_D)	80%
Maximum temperature (T_{max})	60 °C
Minimum temperature (T_{min})	30 °C
Latent heat of evaporation (h_{fg})	2345 kJ/kg*k

on these assumptions, the other main design parameters for HDH air heated cycle can be calculated based on the step-by-step process given by Sharqawy et al. [18] as the following:

a) The thermal heat input rate of solar air collectors ($\dot{Q}_{in}$).

b) The rate amount of supply feed seawater ($\dot{m}_w$).

c) The amount of air that circulated in the cycle ($\dot{m}_a$).

d) The width and height of the humidifier packing material (W and H).

e) The dehumidifier area (A).

Figure 3. 2 shows that the effectiveness of the humidifier and dehumidifier with the gain output ratio (GOR) as presented in [18]. The GOR of the HDH system increases with the increase in the effectiveness of the humidifier and dehumidifier. It is meaningful to realize that at higher humidifier effectiveness, the gain output ratio is high.

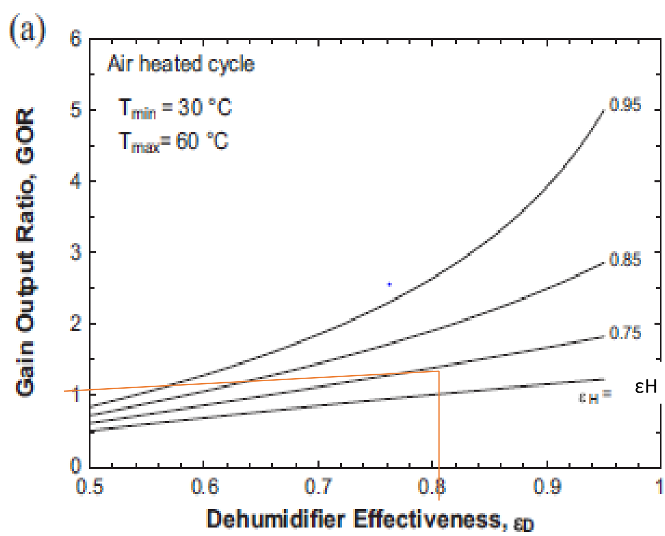

Figure 3. 2 Gain output ratio vs humidifier and Dehumidifier effectiveness [18].

From figure 3. 2, for the assumed effectiveness of humidifier and dehumidifier which is 0.8, the GOR of the theoretical design of air-heated cycle is about 1.4. Then, the amount of heat required to operate the HDH system to produce the required amount of fresh water can be calculated as follow:

$$GOR = \frac{\dot{m}_{fw} \times h_{fg}}{Q_{in}}$$

$$1.4 = \frac{0.0014 \times 2345}{\dot{Q_{in}}}$$

$$\dot{Q_{in}} = 2.34\ kW$$

So, theoretically the heat input for the air-heated HDH system to produce 5 L/hr is 2.34 kW. This amount of heat input can be used to heat the air as we neglect the pumping and fan powers. Figure 3. 3 shows the dehumidifier effectiveness variation with the ratio of the optimum mass-flow rate at which GOR is maximized for the cycle at the given operating conditions where an effectiveness of 80% is assumed for both the humidifier and dehumidifier.

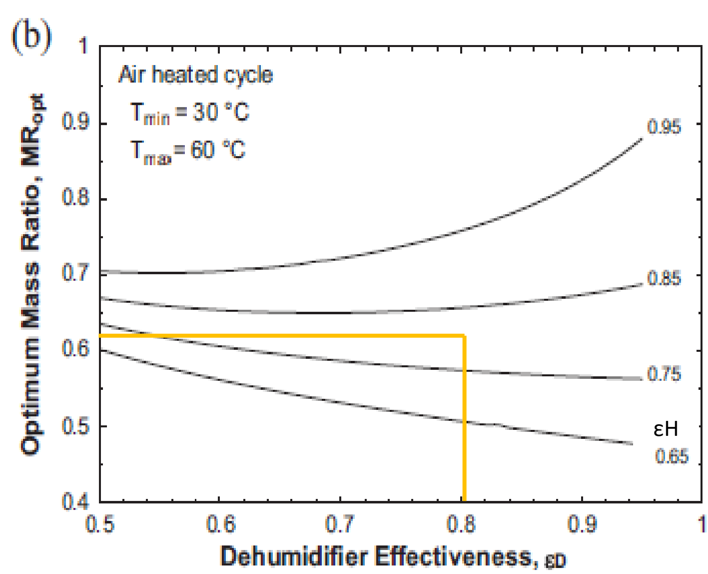

Figure 3. 3 Optimum mass flow rate ratio vs Dehumidifier effectiveness [18].

From figure 3. 3, the ratio of mass flow rate (MR) is found as 0.62 with respect to the dehumidifier effectiveness. After that, the amount of heated air required for the HDH system to heat the inlet cold sea water is calculating as the following:

$$MR = \frac{\dot{m_{sw}}}{\dot{m_a}}$$

$$\dot{m_a} = 0.081 \text{ kg/s}$$

So, the amount of recycle air required to heat the inlet sea water is 0.081 kg/s. As shown in figure 3.4, at lower effectiveness of humidifier, with increasing effectiveness of dehumidifier the ratio of mass decreases because the product water is less. Conversely, higher effectiveness of humidifier needs higher ratio of mass as the effectiveness of dehumidifier increases because of the amount of vapor that leaving the humidifier is increased. Comparable for recovery ratio to the cycle of air-heated where higher recovery ratio corresponds to higher effectiveness of both the humidifier and dehumidifier because the amount of vapor leaving the humidifier is increased as well as the amount of fresh water that produced by the dehumidifier.

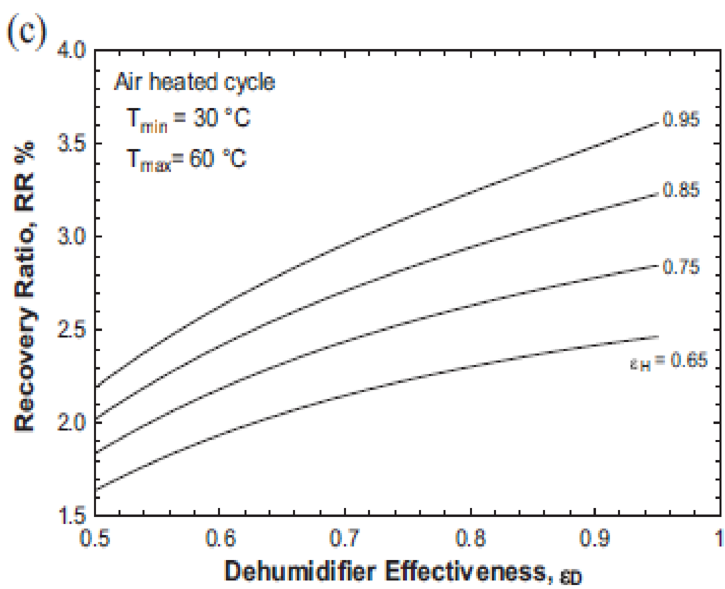

Figure 3. 4 Recovery ratio vs Dehumidifier effectiveness [18].

From figure 3. 4, we can predict the recovery ratio (RR) for the HDH system which is found about 0.0275. After that, the sea water flow rate required for the HDH system is calculated as follow:

$$RR = \frac{\dot{m}_{fw}}{\dot{m}_{sw}}$$

$$0.0275 = \frac{0.0014}{\dot{m}_{sw}}$$

$$\dot{m}_{sw} = 0.051 \text{ kg/s}$$

$$0.62 = \frac{0.051}{\dot{m}_a}$$

Therefore, the sea water flow rate required producing 0.0014 kg/s of fresh water is 0.051 kg/s.

3.3 Performance and Sizing of the Humidifier and Dehumidifier

3.3.1 Humidifier model.

In this HDH cycle, the humidifier that is used is a packed bed counter-flow humidifier. The air inlets from the bottom of the humidifier and pass through the packing material, hot supply water is sprayed from the top of the humidifier.

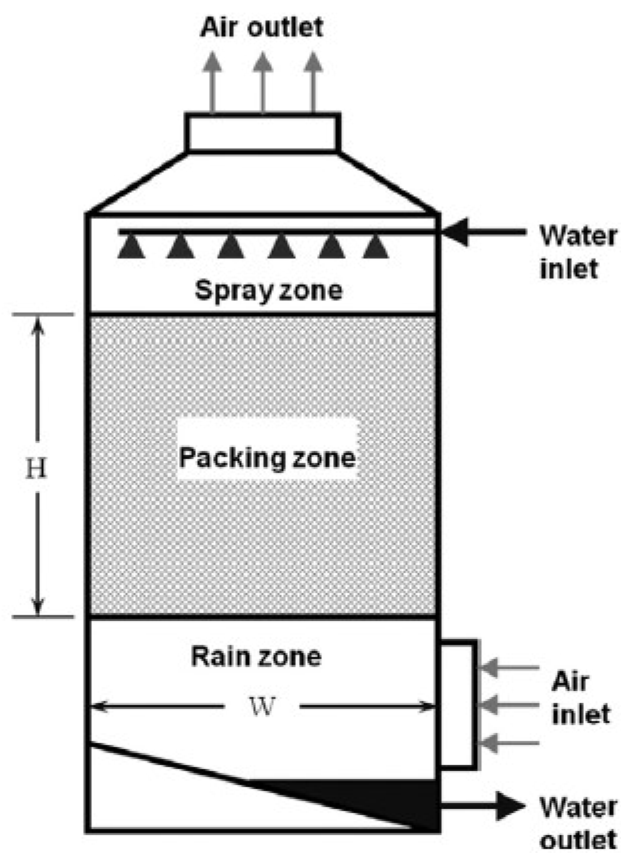

Figure 3. 5 A schematic of the humidifier [18].

In this process, the packing material helps to increase the area of mass transfer contact. The hot water in the humidifier is used to heat and humidified air. Then it leaves the humidifier as a brine with higher salinity compared to its condition at the inlet. A schematic of the humidifier is shown in figure 3. 5. The humidifier can be divided into 3 main zones. start from the top of humidifier which is the spray zone where the nozzle of spread water exists in the middle of the humidifier.

Then, there is the packing material to maximize the contact surface area between hot water and warm air (packing zone). The lowest zone is where the air enters the humidifier and it is the first contact between air and water (rain zone).

the main purpose of this design is to determine the required width , height and cross sectional area) for the humidifier which is the most important part for the system because almost 90% of the mass and heat transfer takes place [30]. Also, to find Merkel number which is a dimensionless number used to describe any equipment that is used to exchange mass and heat transfer for example humidifiers and cooling towers. It helps to design the packing materials because the relationship between the mass flow rate ratio, Merkel number, and packing height. the following correlation (3.11) is given to relate Merkel number to height [7] and the mass flow rate ratio

$$Me = 2.049 \times MR^{-0.779} \times H^{0.632} \tag{3.11}$$

The following assumptions are considered to design the counter-flow packed-bed humidifier [31].

- Negligible convection and radiation between the walls of humidifier and environment;
- U cross-sectional area of the humidifier is uniform;

Now, from the design calculation presented in the previous section, we can come up with the design specifications for the humidifier and dehumidifier. The humidifier cross section area can be calculated using Eq. (3.11).

$$\text{Humidifier Cross section area} = \frac{\dot{m}_{sw}}{\text{water mass flux}} \tag{3.12}$$

The water mass flux is assumed to be 1 kg/m^2. s. So, the required cross-sectional area of the humidifier is found as 0.05 m^2. After that, assuming square cross-sectional area for the humidifier, hence the required width is 0.22 m. Figure 3. 6 shows the height of packing rely on the ratio of mass-flow-rate, temperature of inlet water and effectiveness of humidifier. From figure 3. 6, for a humidifier effectiveness of 0.8 and optimum mass-flow rate ratio of 0.62, making an interpolation for the water-inlet temperature of 60 °C, the Markel number is 0.7 and the required packing height of the humidifier is found as 0.091 m.

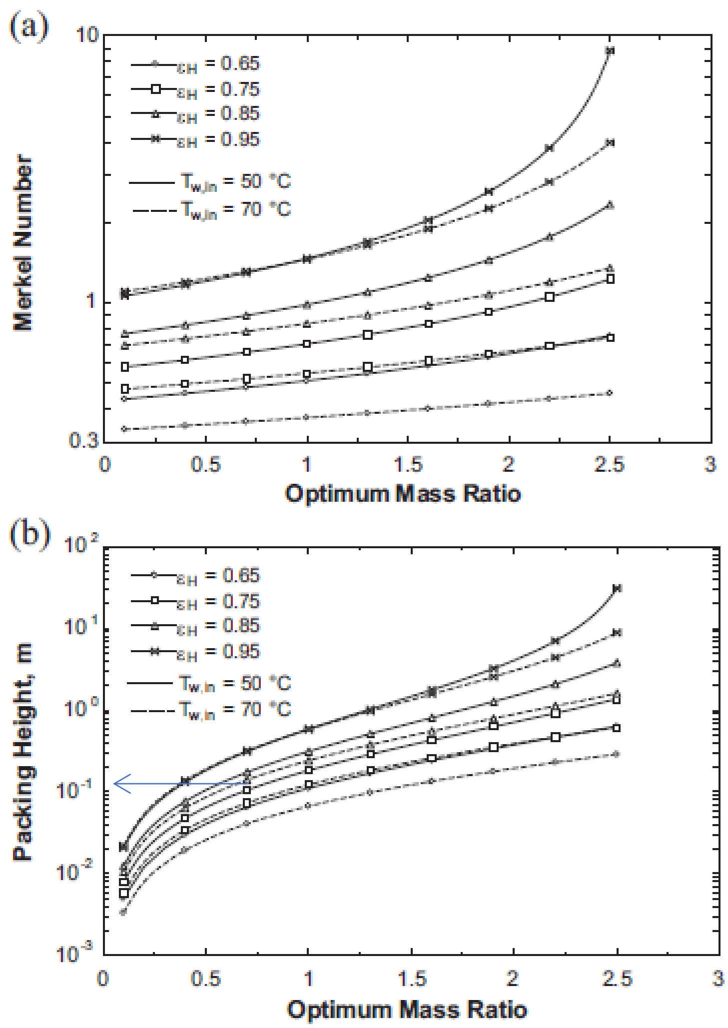

Figure 3. 6 (A) Merkel number, (b) packing height vs. optimum mass-flow-rate ratio for packed-bed humidifier [18].

3.3.2 Dehumidifier model

A schematic of the dehumidifier is shown in figure 3. 7 that shows the length of tube and its fins. The effectiveness – number-of-transfer unit (ε-NTU) is one of the most main ways to design dehumidifier or heat exchangers. This method is used to find the surface area that is needed with a given information of mass-flow-rate ratio and dehumidifier effectiveness. The dehumidifier demonstrated in figure 3. 7 is considered as a cross-flow of unmixed fluid heat exchanger. To calculate the size of humidifier we assumed that , the latent heat transferred by condensation of water vapor in the moist air is neglected since it small amount compared to the feed water.

Therefore, the NTUs is found by using the assumed effectiveness of dehumidifier and the minimum heat-capacity ratio using the effectiveness and number transfer unit ε-NTU relationship of the cross-flow heat exchanger.

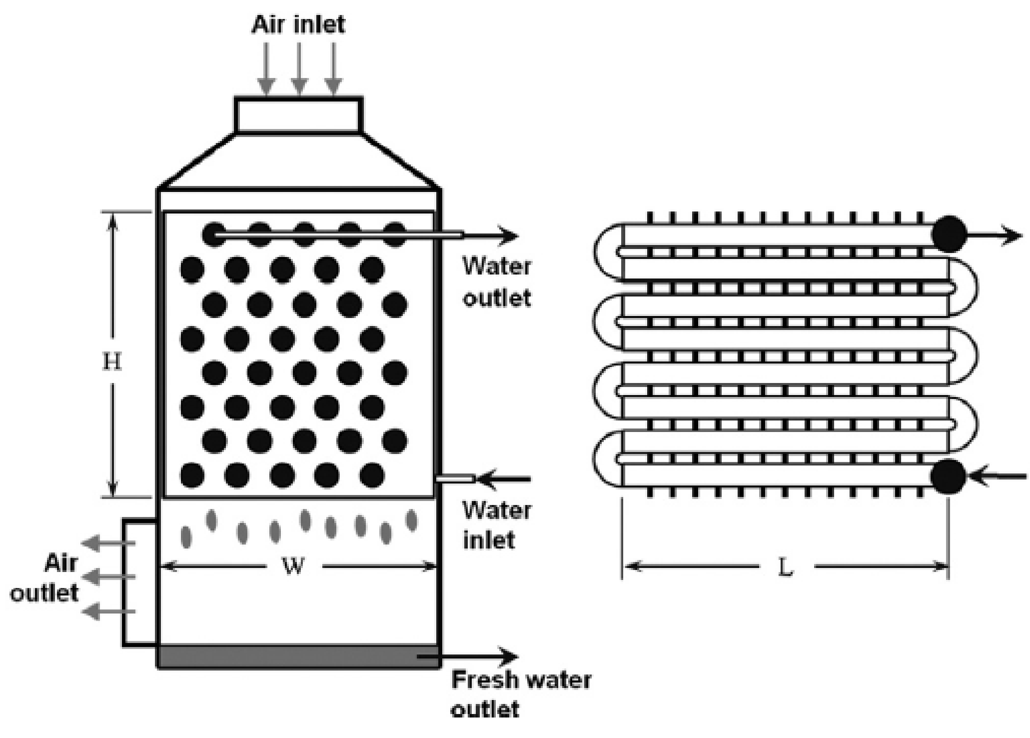

Figure 3. 7 A schematic of the dehumidifier [18].

For the dehumidifier, the heat-capacity rate of the inlet air to the dehumidifier is calculated from Eq. (3.12),

$$\text{Heat capacity rate of inlet air} = \dot{m}_a \times C_{ma} \tag{3.12}$$

$$0.081 \times 1.009 = 0.081 kW/k$$

The heat capacity rate of inlet seawater to the dehumidifier is calculated as,

$$\text{Heat capacity rate of inlet water} = \dot{m_{sw}} \times C_{sw} \tag{3.13}$$

$$0.051 \times 4.19 = 0.21\ kW/k$$

Therefore, the minimum heat capacity of the air and water streams (C_{min}) is related to the mass flow rate ratio of the HDH cycle, and given by Eq. (3.14),

$$C_{min} = min\left[\frac{MR \times C_{sw}}{C_{ma}}, \frac{C_{ma}}{MR \times C_{sw}}\right] \tag{3.14}$$

$$C_{min} = min\left[\frac{0.62 \times 4.19}{1.009}, \frac{1.009}{0.62 \times 4.19}\right]$$

The minimum heat capacity is 0.38 from Figure 3. 7 for heat capacity ratio and the effectiveness of the dehumidifier. Figure 3. 8 shows the different of the number of transfer units (NTUs) of a dehumidifier with the ratio. The number of transfer unit can be determined which is found about 2.2.

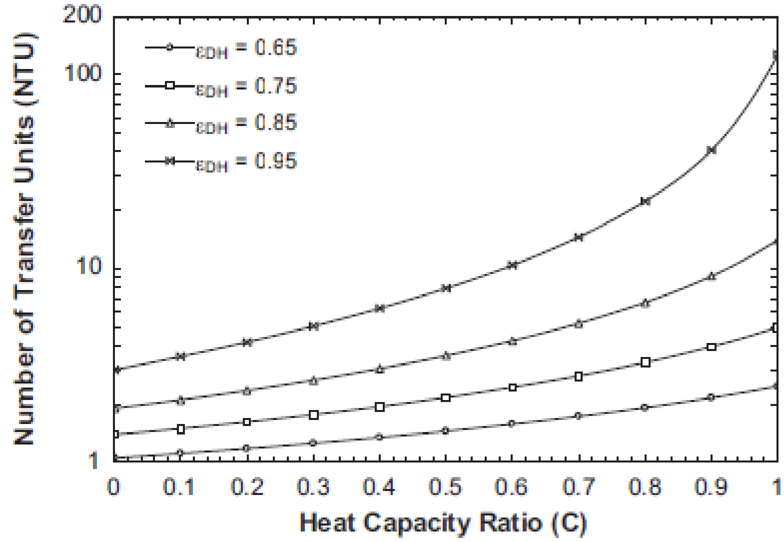

Figure 3. 8 Number of transfer units vs. heat-capacity ratio for the dehumidifier [18].

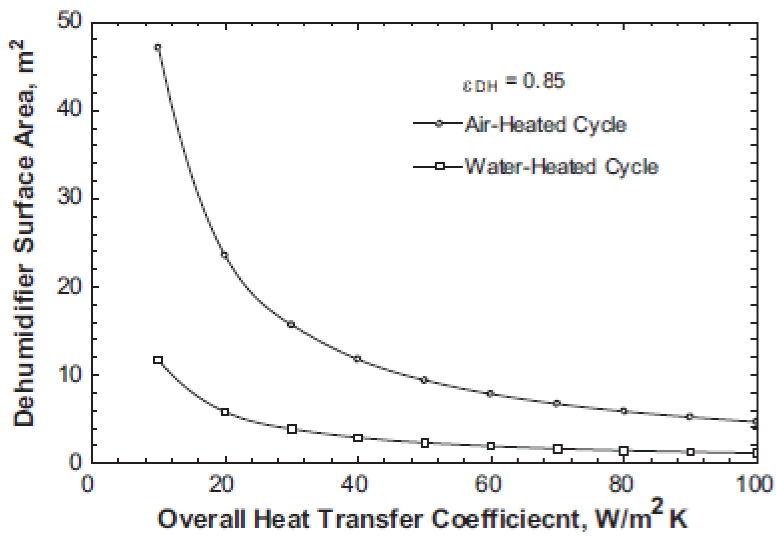

Figure 3. 9 The total surface area of the dehumidifier given in the example changing with the overall heat transfer coefficient [18].

Finally, the number of transfer units for a dehumidifier is 3.1 and interpolating the value of overall heat transfer coefficient from El-Dessouky book [32].

$$T_C = (1617.5 + 0.1537\,T + 0.1825\,T^2 - 0.00008026\,T^3)\ 1 \times 10^{-3}$$

Form dehumidifier water flow rate we assumed the overall heat transfer coefficient is 100 W/m^2 K, so from figure 3.9 we can determine the total surface area required which would be 5 m^2.

To conclude that, Table 2 summarizes the results of the theoretical design for air-heated HDH cycle.

Table 3. 2 Air heated HDH result design.

Parameters	Values
Freshwater production rate	5 L/h
Gain-output ratio	1.4
Recovery ratio	0.0275
Optimum mass-flow-rate ratio	0.62
Heat-rate input	2.34 kW
Seawater flow rate	0.051kg/s
Air-flow rate	0.081 kg/s
Humidifier Merkel number	0.7
Humidifier width	0.22m
Humidifier height	0.09m
Dehumidifier number of transfer units	2.2
Dehumidifier surface area	5m^2

CHAPTER 4 EXPERIMENTAL SETUPS

4.1 Introduction

In this chapter, different setups for the closed-air open-water solar air heated HDH system is discussed. Evacuated tube solar collectors are used to heat the air after it leaves the humidifier. Based on the theoretical calculation we tried different setups to produce a sufficient quantity of fresh water for the system. In some of the setups the components designs were changed, or components are rearranged to build a suitable HDH system for remote area. It took over a year to start the production with the HDH system.

4.2 HDH System Setups

4.2.1 The First HDH setup:

In this setup, the (CAOW) air-heated HDH desalination system is built based on the theoretical calculations shown in the Chapter 3. The main components as seen in figure 4.1 are dehumidifier, humidifier, blowers and the solar collectors for air heating. The process of this setup starts by pumping water from a large tank and blowing air in closed cycle inside the system. At the coiled tubes dehumidifier, the pumped water enters with an ambient temperature to cool the inlet humid and hot air leaving the solar collectors through direct contact between humid air and the tubes of cooler water. Furthermore, the cold water absorbs the latent heat of hot humid air after that the condensation process begins, and the fresh water is produced. The produced water as seen in figure 4.1 is collected from the bottom of the dehumidifier in a small tank. Then, warm air enters the humidifier below the packing material in counter flow direction to the inlet warm water sprayed on the packing material. The process of humidification occurs when the Shower nozzle sprays hot water downward whereas humid air flows to the top of humidifier. The packing material is used to increase the contact area for heat and mass transfer and accordingly increase the humidity of air. Humid air leaves the humidifier with higher temperature and with relative humidity of almost 95%. Then, humid air leaves the humidifier and enters the blowers whereas water leaves the system to a small container. There are two blowers used to circulate the air throughout the system because one blower not sufficient to our system. After the humid air is blown through the pipelines it enters the solar collectors to be heated. There 8 solar collectors where each one of them generates a maximum heating energy equivalent to 0.3 kW. The air solar collectors are tilted and setup with angle same as latitude of Dhahran city (26°). Humid air leaves the solar collectors and enters the dehumidifier with almost 100 °C; which is the maximum temperature. The system is operated from 8 am to 4 pm. The piping system of the humid air is 3” size and is made from PVC with maximum pressure 90MPa while water pipes have a diameter of 1.5 in.

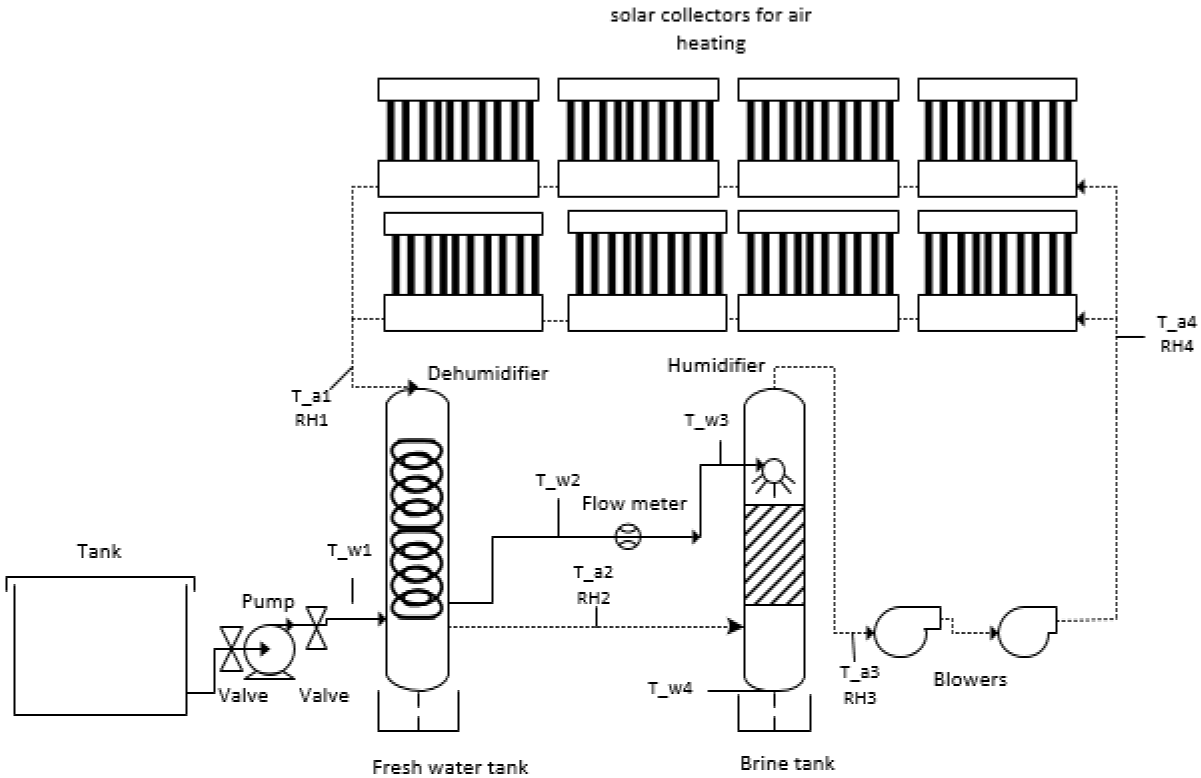

Figure 4. 1 Schematic diagram for first setup of (CAOW) air-heated HDH.

4.2.2 The Second HDH Setup:

As seen in figure 4.2 the demonstration of the system is the same as previous one. However, there is a change that is occurring in one of the main components which is the dehumidifier. The dehumidifier is changed into a cross flow unit that has three finned tube units. This dehumidifier specification is discussed in 4.2.2. As the flow of the humid air enters the dehumidifier from the top the cold water enters the tubes of the condensers from the bottom. Humid air will be distributed inside the dehumidifier and will condense on the surface of the box, the tubes and the fins. As a result, we find that this setup is better than the previous one. However, the amount of condensation water still needs to be improved.

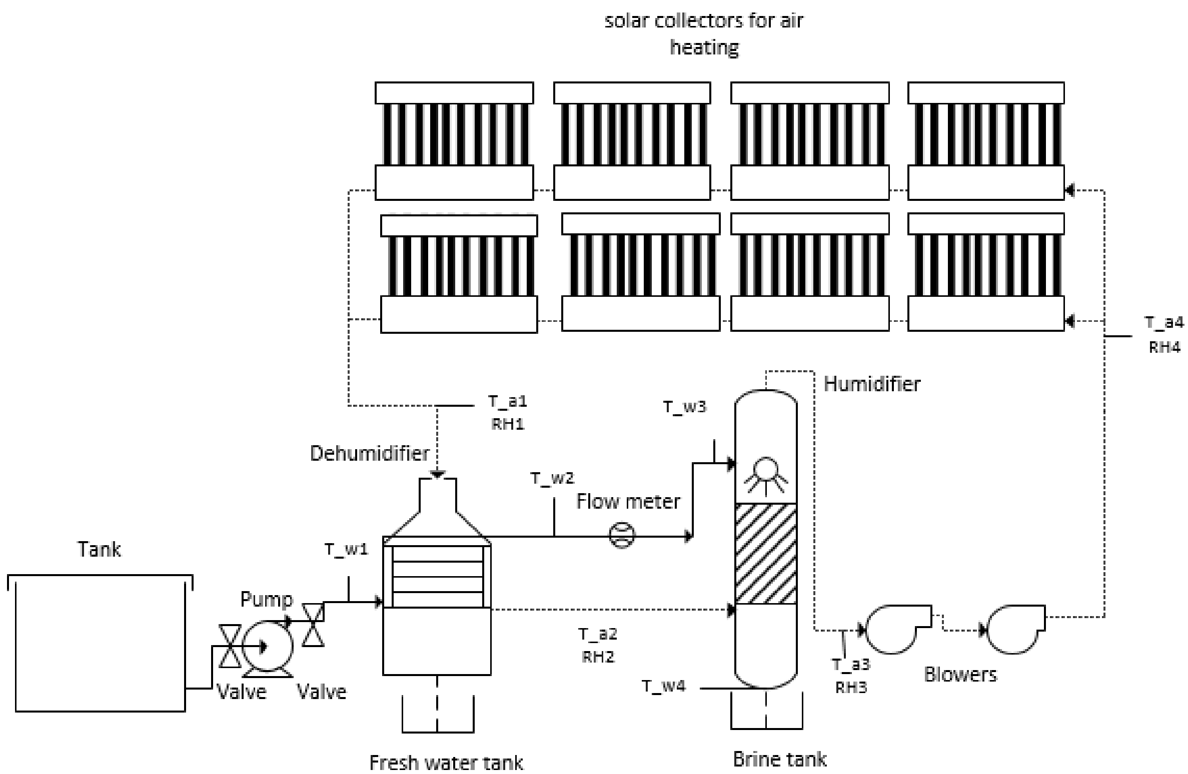

Figure 4. 2 Schematic diagram for second setup of (CAOW) air-heated HDH desalination system.

4.2.3 **The Third HDH Setup:**

After we examined the new cross flow dehumidifier and we found that this change gave a better result we decided to change the arrangement of the setup. After a couple of readings from the first two setups, we found that there is condensation of a portion of the humid air takes place inside the blowers and pipes located between humidifier and solar collectors. This condensation happens because that the humid air is transported in a relatively long distance, which is about 3 meters of piping. As a result, we decide to change the location of them to be between the dehumidifier and humidifier as seen in figure 4.3. This change will reduce the distance after the humidifier and decrease the condensation through the pipe.

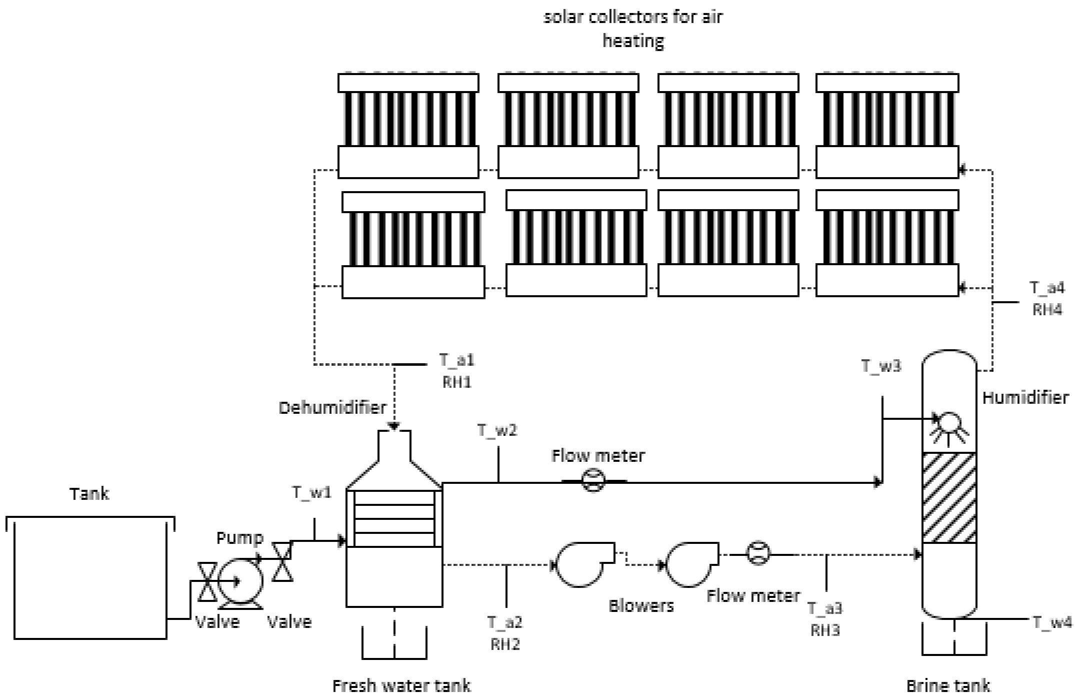

Figure 4. 3 Schematic diagram for third setup of (CAOW) air-heated HDH desalination system.

4.2.4 The Fourth HDH Setup:

This setup is like the third setup. However, there is a small change that make a massive effect in the results. usually, the inlet water to the humidifier is changed as we change the flow, or the weather is changed. because of that, the system needs something to make the temperature of water under control. As we see in figure 4.4, a heater is placed before the inlet of the humidifier to increase and control the inlet temperature of water.

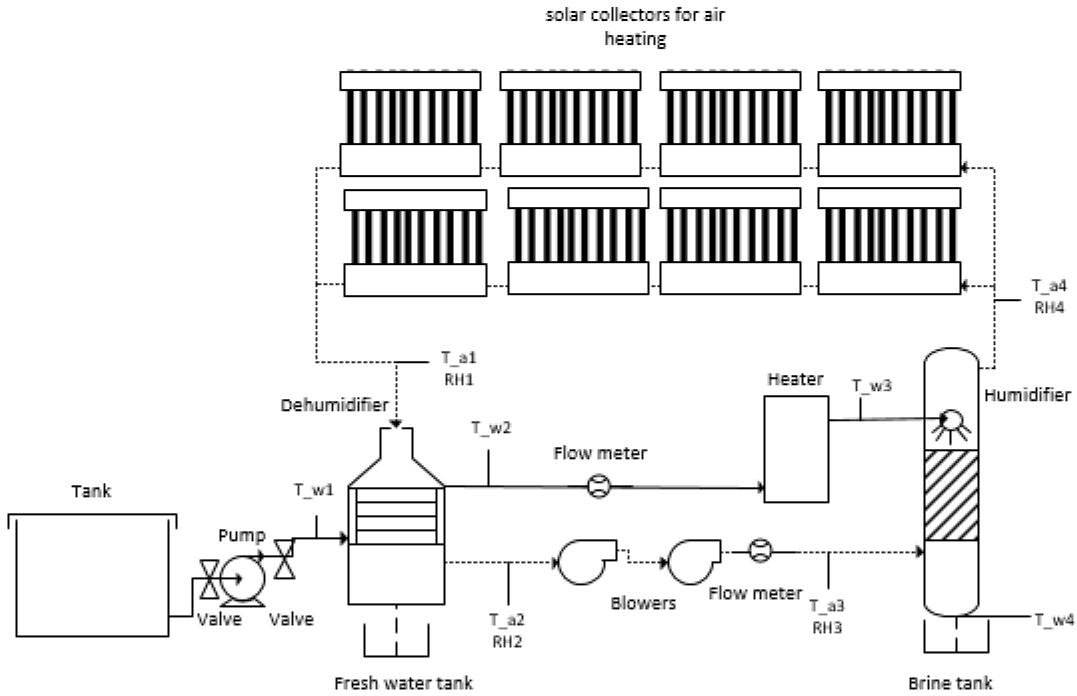

Figure 4. 4 Schematic diagram for fourth setup of (CAOW) air-heated HDH desalination system.

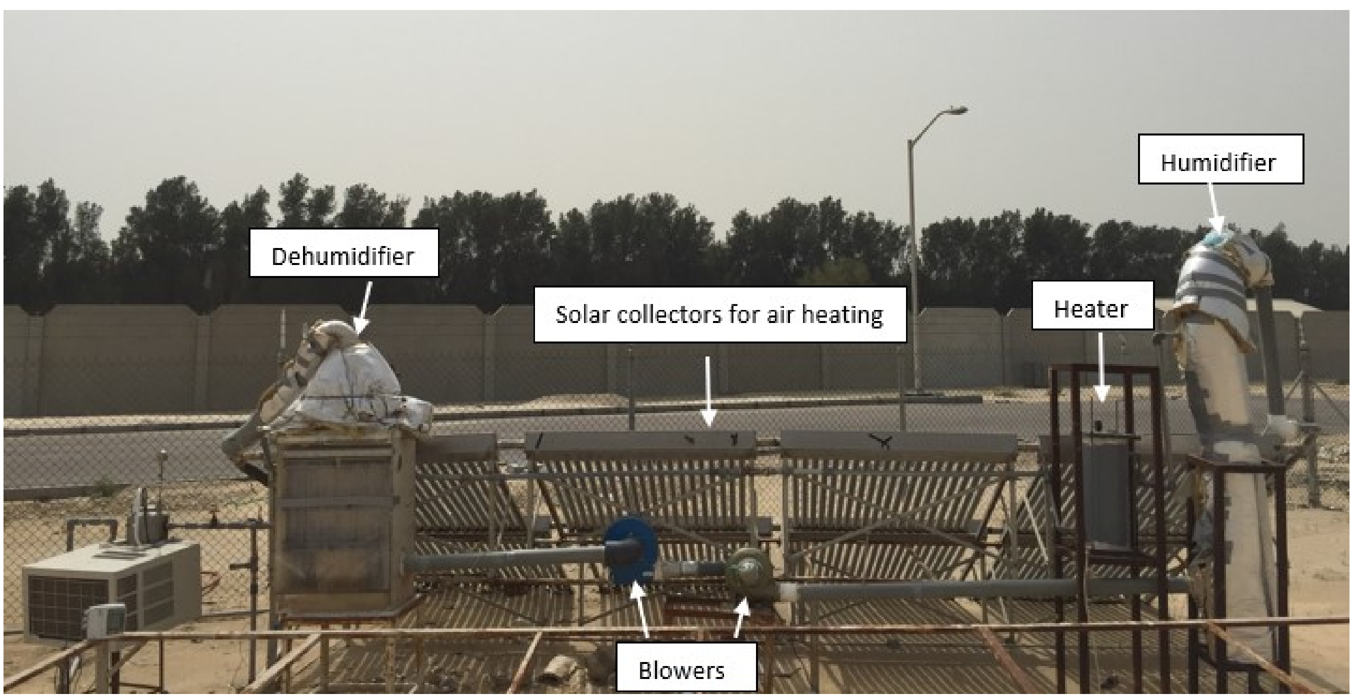

Figure 4. 5 The fourth setup of (CAOW) air-heated HDH desalination system at the beach.

Figure 4. 6 The fourth setup of (CAOW) air-heated HDH desalination system at the beach.

4.3 System Components

4.3.1 **Humidifier**

The humidifier is one of the main components at the HDH system. It is similar to cooling towers in principle of operation or like an evaporator in a thermodynamic cycle. The main purpose of the humidifier to exchange the heat and mass between water and air. Therefore, it increases the humidity of the inlet air. There are three main components for the humidifier casing, spray zone and packing material. The studied HDH system casing is made from PVC with cylindrical shape its diameter is 8 inches. The spray is located at the top of the humidifier and it is made from hard plastic material that is suitable for high water temperature up to 80 degrees Celsius. The packing material is designed to distribute the water and increase the contact area between air and water that increases the humidity ratio of exit air for the system. The packing material is made from fibers with a width of 8 inches and 15 inches in height. At the humidifier there are two inlets, one for air and one for water. Also, there are two exits, one for water and one for air. Air enters the humidifier with almost 30 degrees Celsius and 50% relative humidity. Also, water enters the humidifier with high temperature between 50 to 70 and it sprays inside the humidifier. The contact between humid air and hot water occurs. The contact increases dramatically between them at the packing material region. After the contact occurs the humid air will be more humid and hot. The temperature of humid air leaving the humidifier is between 40-50 degrees Celsius and its relative humidity between 90-100%. The remaining water or saline water will be discharged from the humidifier at the bottom exit to the environment at almost 40 degrees Celsius.

The humidifier is held by a manufactured stand that is made in KFUPM workshop to support it and be protected from environment hazards. The height of humidifier is 2 meters and 0.2 meter in width. The inlet and the exit of the air is 3 inches in diameter and made from uPVC material. However, the water pipe size is 1 inch.

Figure 4. 7 Humidifier.

1: inlet of humid air.

2: outlet of hot humid air.

3: Inlet of hot water.

4: outlet of water.

4.3.2 The Coiled Dehumidifier

The water cycle inside the dehumidifier begins from its bottom section. There are two coiled tubes that cover most of the volume of the dehumidifier. Hot humid air enters from the top and leave from bottom section after it cools down by the inlet water. The produced fresh water is designed to leave the system from the lowest point and it is controlled by a valve. the specifications of the coiled tubes are shown in table 4.1.

Table 4. 1 The specifications of coiled tubes dehumidifier.

Parameters	Values
The diameter of big cycle (D_{bc})	0.18 m #40 cycles
The diameter of small cycle (D_{sc})	0.1m #50 cycles
$T_{max, a}$	102 °C
$T_{min, a}$	35 °C

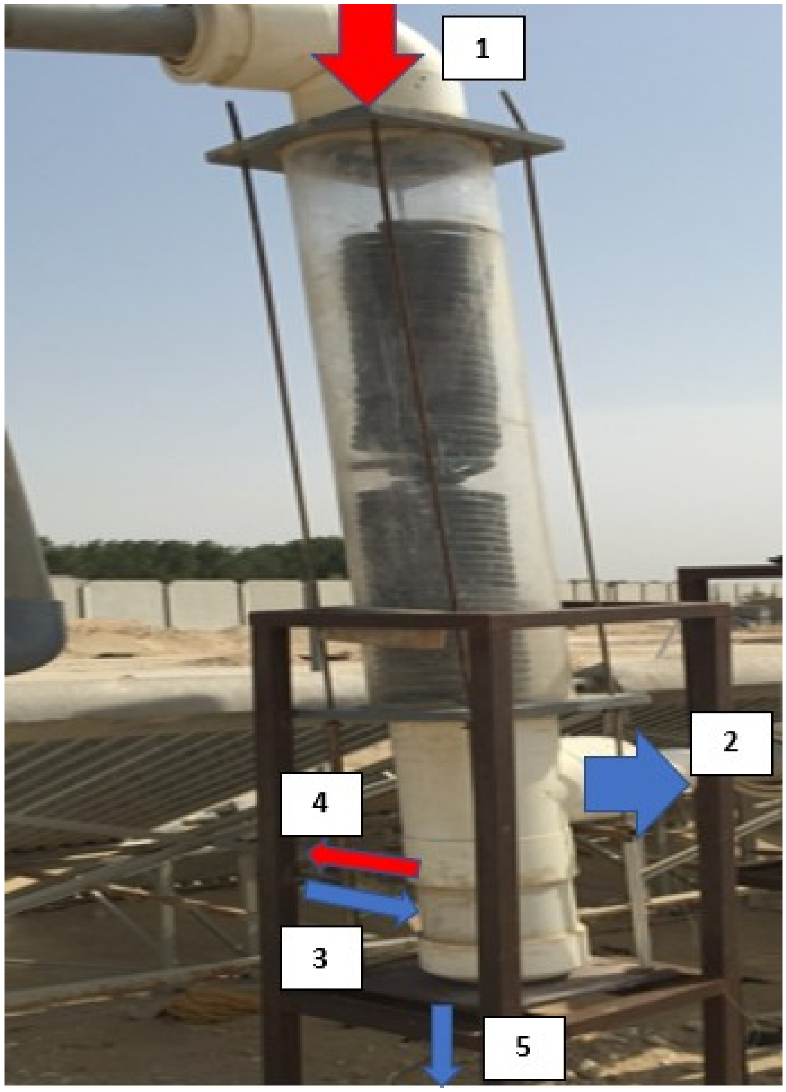

Figure 4. 8 The Coiled Tubes Dehumidifier.

1: Inlet of hot humid air.

2: Outlet of humid air.

3: Inlet of water.

4: Outlet of hot water.

5: Outlet of fresh water.

4.3.3 **The Cross-Flow Dehumidifier**

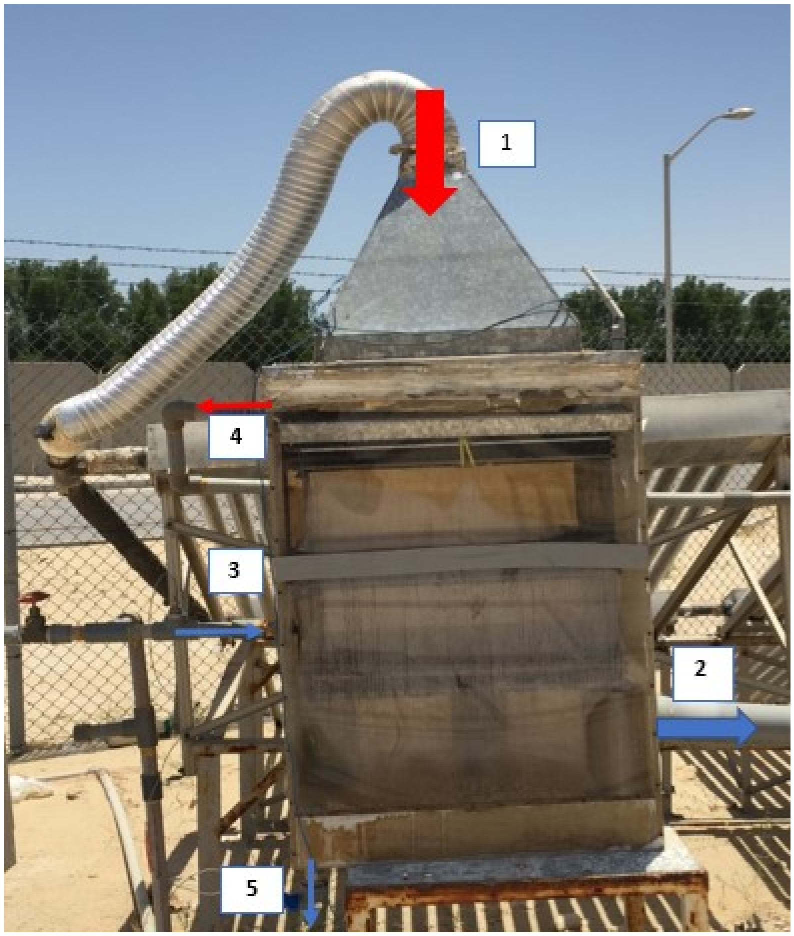

Figure 4. 9 The cross-flow dehumidifier.

1: Inlet of hot humid air.

2: Outlet of humid air.

3: Inlet of water.

4: Outlet of hot water.

5: Outlet of fresh water.

The dehumidifier is one of the main components of the HDH system or any desalination process. It allows the humid air to condense and make fresh water. The dehumidifier is manufactured and designed to carry and handle the hot water and to produce about 5 L/hour at ideal conditions. In this experiment, the dehumidifier has two entrances and three exists. For water there is one for the produced fresh water and the others are for cooling water (inlet and exit). Air has one entrance and one exit. As shown in Figure 4.9, the hot air enters the dehumidifier from the top with almost 100 degrees Celsius and about 4% relative humidity. Humid air leaves the dehumidifier at almost 30 degrees Celsius to be recirculate again in the HDH system. Also, we can see from figure 4.9 that the water entrance at the left bottom corner (3). It enters the dehumidifier at about 25 degrees in winter and it increase to reach 35 degrees in summer. After the hot air transfers its latent heat to the water, the hot water leaves the dehumidifier as seen in the top left corner (4) and its temperature is verified between 40 -60 degrees Celsius. This range depends on many factors such as, the temperature of hot air, the flowrate of air, and the flowrate of water. Furthermore, to get fluids into and out of a humidifier and make sure that heat transfer occurs efficiently we selected copper tubes for water that is surrounded by aluminum fins to increase the rate of heat transfer between cold water and hot air. There are 3 condensers elements inside the dehumidifier that are separated from each other and attached vertically by aluminum sheets that is 10 cm high. Each condenser contains 32 tubes with 3/8 inches the width of each condenser is 21”, the length is 60 inches and the height is 7 inches. The inlet and the outlet pipes of dehumidifier are made of PVC that is designed for high temperatures and its size is 1”. For the air side, we chose aluminum that used for duct and it is well insulated to prevent heat exchange with the environment. The size of the inlet is 4 inches in diameter and the material for the inlet hot air as well as the material of the outlet air is PVC and its size is 3 in. We decide to choose a higher diameter to reduce the compression of the air inside the system. the casing of the dehumidifier is made from hard fiber glass with 10 mm thickness. finally, the height of dehumidifier is 1m, the length is 62 and the width is 22 cm.

4.3.4 **Heater**

The heater is used to increase temperature of water that leaves the dehumidifier to be in the rage of 50 to 70 degree Celsius before it enters the humidifier. The heater is manufactured and modified at KFUPM. Water enters the heater from the bottom and leaves when its compressed from the top. The flow is steady. The input power is 1200 watt which is used for home heaters and it is located at the bottom. The increase in water temperature depends on the rate of steady flow and the input power to the heater. This heater is modified to inlet power one from the top and the original one that allow to increase the water temperature further and control the exit water temperature. The heater is cylindrical in shape as seen in Fig 4.10 and its height is 50 cm and diameter is 8 inches. The heater cabinet is made of grey PVC and the heater input is made from copper with U shape.

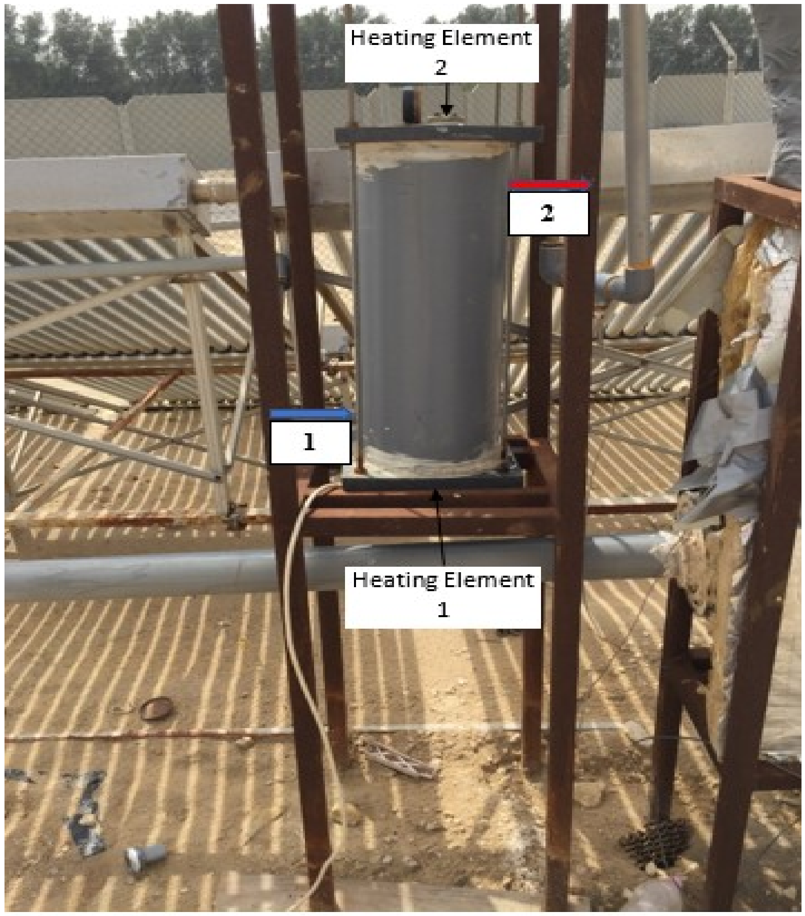

Figure 4. 10 Heater.

1: Inlet of warm water.

2: Outlet of hot water.

4.3.5 **Blowers:**

The modified air heated HDH system has two blowers which are needed to circulate the humid air throughout the closed cycle and to reach the needed amount of air flow rate during the experiment. This closed path allowed to keep most of moist air inside the system to increase the amount of intake humidity from the humidifier and increase the amount of produced fresh water. The two blowers are centrifugal blowers while each one has specific features because that there are insufficient markets that sell blowers with same features. The factors considered to choose these blowers are the price, quality, and the maximum amount of delivered air that would not cause flooding of water at the top of the humidifier. However, the market controls the product. The first blower is a centrifugal blower which is made in Slovakia. The material of casing, the blade and all parts are stainless steel. The stainless steel is painted to protect the metal from corrosion and increase the product life. The suction inlet is circular with 5 inches diameter whereas the outlet is square, and its width and length are 3 inches. The produced power is 1/2 HP and its speed of rotation is 3450 rpm. The other blower is made from FRB composite in Taiwan. The volumetric rate of delivered air is 12,05m^3/min. its speed of rotation is between 3000 to 3600 RPM. The diameter of the suction side is 4 inches. The two blowers are attached to each other by 3 inches PVC pipe and give an average velocity 3 m/s which is equivalent to 821 L/min. Each of them has its stand, Stands are manufactured at KFUPM. The blowers are operated by electrical power of 220V.

Figure 4. 11 stainless steel blower.

Figure 4. 12 FRB composite blower.

4.3.6 Pump

The pump is used to deliver water from the tank to the system. There is only one centrifugal pump which is located after the tank and it has a valve before and after with a union to dismantle it easily when it needs maintenance. The specifications of the pump are shown in table 4.2.

Table 4. 2 Pump specification.

Casing material	Stainless steel
Power	1 HP
Maximum load	0.9 kW
Input voltage	127/220V

Figure 4. 13 Pump.

4.3.7 **Air Heated Solar Collectors**

|One of the main components which are used to decrease the amount of used input electrical power for the system is air heated solar collectors as a source of clean energy. They are tilted in 26^{o} to get the maximum input solar irradiation. They are divided into two groups that are connected parallel to each other. The first group contains four air heated solar collectors with their stands on the ground. The others are the same number are elevated 1 m from ground to be outside the shadow region of the first group. Each air heated solar collector produces a power of 0.3 kW and the total produces power for the system from them are 2.4 kw. This amount allows to increase the temperature of outlet humid air to reach 100 ° C.

Figure 4. 14 Air Heated Solar Collectors.

4.3.8 Storage Tank

The raw water needed for the system that is stored in the beach is a 20000 L horizontal fiberglass storage tank. This tank is chosen to provide the sufficient raw water for the remote area. Furthermore, to save the temperature of water from the hot weather the 20000 L is chosen. the following in table 4.1 is the specifications of water tank.

Table 4. 3 Tank specifications

Parameter	Value
Width	250 cm
Length	415 cm
Height	270 cm
Thickness	8 mm
Capacity	20000 Liter

4.4 Instruments

4.4.1 Thermocouples

A Thermocouple consist of two wires made from different metals. The wires ends are welded together and create a junction which is the point where the temperature is measured. The type of thermocouples that we used to measure water and air temperatures is a K Type Thermocouple (Nickel-Chromium) as seen in figure 4.15.

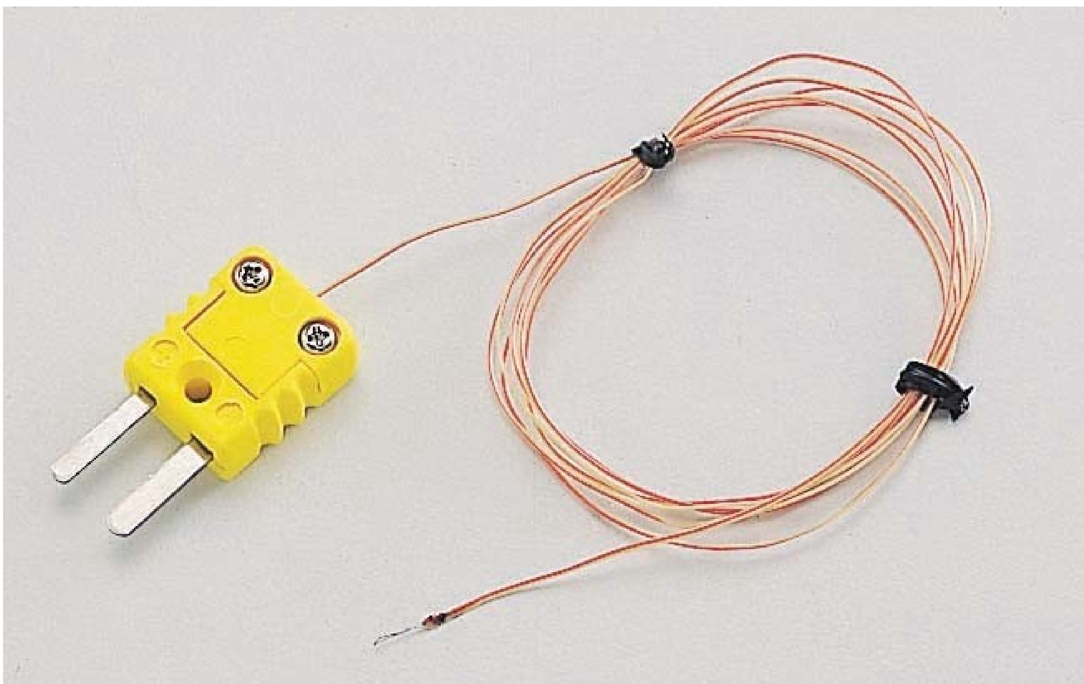

Figure 4. 15 Thermocouple.

4.4.2 Portable Thermometer readout

The portable RDXL4SD is a handheld thermometer/data logger. Data loggers are powered by an internal battery and are capable of sampling, processing and displaying measurements without being connected to a computer. The unit we used can record up to 12 temperatures. The **accuracy** of thermometer is ± (0.4% + 1ºC).

Figure 4. 16 Portable Thermometer.

4.4.3 **Flow meter**

The flow meter is FLC Series that is made by Omega company. It is an economical way to measure the water flows rate . It fixed after the dehumidifier with a horizontal installation.

Table 4. 4 FLC series flow meter specifications.

Performance	
Measuring accuracy	±5% of full-scale
Repeatability	±1% of full-scale
Flow Measuring Range	1-30 GPM (5-110 LPM)
Maximum operating pressure	325 PSIG (22.4 bar
Maximum operating temperature:	200°F (93°C)

Figure 4. 17 Water flow meter.

4.4.4 **Portable Anemometers**

The OMEGA™ HHF-SD1 combination hot wire and standard thermistor anemometer is used to measure the velocity and air temperature. Also, it suitable to use in such applications as environmental testing, balancing of fans/motors/ blowers, air conveyors, clean rooms, and flow hoods. We can measure the velocity of air inside the pipe through a small circular diameter that is almost bigger than the probe. Then, we fit the probe through the center of the pipe and took the reading.

Table 4. 5 OMEGA™ HHF-SD1 specifications.

Performance	
Measurement range for temperature,	(0 to 50ºC);
Measurement range for air speed	0.2 to 25 m/sec
Measurement accuracy for air speed:	± (5% + 0.1 m/sec)
Measurement accuracy for temperature:	(± 0.8ºC)
minimum SD card capacity	1 GB to 16 GB
Operating temperature	(0 to 50ºC)
Operating relative humidity	0 to 85%
Weight of instrument	(515g)
Dimensions of probe	(12mm(diameter)x280mm.(collapsed)/940mm.(extended))

Figure 4. 18 The OMEGA™ HHF-SD1 combination hot wire and standard thermistor anemometer.

4.4.5 **Omega Humidity Ratio**

The RH318 is a low cost, good performance with data classification ability. It used to measure the humidity, temperature and dew point temperature. The temperature/humidity sensor that is used in the probe is a semiconductor and a thermistor temperature and polymer capacitive sensor.

Table 4. 6 Handheld Hygro Thermometer specifications.

SPECIFICATIONS	
Sensor Type	Electronic capacitance polymer film sensor/NTC
Relative Humidity Range	0 to 100% RH
Temperature Range	-20 to 60°C
Resolution	0.1% RH, 0.1°C, 0.1°F
Accuracy Probe (RH318-RP)	<10% RH, >90% RH ±4.0% RH 10% RH to 90% RH ±2.0% RH -20 to 60°C ±0.8°C
Response Time (In Slow Moving Air)	Humidity: 180 s Temperature: 10s
Operation Temperature	0 to 40°C (32 to 104°F)
Operation Humidity	10 to 90% RH
Storage Temperature	10 to 60°C
Storage Humidity	10 to 75% RH
Dimensions Probe	15 D x 94 mm L
Weight	Approx. 285 g

Figure 4. 19 Handheld Hygro Thermometer.

CHAPTER 5 RESULTS AND DISCUSSIONS

5.1 Introduction

The open water closed air HDH air heated cycle have been theoretically and experimentally design as it was descried in the previous chapters.

In this chapter the reading for the modified CAOW air heated HDH system is classified based on different mass ratios from 0.7 to 2.2 to specify the optimum mass ratio. The first value of the mass ratio is chosen randomly. Then, we increased it until the result show that the performance dramatically decreasing and vice versa. In addition, we conducted the experiments to study the effect of weather conditions during the day-time on the GOR, humidifier effectiveness, dehumidifier effectiveness, humidity ratio of the inlets and outlets of humidifier and dehumidifier, the inlet water temperature of dehumidifier, the input energies of humidifier, dehumidifier, solar collectors, and water heater. Also, the effect of maximum water temperature on maximum humidity ratio for different mass ratio will be discussed in this chapter.

5.2 The Behavior of Humidity Ratios Inside the System During Operation Hours for Different MR

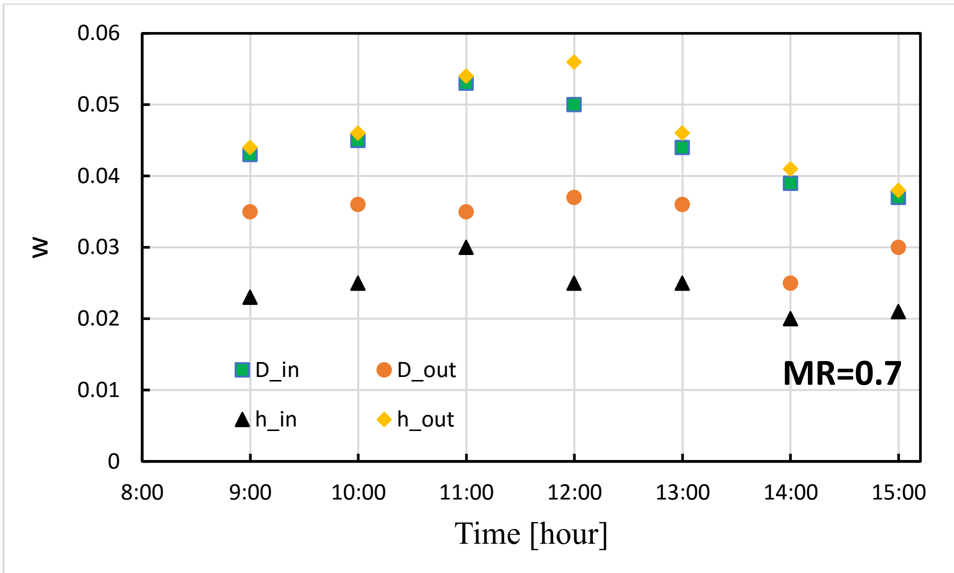

Figure 5. 1 The behavior of humidity ratio inside the system during system operation hours for MR=0.7.

Test Conditions: average air temperature of 37°C, air flow rate of 821 L/min, water flow rate of 0.5 L/min, and date 11/May/2017

Note from Fig. 5.1 that the humidifier increases the humidity ratio substantially (For example at 9:00 AM) from 0.023 to 0.042. This value also represents the humidity ratio of air entering to the dehumidifier. Then due to condensation in the dehumidifier, the value of the humidity ratio reduces to 0. 035.It further decreases to 0.023 upon condensation in the fan and air conduit through which air passes to the humidifier. Similar trends can be seen for each hour of the presented data. The insignificant decrease of the humidity ratio values between the exit of the humidifier and inlet of dehumidifier is due to minute air leaves within the solar collectors and the pipes connecting them.

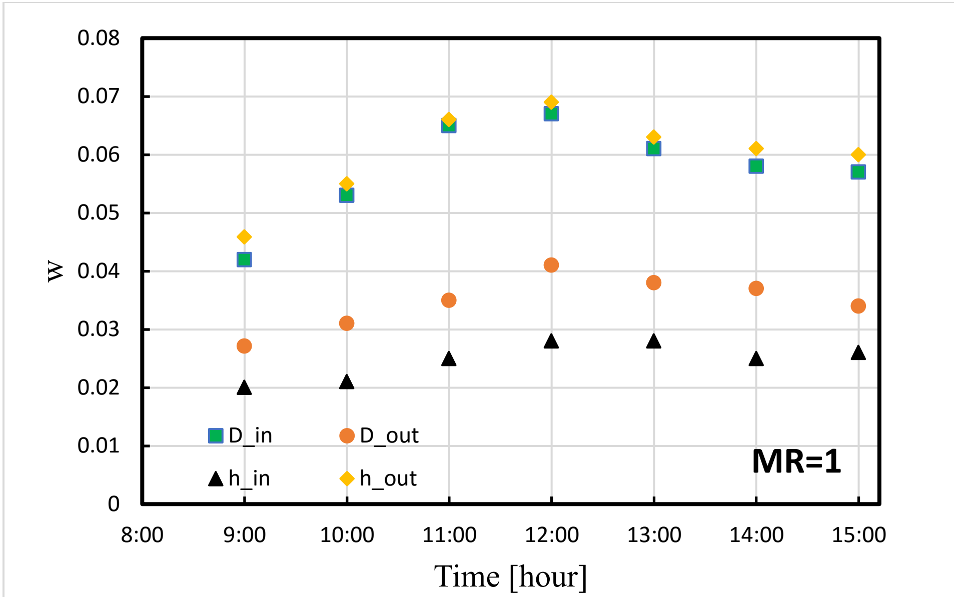

Figure 5. 2 The behavior of humidity ratio inside the system during system operation hours when MR=1.

Test Conditions: average air temperature of 33^{o}C, air flow rate of 821 L/min, water flow rate of 0.7 L/min, and date 26/April/2017

Figure 5.2 shows the humidity ratio values at different locations inside the system during operating hours for MR equal to 1. The graph depicts that, the humidity ratio values increase with time until 12 PM where they reach the maximum values. Then, they decrease until the last hour of experiment. The humidity ratio values of humidifier exit, and dehumidifier inlet have a close result and their range are from 0.04 to 0.07. However, after the condensation process, the humidity ratio values are between 0.02 and 0.04. There is a reduction of humidity ratio between the exit of dehumidifier and the inlet of humidifier because of the losses in humid air during the condensation and the blowing process inside the pipes in addition to the accuracy of measuring probe.

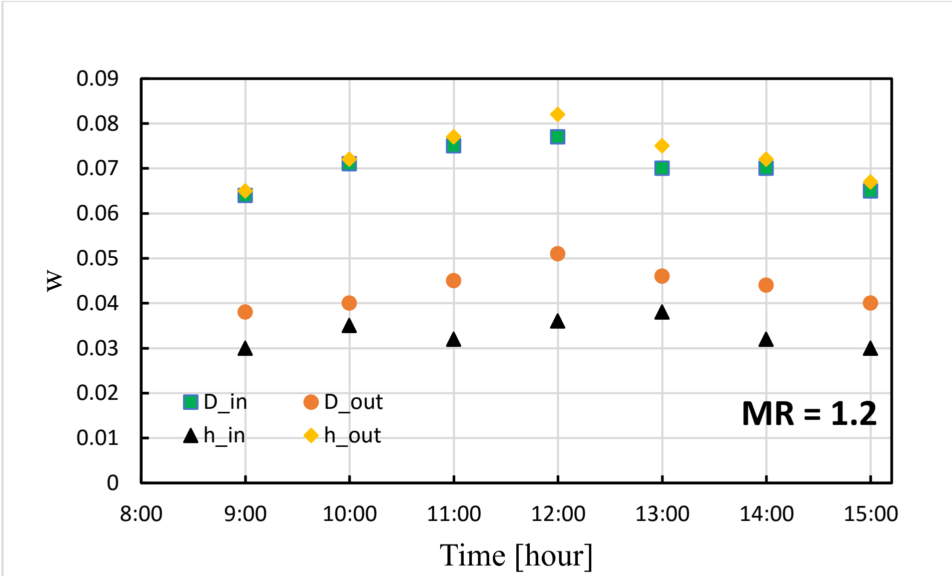

Figure 5. 3 The behavior of humidity ratio inside the system during operation hours when MR=1.2.

Test Conditions: average air temperature of 37°C, air flow rate of 821 L/min, water flow rate of 0.8 L/min, and date 2/May/2017

The values of humidity ratio inside the system start with increasing trend until they reach the peak at 12 PM. After that they decrease till the last hour of the operation. The humidification prosses the humidity ratio increases (for example) at 12 PM the humidity ratio increases from 0.038 to 0.082. However, the humidity ratio of the air after the heating process by solar collectors there is a minor loss by almost 0.002 due to the losses of some humid air to the environment through the pipe lines. Then, the dehumidification prosses decreases the humidity ratio for example at 12 PM the value decreases from 0.08 to 0.05 due to the condensation of some humid air. At 12 PM where the maximum values of the humidity ratio, the humidity ratios values of dehumidifier outlet and humidifier inlet are 0.05 and 0.038 respectively. This decrease of humidity ratio between outlet dehumidifier and inlet humidifier because that there is some loss of moist air to outside environment during air blowing by blowers.

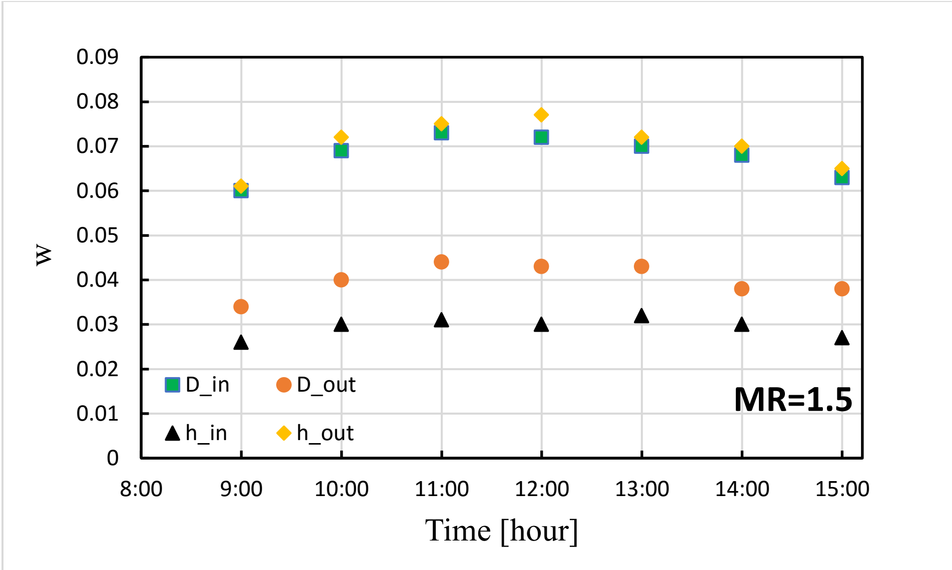

Figure 5. 4 The behavior of humidity ratios inside the system during operation hours when MR=1.5.

Test Conditions: average air temperature of 37°C, air flow rate of 821 L/min, water flow rate of 1 L/min, and date 3/May/2017

The values of humidity ratio inside the system versus time for MR equal to 1.5 are shown in figure 5.4. The values of humidity ratio increase with time until it reaches their peak at 12 PM then start to decrease until the last hour of the operation duration. Values of humidity ratio of the dehumidifier inlet and humidifier outlet are close to each other. The values range is between 0.06 and 0.077. After dehumidification, the values range is between 0.025 and 0.045. There is a reduction of humidity ratio between outlet of the dehumidifier and inlet of the humidifier by almost 0.01 due to the humid air losses and some condensation through the pipe line and its connections with blowers. In addition, there is an insignificant reduction of humidity ratio values between outlet of the humidifier and inlet of the dehumidifier because of heating by air heated solar collectors.

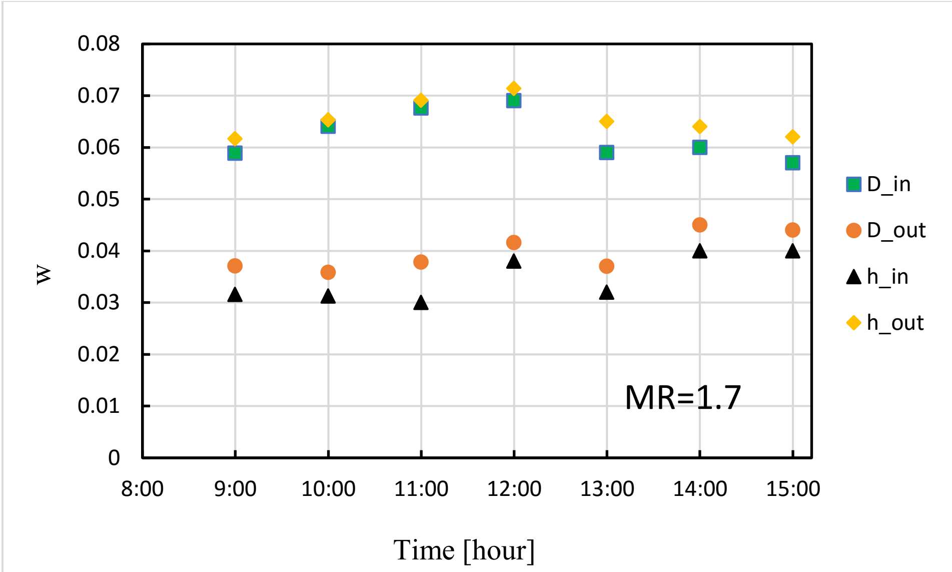

Figure 5. 5 The behavior of humidity ratios inside the system during operation hours when MR=1.7.

Test Conditions: average air temperature of 39°C, air flow rate of 821 L/min, water flow rate of 1.1 L/min, and date 28/March/2017

Figure 5.5 shows that humidity ratio of the humidifier and dehumidifier during operation hours for MR equal to 1.7. The humidity ratio values range of humidifier inlet and dehumidifier outlet is between 0.03 and 0.045. However, the humidity ratio values range after the humidification is between 0.057 and 0.071. There is an insignificant decrease of the humidity ratio values between the exit of the humidifier and inlet of dehumidifier is due to miniature air leaves within the solar collectors and the pipes connecting them in addition to the accuracy of the measuring probe. Also, there are some losses of moist air to the outside environment during air blowing by blowers between the exit of the dehumidifier and the inlet of humidifier.

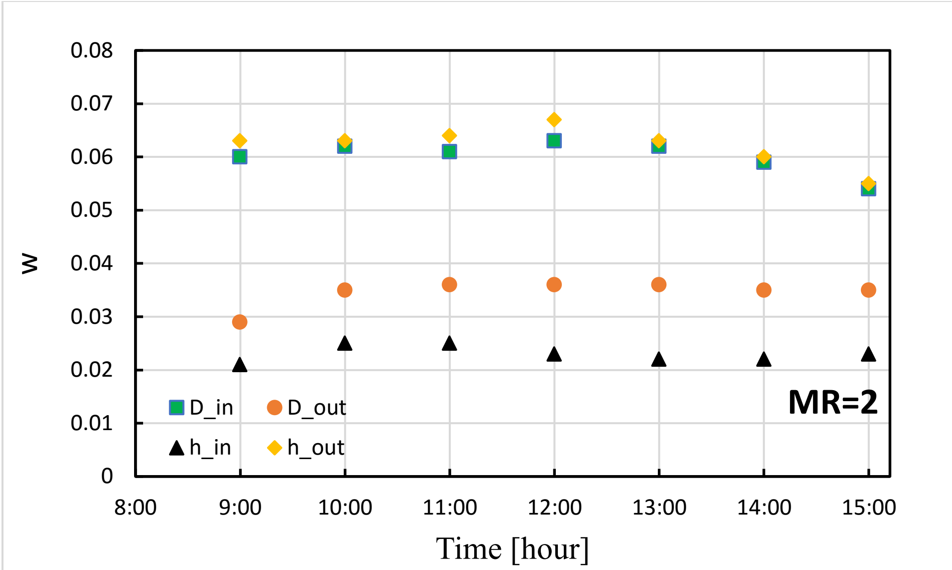

Figure 5. 6 The behavior of humidity ratios inside the system during operation hours when MR=2.

Test Conditions: average air temperature of 36°C, air flow rate of 821 L/min, water flow rate of 1.4 L/min, and date 27/April/2017

Humidity ratio of the system increases until it achieves its peak at 12 PM then it decreases until the last hour of operation as shown in Fig. 5.6 for a Mass flow rate ratio MR = 2. The humidity ratio values of the dehumidifier inlet and humidifier outlet are close to each other. These values are between about 0.054 and 0.067. After the condensation process, the values of the humidity ratio reduce to a range between 0.021 and 0. 036. There is a reduction of the humidity ratio values between the exit of dehumidifier and humidifier inlet by about 0.01 because there are some losses of moist air during air blowing. Also, there is an insignificant reduction of humidity ratio values between exit of the humidifier and inlet of the dehumidifier because of the possibility of air leak while heating in the solar collectors and flowing out form the humidifier and into the dehumidifier in addition to the accuracy of the measuring probe.

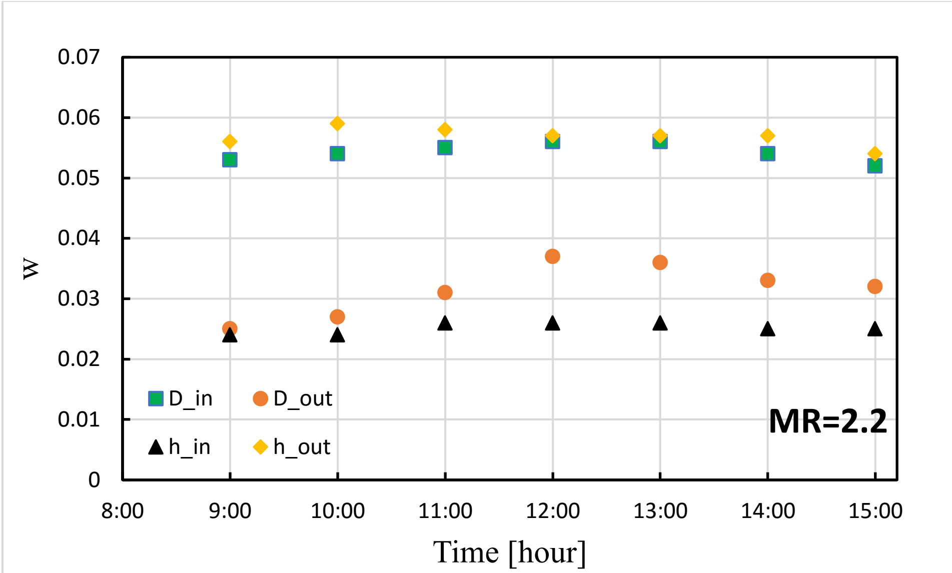

Figure 5. 7 The behavior of humidity ratios inside the system during operation hours when MR= 2.2.

Test Conditions: average air temperature of 35°C, air flow rate of 821 L/min, water flow rate of 1.5 L/min, and date 4/May/2017

The humidity ratio values for the system versus time for MR= 2.2 are shown in figure 5.7. It can be clearly seen that the humidifier increases the humidity ratio considerably (For example at 9:00 AM) from 0.025 to 0.055. Also, the humidity ratio value of air entering to the dehumidifier almost same value with insignificant reduction due to the losses through pipe connection between the components such as humidifier, dehumidifier and solar collectors. Then due to condensation in the dehumidifier, the value of the humidity ratio reduces to 0.025. Similar trends can be seen for each hour of the presented data. There is a reduction of values between outlet of the humidifier and inlet of the dehumidifier because of air leakage in various passages and condensation in colder conduits as indicated previously.

5.3 The Effectiveness at Different Mass Ratios

The effectiveness for the humidifier and dehumidifier has been defined as the ratio of the change of actual enthalpy for either stream (air or water) to maximum change of enthalpy:

$$\varepsilon = \frac{\Delta H}{\Delta H_{max}}$$

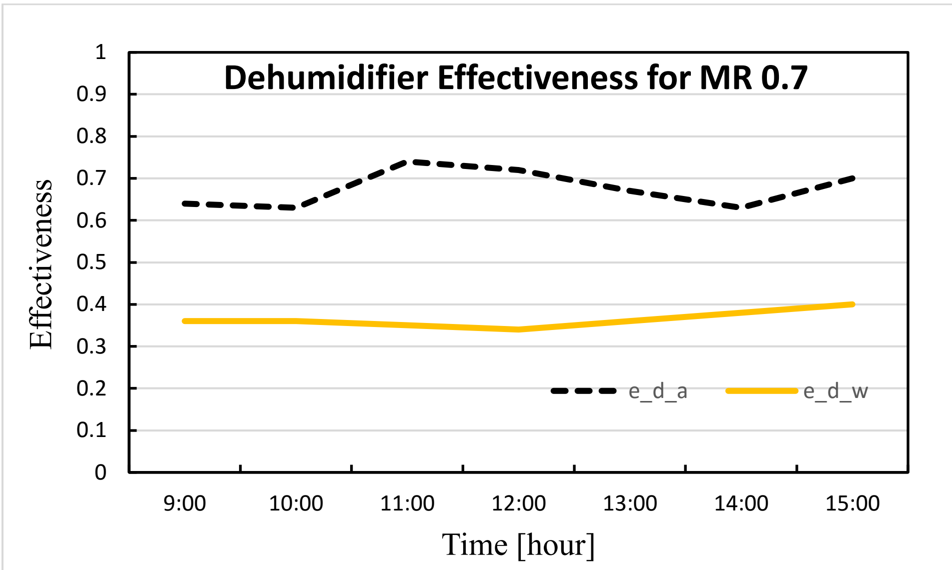

Figure 5. 8 Dehumidifier effectiveness of MR=0.7.

Test Conditions: average air temperature of 37^{o}C, air flow rate of 821 L/min, water flow rate of 0.5 L/min, and date 11/May/2017

Figure 5.8 shows that the behavior of the dehumidifier effectiveness during operation when mass ratio is 0.7. It can be clearly seen the effectiveness of air inside the dehumidifier, which has relatively high values between 0.63 and 0.75. However, for the dehumidifier effectiveness of water stream, the values are less than the effectiveness of air which they are between 0.35 and 0.45. the effectiveness of the dehumidifier for the air side can be defined as the difference between the inlet and outlet of enthalpy of the air over the difference between the enthalpy of the inlet air and the enthalpy of air at the inlet water temperature to the dehumidifier. The high value of the effectiveness means that ratio of the change of actual enthalpy for either stream (air or water) is almost close to maximum change of enthalpy for the dehumidifier. This indicates that the dehumidifier achieved a good performance for the airflow. Whereas, water flow inside the dehumidifier have a lower performance because the change of enthalpy between outlet and inlet water over the change of enthalpy of inlet air to the dehumidifier when the relative humidity is 1 and the enthalpy of inlet water is low.

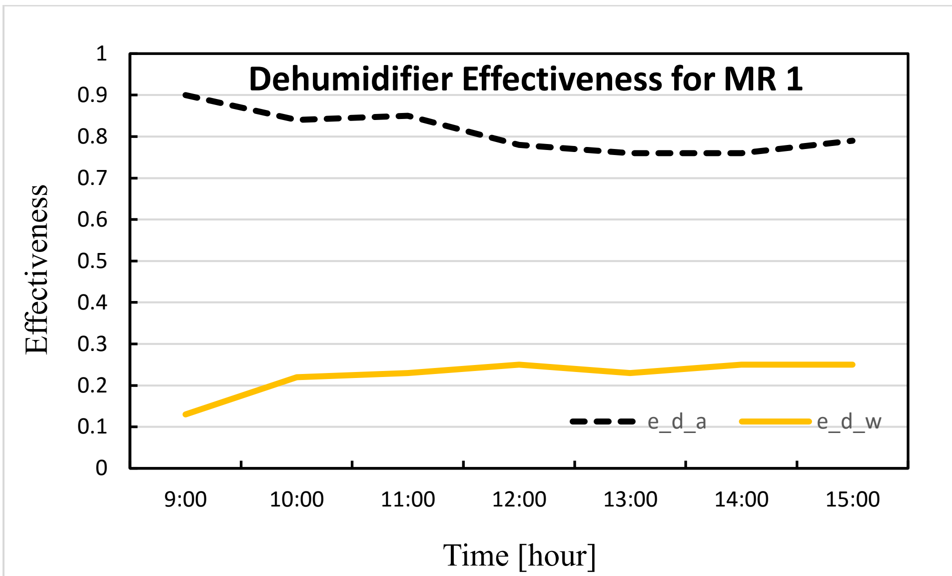

Figure 5. 9 Dehumidifier effectiveness of MR=1.

Test Conditions: average air temperature of 33ºC, air flow rate of 821 L/min, water flow rate of 0.7 L/min, and date 26/April/2017

Dehumidifier Effectiveness for mass ratio equal to 1 is shown in figure 5.9. The maximum effectiveness of the air side is about 0.9 which is at the beginning of the experiment. After that the dehumidifier effectiveness of air start to decrease for the remaining working hours until it reaches almost 0.8. For the water, the minimum effectiveness is almost 0.12 at 9:00 am. Then, it slightly increases until the end of the experiment to reach the maximum at about 0.25. The concept is similar to previous figure 5.8.

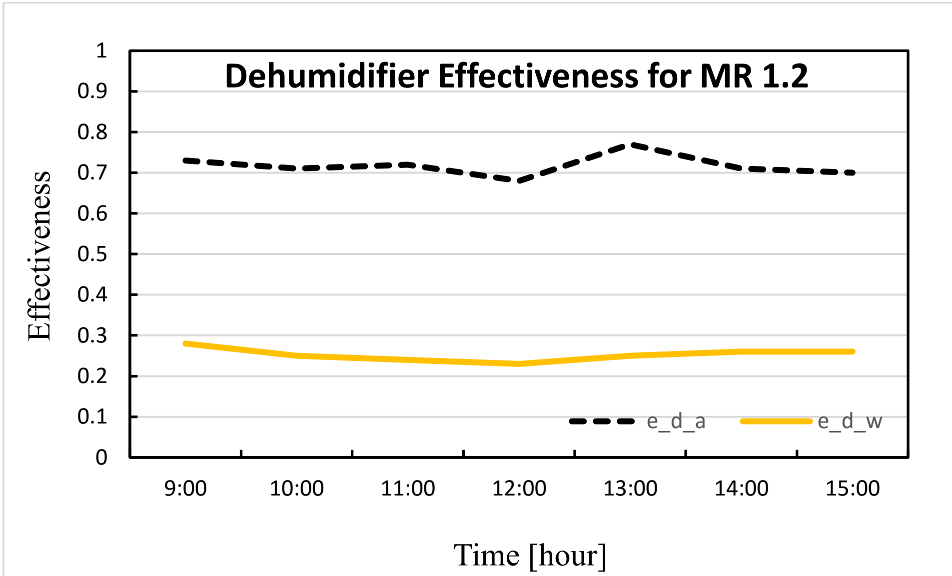

Figure 5. 10 Dehumidifier Effectiveness for MR 1.2

Test Conditions: average air temperature of 37°C, air flow rate of 821 L/min, water flow rate of 0.8 L/min, and date 2/May/2017

Fig. 5.10 shows the dehumidifier effectiveness for mass ratio equal 1.2 where water side effectiveness has better values than compared with the case of mass ratio equal 1. The maximum value for water dehumidifier effectiveness is about 0.3 when the time is 9:00 am. Then, the values remain almost similar to each other at 0.25 until last hour of the operation duration. However, the effectiveness values of the dehumidifier for the air stream are between 0.77 and 0.77. The reason for the low values for the effectiveness of the dehumidifier for water is because of high inlet temperature of air to the dehumidifier, which is between 110 and 130 °C.

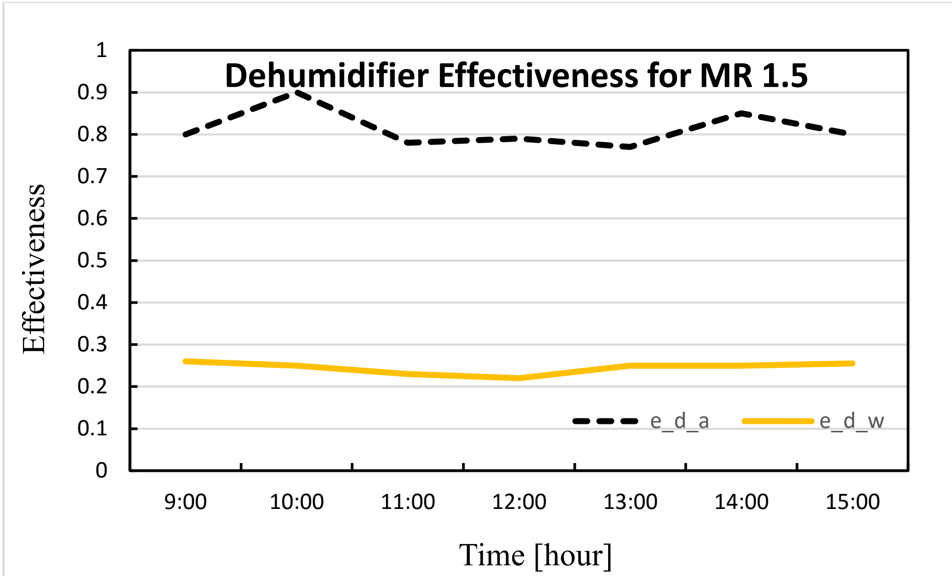

Figure 5. 11 Dehumidifier effectiveness for MR=1.5

Test Conditions: average air temperature of 37°C, air flow rate of 821 L/min, water flow rate of 1 L/min, and date 3/May/2017

Figure 5.11 shows that the dehumidifier effectiveness for MR 1.5 during the whole experiment. for the air, the dehumidifier effectiveness values are in the best conditions during the experiment which are between 0.8 and 0.9. However, the water side have almost the same low values during the experiment time at 0.25. The effectiveness as it explained before is the ratio of the change of actual enthalpy for either stream (air or water) to maximum change of enthalpy.

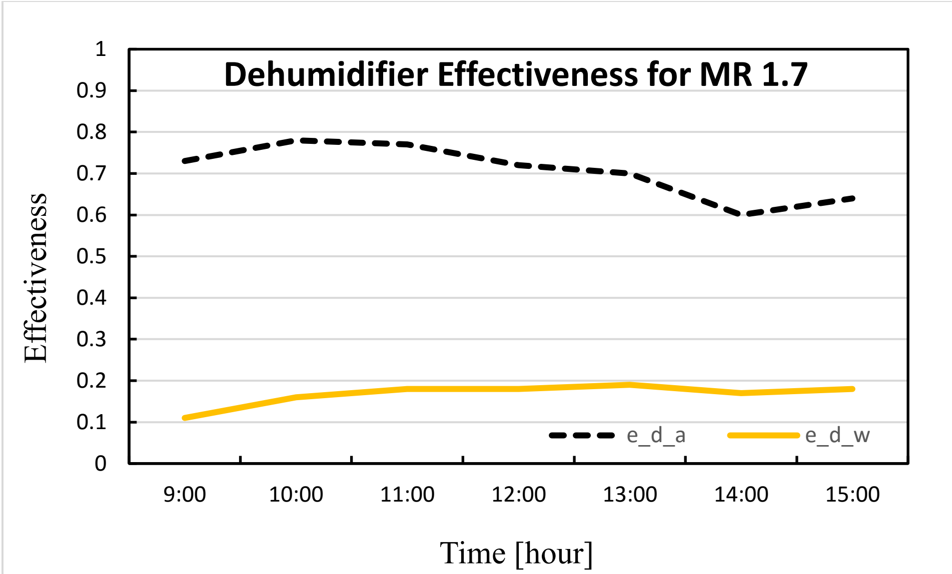

Figure 5. 12 Dehumidifier effectiveness for MR=1.7.

Test Conditions: average air temperature of 39°C, air flow rate of 821 L/min, water flow rate of 1.1 L/min, and date 28/March/2017

For MR equal 1.7, the water stream dehumidifier effectiveness is the lowest values compared to previous mass ratios. The values vary between 0.1 and 0.2. This low performance is a result of high inlet air temperature, which increases the change of maximum enthalpy of the dehumidifier. For the air stream, the effectiveness is much higher than water. When the experiment starts at 9:00 AM. The effectiveness is about 0.72. Then it increases to the maximum value at about 0.8. After that, it decreases until the end of experiment to reach its minimum at 0.6. The variation in effectiveness values is because of the change of the air temperature and its relative humidity and water temperature.

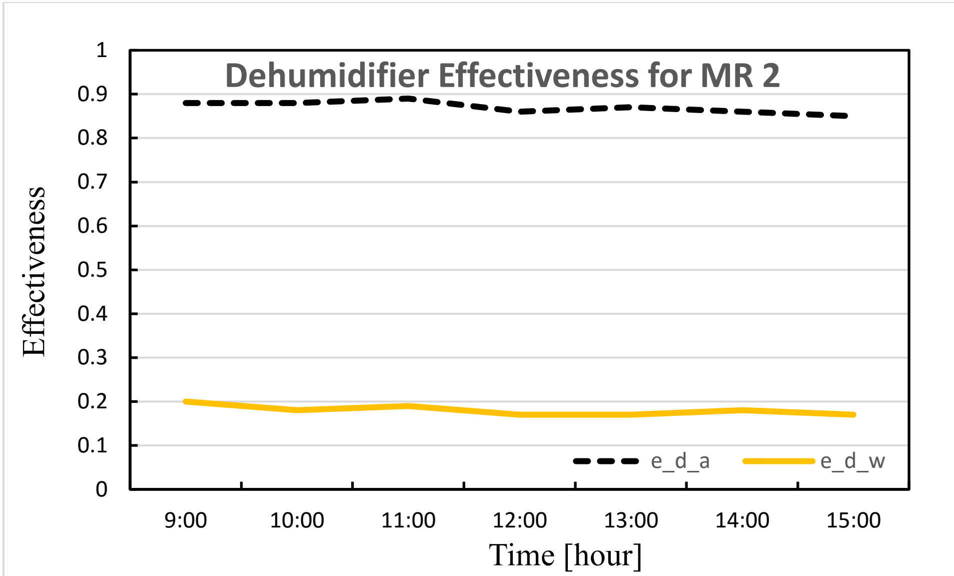

Figure 5. 13 Dehumidifier effectiveness for MR=2.

Test Conditions: average air temperature of 36°C, air flow rate of 821 L/min, water flow rate of 1.4 L/min, and date 27/April/2017

Figure 5.13shows that a comparison between air and water dehumidifier effectiveness when the experiment runs at mass ratio equal to 2. It can be clearly seen that the difference between the effectiveness of water and air. For water the dehumidifier effectiveness almost in the range of 0.2 from 9 am to 3 pm. While, the effectiveness of the air stream maintains its high performance at 0.9 for most of the daytime. The reason of high air effectiveness is that the enthalpy of outlet air is almost near to the enthalpy of inlet water of the dehumidifier. However, the reason for low water effectiveness is that the difference between the enthalpy of inlet air and the enthalpy of outlet water of the dehumidifier is high.

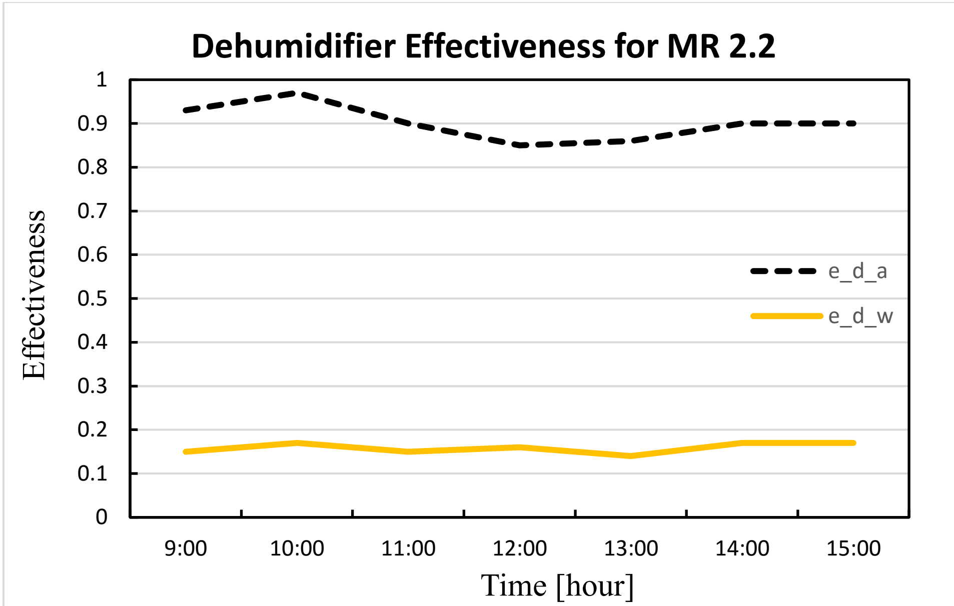

Figure 5. 14 Dehumidifier effectiveness for MR=2.2.

Test Conditions: average air temperature of 35°C, air flow rate of 821 L/min, water flow rate of 1.5 L/min, and date 4/May/2017

The highest effectiveness of the dehumidifier for air when mass ratio is 2.2 compared to previous mass ratios. The maximum value is almost reach its best condition and performance at 1 when the time is 10 AM. For the remainder of the experiment, values of dehumidifier effectiveness of air are in the range of the 0.9. However, one of the lowest dehumidifier effectiveness for water for MR equal 2.2. Values are in the range of 0.2 for most of the day time.

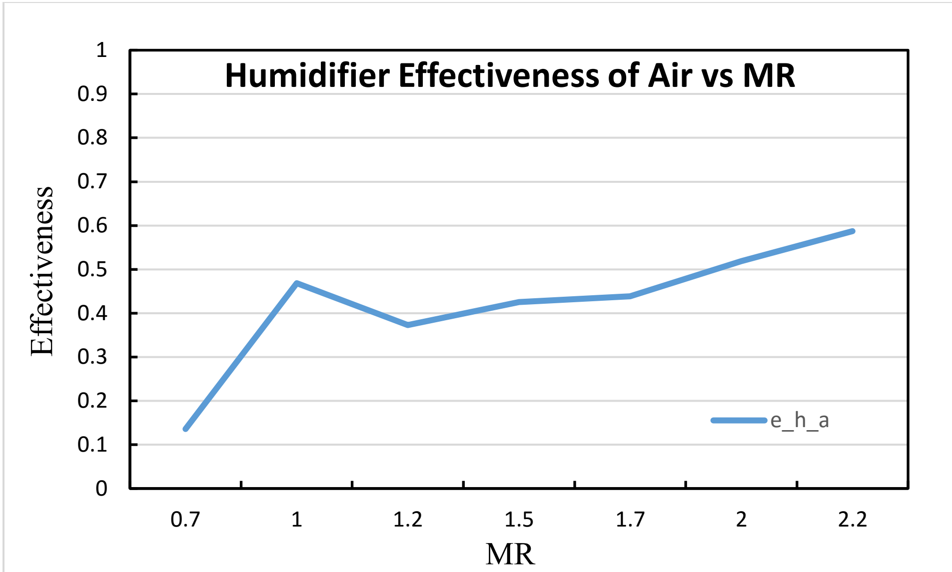

Figure 5. 15 The effect of MR on the humidifier effectiveness of air.

Figure 5.15 shows that the effect of the mass ratio on the humidifier effectiveness of air side for open water – closed air HDH system that is heated by air. From Fig.5.15, we notice the relation between MR and humidifier effectiveness that are proportional when MR is between 1.2 to 2.2. In this experimental setup, as the mass ratio increase the humidifier effectiveness of air will increase. The lowest value of the effectiveness is about 0.15 when MR is 0.7. Then, there is a rapid increase in the effectiveness to be about at MR equal to 1. However, the rapid increase is followed by a decrease to reach about 0.4 when MR is 1.2. Then, the humidifier effectiveness of air starts to increase gradually until it reaches its maximum 0.6 when MR is 2.2. In this setup, the air flow rate is fixed, and the mass ratio increases with the flow rate of water. Because of that, the enthalpy of the inlet water is decreasing, its temperature and the enthalpy of the outlet air from the humidifier increases by increasing its humidity ratio.

5.4 Collective Data

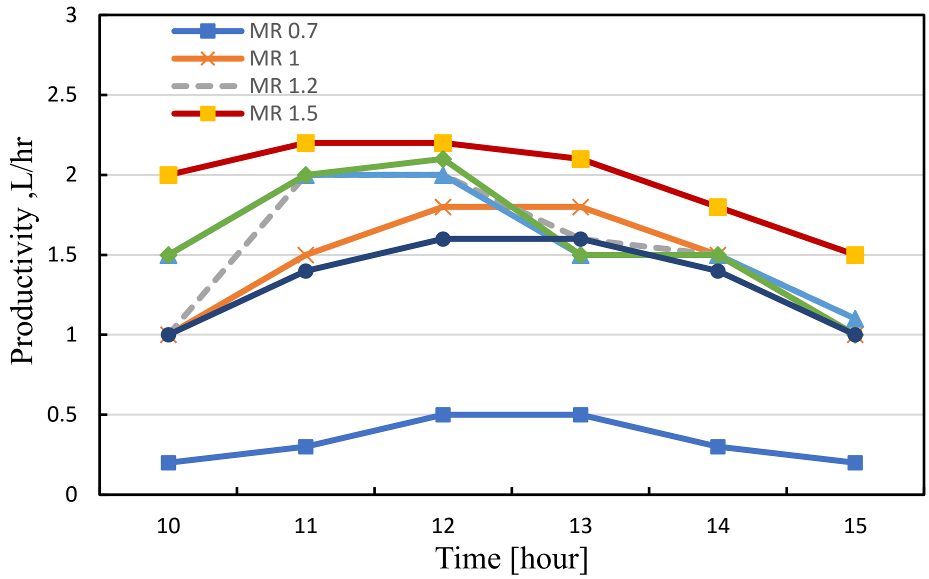

Figure 5. 16 Hourly productivity of closed air open water HDH powered by air heated solar collectors for different mass ratio.

The production rate for different mass flow rate ratio is shown in figure 5.16. It can be clearly seen that the best production rate throughout the day is when MR equal to 1.5 where is the production rate is about 2 L/hr. On the other hand, the lowest production rate for the experiment when the MR is 0.7 and its production rate is about 0.5 L/hr. The best time for production rate for different mass ratio is between 11 AM to 1 PM. The production rate depends on the amount of water vapor in the air. When the amount of water vapor increases, the production rate increases.

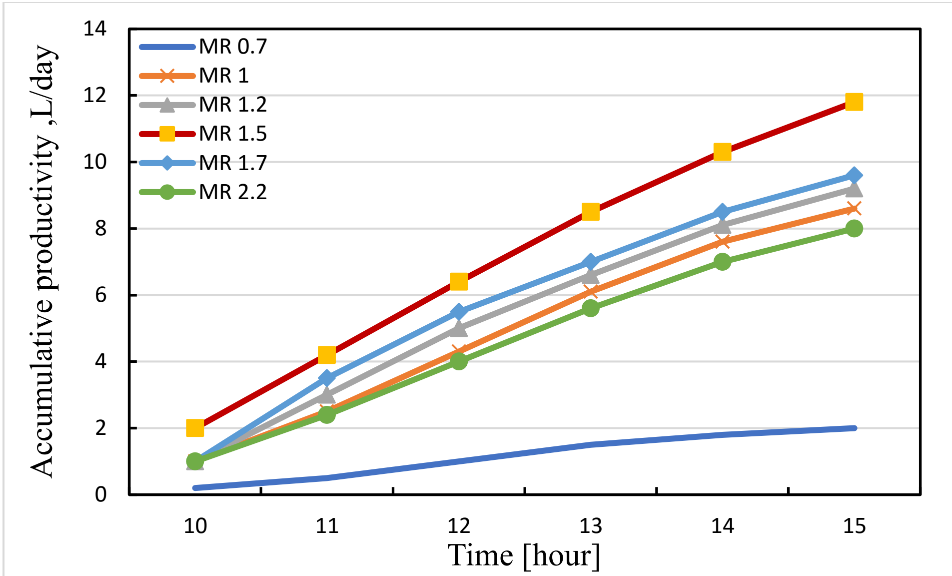

Figure 5. 17 Hourly accumulative productivity of closed air open water HDH powered by air heated solar collectors for different MR.

Figure 5.17 shows that accumulative productivity, L/day for different mass ratios of closed air open water HDH air heated cycle. The accumulative productivity increases with time which mean the production is going on until last hour of the experiment. The lowest accumulative productivity is about 2 L when the mass ratio is 0.7. As the value of MR increases, the accumulative productivity increases until MR equal to 1.5 then start to decrease. For MR equal to 1.5, the accumulative productivity is 12 L which is the maximum compared to other MR values, this mean that the amount of water flow is the best for air flow rate for this experiment setup.

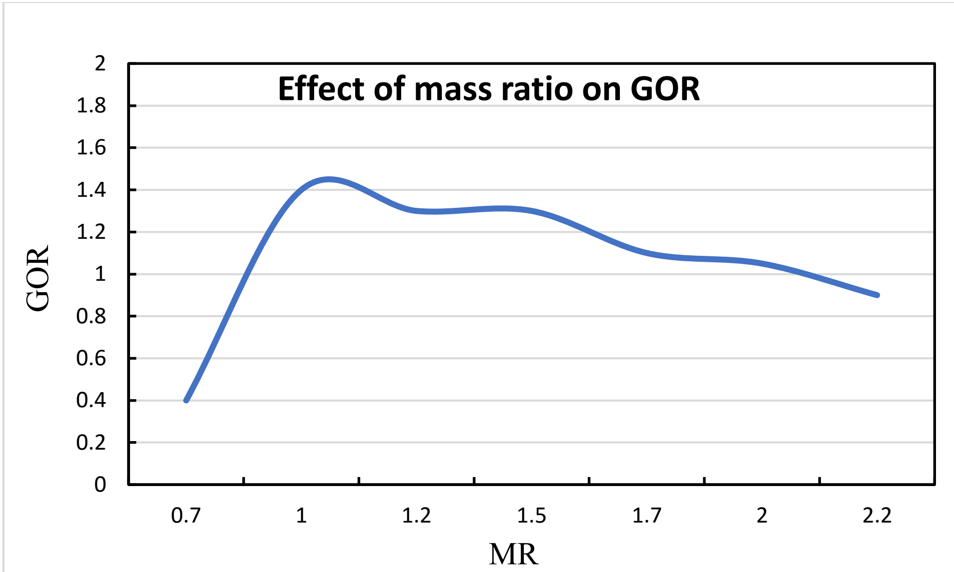

Figure 5. 18 Effect of mass ratio on GOR.

Figure 5.18 shows that the effect of different mass ratios on the GOR of the system. It can be clearly seen that, if the mass ratio is below or greater than 1 that will decrease the GOR. The lowest GOR for the system is 0.4 when the MR is 0.7. However, the maximum value of the GOR is 1.4 when the MR is 1. When MR is 1.2, the GOR is about 1.3 after that it will continue to decrease while MR increases to reach almost 0.9 when MR is 2.2. As the mass ratio increases the amount of water flow rate. This will result in the increase of energy input to the water heater which decrease the GOR of the system. For a mass ratio less than 1, the production of the system is too low compared to other value of MR as a result of the decrease in the GOR.

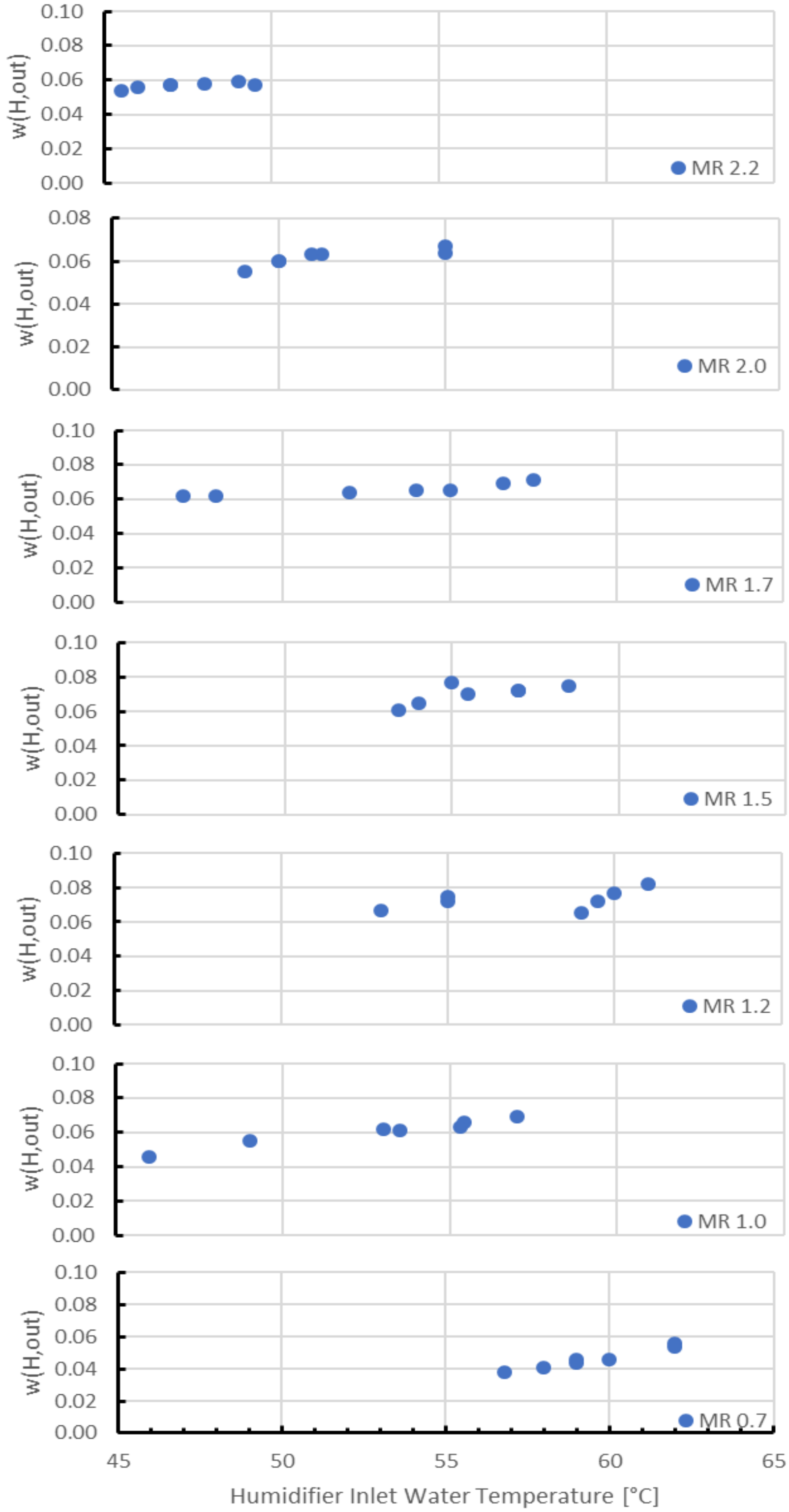

Figure 5. 19 The effect of inlet water temperature on exit humidity ratio of humidifier for selected mass flow rate ratios

Figure 5.19 shows the change of the humidity ratio of air leaving the humidifier with the humidifier inlet water temperature for different mass flow rate ratios (MR). It is clear that there is a slight increase in the air humidity ratio as water temperature increases. This is attributed to the enhancement of the evaporation of water within the humidifier as the water temperature increases leading to better heat and mass transfer within the humidifier. The figure also shows the increase in the humidity as the mass flow rate ratio increases because of the increase in the mass flow rate of water leading to more water flowing and hence better evaporating in the humidifier (recall that increasing the mass flow rate ratio is achieved by fixing the airflow rate and increasing water flow rate). On the other hand, it is important to note that achieving higher temperature of water inlet to the humidifier occurs only at low water flow rates (and hence for low values of MR) since the heater capacity (power) is kept constant. Therefore, higher water flow rate results in smaller temperature leaving the water heater (for fixed inlet water temperature). A closer look at the figure shows also that there is an increase in the humidity ratio with MR till a certain range of MR (1.2 to 1.5). Then, the outlet humidity ratio witnesses no further increase (it may even experience an insignificant decrease) that maybe attributed to flooding of water in the humidifier for a fixed airflow rate and for a fixed humidifier size.

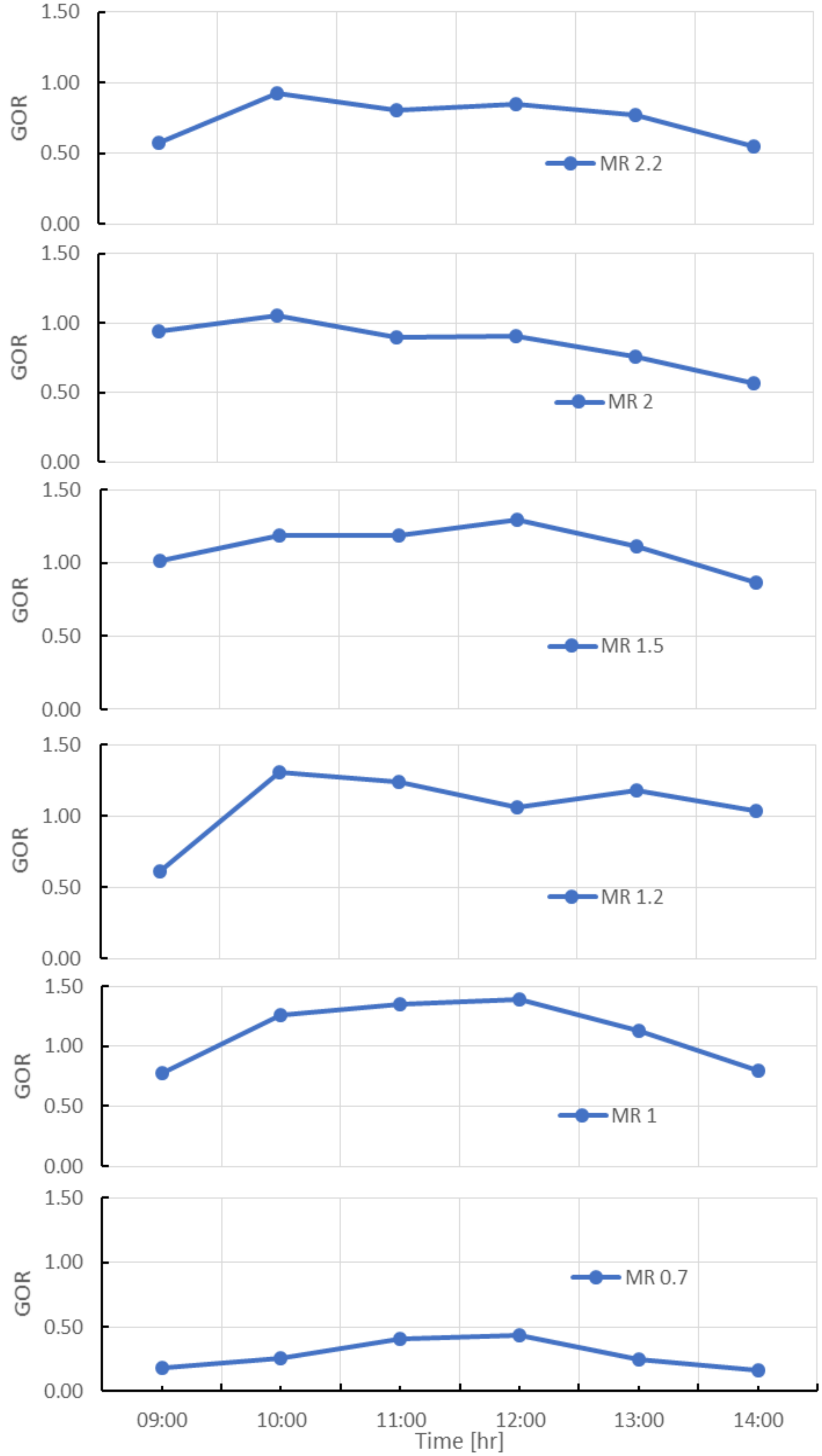

Figure 5. 20 The change in GOR with time for selected mass flow rate ratios.

Figure 5.20 shows the change of the gain output ratio (GOR) with day time for different mass flow rate ratios (MR). The rate of gain output ratio (GOR) for the difference mass flow rate ratios (MR) have a similar trend. For the mass flow rate ratio (MR = 0.7) the GOR increases with time and attains a maximum (0.5) at noon (12 PM). Thereafter, the GOR decrease with time reaching almost 0.2 at 2 PM. Similarly, for the mass flow rate ratio (MR) of 1.0, the GOR equally increases just like that of MR = 0.7 and attains a maximum value (1.4) at noon (12 PM) and then decreases to 0.7 as time elapses from 12:00 PM to 2:00 PM. In a related development, at mass flow rate ratio (MR = 1.2), the gain output ratio (GOR) increases from about 0.6 to maximum value (1.3) at 10:00 AM, which is almost the same as MR = 2.0 except that the GOR has maximum value of 1.0 in 10:00 AM. However, in the case of mass flow rate of 1.5 the GOR attained maximum (1.2) at noon time. Also, for MR = 2.2, the GOR increases up to maximum value (almost 1.0) at 10:00 AM. It is important to know that the initial increase in GOR with time at any mass flow rate ratio is because of the increase in solar energy that is collected by air solar collector from the sun as the solar energy intensity increases from sunrise. For the MR (0.7, 1.0 and 1.5), the maximum value of GOR was attained at 12 noon and this is expected as solar intensity is highest at 12 PM. After 12 PM (12 noon) the gain output ratio (GOR) decreases as solar energy flux reduces. Again, as MR value is small, the maximum value of GOR is equally small as the initial water/air mixture inputs into the system is equally small. For the MR values (1.2, 2.0, 2.2), the maximum value of GOR is achieved at 10:00 AM and the reason is probably because of the weather conditions, which change from normal after 10:00 AM of the day. This deviation could trigger the condensation of water vapor in the atmosphere that reduces the solar energy intensity. Besides, if the velocity of air impinging on the surface of the dehumidifier is high, then the condensation of humid air would equally take place and consequently increase the GOR. In all cases, the MR value of 1.2 gives the maximum value of GOR. Thus, the optimum value of MR occurred at 1.2. At MR less than 1.2, the amount of water/air mixture is small, and this give rise to smaller value of GOR. However, as the mass flow rate ratio (MR) is higher than 1.2, the amount of solar energy input is not sufficient to heat the water and increase the GOR value. Thus, to increase the GOR value after mass flow rate ratio of 1.2, more input energy is required.

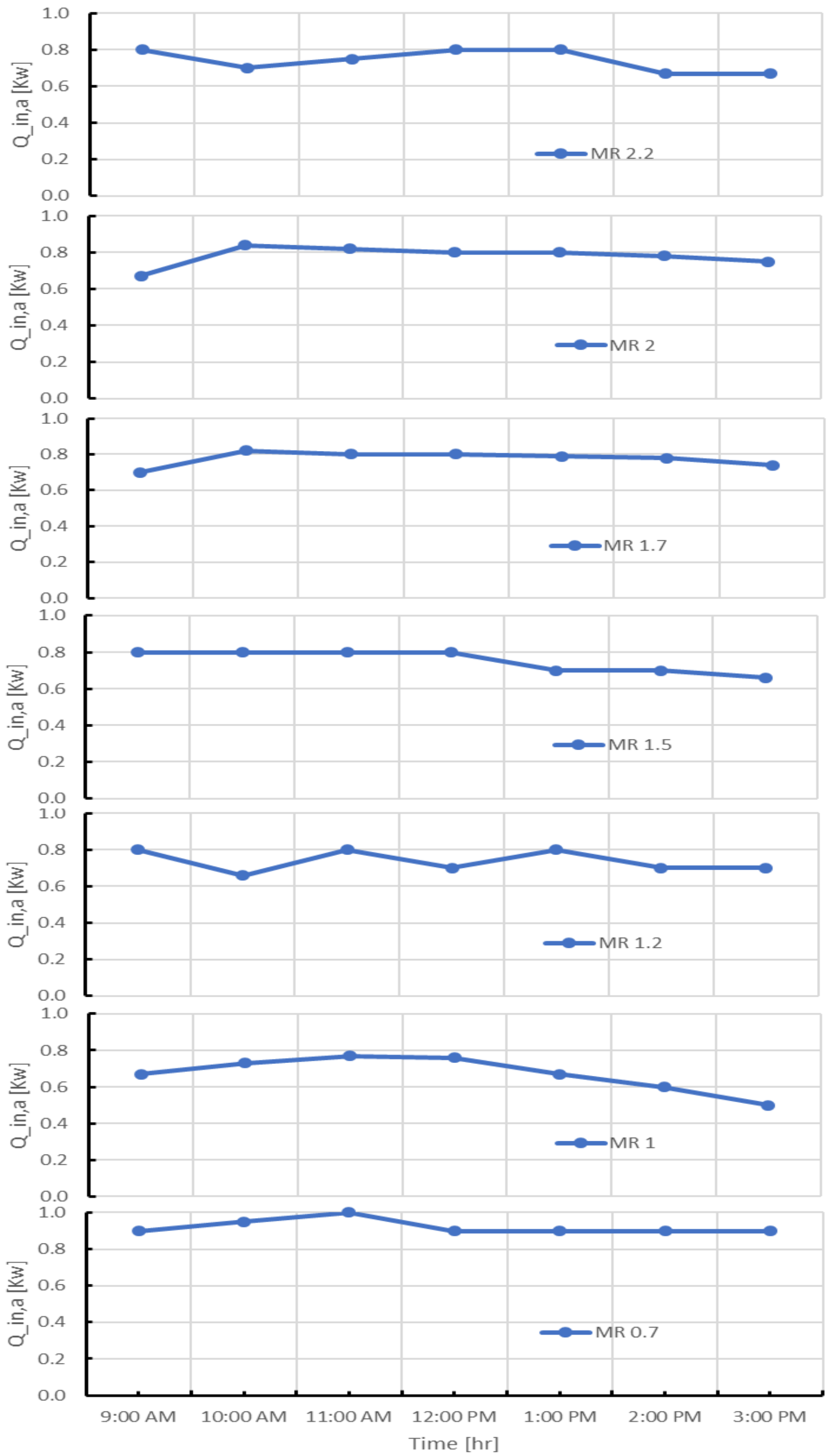

Figure 5. 21 The change in input energy of air solar collectors with time for selected mass flow rate ratios.

Figure 5.21 compares the amount of solar energy input (Q_in,a) to the air with time at different mass flow rate ratio (MR) . It is obvious that the amount of solar energy input first increases with time for the first three hours for all mass flow rate ratio (MR) except MR of 1.2. In all cases, the maximum solar energy input (0.8 Kw) occurred at the range (10 AM to 12 PM). However, for the MR = 1.2, the case is different, and this could be attributed to the fluctuation in the solar energy intensity due to variation in the weather conditions. Again, the increase in solar energy input value for the first three hours of the day is because of the increasing in the solar energy flux that a-roaches a maximum (0.8 Kw) value at 12 PM. As the time elapses beyond 12 PM, the amount of solar energy input decreases, which is manifested in the graph at all values of MR. It reasonable to conclude that the amount of solar energy input does not vary significantly with the change in mass flow rate ratio (MR).

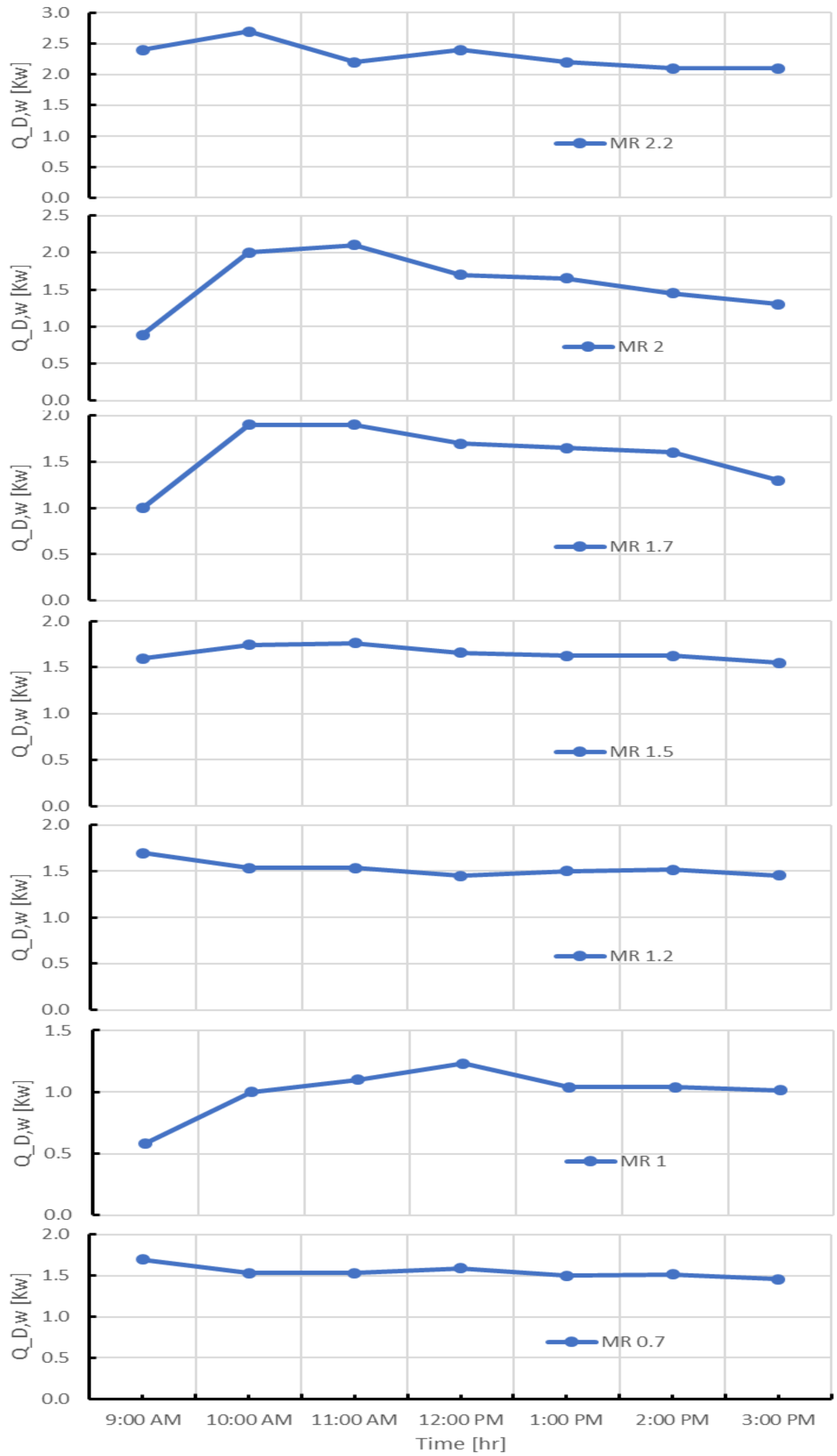

Figure 5. 22 The change in Input energy of water in the dehumidifier with time for selected mass flow rate ratios.

Figure 5.22 shows the change in input energy (Q_D,w) of water in the dehumidifier with time for different mass flow rate ratios. The input energy of water in the dehumidifier increase with time and reaching maximum for the first 10 AM to 12 PM of the day and thereafter decrease slightly and remain constant throughout the rest of the day. Similarly, the input energy of water in the dehumidifier do not change significantly with the mass flow rate ratio until it exceeds a mass flow rate ratio of 1.5. For example, at mass flow rate of 0.7, the maximum input energy of water in the dehumidifier is about 1.5 Kw and when the mass flow rate ratio increased to 1.5, the maximum input energy of water in the dehumidifier is about 1.8 Kw. It is therefore reasonable to say that at low mass flow rate ratio (below 1.5), the input energy was enough to bring about the necessary gain output ratio. However, as the mass flow rate ratio increased beyond 1.5, more energy is required to heat the water and that is the manifestation of higher input energy at higher mass flow rate ratio (MR).

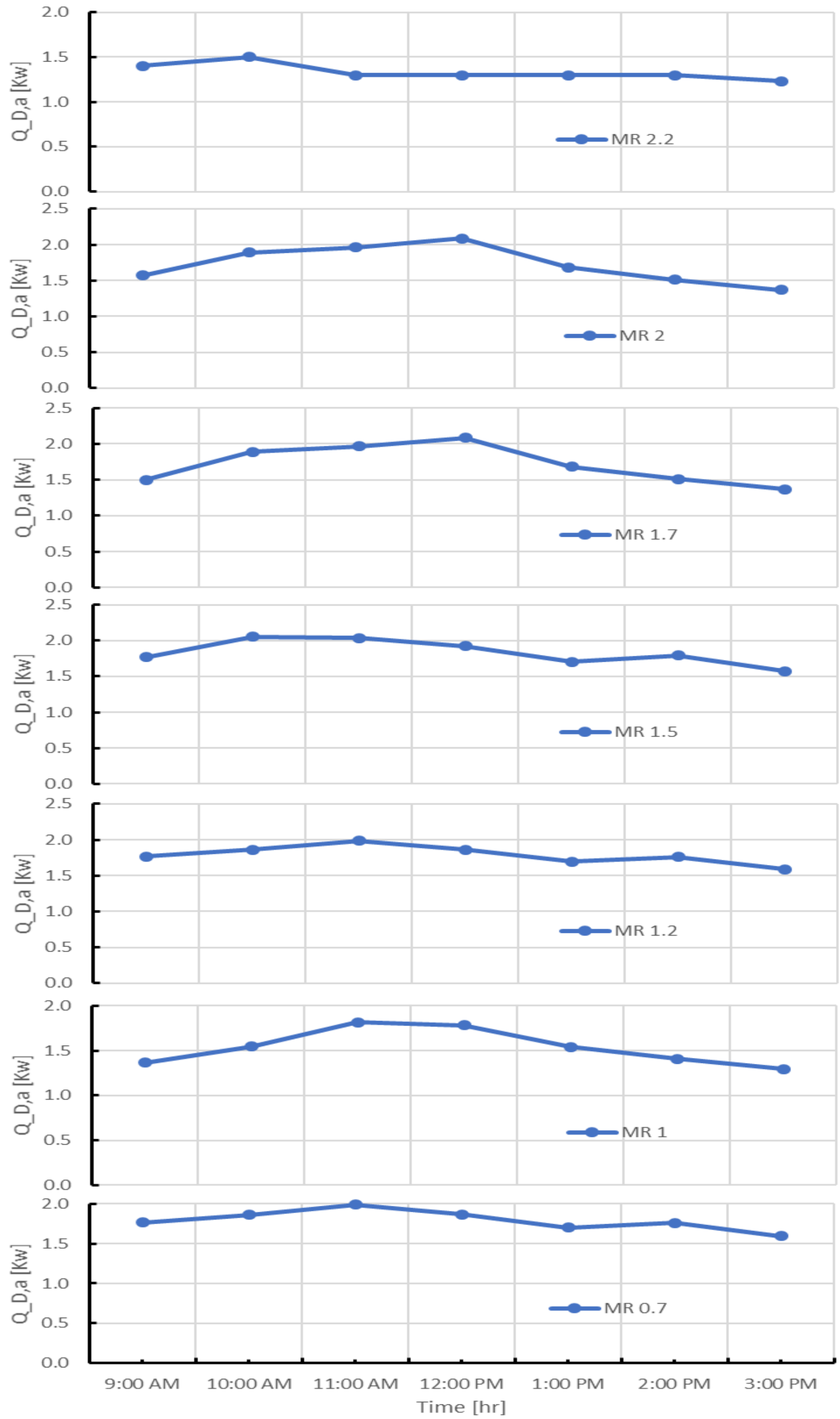

Figure 5. 23 The change in Input energy of air in the dehumidifier with time for selected mass flow rate ratios.

Figure 5.23 shows the change in input energy of the air in the dehumidifier with time at different mass flow rate ratio. The input energy is found to increase and attain a maximum at 11 AM-12 PM of the day. It then decreases for the rest of the experiment due to the decrease in solar energy flux. The input energy does not vary with the mass flow rate ratio. The maximum change in input energy of the air in the dehumidifier at all the selected mass flow rate ratio is constant almost at 2.0 kW except at mass flow rate ratio of 2.2 which slightly lower than 2.0 kW. This is because the amount of air in the input process stream for all the mass flow rate ratio is the same, so the same amount of energy is required.

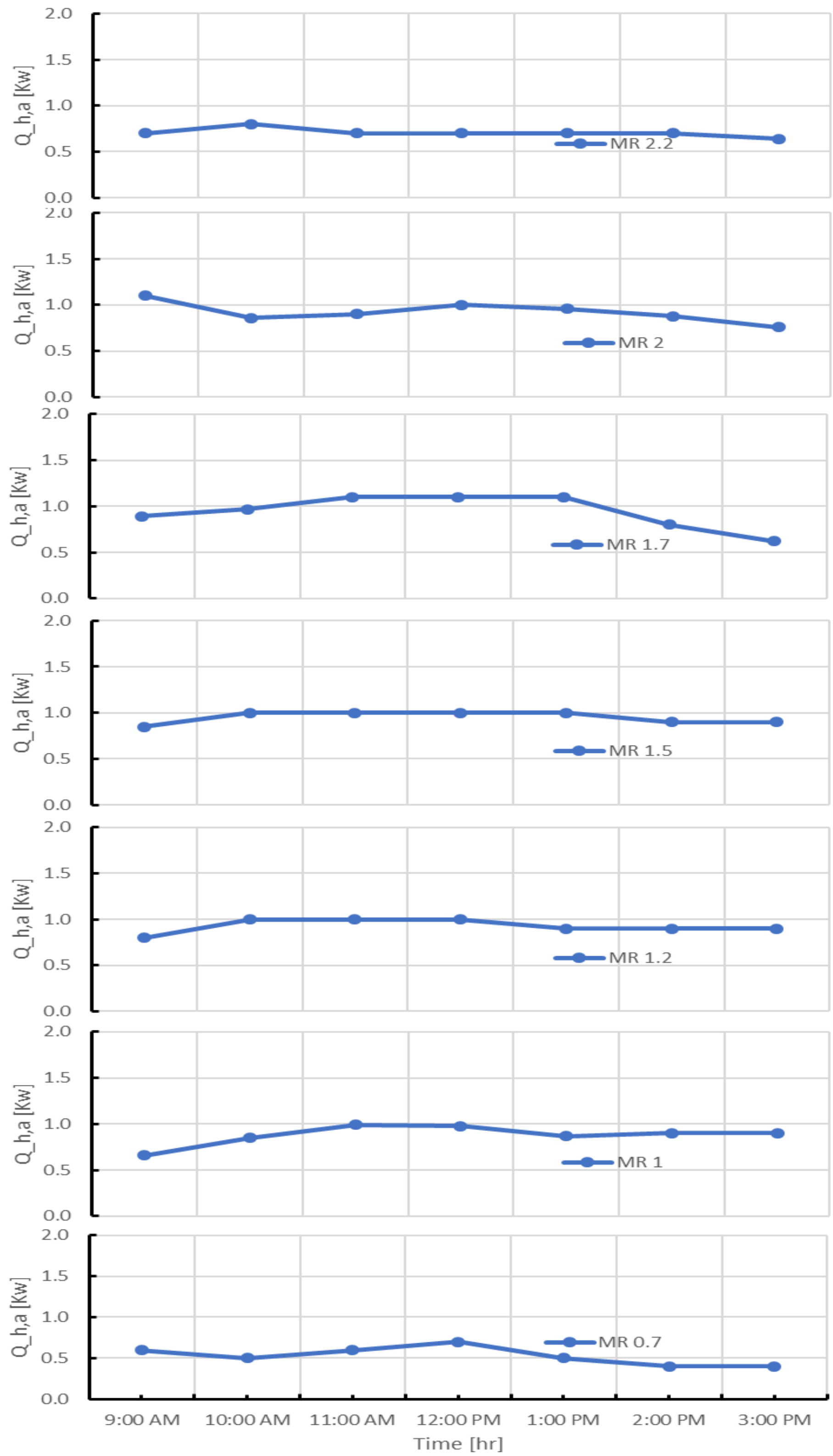

Figure 5. 24 The change in input energy air in the humidifier with time for selected mass flow rate ratios.

The change in input energy (Q_h,a) of air in the humidifier with time for a selected mass flow rate ratios is presented in figure 5.24. The input energy of air in the humidifier is found to increase slightly with time from 9 AM up to 12 PM for all the mass flow rate ratios. It then reduces as the with time from 12 PM to 3 PM. The increasing input energy of air in the humidifier up till 12 PM is attributed to the increase in solar energy flux as the sun rises. The highest flux is reached at 12 PM. It later declines for the rest of the day. Similarly, the input energy of the air in the humidifier increases progressively with increasing mass flow rate ratio. For example, the input energy of the air in the humidifier at mass flow rate ratio of 0.7 and 12 PM is 0.7 Kw while the input energy of air in the humidifier at mass flow rate ratio of 1.5 and 12 PM is 1.0 Kw. Again, above mass flow rate ratio of 0.7, the maximum input energy of air in the humidifier remain the same (1.0 Kw). The reason for the same input energy at different mass flow rate ratio could be because the mass of air in the mass flow rate do not change, hence the same amount of energy is required to heat the air in the different mass flow rate ratio.

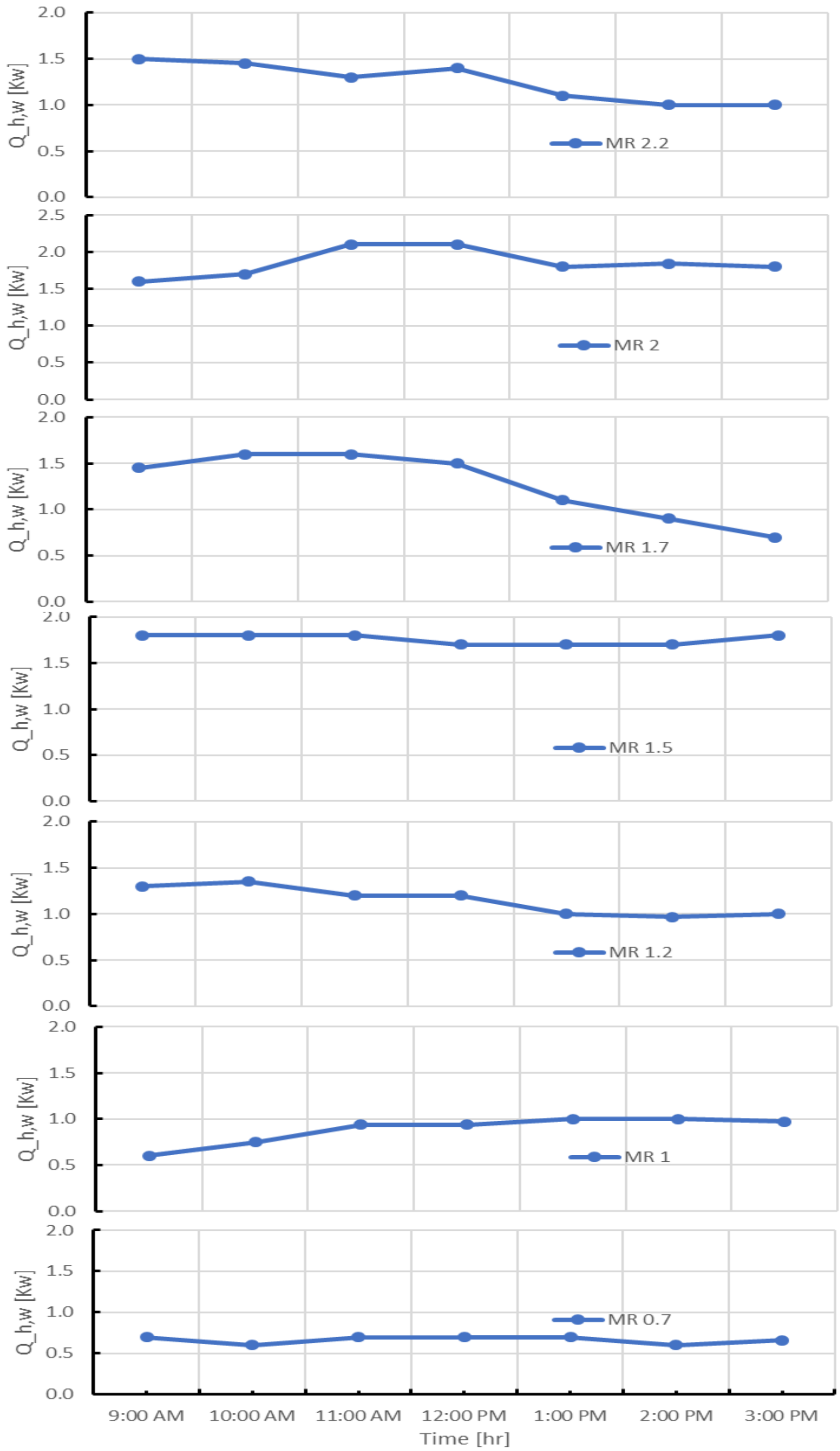

Figure 5. 25 The change in input energy of water in the humidifier with time for selected mass flow rate ratios.

Figure 5.25 describe the change in input energy of water in the humidifier with time for selected mass flow rate ratio. The change in input energy of water in the humidifier with time and mass flow rate ratio do not show any distinct trend. For instance, at mass flow rate ratio of 0.7 and 1.0, the input energy of water in the humidifier increase with increasing time. However, at mass flow rate ratio of 1.2, 1.5 and 1.7 the input energy of water in the humidifier decrease with increasing time and almost remain constant after 2 PM. For mass flow rate ratio of 2.0, the input energy of water in the humidifier increase again and reaching maximum at 11 AM to 12 PM. It thereafter declined slightly for the rest hours on the day. In addition, the input energy of water in the humidifier at mass flow rate ratio of 2.2 decrease with time and remained constant from 2 PM to 3 PM. Thus, the disparity in the behavior of change in input energy of water in the humidifier at different mass flow rate ratio and time may be due to the uncertainty or irregular fluctuations in the condition of weather which affect the solar energy input from the sun.

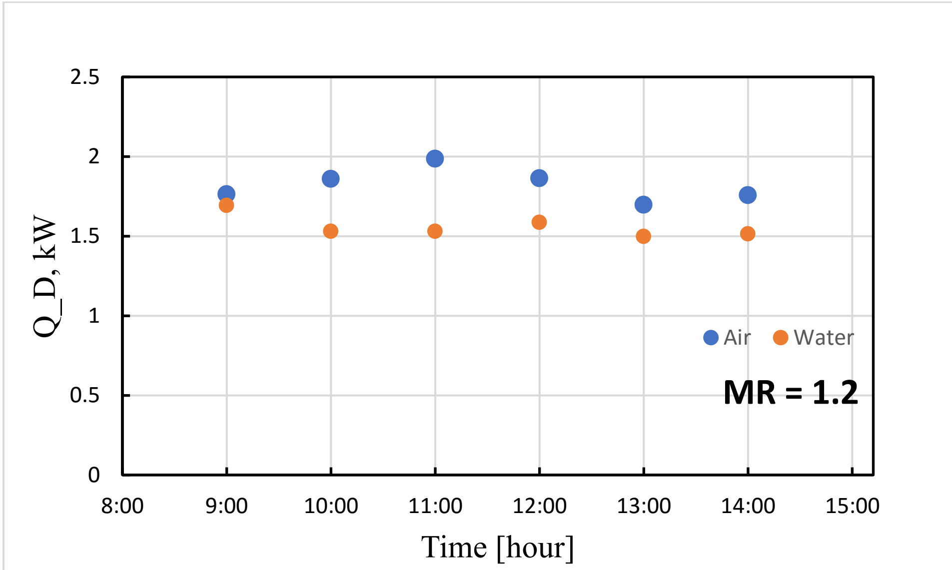

Figure 5.26. Input energy of water and air in the dehumidifier during operation hours when MR= 1.2.

Test Conditions: average air temperature of 37ºC, air flow rate of 821 L/min, water flow rate of 0.8 L/min, and date 2/May/2017

As shown in figure 5.26, the relationship between the input energy of dehumidifier for air and water is almost identical at the first hour then for the remains hours there is some of heat loss from the air inside the dehumidifier. At 9 PM the water and air input energy are almost 1.8 Kw. However, from 10 AM to 12 PM the average difference between air and water input energy is about 0.4 Kw. The last two hour there is minor losses between air and water input energy which is about 0.2 Kw and the input energy for air and water are 1.7 Kw and 1.5 Kw respectively. The maximum input energy for the dehumidifier is almost 2 Kw and 1.8 Kw for air and water respectively. For the air in most of experiment the inlet enthalpy depends on the solar radiation of the sun because of that the input energy of the air in the dehumidifier increase with inlet temperature of dehumidifier and vice versa. For the water as the dehumidifier inlet temperature of the air increases the water outlet temperature of the dehumidifier increases this result to increase the input energy of water. The losses inside the system because of the expansion due to the geometric differences. Also, the uninsulated dehumidifier caused losses of heat through the wall to the environment.

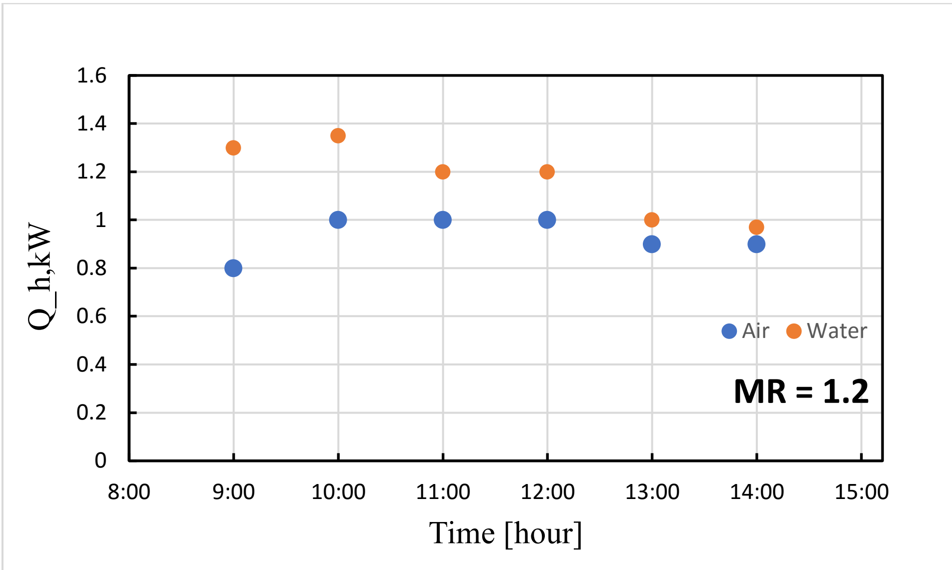

Figure 5.27. Input energy of water and air in the humidifier during operation hours when MR=1.2.

Test Conditions: average air temperature of 37°C, air flow rate of 821 L/min, water flow rate of 0.8 L/min, and date 2/May/2017

Figure 5.27 shows the input energy of water and air in the humidifier during operation hours when MR=1.2.From the equations of energy balances for the humidifier, there is a balanced energy flow between air and water. The inlet sprayed water heats up and increases the humidity of inlet air in the humidifier. The maximum energy input for the humidifier is 1.4 kW and the lowest is 1 kW. However, in the first couple of hours there are some loss in the energy of the water because the humidifier is not insulated, and the ambient temperature is less than the inlet temperature of water.

5.5 The Best GOR And Production

In 13th of march, 2017, the weather was windy and cloudy with average environment temperature of 35 degree Celsius. The experiment of open water and closed air HDH system that is air heated by solar collectors at 10 am and the optimum mass ratio was 1.8. For the experiment the best GOR for the system, production rate and the accumulative production was reached because of the unique and best environment conditions compared to others experiments. At 10:30 AM, the GOR of the system reached 2.13 and the production rate for the first hour was 3 L/hr. The accumulative production rate for the running time (5 hours) was 14 L. The reasons for this high performance is the conditions of the weather that influenced the outside surface of the dehumidifier to increase the production rate and the GOR. The tables below summarize most of the variables and the results for this experiment.

Table 5. 1 Weather condition in 13th of March 2017.

Wind speed	About 10/hr.
Environment temperature	35 °C
Whether condition	Partly cloud

Table 5. 2 The best GOR and Production.

Maximum water temperature	52 °C
Maximum air temperature	125 °C
Dehumidifier inlet water temperature	18 °C
Water flow rate	1.25 L/min
Air flow rate	684 L/min
Optimum mass ratio	1.8
Water heater input energy	0.8
Solar collectors input energy	0.42
Production rate	3 L/hr.
Accumulative production (6 hours)	14 L
Gain output ratio (GOR)	2.12

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

In this study, an innovative open water and closed air HDH system is designed theoretically and experimentally. The HDH is designed to produce fresh water with average production rate of 5 L/hr. Based on that, we assumed some main parameters of HDH system to reach our target of the produced fresh water. Then, the theoretical design of the main components of the system is found. The heat input rate for the system is 2.23 kW and this is used in air heated solar collectors to increase the temperature of humid air before it condensed. For the humidifier the calculated width and height of packing material are 0.22 m and 0.09 m respectively and the required cross-sectional area of the humidifier is 0.05 m^2. The required surface area of the dehumidifier is being 5 m^2 and the number of transfer unit is 2.2. In the experimental work, four setups for the closed-Air Open-Water Solar Air Heated system is discussed and the fourth setup is chosen. To heat the humid air inside the system, eight evacuated tube solar collectors are used with maximum total input energy of 2.23 Kw. For the manufactured humidifier, its height is 2 meters and 0.2 meter in diameter. Moreover, the height of dehumidifier is 1 m, the length is 0.62 m and the width are 0.22 m. There are two blowers that give maximum air flow rate 821 L/min inside this closed system. For the water heater the maximum input power is 1200 watt. The readings for the fourth setup of closed air open water HDH system is classified based on different mass ratios from 0.7 to 2.2 to specify the optimum mass ratio. Also, these different running experiments to study the effect of time on the GOR, humidifier effectiveness, dehumidifier effectiveness, humidity ratio of the inlets and outlets of humidifier and dehumidifier, the inlet water temperature of dehumidifier, the input energies of humidifier, dehumidifier, solar collectors, and water heater. Also, the effect of maximum water temperature on maximum humidity ratio for different mass ratio are discussed.

The experiments reading of OA-CW air heated HDH system were taken between March and April in 2017 during the winter season. The effect of mass flow rate ratio (MR) is studied to find its optimum. The flow rate of air was fixed, and the slow rate of water is changing to change the mass ratio. The optimum mass ratio for this setup on clear weather during winter is 1 and its maximum GOR is 1.4 with an accumulative production 9 L. However, the maximum accumulative production is 12 when mass ratio is 1.5. For a unique condition, when the weather was windy and cloudy with average environment temperature 35 °C the experiment reaches a better GOR and production. In March 18, 2017 at 10:30 AM for mass flow rate ratio (MR) is 1.8 the GOR for the system was 2.13 production rate for the first hour was 3 L/min. Also, the accumulative production rate for (5hours) running time was 14L. The reasons for this high performance is the conditions of the weather that influenced the outside surface of the dehumidifier to increase the production rate and the GOR.

In conclusion, increasing mass flow rate ratio promote humidity as the mass fraction of water increase which enhances evaporation in the humidifier. The gain output ratio significantly depends on the time of the day and maximum value was attained at midday (12 PM). Thus, the higher the solar intensity the greater the output ratio. Furthermore, the input energy of air in the solar connector do not dependent on the mass flow ratio and time as the mass fraction of air the mass flow rate ratio do not change however, the input energy of water in the humidifier varied significantly with mass flow rate ratio and time. In the case of humidifier, the input energy of air change with time of the day but do not vary with the mass flow rate ratio. Finally, the input energy of air in the humidifier increase with time and remain constant between 10 AM and 12 PM as the solar energy intensity is high between this time interval however, the input energy of water in the humidifier do not have observable trend with both time and mass flow rate ratio and this is attributed to the fluctuation in the weather conditions.

The studied HDH system can be improved by many recommendations based on the previous results and our experience in this experiment. It could be improving by replacing one of evacuated tube solar collector and install a new column bubble humidifier between the dehumidifier and other evacuated tube solar collectors. This improvement will increase GOR by increase the production rate and decrease the input energy of solar collectors. Also, it is recommended to change the main humidifier with another one that is more effective to ensure a better humidification process inside the system. Moreover, to increase the flow rate of air inside with the same blowers of the system it is recommended that to start a new setup of open water-open air HDH air heated system. Also, for water heater is better to change it to a new insulated heater with capacity of 15 L and minimum input power 1200 W.

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