Theoretical simulation of small scale psychometric solar water desalination system in semi-arid region

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HIGHLIGHTS

• An affordable small scale desalination system is proposed.
• A mathematical model of the desalination system is developed and programmed using Matlab Simulink.
• The model describes the psychometric processes based on humidification and dehumidification.
• The model is used in optimal selection of elements and operating conditions for solar desalination system.
• The use of solar water desalination contributes significantly to reducing global warming.

ABSTRACT

Many countries around the world suffer from water scarcity. This is especially true in remote and semi-arid regions in the Middle East and North Africa (MENA) where per capita water supplies decline as populations increase. This paper presents the results of a theoretical simulation of an affordable small scale solar water desalination plant using the psychometric humidification and dehumidification process coupled with an evacuated tube solar collector with an area of about 2 m². A mathematical model was developed to describe the system’s operation. Then a computer program using Simulink Matlab software was developed to provide the governing equations for the theoretical calculations of the humidification and dehumidification processes. The experimental and theoretical values for the total daily distillate output were found to be closely correlated. After the experimental calibration of the mathematical model, a model simulating solar radiation under the climatic conditions in the Middle East region proved that the performance of the system could be improved to produce a considerably higher amount of fresh water, namely up to 17.5 kg/m² day. This work suggests that utilizing the concept of humidification and dehumidification, a compact water desalination unit coupled with solar collectors would significantly increase the potable water supply in remote area. It could be a unique solution of water shortages in such areas.

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1. Introduction

Fresh water of acceptable quality has become a scarce commodity in many parts of the world. Water scarcity is expected to affect one out of three people in every continent of the globe, and almost one fifth of the world’s population live in areas where water is physically scarce. It is projected that by the year 2025 water demand will exceed supply by 56%, due to persistent regional droughts causing population shifts to urban coastal cities [1]. Currently, about three billion people have no access to potable water and another 1.76 billion people live in areas facing severe water shortage [2]. This situation will get worse with population growth, more urbanization, climate change impacts and increases in household and industrial uses of water [3]. The total global water reserves are about 1.4 billion cubic kilometers, of which around 97.5% is in the oceans and the remaining 2.5% is fresh water present in the atmosphere, ice mountains and ground water. Of the total, only about 0.014% is directly available for human beings and other organisms [4].

Currently, large commercial desalination plants using fossil fuel are in use in most countries that have water shortages and particularly in oil-rich countries. In contrast, people in many other parts of the world have neither the financial nor oil resources to
install such technologies [5]. Most of the current desalination technologies are not economically viable in remote areas, even those near a coast, or in areas that experience an intermittent electricity supply. In addition, they cause massive environmental pollution. The development of alternative, compact, small scale water desalination systems is imperative for the populations of such areas [6]. Thermal solar energy water desalination is known to be a viable method of producing fresh water from saline water in remote areas [4]. Humidification and dehumidification solar water desalination units and conventional basin solar stills with a relatively large footprint are examples of such simple technologies.

Extensive research and development (R&D) using renewable energy technologies have been carried out by many researchers aiming to create an affordable and feasible method to produce drinking water [7]. A significant number of publications have focused on improving the design and performance of small scale solar water desalination. For example the conventional basin solar still without additional concentration of solar energy produces an average water output capacity of about 2.5–3.0 L/m²/day at a thermal efficiency of around 25% due to large heat losses [8,9].

The effect of coupling a flat plate solar collector with humidification and dehumidification processes and a basin solar still have been investigated in a series of R&D projects. For example, Zhang and Yuan (2007) [10] studied a closed circulation solar desalination unit and focused on 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 (2011) [11], and Eames et al. (2007) [12] described the theoretical and experimental investigation of a small scale solar powered barometric 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 (2009) studied the same concept but with the use of geothermal energy [13]. Gude et al. (2012) studied low temperature desalination using solar collectors of area 18 m² augmented by thermal energy storage of 3 m³ volume; their work included theoretical and experimental investigation with water production of 100 L/day [14].

Hou and Zhang (2008) [15] proposed a hybrid desalination process in a multi-effect humidification–dehumidification system heated by solar collectors and they showed that the distilled water output increased by a factor of 2–3 when the rejected water was reused. In their study, they maximized condenser heat recovery through composite curves and found that there is an optimum value for the water to air flow rate ratio, but they did not take the effect of the humidifier inlet temperature and the solar collector efficiency into account. Garg and Adhikari et al. (2003) tested a multi effect humidification (MEH) solar system to provide continuous hot water to a desalination unit over a 24 h period by system modeling based on solving heat and mass transfer equations. The results showed that the rate of distilled water production varied linearly as a function of water temperature at the humidifier [16]. Similarly, Muller-Holst et al. (1999) studied the same concept on a small scale thermal seawater desalination apparatus and showed that the water productivity depended on the magnitude of the thermal energy used in the evaporation process [17]. Soufari et al. (2009) [18] studied parametric effects on the performance of an HDD system and optimized the operating parameters. These studies show that an HDD system may operate at a temperature as low as 50 °C, and therefore could be suitable for incorporation with a Rankine cycle power generation system. However, water quality needs attention here because biological contamination can occur at low operating temperatures.

This paper presents an affordable novel desalination system that requires a very small energy input using hybrid psychometric energy either by electric heater or solar energy supply. This system was built on the humidification and dehumidification principle with two specially designed humidifiers. It was also coupled with an evacuated solar collector panel. Unlike most previous experimental and simulation work that was restricted to the steady state operation at a fixed value of insolation as in Refs. [14,15], this work validated a mathematical model of the psychometric process with evaporation and condensation for transient numerical simulations of daylight insolation variations for daylight under Middle East climate conditions. Furthermore, the development of such a mathematical model means that carrying out the experimental investigations is no longer restricted to a specific solar insolation region; it is possible to simulate solar insolation conditions anywhere in the world. This simulation was extended to the night-time period utilizing the heat stored during the day using the developed Simulink matlab model.

2. System description

The system employs the concept of humidification and dehumidification based on the psychometric energy process using a specially designed heat recovery system converting the saline
water into fresh water. Fig. 1 shows the behavior of the desalination system and components. This system includes the water desalination unit and the heat source which is based on an evacuated tubes solar collector, an air fan and auxiliary components such as water circulation pumps. The desalination unit consists of the main humidifier and pre-humidification chambers for humidifying the moist air and improving heat recovery respectively. The dehumidification chamber contains a heat exchanger where the condensation and recovery of the latent heat of condensation take place for energy recycling and water production respectively.

The key innovation is the re-use of the latent heat from the condensing moisture in the carrier gas. Because the system utilizes a small amount of thermal energy for the humidification and dehumidification process, it is unique and more affordable. Also, it can be integrated with renewable energy sources, notably solar energy harvested through solar collectors.

2.1. Dehumidifier

The dehumidifier with the condenser is an efficient process of condensation and heat recovery. The seawater or brackish cooling water is pumped from the water storage tank which is located at the bottom of the pre-humidification chamber and passes through the dehumidifier to the pre-humidification chamber again in order to extract the heat and humidify the incoming air. The cooling seawater and fresh air are mixed in order to aid evaporation and recover the waste heat of condensation. At the same time they aid in the condensation process by extracting heat from the vapour.

Therefore, most of the heat in the system is utilized to produce fresh water. The moist air is then transferred from the secondary humidification chamber to the second primary humidifier where the air is further humidified by the circulation of sprayed hot salty water.

2.2. Humidifier

The humidification chamber consists of porous media made of cellulose material and a single tube water sprayer. The cross sectional area of the pad is 0.7 m × 0.5 m, while the thickness of each pad is 0.20 m. The pad humidifier unit is a rectangular cassette of corrugated cellulose packing material and this constitutes the wetted surface. At the top, a liquid sprayer showers the hot sea water into the humidifier while, at the bottom, a liquid collector gathers the water as it drains down the cassette. Thus, the water flows downward while the air passes in a cross flow direction through the openings in the cassette. The air is humidified as it comes into contact with the wetted surface of the pad. Fig. 2 shows the pad humidifier and cellulose material.

2.3. Evacuated solar collector and storage tank

The desalination unit is connected to a hot water storage tank through the humidifier with a circulation pump and flow regulator to adjust the mass flow rate of hot water. This storage tank is well insulated to minimize heat losses and to operate the system during the night utilizing the heat stored from solar energy during the day. The water inside the storage tank is heated by a helical copper tubular heat exchanger. The inlet and outlet of the heat exchanger are connected, respectively, to the inlet and outlet manifold at the top of evacuated solar collector so that these form a closed loop.

3. Working principle

The energy generated by the solar collector is utilized to increase the temperature of the saline water in the storage tank which is continuously circulating in the humidifier of the desalination unit. The water temperature increases gradually and then the saline hot water is sprayed into the humidification chamber to humidify the incoming air. The process of humidification and dehumidification goes through four stages as follows.

1. The outside air at point 1 gets humidified in the pre-humidification chamber and the energy required is supplied from the latent heat of water condensation recovered by cooling water in the condensation chamber so that most of the energy needed for desalination is reused.
2. The circulating air at point 2 passes through the humidifier to become more humidified.
3. Air at point 3 passes through the condensing chamber of the HE to get dehumidified.

Fig. 1. Schematic diagram of desalination system.
The condensation is collected as a condensed fresh water at the bottom of the dehumidifier and the air is discharged as exhaust to the ambient.

The evacuated solar collector with the storage tank system was tested under conditions simulating a typical summer in the Middle East. For this, data on the variation of the solar radiation during summer 2004 was used, as shown in Fig. 3. The electrical power voltage supplied to the floodlights was changed every 20 min using the floodlight irradiation and the measurement results presented in Fig. 4.

4. Mathematical model

The mathematical model presented here shows the energy and mass conservation equations for each part of the system. Fig. 1 illustrates the behavior of the humidification and dehumidification processes for the whole system when it is connected with the solar collector. In building the model, the following assumptions were made:

- the thermo-physical properties of brackish water are identical to those of pure water;
- the effect of non-condensable gases released from water when it is heated or expanded can be neglected;
- the system is adiabatic so heat losses to the ambient are assumed to be negligible;
- the system operates under steady state conditions for each time step;
- the system is working under atmospheric pressure;
- the system has a controlled volume, thus air mass flow rate is constant.

The model was used to simulate and predict the water production of the desalination system over a 24 h period, based on a heat supply during daylight hours with variable solar isolations (W/m²). The energy conservation equations can be expressed as follows:

4.1. Input energy

The energy consumed by the system includes the energy required by the solar collector or the electric heater for heating the seawater in addition to the energy used by the auxiliary components, such as circulation pumps and fans, and this can be expressed as:

$$Q_{input} = Q_{hum} + Q_{aux}$$  \hspace{1cm} (1)

where:

$Q_{hum}$ is the supplied energy at the humidifier chamber and $Q_{aux}$ is the auxiliary energy required by circulation pumps and fans in the system.

4.1.1. The supplied energy to the humidifier

$$\dot{Q}_{hum} = \dot{m}_{water} C_p (T_{h,i} - T_{h,o})$$ \hspace{1cm} (2)

$$\dot{Q}_{hum} = \dot{Q}_{col} + \dot{Q}_{heater} - \Delta \dot{Q}_{losses}$$ \hspace{1cm} (3)
where:
\( m_{w,h} \) is the mass flow rate of hot water sprayed into the humidifier, \( C_p \) is the specific heat of water, \( T_{hi} \) and \( T_{ho} \) are the temperatures of the water at the inlet and the outlet of the humidifier, respectively.

### 4.1.2. The output energy

The output energy can be expressed in terms of the condensation energy, which equates the latent heat of condensation:

\[
\hat{Q}_{\text{out}} = h_{fg} * W_p
\]

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

\[
W_p = \dot{m}_a (\omega_s - \omega_d)
\]

where \( \dot{m}_a \) is the mass flow rate of air, \( \omega_s \) and \( \omega_d \) are the specific humidity of the water at the inlet and the outlet of dehumidification chamber, respectively.

In this stage, it was assumed that the heat losses in the desalination unit are negligible (the diabatic wall condition).

The dependence of the latent heat on water condensation on the temperatures was given as proposed by Cooper P. (1969) [19].

\[
h_{fg}(T) = 1000 T \left( 3161.5 - 2.40741 (T_{hi} + 273) \right)
\]

The specific heat of water is defined as a function of its temperature, as suggested by Eames et al. (2007) [12].

\[
C_p = 1000 \left( 4.2101 - 0.00227 T + 5 \times 10^{-5} T^2 - 3 \times 10^{-7} T^3 \right)
\]

In these equations \( h_{fg} \) is in J/kg, \( T \) in °C and \( C_p \) in J/kg°C units.

Initially, to carry out the modeling, it was assumed that the temperature difference between the inlet and the outlet of the humidifier for hot water was about 5 °C; later it was experimentally proved that the difference in temperature mainly depended on the hot water temperature. Hence a representative formula was derived from several experimental results and used to refine and validate the model. This formula was derived based on several trial tests as a function of air and hot water mass flow rates under different hot water temperatures with validated hot water temperatures between 35 °C and 80 °C. Following model calibration it was found that the theoretical calculations are about 95% correlated closely with the experimental values. The model was calibrated by the experimental results published in Ref. [20].

### 4.1.3. Humidifier effectiveness

The effectiveness of the adiabatic humidification chamber can be calculated according to the following equation:

\[
\eta_{\text{hum}} = \frac{T_{hi} - T_{ho}}{T_{ai} - T_{wo}}.
\]

where \( T_{ai} \), \( T_{ai} \) and \( T_{wo} \) are the dry bulb temperature of the inlet air, the dry bulb temperature of outlet air and the temperature of the wet surface, respectively.

The heat balance equation inside the humidifier and pre-humidifier can be expressed as:

\[
\dot{m}_a (h_{ai} - h_{ao}) = C_{pw} \dot{m}_{wi} T_{wi} - C_{pw} \dot{m}_{wo} T_{wo}
\]

where \( \dot{m}_a, \dot{m}_{wi}, \dot{m}_{wo} \) are the moist air and salt water mass flow rate (kg/sec) at the inlet and outlet of the humidifier and pre-humidifier respectively.

\( T_{hi} \) and \( T_{ho} \) are the water temperatures for the inlet and outlet of humidifier and pre-humidifier respectively, \( C_{pw} \) water specific heat (KJ/kg °C), \( h_{ai} \) and \( h_{ao} \) are the enthalpies of moist air at the inlet and the outlet of humidifier and pre-humidifier, respectively.

The effect of different ratios of water to air mass flow rates was investigated to measure the efficiency of the humidification process in addition to the dependency of the efficiency on the air velocity in the humidification chamber. It was found that the effectiveness of the humidifier could reach up to 99%, and therefore it can be assumed that the air at point 3 is fully saturated while the relative humidity in the pre-humidifier chamber increases from 40% to 70%.

### 4.1.4. Dehumidifier

The efficiency of the condenser heat exchanger can be defined as the ratio of the latent heat of condensation given to the circulated cooling water through the condenser (dehumidifier) to the input heat energy, as shown in the following formulas.

#### 4.1.4.1. The heat input into the condenser through the moist air.

\[
Q_{\text{input}} = \dot{m}_a (h_{a3} - h_{a4})
\]

where \( h_{a3}, h_{a4} \) and \( \dot{m}_a \) are the moist air enthalpies at the inlet and the outlet of condenser, and air mass flow rate, respectively.

#### 4.1.4.2. Heat energy balance cross the dehumidifier.

\[
\dot{m}_a (h_{a3} - h_{a4}) = \dot{m}_{cw} C_p (T_{w2} - T_{w1}) + W_p C_p T_{\text{distillate}}
\]

where \( T_{w2}, T_{w1} \) and \( \dot{m}_{cw} \) are the temperatures of the cooling water at the outlet and the inlet of the condenser pipe and the cooling water mass flow rate, respectively. \( W_p \) and \( T_{\text{distillate}} \) are the rate and the temperature of the fresh water collected from the condenser.

### 4.1.5. Solar collector efficiency

The solar collector efficiency can be defined in terms of the inlet and outlet fluid temperatures of the collector manifold, the area of the collector, and mass flow rate as suggested by Yuan and Zhang (2007) [10].

\[
\eta_i = \frac{\dot{m}_a C_p (T_{SCi} - T_{SCo})}{C_{A_{col}}} 
\]

where:
\( T_{SCi}, T_{SCo} \) are the inlet and outlet fluid temperatures of the collector manifold [°C], \( C_{A_{col}} \) is the area of the collector [m²].

The efficiency of the evacuated solar collector used can also be represented as in Ref. [21].

\[
\eta_i = 0.84 - 2.02 \frac{T_m - T_a}{G} - 0.0046 \left( \frac{T_m - T_a}{G} \right)^2
\]

where:
\( T_m \) mean collector temperature, \( T_m = (T_{SCi} + T_{SCo})/2 \) [°C], \( T_a \) ambient air temperature [°C], \( G \) solar irradiance [W/m²]

### 4.1.6. Storage tank

In this model, a water storage tank was incorporated into the system to allow the system to run for 24 h. A completely mixed system to allow the system to run for 24 h. A completely mixed storage tank content is assumed.

The energy balance equation for the storage tank with a solar collector heat exchanger is given by Ref. [6].

\[
M_s C_p \frac{dT_s}{dt} = \dot{Q}_{\text{col}} - \dot{Q}_{\text{losses}} - \dot{Q}_{\text{humid}}
\]
\[ M_s C_p \frac{dT_s}{dt} = m_{w,h} C_p (T_{h,o} - T_s) + m_c C_p (T_{SCi} - T_{SCO}) \]  

(15)

where:

- \( m_{w,h} \) and \( m_c \) are the mass flow rate of hot water sprayed in the humidifier and through the solar collector, respectively. \( C_p \) is specific heat of water.
- \( T_s = T_{h,i} \) and \( T_{h,o} \) are the temperatures of the water at the inlet and the outlet of the humidifier.

4.1.7. Psychometric definitions and formulas

The psychometric parameters were calculated for the analysis of the desalination system of humidification and dehumidification based on the formulas obtained from ASHRAE 1997 Handbook Fundamentals and Hyland and Wexler’s (1983a) formulas [22].

4.1.8. Specific humidity

\[ \omega = 0.62198 \left( \frac{P_s}{P_i - P_s} \right) \]  

(16)

\[ p_s = e^{ \left( \frac{25.5771 - 4042.9}{T_s - 37.58} \right) } \]  

(17)

In these equations the temperature is in °C and pressure is in Pa units.

4.1.9. Relative humidity (RH)

\[ RH = \frac{P_w}{P_{ws}} \]  

(18)

4.1.10. Enthalpy of moist air (h)

\[ h = C_{pa} T_i + \omega (2501 + 1.805 T_i) \]  

(19)

5. Results and analysis

5.1. Modeling and simulation

A mathematical model has been developed and programmed using the Simulink Matlab software, as shown in Fig. 5. In this model all desalination components including the solar collector and solar storage tank were developed and calibrated with the experimental results published in Ref. [20]. In this program, energy
and mass balance equations and boundary conditions are solved simultaneously using the analytical methods described above.

5.2. Model calibration and validation

The mathematical model has been calibrated and validated using the experimental results published in Ref. [20]. A comparison was made between the numerical predictions and the experimental results for the desalination system components and the thermophysical properties as well as the operating and geometrical parameters were taken into consideration. The experimental and theoretical values for the temperatures and total daily distillate output were found to be closely correlated, as shown in Fig. 6. The accuracy between the measured and simulated temperatures inside the storage tank ranged from 93.9% to 99%. The validated model was then used to investigate the effects on the productivity of potable water of different design parameters, such as temperatures, mass flow rates and solar insolation under different climatic conditions in the Middle East for summer, spring, autumn and winter. In this paper we will focus mainly on the summer semester. Fig. 8 shows the variation of water temperature inside the storage tank in addition to the solar insolation during spring in the Middle East.

5.3. Operational schemes of simulation

Three operational scenarios were adopted and run under the Middle East region climate conditions. The operational schemes were:

1. Scheme (1). The solar collector and the desalination unit were operated at the same time from 7:00 am until 5:00 pm and the desalination unit was left working after sunset.
2. Scheme (2). The solar collector was operated from 7:00 am until 5:00 pm while the desalination unit was switched on 5 h later at 1:00 pm.
3. Scheme (3). The solar collector was operated from 7:00 am until 5:00 pm while the desalination unit was switched on at 5:00 pm after sunset and continued operation overnight.

5.4. Simulation of evacuated solar collector

Due to the variable nature of the weather around the world, it is critical to note that solar thermal collectors have a variable efficiency, dependent on solar insolation, fluid temperature and air temperature. Hence this part of the model aims to simulate and provide the power output needed to heat the saline water to meet water desalination process requirements under different climate conditions. Various storage tank volumes and various solar collector areas have been simulated to provide the optimal size for both of these components in order to achieve the desalination requirements outlined in operational Scheme 3.

To eliminate the need for biological treatment and to avoid scaling problems, it is necessary to achieve temperatures of between 60 °C and 80 °C for the hot saline water [17,23]. For instance, a transient simulation using the weather data for summer, spring and winter semesters with an evacuated tube solar collector area of about 2.02 m² was performed and the results showed that the...
maximum temperatures which could be reached are 100 °C, 83 °C, 73 °C, 63 °C and 60 °C for solar tank sizes of 80 L, 100 L, 120 L, 140 L and 160 L respectively. Both the literature and our results show that a saline water temperatures of 60 °C to 80 °C can be achieved with a 120 L storage tank during summer and spring in the Middle East as shown in Fig. 7.

From Fig. 7, it can be seen that the water temperature in winter reaches only 50 °C which means that an attention should be paid to the biological contamination. Consequently, in order to raise the temperature to 60 °C, an external heater or a smaller, 80 L, storage tank is required. Alternatively, a hypochlorite solution can be used to avoid the contamination risk but this option is mainly dependent on the biological quality of the available saline water [24]. In contrast, it can be seen that the temperature in summer can reach 100 °C and thus risks of scaling. Therefore, it is recommended that the system should be operated according to operational Scheme 1 or 2 in order to reduce the higher temperatures as well as heat losses.

5.5. Simulation of desalination process

Here, the simulation of the summer semester with an 80 L storage tank based on operational Scheme 1 will be presented. In this scheme the desalination unit using energy delivered by the solar collector is operated during the day light period from 7:00 am until 5:00 pm and the desalination process continues to operate during the night utilizing the energy stored during the daylight hours.

Water temperatures at different points in the desalination system, namely the inlet and exit points of the humidifier, the cooling water and the recovered heat through the dehumidifier, have been simulated, as shown in Fig. 8. This simulation was performed for Middle East summer conditions with a solar collector area of 3 m² and an 80 L storage tank volume. It can be seen that the maximum temperature achieved at the humidifier inlet was about 61 °C with a cooling water temperature of 21 °C. The heat recovered from the dehumidifier was found to be directly proportional to the humidifier inlet and exit temperatures. Similarly, a simulation using a 2.02 m² solar collector was carried out. Here, 50 °C was the highest temperature achieved. Hence, this simulation was not analysed further due to water quality issues and the fact that other seasons would provide temperatures that are too low for thermal water desalination.

Similarly, the air enthalpies at various points were also simulated, as illustrated in Fig. 9. This figure shows consistent values between the air enthalpies and the water temperatures at the same points compared with values presented at Fig. 8. This is reasonable due to the fact that the inlet air at the humidifier inlet gets humidified when faced with the circulated hot water and because the higher is the inlet water temperature the greater is the associated air enthalpies at the same point. Similar behavior can be seen for the rest of design parameters at various locations in the desalination system.

The simulation was extended to cover the rate of fresh water production, as shown in Fig. 10. Here it can be seen that the highest water production rate of 1.14 g/sec occurred in the afternoon after 2:00 pm when solar insolation was greatest. Then, as solar insolation decreased and the saline water temperatures reduced, the fresh water production also decreased. This means that the water production rate is proportional to the solar insolation.
Figs. 11 and 12 show the variations of simulated water production and temperature inside the water desalination system for the summer season with different sizes of solar collector. In this scheme, it can be seen that the desalination unit and solar collectors started to work together from 7:00 am and continued until 5:00 pm, after which the desalination unit continued to operate utilizing the energy stored in the storage tank. It can also be seen that the optimization of different solar collector areas has a significant effect on the variation of saline water temperatures in the storage tank, as shown in Fig. 13, the maximum achieved temperatures in the afternoon were 36 °C, 43 °C, 48 °C, 54 °C, 61 °C and 67 °C for solar collector areas of 1 m², 1.5 m², 2.02 m², 2.5 m², 3 m², and 3.5 m², respectively. Meanwhile, water production was still reasonable with a quantity of 13 kg/m²/day, as shown in Fig. 14. This amount of water is an acceptable quantity compared with similar previous research conducted in Refs. [8,14] though the water quality needs to be monitored to eliminate the need for post treatment as explained above and in the literature [18].

The desalination system was also simulated for the other two operational schemes. In the second scenario, the saline water in the storage tank was heated by solar energy from 7:00 am until 1:00 pm and then the desalination system was started to produce fresh water. In the third scheme, the solar energy delivered by the solar collector was stored in the saline water storage tank during
the day light period from 7:00 am until 5:00 pm before the desalination system was started and operated during the night. The results of simulation showed that the third scheme should be preferred because it allows the saline water to reach a temperature above 65 °C, which eliminates the need for biological treatment of the distillate.

For the third operational scheme, it can be seen from Fig. 14 that, during the spring season simulation, the highest temperature obtained in the water tank connected with a 2.5 m² solar collector was 89 °C. However, simulated summer insulations showed that the temperature of saline water can reach 100 °C. Therefore, it is recommended that, during summer time, the second operational scheme should be adopted in order to avoid excessive temperatures and this will also reduce the heat losses during the energy storage period. Operating the desalination system with saline water temperatures between 60 °C and 80 °C would also eliminate salt scaling. Hence, the desalination system should be operated according to the first scheme during spring, autumn and winter but the first and second operational schemes are more suitable for the summer.

Fig. 15 shows that the average daily water production of the system using a solar collector of 2.5 m² operated on the third operational scheme in summer, spring, autumn, and winter are 28.8, 25.5, 23.7 and 15.8 kg per day respectively, with an average annual daily production of 24 kg/day for solar collector of 2.5 m² operated on the third operational scheme. This amount of fresh water could be sufficient for a family of 5 persons for drinking and cooking purposes [25]. It has also been proved that the system could produce up to 14.5 kg/m² day in summer, as shown in Fig. 16. This is significantly higher than the 6 kg/m²/day of fresh water produced by an evacuated tube solar collector coupled with four stage stills [26].

6. Conclusions

A mathematical simulation model of an affordable, small scale desalination system based on the humidification and dehumidification process coupled with an evacuated tube solar collector was developed and programmed using Simulink Matlab software. This work describes the mathematical model of the psychometric process with evaporation and condensation at the humidifier and dehumidifier respectively. Transient numerical simulations were conducted as solar insolation varies during the daylight period and the model was extended to the overnight period.

The mathematical model was calibrated and validated using the experimental results in Ref. [20]. A comparison between the numerical predictions and the experimental results for the desalination system's components was carried out and these were found in good agreement. The evacuated solar collector provided 69% efficiency for heating the input water. Running the system coupled with an evacuated solar collector in summer can produce up to 14.5 kg/m²/day, which is significantly higher than the 6 kg/m²/day of fresh water produced by an evacuated tube solar collector coupled with a four stage still system which is found to be about 6 kg/m²/day [26].

This model can be applied for this solar water desalination system in any climate zone and local weather condition for any
particular region of the world. The model could be also helpful in selecting the optimal elements and operating conditions for solar desalination systems anywhere in the world. Furthermore, this work has shown that experimental investigations need no longer be restricted to a specific solar insolation region because the developed model makes it possible to simulate solar insolation conditions anywhere in the world. Further research will be concentrated on improving the system’s performance and greater attention will be paid to reducing heat losses from the system. The development of compact, small scale communal systems for water desalination coupled with solar energy sources has great potential for tackling water supply problems, especially in remote and semi-arid areas where sun is plentiful. Such systems would also contribute significantly to reducing global warming resulting from CO₂ emissions.

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