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Experimental Investigation of a Novel Solar Powered Psychometric Low Grade Water Desalination System

Mahmoud Shatat *, Saffa Riffat, Mark Worall

Institute of Sustainable Energy Technology, University of Nottingham, Nottingham, NG7 2RD, UK

Abstract

Many countries around the world and especially in the Middle East and MENA region are struggling to provide their people with clean water under the rapid global climate change circumstances. Hence Drinking water of acceptable quality has become a scarce commodity. This paper describes the results of experimental and theoretical investigations of the operation of an efficient small scale water desalination system using the psychometric humidification and dehumidification process. The test results demonstrate that at temperatures in the range 54 ^{o}C to 63^{o}C, the system produces about 3.5 kg/hr of fresh water with high desalination efficiency. The experimental and theoretical values for the total daily water output were found to be closely correlated. A synthetic brackish water solution was used for the tests and its total dissolved solids (TDS) and electrical conductivity (EC) were measured. The analysis of the product water showed that its quality was within the World Health Organization guidelines. Following the experimental calibration of the mathematical model, it was demonstrated that the performance of the system could be improved to produce a considerably higher amount of fresh water and it would be an ideal solution to produce drinkable water for local residents in remote areas.

Keywords: *Water Desalination, Psychometric, Humidification, Dehumidification, Water Quality*

1. Introduction

At present the scarcity of fresh water is a dominant issue in many countries around the world and especially in developing countries and countries in the Middle East region where about three billion people have no access to a potable sources ofwater and about 1.76 billion people live in areas already facing a high degree of water shortage[i]. The United Nations Environment Programme (UNEP) stated that one third of the world's population lives in countries with insufficient freshwater to support the population and, by 2025, two thirdsof the world population will face water scarcity [ii].

Currently, large fossil fuelled commercial desalination plants are in use in many regions which suffer from water shortages where financial resources and infrastructure are available such as the oil-rich countries in the Gulf region. However, in poorer regions of the world, there is a lack of provision of fresh water due to the high capital and running costs, and poor infrastructure [iii]. Most of the current desalination systems use conventional technologies, whilst producing large quantities of waste heat and the emission of greenhouse gases resulting in increase in pollution and environmental degradation. In addition, they are becoming economically unviable in remote areas. Desalination using renewable resources, especially solar thermal energy has the potential to dominate the market by 2030, and solar desalination is emerging as a successful renewable energy source for the production of fresh water [iv]. The development of alternative, small-scale water desalination systems is imperative for the population in such areas [v]. Solar thermal water desalination is known to be a viable method of producing clean water from saline water in remote areas [vi], humidification and dehumidification solar water desalination units are an example of such a technology. Conventional basin solar stills with relatively large footprint areas are an example of a simple technology that uses solar energy for desalination, however, it has a relatively low performance due to excessive heat losses to the environment and a reduction in efficiency because of the scaling process and accumulation of salt impurities [vii]. A large number of publications have been produced, but most of these have focused on improving the design and performance of small scale solar water desalination systems. The effect of coupling solar collectors with humidification and dehumidification processes and a basin solar still have been investigated in a series of research and development projects. For example, Zhang and Yuan [viii] studied a closed circulation solar desalination unit and focused on an analysis of water production and system performance by investigating the effect of the cooling water flow rate, the feed water rate and the structural dimensions. Similarly, Mohamed and El-Minshawy [ix], and Eames et al [x] described the theoretical and experimental investigation of a small scale solar poweredbarometric desalination system. The results showed that the production rate of fresh water depended on three main factors, namely, the heat exchange effectiveness of the condenser, solar insolation and pressure. Mohamed and El-Minshawy [11] studied the same concept but with the use of geothermal energy. Gude et al [12] studied low temperature desalination using solar collectors augmented by thermal energy storage; their work included theoretical and

* Corresponding author.

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experimental investigation with water production of 100 litres /day.This paper presents a novel small scale desalination system that requires a very small energy input using hybrid psychometric energy desalination system built on humidification and dehumidification principle utilising a low grade and waste heat sources. A reduction in energy consumption makes the system more feasible and a unique thermal technique for small scale applications due to its high efficiency, the possibility of directly integrating it with a renewable energy source, and its lower maintenance and technical support needs. Utilising the concept of humidification and dehumidification in water desalination in a compact unit coupled with solar collectors would have a significant improvement on water production. Hence this research aims to develop a novel desalination system that is more affordable and energy efficient.

2. System Description

A novel water desalination system was developed and investigated at the Institute of Sustainable Energy Technology Laboratories at the University ofNottingham, UK. This system employs the concept of humidification and dehumidification based on the psychometric energy process using a special designed heat recovery system converting saline water into fresh water. Figure 1 shows a schematic diagram of prototype of the proposed desalination system and its components.

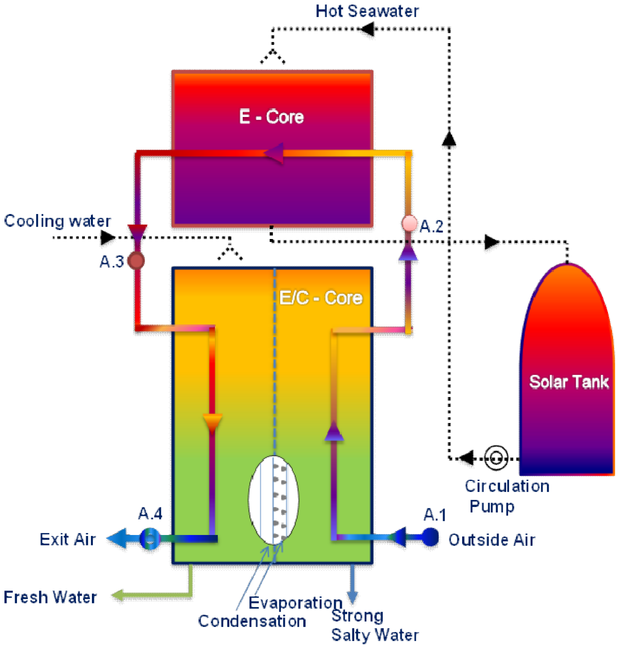

Fig.1: Schematic diagram for the desalination system

This system includes the water desalination unit, either solar collector or an electric heating coil as heat source submerged into a water storage tank, circulation pumps, air fan and auxiliary components such as float controls, collection containers.

The desalination unit consists of one well designed humidifier with special wet film material for humidifying the moist air which called (E-Core), where humidification process takes place and dehumidification chamber which contains a special membrane core (E/C-Core) where the condensation and the recovery of the latent heat of condensation takes place for energy recycling and water production respectively in this core as shown in figure 2.

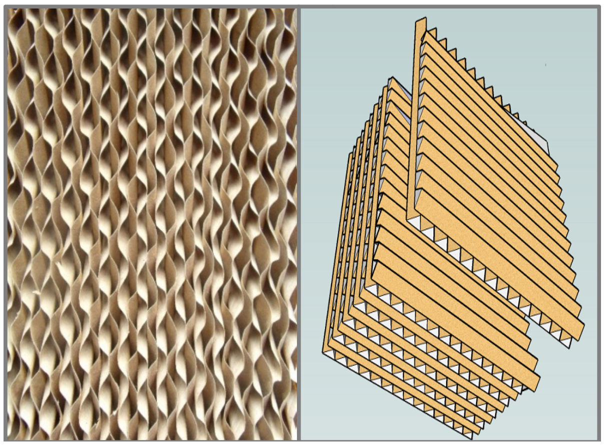

Fig.2: Honeycomb cellulose materials for (E- core) and E/C core Multi-layer fiber materials

The key innovation of this system is the re-use of the psychometric energy created by the condensing of the moisture in the carrier air: a small amount of thermal energy is supplied to the humidification and dehumidification process which makes the system a unique and more affordable system that can be integrated with renewable energy sources and particularly the solar energy sources through solar collectors. The HDD system could operate in a single stage or in multiple stages.

3. Working Principle

In the schematic diagram system in Figure 1, the supplied energy was initially generated by the immersed electric heater of 2.75 KW in the water storage tank. First, the energy absorbed is utilised to increase the temperature of the liquid which is continuously circulating in the humidifier of the desalination unit. The temperature of the saline water in the tank increases gradually and then the saline hot water is sprayed into the humidification chamber (E-core) to humidify the incoming air. This humidified air enters the dehumidification chamber (E/C core) and is cooled by the incoming seawater, while the seawater is pre-heated by the latent heat of condensation absorbed through the condensation process to recover heat and finally the moisture condenses as pure water at the base of the chamber, and the dehumidified air is discharged to the outside as an exhaust air. Therefore all supplied heat into the system is utilized and converted into useful heat to produce fresh water. Further, the seawater or brackish cooling water is pumped from the water storage tank which is located at the bottom of E/C core and sprayed on the top of dehumidification chamber in order to humidify the incoming air where the cooling seawater and fresh air are mixed in order to aid evaporation and recover the heat of condensation. At the same time they aid in the condensation process by extracting heat from the vapour.

The process of humidification and dehumidification goes through four stages.

(1) The outside fresh air at point A1 gets humidified in the evaporation and condensation core (E/C-core) to become point A2; the energy required is supplied from the latent heat of condensation recovered by the incoming air and cooling water so that most of the energy needed for desalination is reused.

(2) Air at point A2 passes through the E core to get humidified further to become point A3.

(3) Air at point A3 then passes through the E/C core to get dehumidified.
(4) The air is discharged as exhaust, leaving the condensed water produced to be collected in the metering cylinder as fresh water distillate.

4. Experimental Setup and Test Procedure

The main components of the desalination system was designed and assembled, as shown in figure 3. Preliminary investigation trials were carried out using an electric heater as the energy source to heat the seawater in the storage tank but, in the second stage, the energy source will be an integral of solar collector which is already designed and tested with solar light simulator at the Institute of Sustainable Energy Technology [xi].

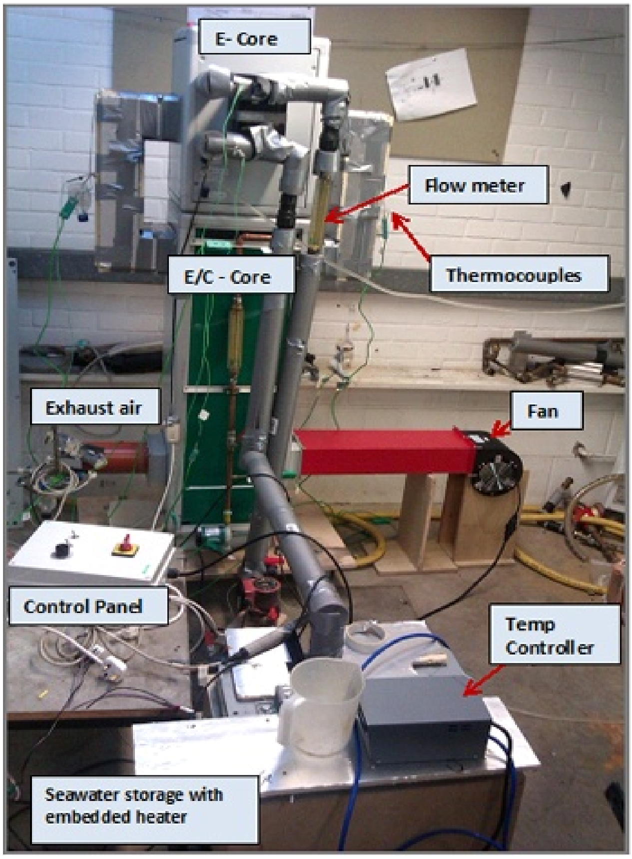

Fig.3: Experimental test rig setup of the desalination system

All experimental parameters, such as dry and wet bulb temperatures, air flow, water flow, and relative humidity, were measured and recorded using a data logger (Datataker DT500). Temperatures were recorded using K-type thermocouples with an accuracy of 0.1°C. Relative humidity was measured and calculated in two ways, initially using humidity sensor of type Vaisala HMP45A at the inlet and exit of desalination system and in the second method it was calculated based on the measured dry bulb and wet bulb temperatures.

To ensure that all the sensors provided approximately the same reading, they were exposed to the ambient temperature and compared to a mercury-in-glass thermometer with ±1 division accuracy. They were also immersed in a hot water bath and the same readings were obtained. The accuracy of the thermometer was checked with a handheld digital thermometer which has 0.1°C accuracy. An anemometer of type TSI digital was used to measure the exhaust air velocity in the desalination unit. Prior to carrying out the experiments, the desalination system with all its components was assembled so that all its sections were horizontal and covered by thermo-insulation materials of thickness 25 mm, as shown in Figure 3.The synthetic brackish water with a high level of total dissolved solids (TDS) and electrical conductivity was prepared and used to fill the system. The datataker was programmed and it instructed the connected instruments to read and store the measured data on the display of computer at frequency of one minute intervals. The operating parameters of the test system, such as dry and wet-bulb temperature, relative humidity and air velocities, were controlled by adjusting the inlet heater, humidifier and associated fan speed to desired conditions, which can be monitored on the display screen of computer. The system was investigated for water production under different hot seawater, and cooling water mass flow rates and then with various air flow rates. The tests were repeated several times and the water that condensed during the experiments was collected into a metering cylinder and measured. An analysis of the water quality was also performed at certain periods of the experiments using Hanna EC/TDS instrument.

5. Results and Analysis

The experimental investigations were conducted to assess the performance of an innovative high performance desalination system which was designed based on the psychometric humidification and dehumidification concept utilizing an efficient high energy recovery technology. The effect of the different working parameters on the production of fresh water was also investigated as described previously in the test procedure.

5.1 Temperature and relative humidity

Figure 4 presents the temperature variations inside the desalination system at different locations. It can be seen that the maximum temperature difference between the inlet and the outlet of the evaporation core is about 5 -12 ^{o}C degrees. The salty hot water was sprayed for 15 minutes into the E-core without injecting air into the system in order to increase the efficiency of humidifier as it can be seen that the desalination system reached the steady state after 35 minutes of operation with hot water circulation, then the air at the top of the humidifier (E-core) became fully saturated and the humidity sensors got wet and faulty. To overcome this problem, dry and wet bulb temperature sensors were then used to calculate the relative humidity. The cooling water was monitored and maintained at a lower temperature than the water distillate temperature in order to improve the condensation process. Figure 4 shows that there are fluctuations in the cooling water temperatures and this is due to automated cooling water supply as the maximum reached temperature was about 37 ^{o}C and then reduced to 22 – 25 ^{o}C by adding a new cooling water and utilizing the heated cooling water to feed the hot seawater in the storage tank and recovering the heat absorbed through the condensation process.

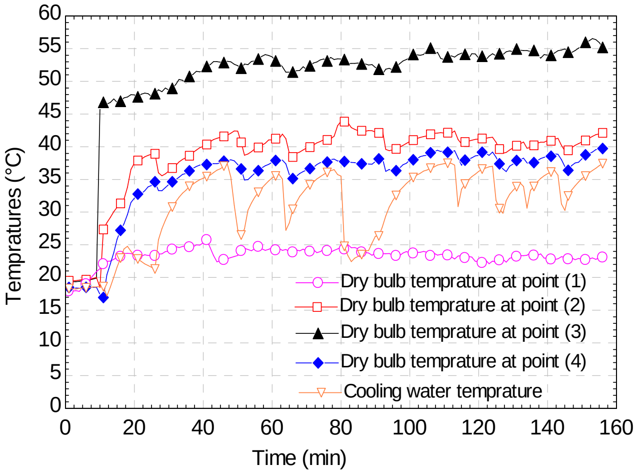

Fig.4: Variations of the dry bulb temperatures at various points in the desalination unit

From the multiple experimental investigations, it was proved that the relative humidity achieved at exit of E-core (point A3) was 90% at the beginning of operation and then increased gradually reaching the saturation point of 95% - 100% after one hour when the supplied hot water temperature was greater than 55 ^{o}C as presented at figure 5. This is reasonable because the system is fully tight and closed with continuous hot seawater supply while the relative humidity of the exhaust air at point A4 was about 84% - 93 % with lower temperatures between 34 – 37 ^{o}C. Further, it can be seen that the relative humidity of injected ambient air varied according to the laboratory conditions from 30% to 40 % with ambient dry bulb temperature of 20 - 25 ^{o}C.

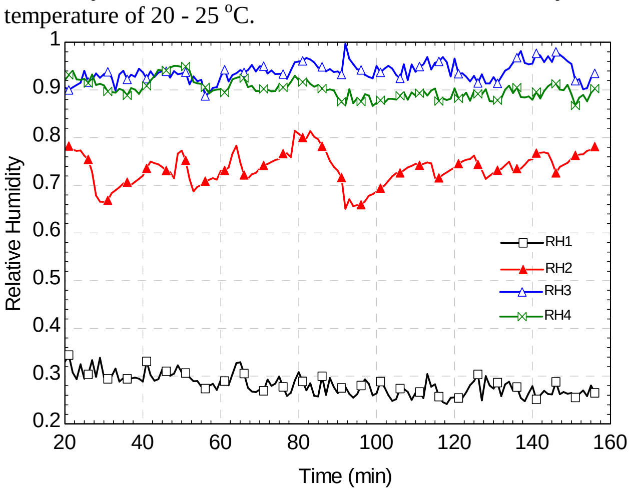

Fig.5: Variations of air relative humidity at different locations in the desalination system

5.2 Air mass flow rate

The fresh air in the desalination unit goes through two processes, namely evaporation and condensation. Normally, a constant mass flow rate of air is supplied from the fan. As the air temperature increases, the air becomes less dense at constant volume; hence more mass is supplied as the temperature increases. Air velocity was measured using a hot-wire anemometer placed at the main four locations namely at the points A1, A2, A3, and A4 respectively in order to monitor the flow of air in the system. It was noticed that the air speed varied because of the change in the duct cross sectional area. For this, a volumetric flow rate was calculated according to ASHRAE method for air measurement as in Equation 1 [xii]

$$V_f = \sum_{i=1}^{n} \frac{V_{fi} * A_i}{A} \qquad (1)$$

where

V_{fi} = Measured velocity in each small cross sectional area (m/sec)

A_i = each small area (m^2)

It was observed that the volumetric mass flow rate at point A1 & A2 is approximately equal and similarly the volumetric mass flow rate at point A3 & A4 are equal with slight differences due to the device measurement accuracy. However the most important observation is that the air flow is reduced significantly after the E-core when the air goes from point A2 to point A3 as it can be seen at figure 6 that the air flow at point A2 is about 165 m^3/hr while at point A3 is about 100 m^3/hr and this can be explained that initially the injected air was exposed to different conditions of heating and cooling in addition to that when the air pass through the humidifier and then pass through the condenser to be dehumidified, it was resisted by the physical features of the system components which results in a high velocity losses and also affected by the pressure drop in the humidifier. It was noticed that to measure the velocity of the air using the wire anemometer is unlikely accurate due to the strong effect of exit air humidity on the measurements so it has been decided to calculate the air velocity from the energy balance and compare it with the measured values. However the measured air speed values showed a relatively constant air velocity changes between 90 to 100 m^3/hr during the operation of the system at the exit air point A4.

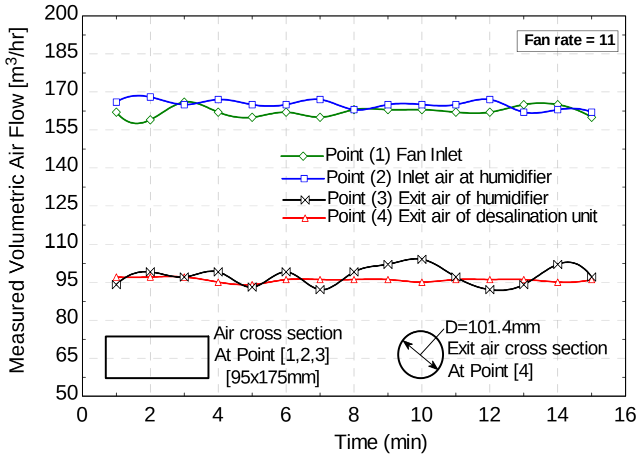

Fig.6: Measured air volume at various points of the desalination unit

The desalination system was then investigated under different air mass flow rates through integrating the system with high variable speed fan. It has been found that the mass flow rate has a significant effect on the water productivity as the higher the air mass flow rate the greater the water productivity. In the another side and when a small fan is used to deliver air into the system the rate of water production was gradually decreased until reached minimum amount of less than 0.5 Litre/hr as shown at figure 7 and it was noticed that the air in the humidifier was fully saturated and the temperatures of dry and wet bulb were increased significantly until they reached a balance as the E-core inlet hot seawater temperature increased rapidly, which meant that the amount of injected air was not sufficient to transport the humidity to the E/C core in order to condensate the moist air and produce fresh water. A fan was installed with a higher flow rate to increase the air flow through the humidifier in order to transfer sufficient amount of air into the E/C core. It can also be noted that the maximum water production is 4 Litre/hr when air mass flow rate is equal to 0.92 kg/min under the test conditions illustrated at figure 7.

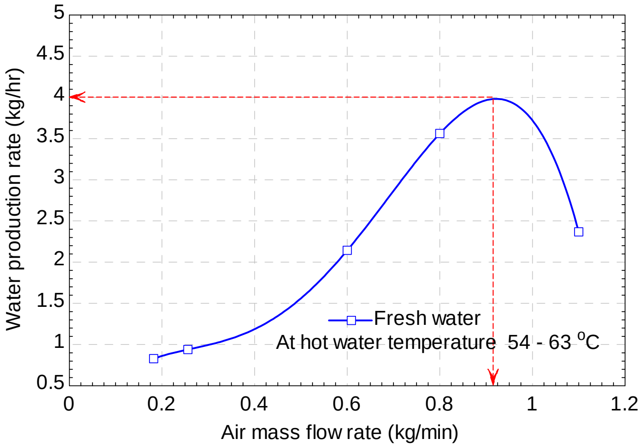

Fig.7: Variation of water production versus air mass flow rates.

5.3 Coefficient of performance (COP).

Figure 8 shows the variation in COP during the testing period at hot seawater temperatures ranges between 54°C and 63°C and hot water mass flow rate of 5 l/min at constant circulation mass flow rate of salty cooling water into the dehumidifier of 2.5 l/min. The COP has been calculated as expressed in Equation 2 where it can be seen that the maximum instantaneous COP obtained ranges between 1.55 to 3 with an average value of 1.9 and this value is reasonable and higher compared with previous work which has been conducted in [xiii]. The improved performance demonstrated by this system configuration shows the potential for running the system coupled with solar thermal collectors and providing cheap and reliable fresh water in semi-arid areas where solar energy is plentiful.

$$COP = \frac{h_{fg} * W_p}{\dot{Q}_{in}} \qquad (2)$$

where: h_{fg} is the latent heat of condensation and W_p is the rate of produced potable water

$\dot{Q}_{in}$ is the supplied energy into the desalination unit including circulation pumps and fan.

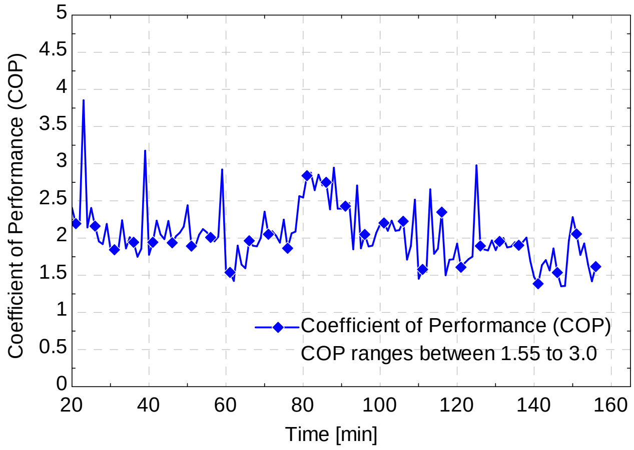

Fig.8: Variations of the coefficient of performance (COP).

5.4 Water production

Figure 9 shows the variation in the water production rate as a function of the supplied hot seawater temperature. There is a gradual increase in the water production during experiment, which is due to the increase of hot water temperature. Water production increases linearly with an increase in hot seawater temperature entering the humidifier.

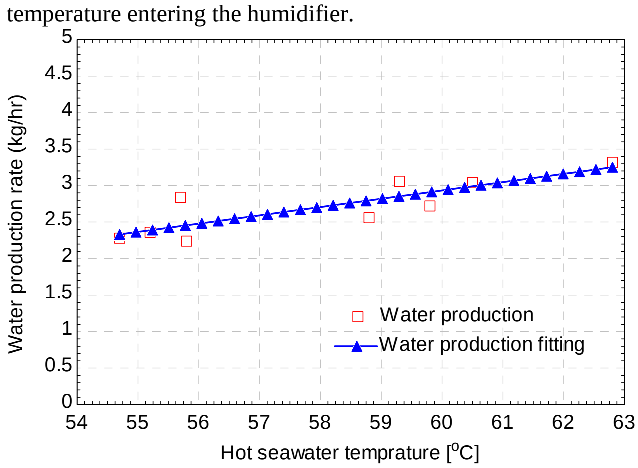

Fig.9: Water production rate as a function of sprayed hot water into humidifier.

Several experiments were carried out and the theoretical calculation was conducted. The theoretical calculations showed an acceptable correlated agreement with the experimental results with high amount of water production rate of about 3.5 kg/hr with an average COP of about 1.9 which is significantly higher than fresh water produced by Shatat and Mahkamov [xiv] as shown in figure 10. However, it can be seen that there is a small difference between experimental results and the theoretical calculations due to the uncertainties and accuracy of measurements and sensors. The water production has been determined theoretically using Equation 3.

$$W_p = \dot{m}_a (\omega_3 - \omega_4) \qquad (3)$$

where $\dot{m}_a$ is the mass flow rate of air , ω_3 and ω_4 are the specific humidity of the water at inlet and outlet of dehumidification chamber, respectively.

Further tests will be carried out to improve the system performance and integrate it with solar collector

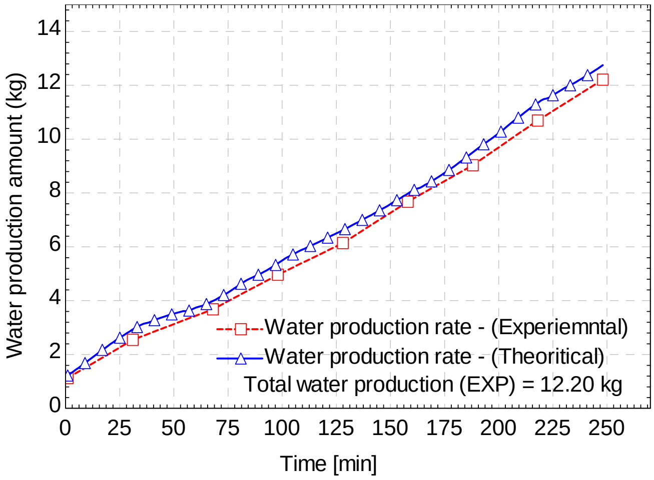

Fig.10: Theoretical and experimental water production rate.

5.5 Humidifier Efficiency

It has been noticed that the efficiency or the effectiveness of the humidifier is significantly affected by the inlet hot seawater temperature and the relative humidity as shown in figure 11. Several tests have been carried out and the results show that humidifier efficiency is linearly proportional to the relative humidity at the humidifier, as shown in Figure 12.

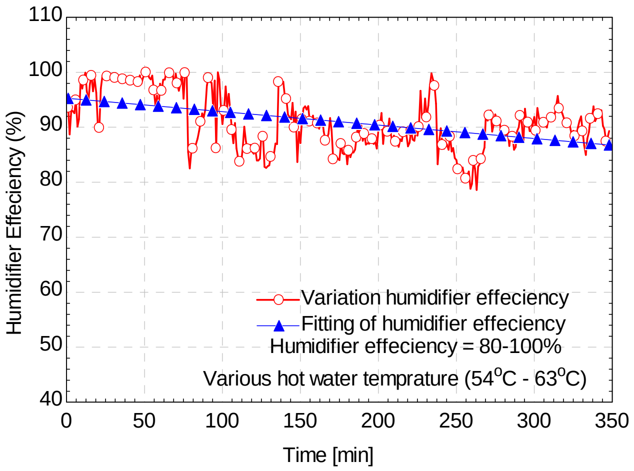

Fig.11: Variations of Humidifier efficiency for several tests conditions

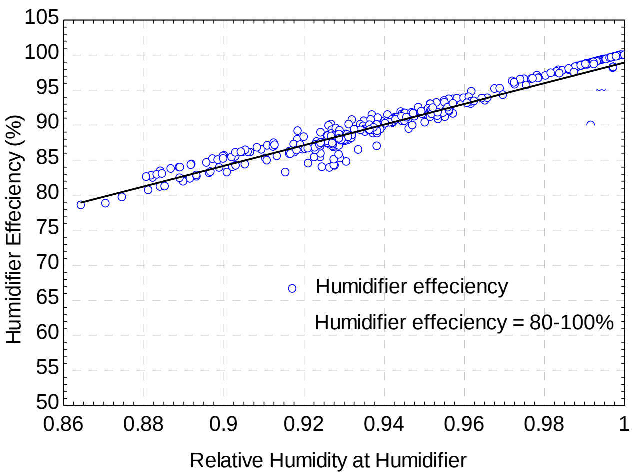

Fig.12: The effect of relative humidity on humidification chamber efficiency

It has been noted that the efficiency of humidifier can reach 99% when a relative humidity is about 98 - 100% and this can be achieved after 45 to 60 minutes of operation when the system reach the steady state. Therefore the humidifier effectiveness was calculated as described at Figure 13 and using the suggested formula in Equation 4 [xv].

$$\eta_{hum} = \left(\frac{\omega_1 - \omega_2}{\omega_s - \omega_1} \right) x100 \qquad (4)$$

where ω_1 inlet humidity, ω_2 outlet humidity, ω_s maximum achievable saturation humidity.

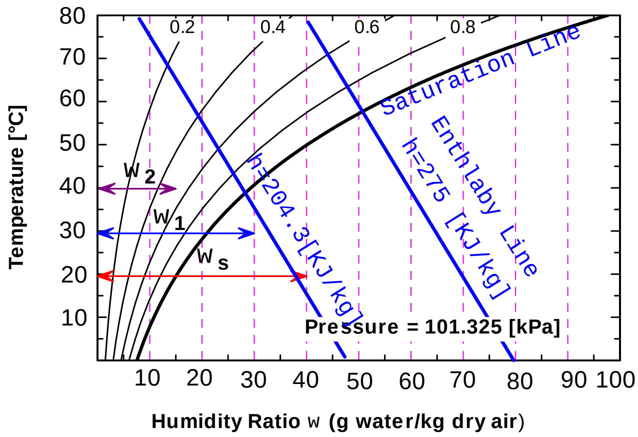

Fig.13: Humidification efficiency definition [xv]

6. Water Quality

Generally thermal water desalination processes produce high water quality and this was confirmed by the analysis conducted in the experiment. Water quality parameters for the total dissolved solids (TDS) and electrical conductivity (EC) were measured every 30 minutes during water production; as the results are presented in Figure 14. The WHO drinking water guidelines (WHO, 2011), state that water with TDS of less than 500 mg/L is considered to be acceptable. The TDS of prepared synthetic brackish water was above 2000 mg/l and TDS of produced fresh water was between 10 and 30 mg/l, which is very pure and well within the WHO drinking water guidelines [xvi] and the quantity of desalinated water could be increased by blending with additional tap water. However, it was noticed that the higher the inlet water temperature the lower were the TDS concentrations and the better was the water quality. Hence it is recommended that the system should be operated at temperatures greater than 50 °C in order to achieve better chemical and biological water quality.

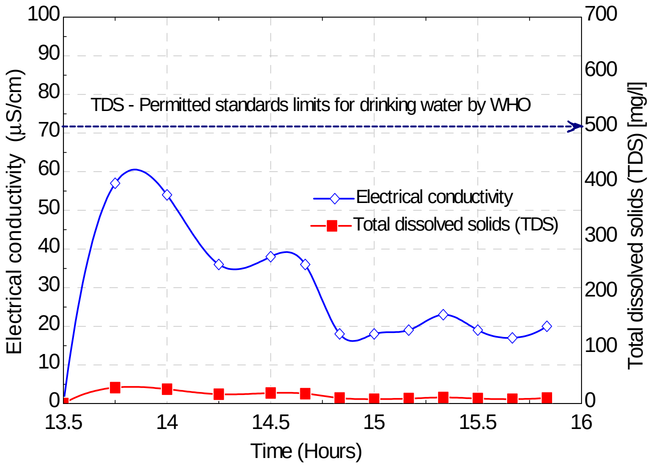

Fig.14: Water quality concentrations of the desalinated water

7. Conclusions

An affordable and efficient psychometric water desalination system was investigated. The experimental results showed that water production was significantly affected by the temperature of the circulated saline water and air mass flow rates. The system produced 3.5 kg/hr fresh water when the input saline water was 54°C - 63 °C. The highest coefficient of performance (COP) obtained was about 1.55-3.0. This is higher than in similar previous work conducted with the same concept and in conventional solar distillation systems [xv] and also with solar stills coupled with a solar collector. Consequently running the system coupled with solar collector could be considered an appropriate solution for tackling the water scarcity in remote and semi-arid areas. The experimental tests proved that, when the system was operated at a higher temperature, the distilled water produced was of high quality and it showed that it was within the range defined by World Health Organization guidelines for drinking water, showing that there was no need for post treatment to prevent biological contamination. The performance of the system could be considerably improved and this will be the subject of further investigations. It is planned to investigate the system with solar collector in the laboratory using the light solar simulator developed as part of this research and under real outdoor conditions in the Middle East. To improve COP and efficiency further, it is planned to reduce heat losses from the system.

Nomenclature

A	Area of cross sectional duct (m^2)
V_f	Measured velocity at cross sectional duct (m/sec)
Q_{in}	Input heat (W)
hfg	Latent heat of vaporization of water (J/kg)
ω	Humidity ratio (kg/min)
$\dot{m}_a$	Air mass flow rate
W_p	Water production rate (kg/min)
η_{hum}	Humidifier efficiency (%)
COP	Coefficient of performance
TDS	Total dissolved solids (mg/l)
EC	Electrical conductivity (µS/cm)
WHO	World health organization
HDD	Humidification and dehumidification process
UNEP	United Nations Environment Programme

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