Experimental Investigation of Parameters Affecting Solar Water Desalination by Humidification-Dehumidification

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Abstract

In this paper an experimental investigation was carried out to study the parameters affecting the solar desalination by humidification-dehumidification. A solar desalination system, which consists of three units was designed, implemented and tested in Sabratha, Libya. The three units of the system are the solar collector for heating salt water; the humidifier, in which warm water is sprayed as a mist to increase the humidity of the air; and the condenser (dehumidifier), which uses the water as a coolant and thus condensation occurs on a set of tubes through which the cooling water passes. The design effect and operational parameters were examined experimentally and the results were presented in the form of graphs showing the effect of different factors on the performance of the system in ten different days. The measurement was conducted in October and November 2020 at the rate of two hours per day from 12:00 to 14:00, while the total number of trials was ten for ten different days. There was an obvious increase in the temperature, relative humidity, and absolute humidity in the humidifier unit according to weather conditions.

Key words: Desalination, Humidification, Dehumidification, Solar collector, Condenser

Introduction

Humans can not drink the seawater as it contains salt and is saline water. However, saline water can be made into freshwater, which means there is enough water for drinking washing and growing crops and for everyday use. Many parts of the world such as dry desert areas simply do not have enough fresh water from surface water such as rivers and lakes. They have little rainfall but it may only be seasonal. The scarcity of fresh water and the need for additional fresh water is already critical in many arid regions of the world. It is very likely that the need for fresh water will soon be considered, in the same category as oil and energy resources, and to be one of the determining factors of world stability and the prosperity of nations. So a regular dependable supply of water is needed in these areas to enable them to have water to grow crops and build their countries to prosper. As our world populations grow we need to be able to guarantee this basic need and avoid which shortages of fresh water. The solution is to look to the abundant supply of sea water and turn salty water into fresh drinking water [1].

Due to large energy consumption in conventional desalination methods that usually use oil and natural gas, along with the growing concern about CO2 emission, there is a strong interest in alternative sources of energy for desalination units, and in particular, renewable energy sources. Among renewable energy sources, solar corresponding energy has a good consistency with climatic conditions in regions which need potable water, Furthermore, conventional desalination methods such as MSF, ME, VC and RO are suitable for large and medium capacity of fresh water production. Conventional thermal desalination methods are not economical for small capacities. A lot of remote arid areas need low capacity desalination systems. Air humidification dehumidification (HD) desalination is a suitable choice for production of fresh water when the demand is decentralized. Furthermore, due to low temperature demand of this method it is very compatible with solar energy and total required thermal energy can be obtained from solar energy [2].

Desalination Processes

Different types of water desalination processes have been developed as shown in figure 1. Mainly desalination processes can be classified into the following two categories; phase change (thermal processes) and single phase (membrane processes). In the phase change process a thermal energy source, such as fossil fuels, nuclear energy or solar energy may be used to evaporate water, which is condensed to provide fresh water. The phase change desalination processes described here include solar distiller, Multi-Stage Flash (MSF) distillation, Multi-Effect (ME) distillation, Vapor Compression (VC) distillation and Freezing distillation. In the single phase processes membranes are used in two commercially important desalination processes, Reverse Osmosis (RO) distillation and Electro Dialysis (ED) distillation [3].

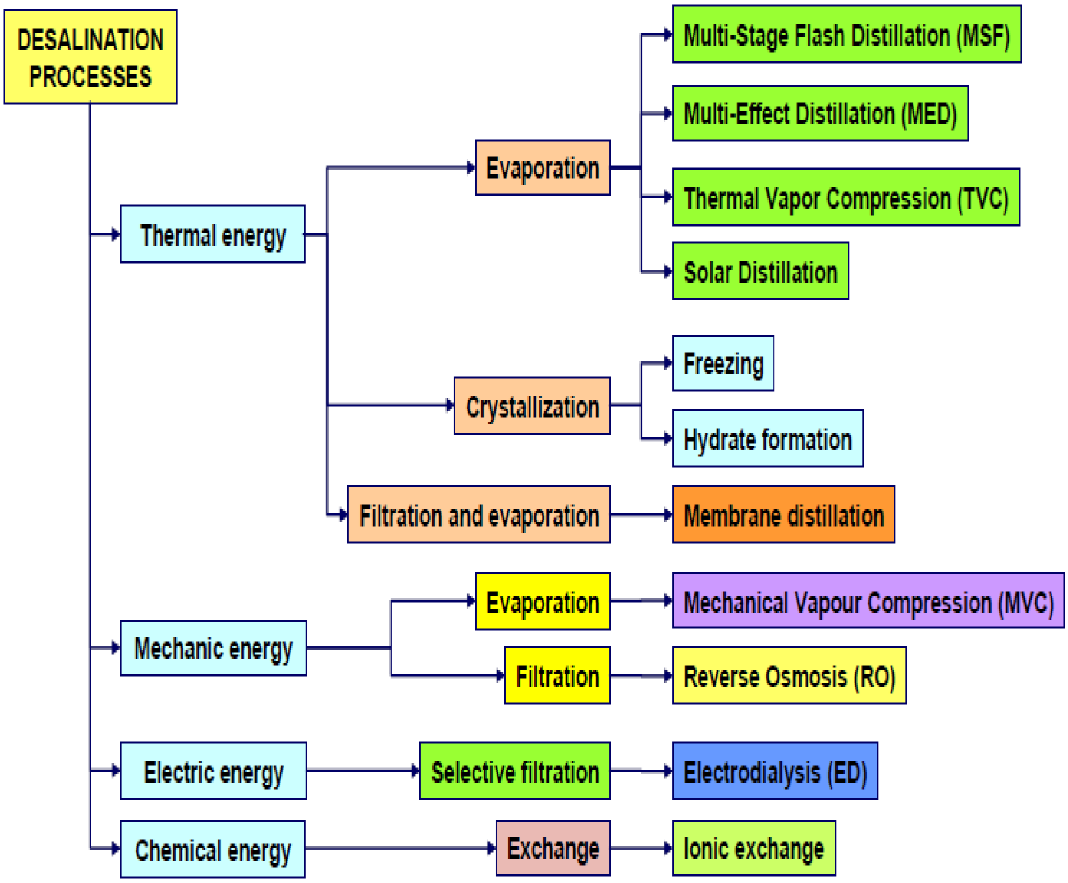


Figure (1) Desalination processes classification

Previous work

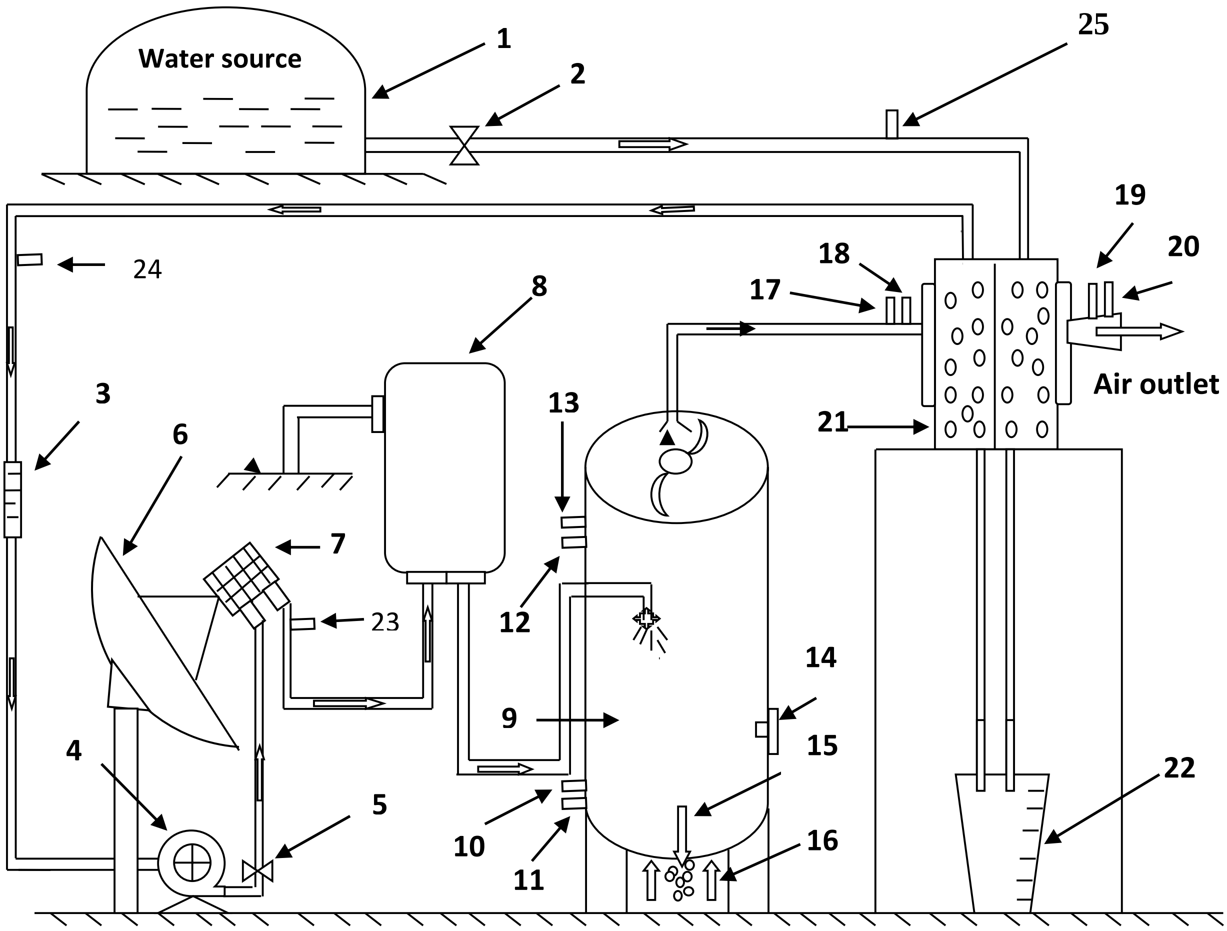
A. E. Kabeel1, Mofreh H. Hamed et al. has reviewed solar humidification-dehumidification desalination technology in detail. From the present review, it is found that the humidification-dehumidification desalination process HDH will be a suitable choice for fresh water production when the demand is decentralized. HDH is a low temperature process where total required thermal energy can be obtained from solar energy. Capacity of HDH units is between that produced by conventional methods and solar stills. Moreover, HDH is distinguished by simple operation and maintenance. Also from the present condensed review, it was observed that an increase in evaporator and condenser surface areas significantly improves system productivity. But prior to implementing any techniques in design improvement, it is necessary to optimize the MEH unit by optimizing its component size to understand the effect of feed water and air flow rates. Although a fair amount of simulation studies have been conducted in the past, further design simulation is required to fully understand the complicated effects of air and water flow rates, the optimum size of individual components or modules of the unit and to generate a comprehensive model for the system [3].

Badran et al. carried out an experimental investigation to study the effect of coupling a flat plate solar collector on the productivity of solar stills was carried out. Other different parameters (i.e. water depth, direction of still, solar radiation) to enhance the productivity were also studied. Single slope solar still with mirrors fixed to its interior sides was coupled with a flat plate collector. It has been found that coupling of a solar collector with a still has increased the productivity by 36%. Also the increase of water depth has decreased the productivity, while the still productivity is found to be proportional to the solar radiation intensity [4].

Eslamimanesh, M.S. Hatamipour et al. an economical study of humidification dehumidification desalination (HDD) pilot plant was made in order to estimate the economic benefits of the process in comparison with a small-scale reverse osmosis (RO) system. The energy recovery of the unit was investigated to be 75%. Some theoretical modifications were made to the HDD system in order to reduce the energy costs of the unit. Exact and clear economic analysis results were obtained using the COMFAR III software including fixed investment costs, production costs, internal rate of return on investment, operating costs, energy costs and some other economical parameters. Based on the energy prices in Iran, the total fresh water production cost was calculated to be $ 6.4/m3 that was nearly the same as produced by an imported RO plant. Finally some points were recommended whether to choose HDD or RO plant in different cases and capacities [5].

Experimental Work

For investigation of the effect of desalination process parameters the system as shown in figure 1 is designed and installed as shown in figure 2. The system operates on open air and water cycle where the air enters the bottom of the humidifier tower compulsively and mixes with the spray of warm water out of the spray units so that the air is saturated with mist due to the total convection.



1) Water source	**9) Humidifier**	**17) Temperature Humidity Sensor**
2) Flow control valve	**10) Temperature Humidity Sensor**	**18) Temperature Humidity Sensor**
3) Water flow meter	**11) Temperature Humidity Sensor**	**19) Temperature Humidity Sensor**
4) pump water	**12) Temperature Humidity Sensor**	**20) Temperature Humidity Sensor**
5) Flow control valve	**13) Temperature Humidity Sensor**	**21) Dehumidifier**
6) Solar still	**14) Air flow meter**	**22) Desalinated water tank**
7) Heat Exchanger	**15) Salty water**	**23)Temperature Sensor**
8) Hot water tank	**16) Dry air inlet**	**24)Temperature Sensor**

Figure (2) Schematic diagram of the experimental setup

Partial pressure of water vapor in air increases with the increase of water vapor in the air, where the partial pressure is defined as the pressure that the steam will receive if it fills the same volume with the air and the total pressure of the mixture is the sum of the partial pressure of air and water vapor. If the humidity is constantly added to the surrounding air, its partial pressure will rise to the maximum temperature of the system and the saturation pressure is reached under these conditions. The air is unable to carry or absorb more humidity and then it is said that the air is saturated with humidity. If the saturated air is cooled, the amount of humidity that exceeds the saturation point will be deposited as water droplets in the air where the partial vapor pressure during the cooling process is equal to the saturation pressure. As the partial pressure of the water vapor increases with increasing humidity and as the partial pressure of the water vapor is determined by the dew temperature, the humidity ratio is greatest when the dew temperature is equal to the dry temperature and the condition reaches saturation.

Figure (3) Photograph of the experimental setup

Mathematical Equations for Data

For the analysis of data obtained from the experiments the following mathematical relations are used:

$$Q = m \times C \times \Delta T \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

Where; (Q) thermal energy (j / sec), (m) is mass flow rate of water, (C) specific heat of water approximately equal (4.18kj / kg k) and (TΔ) is difference between temperatures (°C).

$$m_w = V \times \rho \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (2)$$

(m_w) is mass flow rate of water (kg / sec), (V) is volumetric rate flow of water (L / min) , and (ρ) is density of water (kg / m^3).

$$m_a = \rho \times V \times A \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (3)$$

(m_a) is mass flow rate of air (kg/sec) , (ρ) is air density (kg/m^3) , (V) is air velocity (m/sec) ,and (A) tube cross-sectional area (m^2)

$$m_w = m_a \times \omega \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)$$

(m_w) is mass flow rate of water with air (kg/sec) , (m_a) is mass flow rate of air (kg/sec) , (ω)is absolute humidity (kg_w/kg_a)) → $catt_3$

$$Q = m_a \times h \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. (5)$$

(Q) is thermal energy (j/ sec) , (h) is enthalpy (kj/kgk) , (m_a) mass flow rate of air (kg/sec)

Calculation of the mean velocity of turbulent flow**:**

$$\frac{u_0}{u^*} = \frac{1}{0.41} \ln\left(\frac{R \times u^*}{\nu}\right) + 5 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (6)$$

$$\frac{V}{u^*} = 22.44 \ln\left(\frac{R \times u^*}{\nu}\right) + 1.34 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. (7)$$

(u_0) is velocity at the center, (u^*) is frictional velocity , (ν) is kinematic viscosity

(R) is the half tube diameter, (V) is mean velocity

$$R_e = \frac{V \times D}{\nu} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (8)$$

(Re) is Reynolds number, (D) is tube diameter, (V) is mean velocity, (ν)is kinematic viscosity

Results and Discussion

The results obtained are presented in the form of graphs showing the effect of design parameters on the performance and efficiency of the system. Hence, the amount of added heat and the efficiency of the solar collector is known by knowing both temperatures of the inlet and outlet water to the solar collector, as well as the rate of water flow to the solar collector, where the value is different for all days each day separately and ranges between (0.211075-0.2704 L/min) in addition to the wind speed. There is an obvious effect of wind speed on the efficiency of the solar collector, as the wind speed increases, the efficiency of the solar collector decreases due to the cold currents carried by the wind most of the time, and vice versa, taking into account the disturbance of wind speed from time to time. it is important to direct the solar collector towards the energy source, which is the sun each specific period of time ensures that the solar radiation remains parallel to the axis of the solar collector, making use of the largest amount of heat required to heat the water in the heat exchanger.

Theoretical and True Heat

Figures (4) to (6) illustrate the relationship between the amount of useful heat and true heat with consideration to time for a period of three days, while figure (7) shows the relationship between the efficiency of the solar collector and the days for ten days.

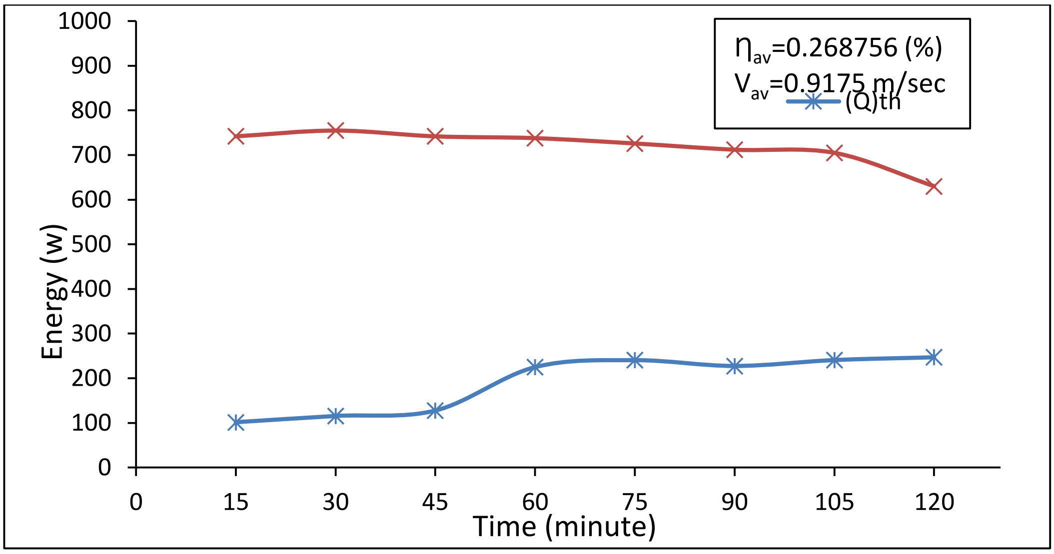


Figure (4) Day 1 solar collector energy (useful + actual)

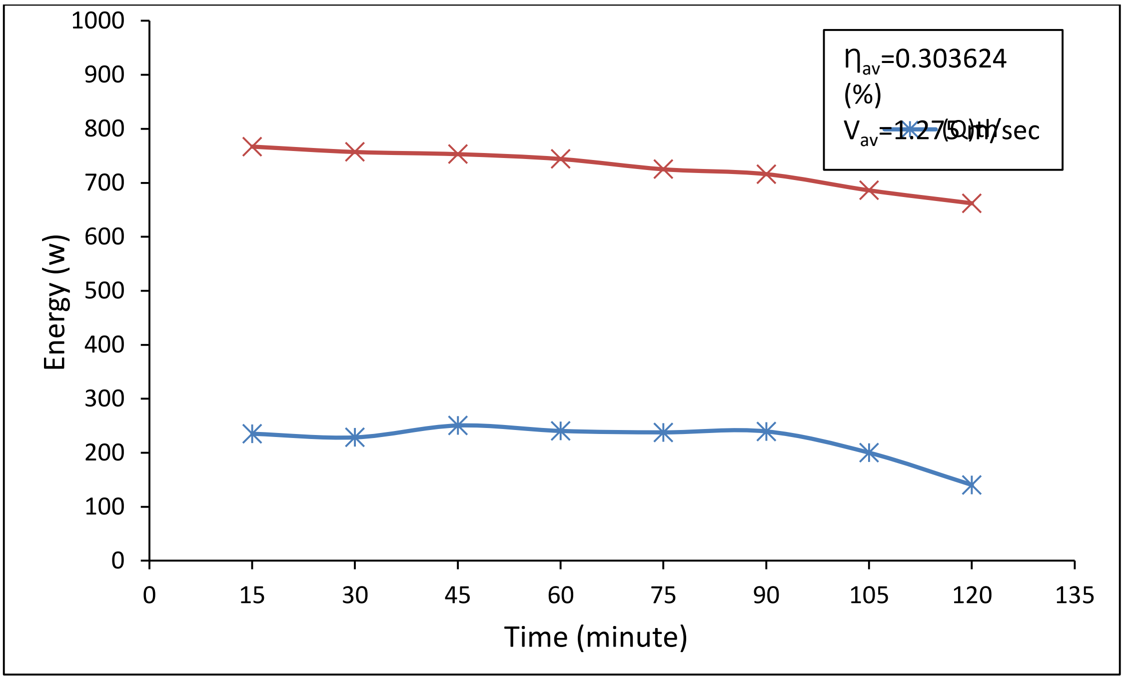


Figure (5) Day 2 solar collector energy(useful + actual)

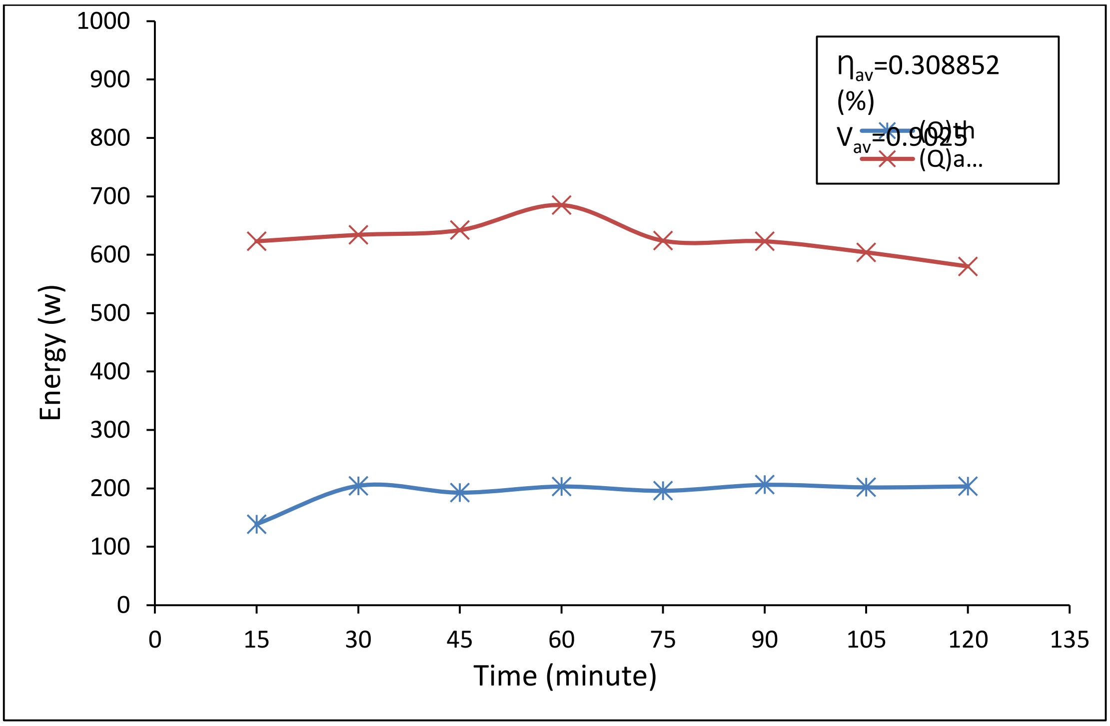


Figure (6) Day 10 solar collector energy(useful + actual)

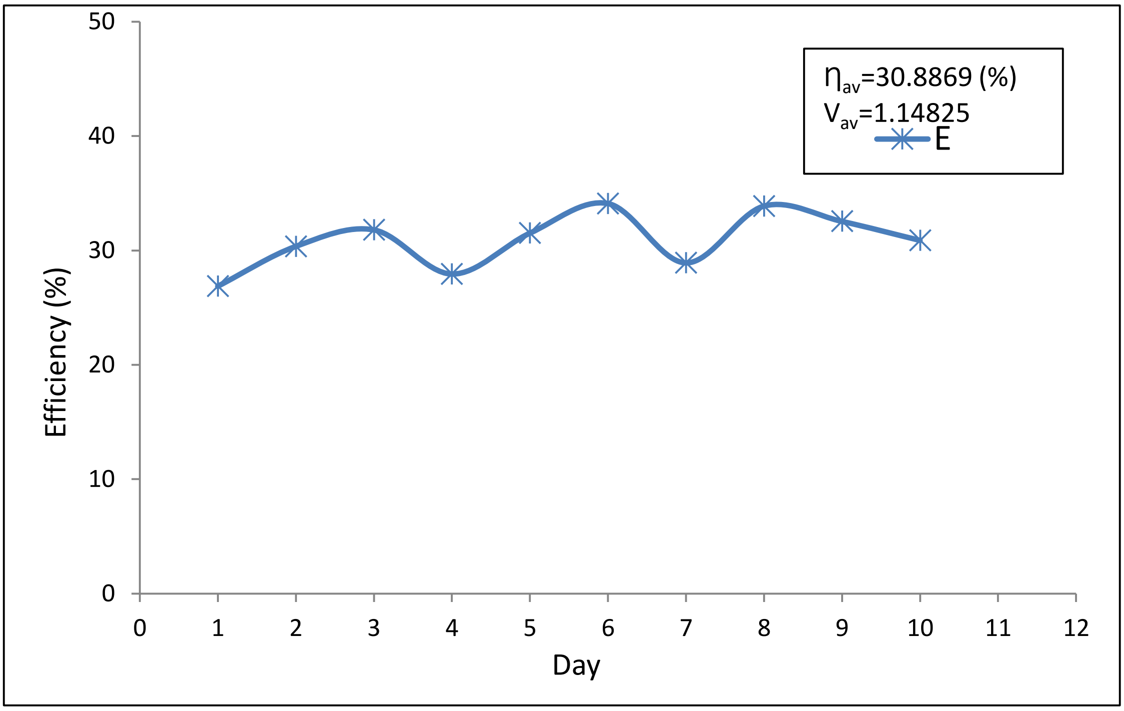


Figure (7) Daily solar collector efficiency

The intensity of solar radiation changes from day to day and from moment to moment, and the maximum radiation intensity recorded for all days of the experiment was (767 W). The lowest intensity of solar radiation was recorded for the same days was (350 W), The maximum energy used for heating was (250 W) and the lowest energy used for heating water was (101 W). The highest efficiency of the solar collector during the period of the experiment was (43.8%) and the lowest efficiency was (13.6%). The highest average efficiency was (34.1%) while the lowest average efficiency was (26.8%). The highest difference between real energy and the useful energy was (640.7W) and the lowest difference between real energy and useful energy was (213.7 W).

Humidity in the Humidifier

Figures from (8) to (10) show the relative and absolute humidity in the humidifier through the three days of experiment.

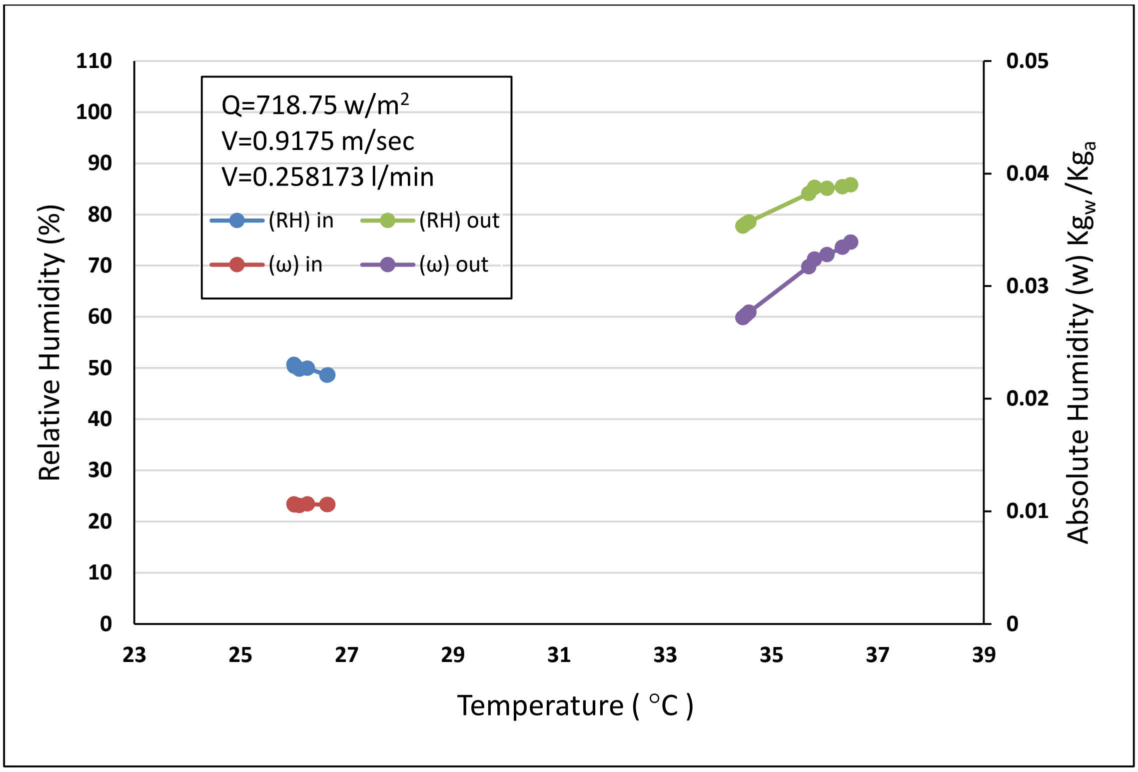


Figure (8): Day 1 Relative humidity and Absolute humidity(input +output) in humidifier

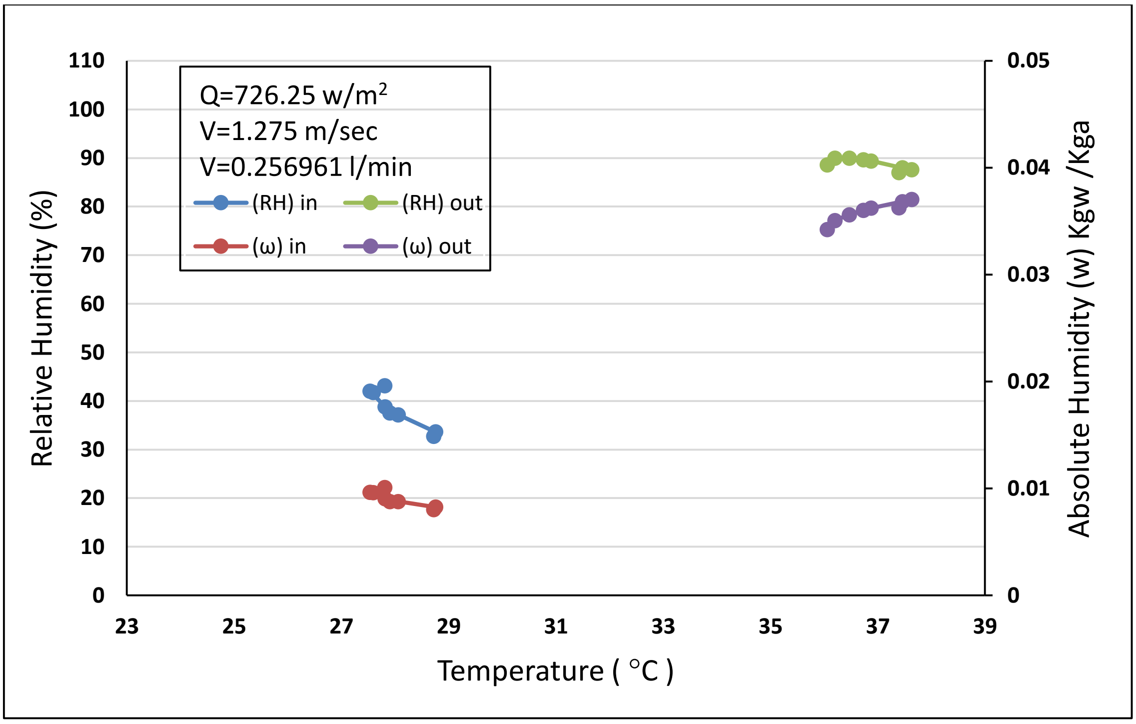


Figure (9) Day 2 Relative humidity and Absolute humidity (input+output) in humidifier

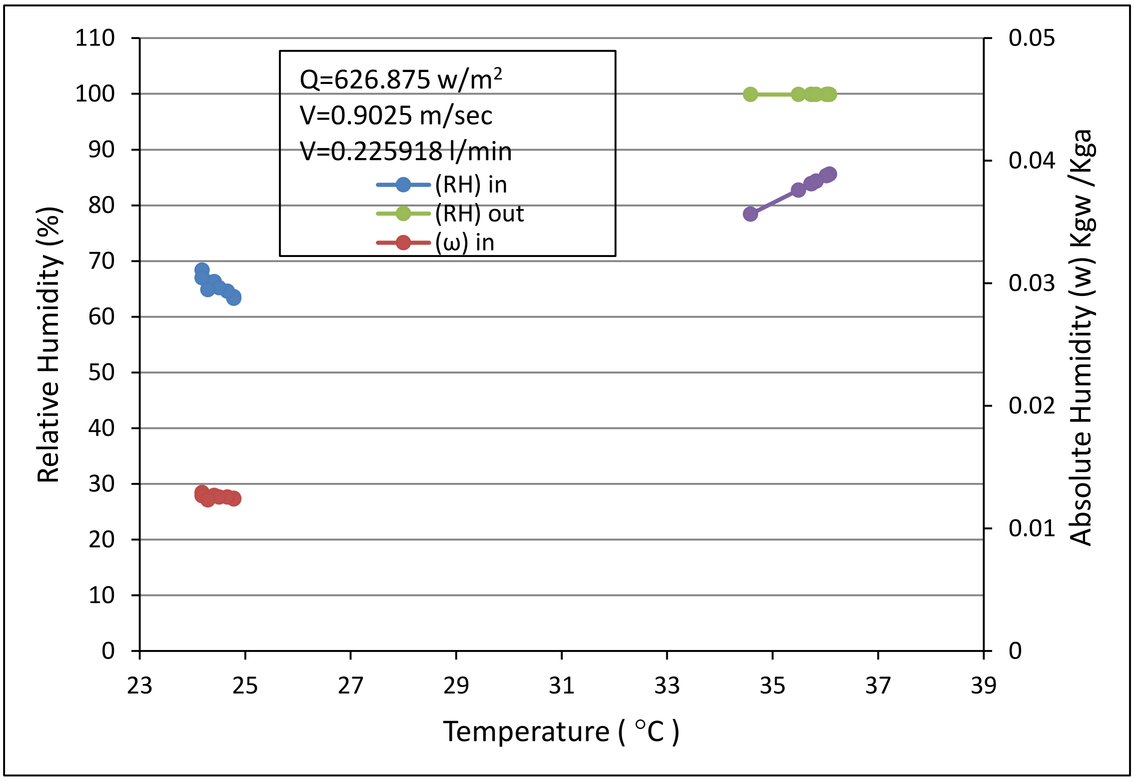


Figure (10) Day 10 Relative humidity and Absolute humidity(input+output)in humidifier

In the humidifier it was noticed that there is an increase in the air temperature, as well as an increase in the relative humidity and an increase in the absolute humidity, which is expressed in the amount of water per kilogram of air. The minimum increase in air temperature at the humidifier was (ΔT=7.2°C), which is expressed as the lowest heating process, while maximum increase in air temperature at the humidifier was (ΔT=11.5°C), which is expressed as the highest heating process. The minimum increase in relative humidity of the humidifier was (ΔRH=27.4%) and the maximum increase was (ΔRH= 54.9%). The minimum increase in absolute humidity at the humidifier was (Δω=0.016 kg_w/kg_a),while maximum increase in absolute humidity was (Δω=0.030 kg_w/kg_a).

Conclusions

A system for water desalination was designed and implemented using humidification and dehumidification in Sabratha, Libya, longitude (N °32 °48.216) and latitude (E °012 °27.716). The changes in temperature, relative humidity, and absolute humidity were investigated experimentally. The measurement process was carried out in October and November 2020 at a rate of two hours per day from 12:00 to 14:00 while the total number of experiments was ten for ten different days.

The main conclusions of this investigation can be summarized in the following points

1- The highest energy for heating water from the solar collector was (250.3 W) and the lowest heating energy was (101.2 W).

2- The highest efficiency of the solar collector during the days of the experiment was (43%) and the lowest efficiency for the same days was (13.6%).

3- Highest average efficiency was (34.1%) and lowest average efficiency was (26.8%).

4- Maximum difference between real and useful energy was (640.7 W),and the minimum difference between them was (213.7 W).

5- Minimum increase in air temperature in the humidifier was (ΔT = 7.2°C),which is expressed as the least heating process and the maximum increase in air temperature in the humidifier was (ΔT = 11.5°C),which is expressed as the highest heating process.

6- Minimum increase in relative humidity in the humidifier was (ΔRH = 27.4%) and maximum increase in relative humidity in the humidifier was (ΔRH = 54.8%).

7- The minimum increase in absolute humidity in the humidifier was ($\Delta\omega = 0.016\ kg_w / kg_a$), and the maximum increase in absolute humidity in the humidifier was ($\Delta\omega = 0.030\ kg_w / kg_a$).

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