Water Reuse

Water Reuse Vol 12 No 1, 92 doi: 10.2166/wrd.2022.095

Performance evaluation of an HDH desalination system using direct contact packed towers: experimental and mathematical modeling study

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ABSTRACT

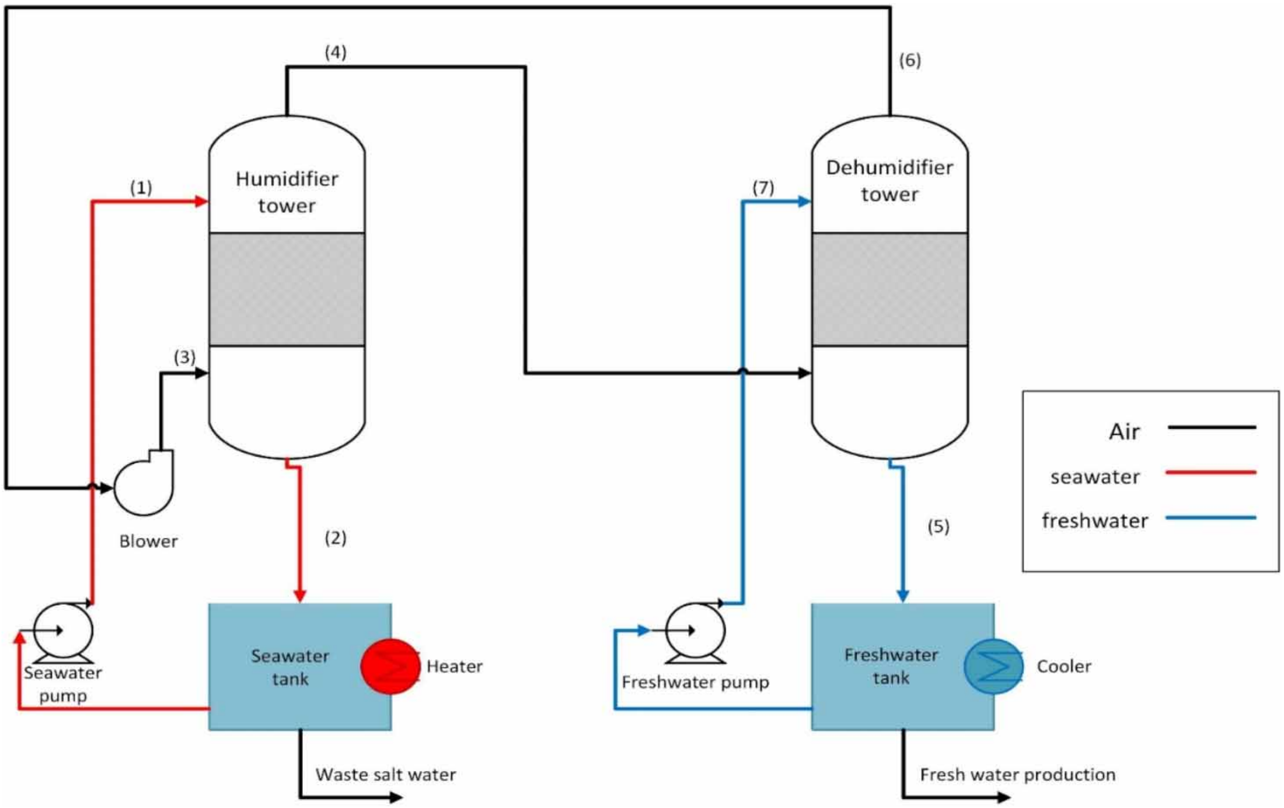
Humidification–dehumidification desalination (HDH) is one of the suitable methods for desalination of saline and brackish water in a small scale. In this research, an HDH desalination method with a direct contact dehumidifier has been analyzed theoretically and experimentally. The setup consists of two similar packing towers for humidification and dehumidification, 10 inches in diameter, which are filled up to 1 m with Rushing packing. In this new HDH configuration, seawater and freshwater recirculation has been used in humidifier and dehumidifier sections, respectively. A steady-state mathematical model based on the mass and energy equations for each system component is presented. The effect of various input parameters on the freshwater production, gain output ratio (GOR) and specific energy consumption has been investigated. The results revealed that the inlet seawater and air temperature to the humidification tower had the highest and the lowest effect on the produced freshwater, respectively. Also, the maximum value of the GOR is 3.3, which is obtained in the equilibrium condition of the dehumidifier. The experiments show that the freshwater production of the proposed HDH device is 300 L/day, which can provide water for the domestic consumption of a small family.

Key words: direct contact condenser, HDH desalination, packed tower, thermodynamic modeling

HIGHLIGHTS

- A new configuration of a humidification–dehumidification desalination process was experimentally and theoretically assessed.
- A direct contact condenser uses cooling of freshwater produced by a vapor compression cycle.
- The maximum GOR value in this system is 3.3, which is obtained in dehumidifying equilibrium conditions.
- The maximum freshwater production in the experiments is 300 L/day.

GRAPHICAL ABSTRACT



NOMENCLATURE

Acronyms

HDH	humidification–dehumidification
GOR	gain output ratio
MR	mass flow rate
SEC	specific energy consumption (kWh/m^3)
HCR	heat capacity ratio

Symbols

$\dot{E}$	energy rate (kW)
h	enthalpy (kJ/kg)
$\dot{H}$	enthalpy rate (kW)
h_{fg}	latent heat of vaporization (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (kPa)
Q_{air}	freshwater volumetric flow rate (m^3/h)
$Q_{freshwater}$	freshwater volumetric flow rate (L/min)
$Q_{seawater}$	seawater volumetric flow rate (L/min)
$\dot{Q}$	heat transfer rate (kW)
$\dot{V}$	volumetric flow rate (m^3/h)
$\dot{W}$	power (kW)

Greek letters

ε effectiveness
ω humidity ratio

Subscripts

a	air
b	blower
br	brine
d, dehum	dehumidifier
da	dry air
fw	freshwater
fwp	freshwater pump
fwt	freshwater tank
h, hum	humidifier
in	inlet
max	maximum
o, out	outlet
pu	pump
sw	seawater
swp	seawater pump
swt	seawater tank

Superscripts

id ideal

INTRODUCTION

Drinking water consumption is widely increasing. The reason for this is population growth and increased industrial, agricultural, and economic activities (Zubair *et al.* 2018; Amirfakhraei *et al.* 2020). The United Nations estimates that by 2025, about 1,800 million people worldwide will face severe water shortages (Amirfakhraei *et al.* 2021a). To relieve serious shortages of potable water supplies, water desalination methods and relevant devices have become attractive (He *et al.* 2018; Amirfakhraei *et al.* 2021b). Existing desalination plants are mostly large-scale. These plants are only cost-effective in advanced countries (He *et al.* 2019). In recent years, humidification–dehumidification (HDH) desalination, which simulates water circulation in nature, has been widely studied. These systems are suitable for small-scale potable production and offer several advantages over other desalination technologies (Elzayed *et al.* 2021; Kaunga *et al.* 2021). The HDH system has a simple construction, so it is easy to maintain compared to other thermal and membrane technologies (Aref *et al.* 2021). Despite the HDH systems, technologies such as multi-stage flash distillation (MSF) and multiple effect distillation (MED) need intensive heat energy sources, and reverse osmosis (RO) systems should be placed where there is an electricity supply (Liberman *et al.* 2020).

A key advantage of HDH desalination plants is their compatibility with renewable energy sources. The most common renewable energy used in HDH desalination systems is solar energy (Aref *et al.* 2021). Zubair *et al.* (2017) optimized a desalination system (HDH) integrated with vacuum tubes for operation in different geographical locations. Wu et al. (2017a, 2017b) investigated a multi-stage desalination system experimentally that was directly heated by a Fresnel lens solar collector. Their results showed that the maximum performance of the unit was about 3.4 kg/h and the maximum gain output ratio (GOR) was about 2.1 when the average intensity of solar radiation was 867 W/m^3. One of the suitable applications of HDH systems is in the seawater greenhouses (Zarei *et al.* 2018; Zarei & Behyad 2019). In these systems, solar energy is used by vacuum tubes located on the roof of the greenhouse. The humid air produced in the evaporator is useful for the culture medium inside the greenhouse. Then, this humid air is dehumidified in a condenser. Therefore, this HDH system can be well compatible with these greenhouses. In another study, performing a detailed thermodynamic analysis is to evaluate the performance of an HDH system with an integrated parabolic trough solar collector (PTSC). Their HDH system was an open-water open-air system that used PTSC as an air heater. Figure 1 shows the schematic of this configuration.

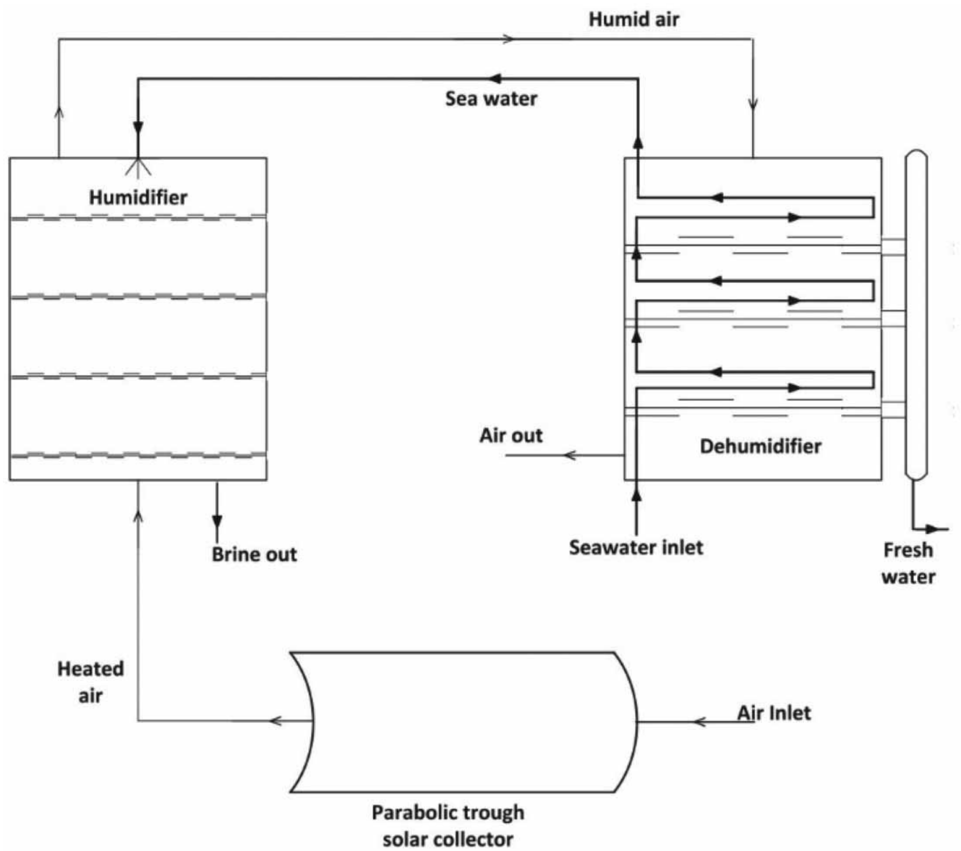


Figure 1 | Open-water open-air HDH desalination system.

Several innovative ideas have been proposed to reduce the energy consumption and improve performance of HDH systems. The conventional HDH process had limitations in terms of its dependence on the stability of the hot and cold sources (Rahimi-Ahar *et al.* 2018). Due to operating at low temperatures, utilization of renewable energy and waste heat sources lead to the modification of HDH systems (Zarei *et al.* 2020). The low energy efficiency makes the conventional HDH systems less competitive. Energy recovery can improve it. HDH systems can be coupled with different desalination methods to enhance the system performance parameters. Coupling the HDH to solar stills, RO unit, humidification–dehumidification–adsorption and water flashing evaporation have been proposed (Rahimi-Ahar *et al.* 2018). On the other hand, multi-effect and multi-stage humidification–-dehumidification systems utilize the technology of several humidification/dehumidification effects and stages to improve components efficiency (Wu *et al.* 2017a, 2017b).

Nada *et al.* (2015) evaluated the performance of the combined HDH system with air conditioning. The obtained results showed that the amount of desalinated water production, compressor work per kilogram of desalinated water production, and refrigeration capacity increased with increasing mass flow and specific humidity. Relative humidity and air temperature increased significantly with increasing freshwater production. Dehghani *et al.* (2018) analyzed a desalination cycle dehumidifier with a direct contact condenser combined with a heat pump. The heat pump provided simultaneous cooling and heating supply. Zhang *et al.* (2019) investigated numerically an HDH method operated by a heat pump. Their device consisted of a heat pump unit, plate heat exchanger, humidifier, and first- and second-stage dehumidifier. A mathematical model based on the conservation equations of mass and heat of each component is proposed, and the model is validated by experimental results. The numerical investigation of the effects of several important parameters such as air and seawater on system performance has been studied. A two-step HDH process to increase the production of desalinated water from brackish water was designed by Zamen *et al.* (2014), who had observed that the two-step process can be increased by 20% compared to the single-stage unit.

HDH can be combined with other large-scale desalination technologies to increase energy efficiency and to improve performance such as HDH-RO by Jamil *et al.* (2018) and a thermoelectric cooler investigated by Yıldırım *et al.* (2014). Kabeel *et al.* (2014) proposed a two-dimensional model for a combined solar desalination system consisting of HDH and single stage flash evaporation unit. The results showed that the studied desalination system had significant operational compatibility between the dehumidification method of air dehumidification and desalination of flash evaporation with daily water production up to 11.14 kg/m^2. Zarei *et al.* (2020) proposed a novel tray humidifier column for HDH desalination. A stainless-steel sieve tray with a rectangular cross-section was used. The effectiveness of the proposed tray humidifier is between 0.67 and 0.87.

A dehumidifier has a significant effect on the water produced compared to a humidifier (Zarei *et al.* 2020). For this reason, attention to the design and characteristics of dehumidifiers is increased. He *et al.* (2018) investigated an HDH desalination system with a dehumidifier packed column that was performed with exhaust gas from a furnace. The results revealed that the peak values of water production and the GOR were 84.60 kg/h and 1.44 kg in dehumidifying equilibrium conditions, respectively. Niroomand *et al.* (2015) introduced a direct contact dehumidification process used in the HDH system instead of using conventional indirect condensers.

Direct contact heat transfer in a packed tower has higher heat transfer coefficients than indirect contact heat transfer. Many of the challenges experienced with indirect contact condensers such as hydraulic pressure drop, saline water leakage and pipe corrosion issues can be solved with the HDH direct contact process. Improvements in dehumidification design can help increase the efficiency of the HDH system. In the present study, a novel process for the HDH system has been proposed, which uses a direct contact dehumidifier for condensation. The proposed configuration has some special characters such as recirculation of seawater in the humidifier and freshwater in the dehumidifier. This recirculation can increase the heat and mass recovery of the system. The effect of various operational parameters such as flow rate and temperature of each stream on freshwater production, GOR and specific energy consumption (SEC) has been investigated. The performance of the system is evaluated by a thermodynamic model based on the mass and energy conservation equations which are supported by experimental data.

METHODOLOGY

Experimental setup description

Figure 2 shows a schematic of the experimental setup in this study. This setup includes three main streams of fluid circulation such as saline water line, freshwater, and air lines as well as containing humidification and dehumidification packed tower. In a seawater tank, three heating electric elements with 3.7 kW have been used for the required energy. The seawater should reach a temperature of 60–70 °C. This hot saline water is pumped to the humidifier (evaporator) tower by a seawater pump (1). Both towers are the same and filled to a height of 1 m with Rushing packing. The towers' diameter is 10 in. The hot seawater is sprayed into the tower by a shower. The packed bed tower provides a very high contact surface for water and air flow. A blower blows air into the bottom of the humidifier tower. After proper air–water contact through the packed bed humidifier, the exit air becomes hot and humid. This hot saturated air enters the bottom of the packed bed dehumidifier tower through a pipe (4). In the dehumidifier tower (condenser), which is similar to the humidifier tower, the air that is in direct contact with freshwater condenses. The produced freshwater associated with the water stream comes out of the bottom of the tower and returns to the freshwater tank (5). The dehumidified air also leaves the tower and returns to the blower in a closed cycle (6). The level of the freshwater in the tank is kept constant and excess water is removed from the tank and used as a product (7). The freshwater tank is cooled by a vapor compression cycle that includes a compressor, expansion device, and evaporator. The compressor has a 1.3 kW power. The evaporator of the vapor compression cycle has been installed inside the freshwater tank, and by a thermostat, the water temperature has been fixed. The cooled freshwater has been pumped to the dehumidifier tower by the freshwater pump (8). All streams, tanks, and towers must be insulated to prevent heat loss. 6 K-type thermocouples were fixed in the test rig to measure the temperature of the inlet and outlet air and water to the towers and inside the tanks. A pitot tube has been used to calculate the air flow rate. The relative humidity of the three streams was measured by a humidity meter.

MATHEMATICAL MODELING

The main assumptions used to obtain the mathematical model of this system are:

- Steady-state conditions and atmospheric pressure are considered.
- Heat losses to the surrounding are neglected.
- The kinetic and potential energy changes are negligible.
- The humidifier and dehumidifier chambers are adiabatic.

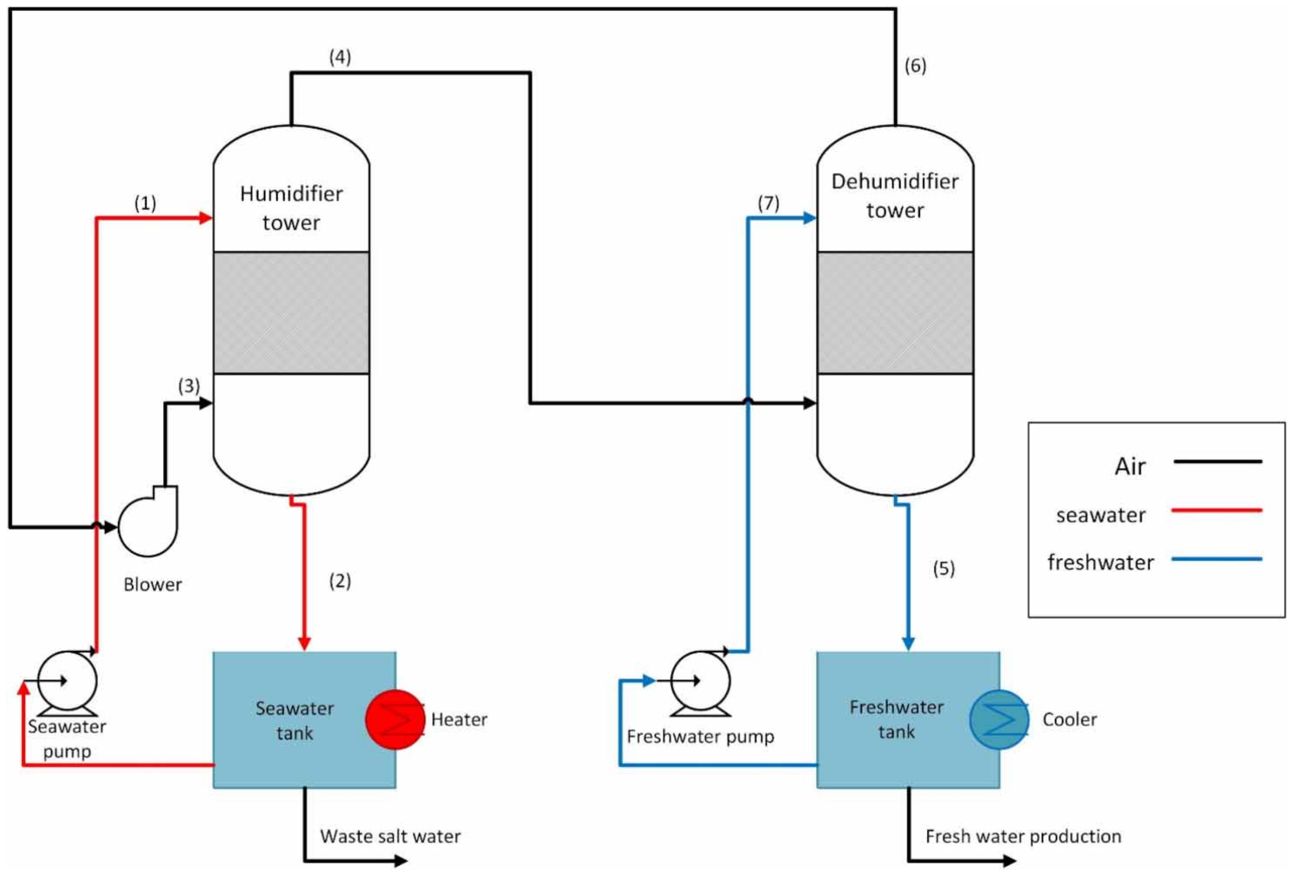


Figure 2 | Experimental setup configuration of the HDH system.

- The dry air and water vapor mixture are assumed as ideal gas.
- The isentropic efficiency of the pump is assumed to be 0.8.
- The dead state conditions (temperature 25 °C, atmospheric pressure, and relative humidity 0.60) are considered.

GOVERNING EQUATIONS

The balance equations of mass and energy for the main components of this desalination system are as follows:

Humidifier:

$$\dot{m}_{sw,H,i} - \dot{m}_{br} + \dot{m}_{da}\omega_{a,H,i} - \dot{m}_{da}\omega_{a,H,o} = 0 \quad (1)$$

$$\dot{m}_{sw,H,i}h_{sw,H,i} - \dot{m}_{br}h_{br} = \dot{m}_{da}(h_{a,H,o} - h_{a,H,i}) \quad (2)$$

Dehumidifier:

$$\dot{m}_{fwp} = \dot{m}_{da}(\omega_{a,D,i} - \omega_{a,D,o}) \quad (3)$$

$$\dot{m}_{fw,D,i}h_{w,fw,D,i} - \dot{m}_{fw,D,o}h_{fw,D,o} = \dot{m}_{da}(h_{a,D,o} - h_{a,D,i}) \quad (4)$$

Saline water pump:

$$\dot{m}_{sw,p,i} = \dot{m}_{sw,p,o} \quad (5)$$

$$\dot{m}_{sw,p,i}h_{sw,p,i} = \dot{m}_{sw,p,o}h_{sw,p,o} + \dot{W}_{swp} \quad (6)$$

Desalination water pump:

$$\dot{m}_{fw,p,i} = \dot{m}_{fw,p,o} \quad (7)$$

$$\dot{m}_{fw,p,i} h_{fw,p,i} = \dot{m}_{fw,p,o} h_{sw,p,o} + \dot{W}_{fwp} \quad (8)$$

Blower:

$$\dot{m}_{a,b,i} = \dot{m}_{a,b,o} \quad (9)$$

$$\dot{m}_{da} h_{a,b,i} + \dot{W}_b = \dot{m}_{da} h_{a,b,o} + \dot{W}_{kinetic} \quad (10)$$

Saline water tank:

$$\dot{m}_{ma} + \dot{m}_{sw,swt,i} = \dot{m}_{sw,swt,o} + \dot{m}_{waste} \quad (11)$$

$$\dot{m}_{ma} h_{ma} + \dot{m}_{sw,swt,i} h_{sw,swt,i} + \dot{Q}_{in} = \dot{m}_{sw,swt,o} h_{sw,swt,o} + \dot{m}_{waste} h_{waste} \quad (12)$$

Freshwater tank:

$$\dot{m}_{fw,swt,i} = \dot{m}_{fwp} + \dot{m}_{fw,fwt,o} \quad (13)$$

$$\dot{m}_{fw,swt,i} h_{fw,swt,i} + \dot{Q}_{out} = \dot{m}_{fwp} h_{fwp} + \dot{m}_{fw,fwt,o} h_{fw,fwt,o} \quad (14)$$

Since the number of unknowns is greater than the number of equations, auxiliary equations are needed to solve the equations. These auxiliary equations can be obtained from the effectiveness of the components.

The efficiency of mass and heat exchangers is defined as the ratio of changing the enthalpy of the flow to its maximum enthalpy change (Rostamzadeh *et al.* 2018):

$$\varepsilon = \frac{\Delta \dot{H}}{\Delta \dot{H}_{max}} \quad (15)$$

The effectiveness of humidifier and dehumidifier is as follows (Lawal *et al.* 2018; Zarei *et al.* 2020):

$$\varepsilon_H = \max\left(\frac{\dot{m}_{da} h_{a,out} - \dot{m}_{da} h_{a,in}}{\dot{m}_{da} h^{id}_{a,out} - \dot{m}_{da} h_{a,in}}, \frac{\dot{m}_{sw,in} h_{sw,in} - \dot{m}_{sw,out} h_{sw,out}}{\dot{m}_{sw,in} h_{w,in} - \dot{m}_{sw,out} h^{id}_{sw,out}}\right) \quad (16)$$

$$\varepsilon_d = \max\left(\frac{\dot{m}_{da} h_{a,in} - \dot{m}_{da} h_{a,out}}{\dot{m}_{da} h_{a,in} - \dot{m}_{da} h^{id}_{a,out}}, \frac{\dot{m}_{fw,out} h_{fw,out} - \dot{m}_{fw,in} h_{fw,in}}{\dot{m}_{fw,out} h^{id}_{fw,out} - \dot{m}_{fw,in} h_{fw,in}}\right) \quad (17)$$

In both the humidifier and dehumidifier, the ideal enthalpy of outlet air ($h^{id}_{a,out}$) occurs when the outlet air is completely saturated at the inlet water temperature and the ideal enthalpy of seawater ($h^{id}_{sw,out}$) is when its temperature is equal to the temperature of the inlet air. The solution of the governing equations was carried out using the Engineering Equation Solver (EES).

PERFORMANCE PARAMETERS

In order to understand the performance of the HDH cycle in terms of thermal efficiency, water production potential, and effectiveness of each component, performance parameters are defined. Basically, these indirect parameters are used as cycle operating criteria to evaluate system behavior. These parameters also provide a useful tool for comparing an HDH cycle with other desalination technologies.

GAIN OUTPUT RATIO

This ratio is a dimensionless parameter from the ratio of latent heat of evaporation of the produced water to total input energy to the cycle, which is defined as follows (Rostamzadeh *et al.* 2018):

$$GOR = \frac{\dot{m}_{fwp} \times h_{fg}}{\dot{E}_{in}} \quad (18)$$

$\dot{m}_{fwp}$ is the mass flow rate of the produced water, h_{fg} is the latent heat of evaporation calculated at the temperature of the produced water obtained from Equation (19) and $\dot{E}_{in}$ is the energy input to the system (Hamed *et al.* 2015).

$$h_{fg} = 2500.79 - 2.36418T + 0.00158927T^2 - 0.0000614342T^3 \quad (19)$$

For the present system E_{in} can be expressed as:

$$\dot{E}_{in} = \dot{W}_{Pump} + \dot{W}_{Blower} + \dot{W}_{Cooler} + \dot{Q}_{in} \quad (20)$$

HEAT CAPACITY RATIO

This parameter is the ratio of the maximum enthalpy change of the cold stream to the maximum enthalpy change of the hot stream in the system. This parameter is used to evaluate the performance of cycle components such as humidifier and dehumidifier according to the second law of thermodynamics (Lienhard 2019)

$$\mathrm{HCR}_{component} = \frac{\Delta\dot{H}_{max,cold}}{\Delta\dot{H}_{max,hot}} \quad (21)$$

In this system, the ratio of heat capacity for the humidifier and dehumidifier is defined as follows (Lienhard 2019):

$$\mathrm{HCR}_h = \frac{\dot{H}^{id}_{a,o} - \dot{H}_{a,i}}{\dot{H}_{sw,i} - \dot{H}^{id}_{sw,o}} \quad (22)$$

$$\mathrm{HCR}_d = \frac{\dot{H}^{id}_{fw,o} - \dot{H}_{fw,i}}{\dot{H}_{a,i} - \dot{H}^{id}_{a,o}} \quad (23)$$

HCR equals 1, meaning that the temperature change of the hot stream is equal to the temperature change of the cold stream. In other words, the heat transfer factor (temperature difference) is equal in the two streams and in this case the system is called balanced. It has also been shown that balancing the dehumidifier chamber on the system efficiency is much more effective than balancing the humidifier chamber.

MASS FLOW RATE RATIO

One of the key parameters in HDH desalination, which mainly appears in relation to other cycle performance parameters, is the mass flow rate (MR) ratio, which is expressed as the ratio of the liquid to the gas flow rate (Zhang *et al.* 2019):

$$\mathrm{MR} = \frac{\dot{m}_L}{\dot{m}_G} \quad (24)$$

According to the system under study, this parameter is defined for saline and freshwater as follows:

$$\mathrm{MR}_h = \frac{\dot{m}_{sw}}{\dot{m}_{da}} \quad (25)$$

$$\mathrm{MR}_d = \frac{\dot{m}_{fw}}{\dot{m}_{da}} \quad (26)$$

Also, in a specific operating condition of the HDH cycle where the saline water temperature is specified, as well as the constant size of the humidifier and dehumidifier, there is a certain amount of mass flow ratio in which the overall efficiency of the HDH system is optimal.

SPECIFIC ENERGY CONSUMPTION

SEC is the total electrical energy used to produce 1 kg of freshwater and can be presented as follows (Lawal *et al.* 2018; Zhang *et al.* 2019):

$$\mathrm{SEC} = \frac{\dot{E}_{in}}{\dot{V}_{fwp}} \tag{27}$$

where $\dot{V}_{fwp}$ is the flow of the produced freshwater (m^3/h). The efficiency of the system was increased when the SEC was decreased.

RESULTS AND DISCUSSION

Model validation

The performance of the dehumidifier tower is evaluated by calculating the effectiveness of the dehumidifier. Figure 3 shows the changes in the dehumidifier effectiveness with respect to the MR ratio of freshwater to air. As this figure shows, the theoretical model result is in good agreement with the experimental results. Figure 2 also shows that the dehumidifier (condenser) increases with an increasing water-to-air mass flow ratio. Condenser effectiveness varies from 0.55 to 0.75 according to the experimental results. A comparison between the experimental and mathematical models has been carried out in Figure 4. The air flow rate is 263.5 m^3/h, and the seawater circulation flow rate in the humidifier is 12 L/min. The result shows an acceptable average error between a mathematical model and the experimental data. The experiments show that the freshwater production of the proposed HDH device is 300 L/day, which can provide water for the domestic consumption of a small family.

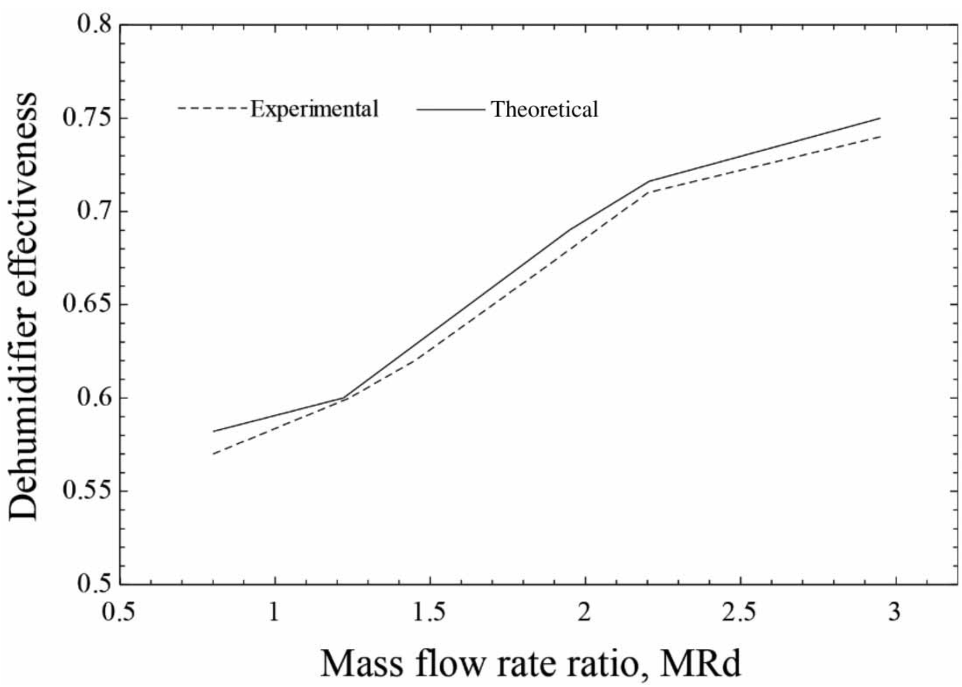


Figure 3 | Experimental and theoretical comparisons of the dehumidifier effectiveness vs. the MR ratio of freshwater.

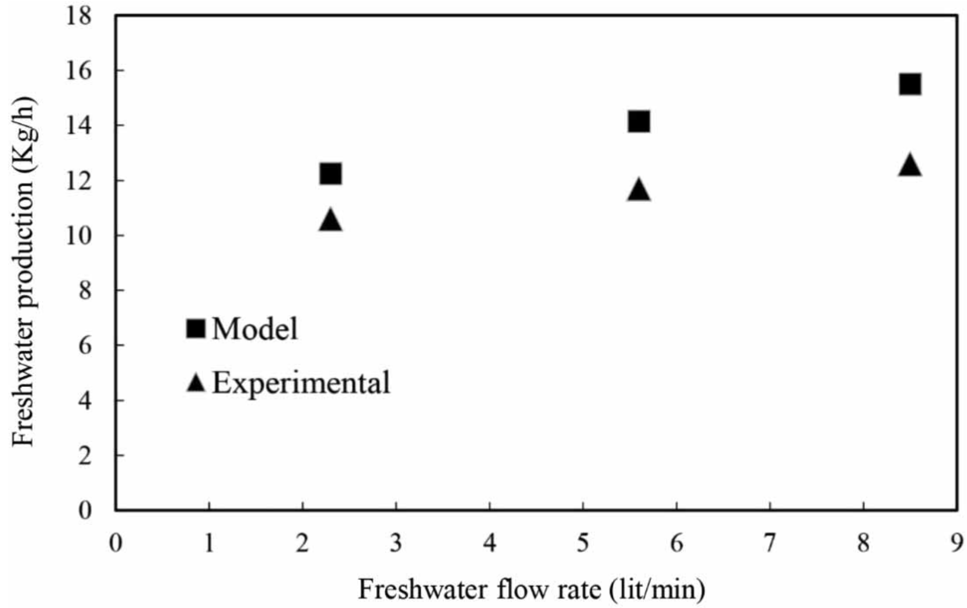


Figure 4 | Theoretical and experimental results of the effect of freshwater flow rate on the produced freshwater.

Effect of an operating parameter on the produced freshwater

Figure 5 shows the effect of the air flow rate on the produced freshwater for different temperatures of inlet air to the humidifier. It is observed that when the air flow rate increased, the produced freshwater also increased. As the air flow rate increases, the mass and heat transfer coefficients increase, and also the air humidification capacity increases. Therefore, the produced freshwater also increases. In fact, as the inlet air flow rate increases, it can carry more water vapor to the condenser than before. On the other hand, Figure 5 indicates the effect of inlet air temperature on freshwater production. The amount of freshwater produced has been studied for the incoming air temperatures to 26–40 °C. As can be seen, by increasing

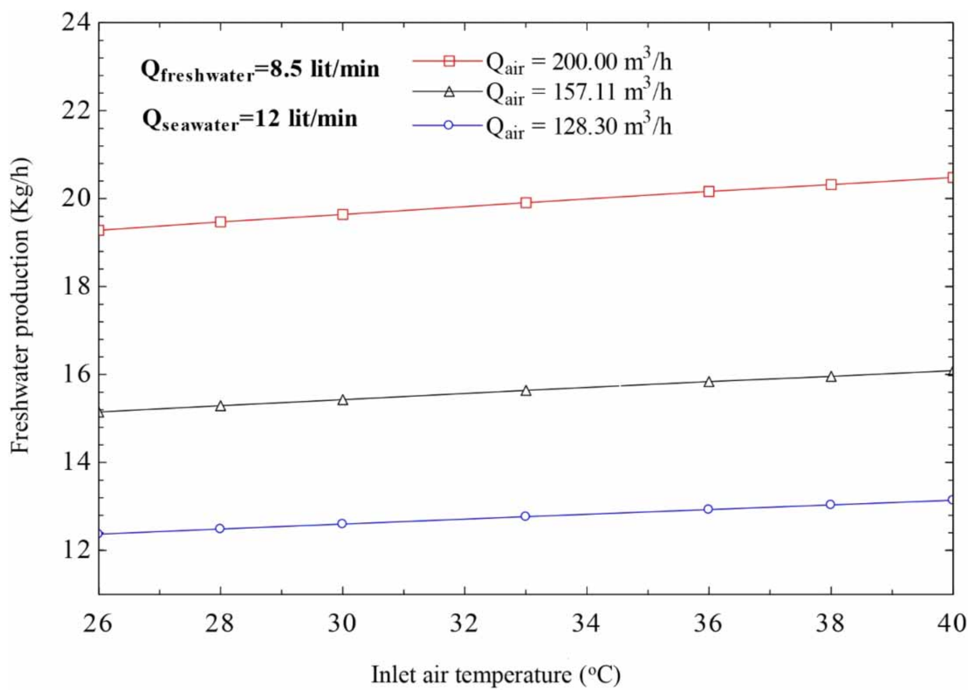


Figure 5 | The effect of flow rate and the inlet air temperature of the humidifier on freshwater produced.

the air temperature to the humidifier, the amount of water produced increases. The ability to carry water in the air increases with an increasing temperature according to the psychrometric chart, making more water available for condensation in the dehumidifier, thus increasing the produced freshwater. This trend is similar to the one obtained by Xiao *et al.* (2021). Increasing the temperature from 26 to 40 °C increases the produced freshwater by 6%.

Figure 6 shows the produced freshwater in different air flow rates and freshwater circulation flow rates into the dehumidifier of 2.3, 5.6, and 8.5 L/min. The seawater circulation flow rate into the humidification tower is 12 L/min. As shown in Figure 6, when the freshwater circulation rate into the dehumidifier was increased, the freshwater production was also increased. Increasing the heat capacity of the circulating freshwater due to increasing its flow rate causes a reduction in outlet air temperature. In other words, the air leaving the dehumidifier is always at saturation. Reducing the outlet air temperature causes more dehumidification from the exhaust air flow from the condenser which means more freshwater production. The lower the outlet air temperature with less absolute humidity (according to the psychrometric diagram) the better the process of dehumidification (Aref *et al.* 2021)

Figure 7 shows the produced freshwater in the different air flow rates and various seawater flow rates of 3.3, 6, and 12 L/min entering the humidification tower at a constant freshwater flow rate of 8.5 L/min entering the dehumidification tower. As can be seen, increasing the seawater entering the humidifier, like freshwater, increases the produced freshwater. On the other hand, by increasing the flow rate of the seawater circulation rate into the humidifier, the outlet air temperature from the humidifier increases. As the content of energy entering the humidification tower increases and Q increases, the amount of heat transfer to the air flow inside the tower also increases. As a result, according to the relation ($Q_{air} = mC_P\Delta T$), the temperature difference between the inlet and outlet air flow also increases, which means that the outlet air temperature increases. Another reason can be increased better contact between air and seawater inside the packed tower (Aref *et al.* 2021).

Experimental results show that the relative humidity of the outlet air from the humidifier is 100%. Therefore, the absolute humidity of the outlet air from the humidifier has been increased by increasing the outlet air temperature.

Figures 6 and 7 also show that the air flow rate has a direct relation with the produced freshwater. The higher air flow rate increases the produced freshwater. Aref *et al.* (2021) also reported the same results for a bubble column humidifier by increasing the air flow rate. The air flow rate increases the liquid–gas contact and improves the heat and mass transfer rate. Substantially, increasing the flow rate of the air means that the air as a carrier is capable of transferring more water (Nada *et al.* 2021).

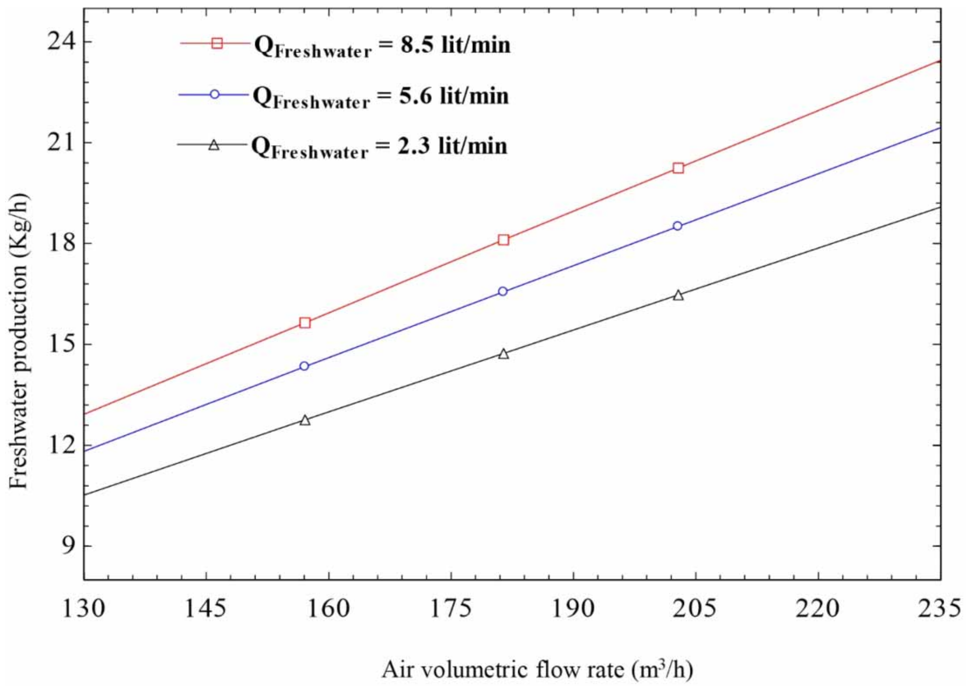


Figure 6 | The effect of freshwater flow rate on the produced freshwater in the constant saline water flow.

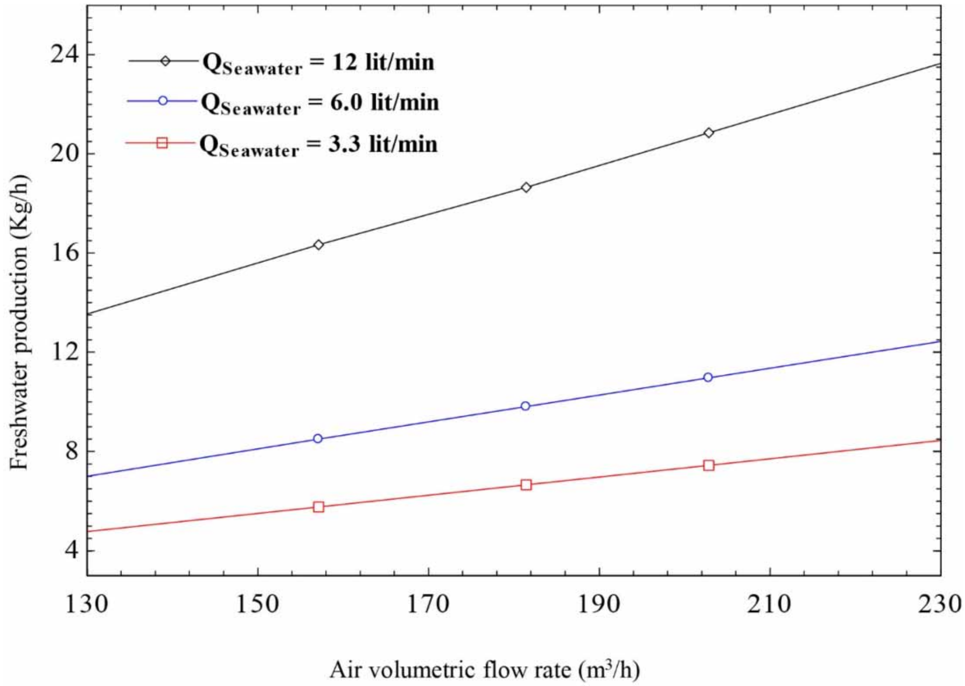


Figure 7 | Seawater and air flow rate effect on the produced freshwater at 8.5 L/min freshwater flow rate.

Figure 8 shows the effect of inlet seawater temperatures on the humidification tower. It is observed that increasing the inlet seawater temperature increases the freshwater production by 185%.

As the inlet seawater temperature of the humidifier increases, the temperature of the air in the humidifier also increases. Therefore, the humidity of the air stream is also increased and finally, the produced water also increases. The dependence of the produced water on this parameter is more than the other parameters. As the temperature of the inlet seawater increases,

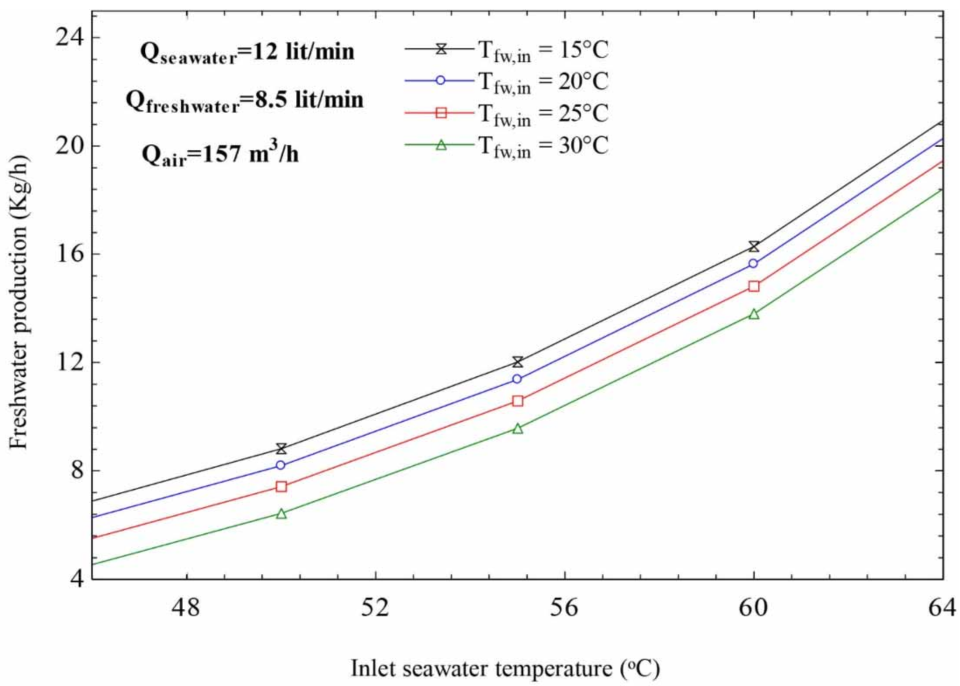


Figure 8 | The effect of inlet seawater and freshwater on the produced freshwater.

this dependency increases. The figure also shows the effect of the inlet freshwater temperature on the produced freshwater. The inlet freshwater temperatures of 15, 20, 25 and 30 °C have been studied. As can be seen, in the inlet seawater temperature of 60 °C into the humidifier, with increasing inlet freshwater temperature from 15 to 30 °C, the freshwater production decreases from 16.39 to 13.8 kg/h (about 15% decrease). This is because of the difference between the inlet air temperature as a hot stream and the inlet freshwater as a cold stream decrease in a dehumidifier. So, the heat transfer between two phases has been decreased and the outlet air from the dehumidifier has higher temperature with more humidity. This means that less freshwater in the dehumidifier has been produced.

In summary, the freshwater productivity increases with increasing air and water flow rates and temperature because of humidification capacity in a humidifier, the increase of the water vapor carried with air by an increasing air flow rate, the increase of air to water contact time and contact area, and the increase of air to water contact time and contact area (Nada *et al.* 2021).

Figure 9 shows the effect of humidifier and dehumidifier effectiveness on the production of freshwater. As can be seen, increasing the humidifier effectiveness increases freshwater production. The high efficiency of the humidifier makes the evaporation process better and as a result, the air carries more water vapor. Also, according to the relation $\varepsilon_h = \left(h_{a,out} - h_{a,in}/h^{id}_{a,out} - h_{a,in}\right)$, increasing the humidifier effectiveness increases $h_{a,out}$ and as a result will increase the exhaust air temperature from the humidifier. As the air temperature increases, the ability of air to absorb water vapor increases. It is also observed that in constant humidifier effectiveness, water production will increase with increasing dehumidifying effectiveness. Increasing the dehumidifying efficiency improves its condensing action. Also, according to the relation $\varepsilon_d = \left(h_{a,in} - h_{a,out}/h_{a,in} - h^{id}_{a,out}\right)$, $h_{a,out}$ (enthalpy of the exhaust air from the dehumidifier) will be reduced. As mentioned earlier, lowering exhaust air temperature from the dehumidifier means that more water is taken out of the air (more dehumidification), resulting in more water being produced (Kaunga *et al.* 2022).

The effect of inlet seawater temperature on the humidifier on the GOR of the system is presented in Figure 10. As can be seen, with an increasing seawater temperature from 50 to 70 °C, the GOR also increases. It is important to emphasize that the GOR is one of the main performance indicators of the HDH system. According to the definition of GOR, which represents the ratio of latent heat of evaporation of water produced to the input total energy into the system, with an increasing inlet seawater temperature, the input energy does not change much.

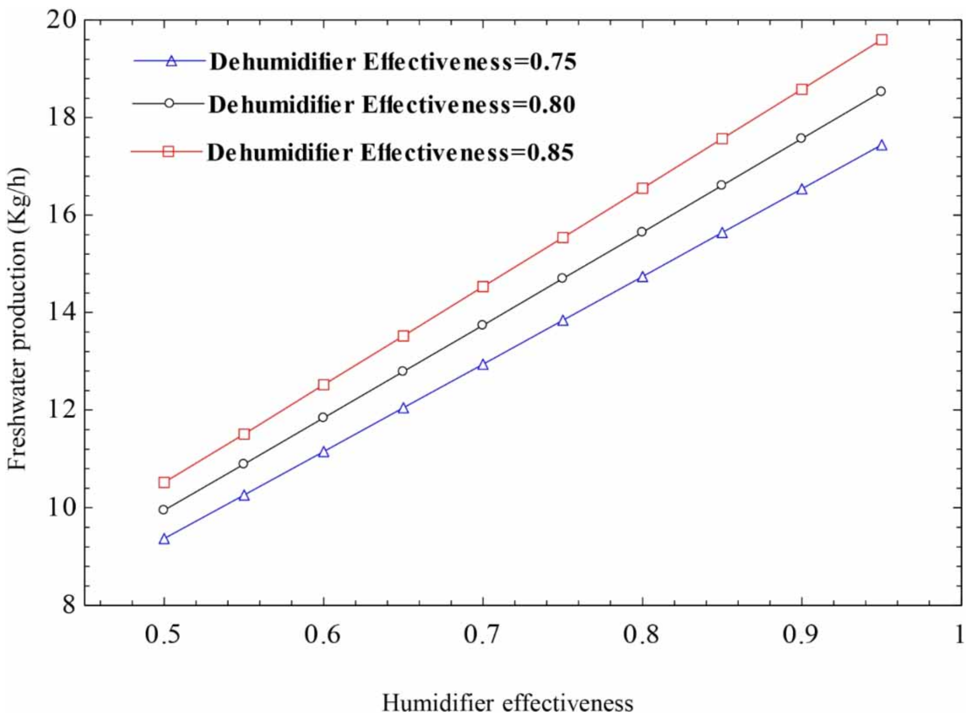


Figure 9 | The effect of the humidifier and dehumidifier on the water production.

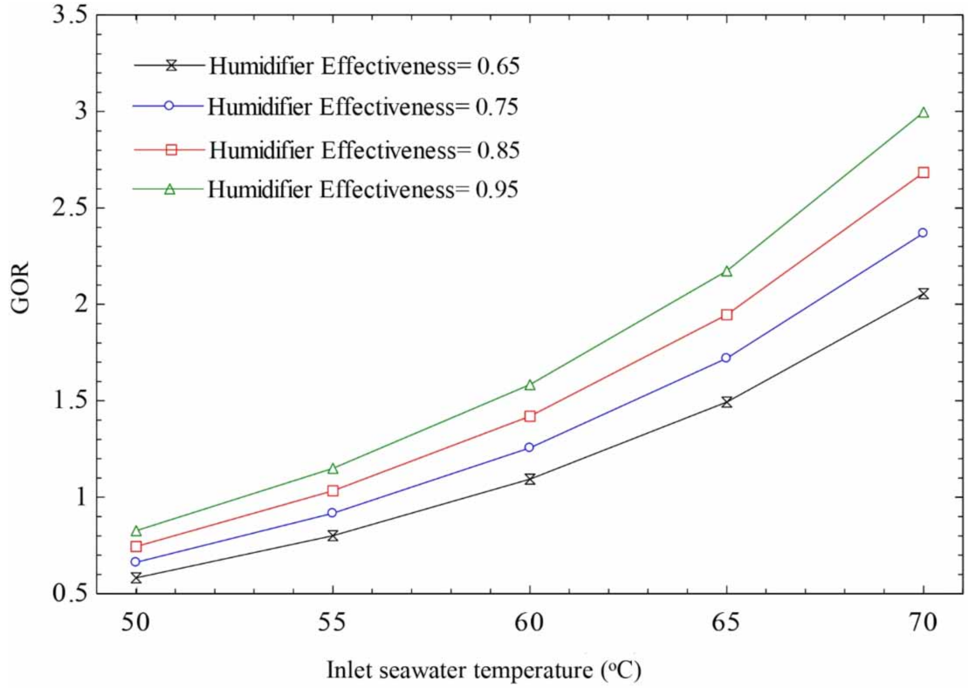


Figure 10 | The effect of inlet seawater temperature into the humidification tower on the GOR at various humidifier effectiveness.

Figure 10 also shows that the GOR increases with increasing the humidifier effectiveness. Increasing the efficiency of the humidifier improves the performance of the system due to better evaporation in the humidifier, which leads to an increase in water production and consequently a higher GOR.

Figure 11 shows the effect of the inlet seawater temperature into the humidifier on the SEC at various humidifier effectiveness. As the inlet seawater temperature increases, the SEC decreases. The reason for this is that as the temperature rises, the produced freshwater grows more than the energy consumed, resulting in a decrease in the SEC. In other words, the quality of

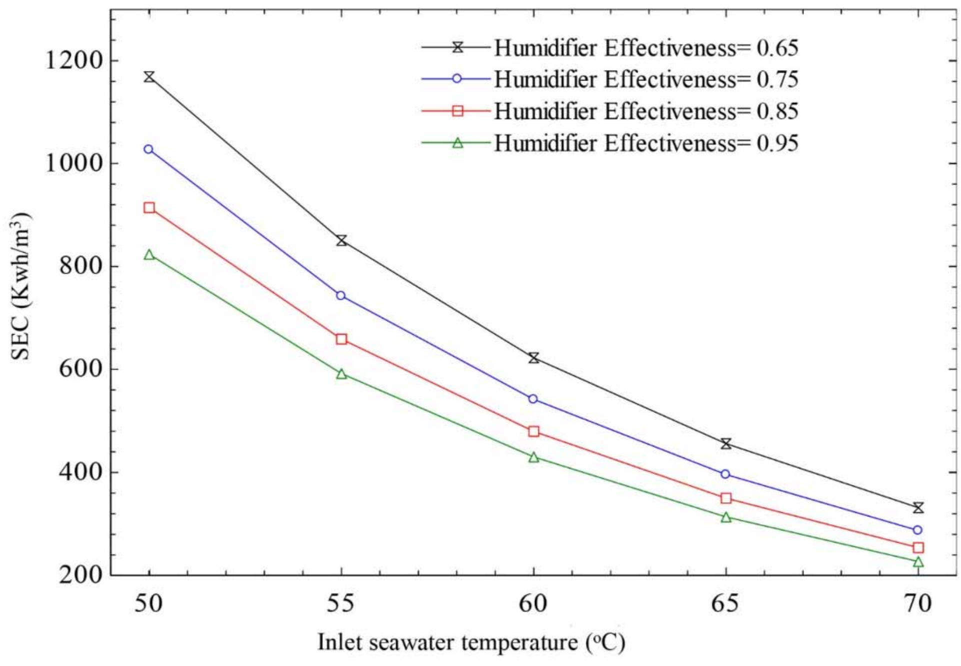


Figure 11 | SEC of the HDH system vs. inlet seawater temperature and humidifier effectiveness.

energies increases with increasing inlet seawater temperature. But the main point is, with an increasing temperature, the intensity of SEC changes decreases. That is, at higher temperatures, temperature changes have less of an effect on SEC changes, and the slope of the changes tends to zero.

Figure 11 also shows the effect of humidifiers on the SEC, and as can be seen, the improvement of humidifier efficiency reduces energy consumption. At a temperature of 50 °C, by increasing the humidifier effectiveness from 0.65 to 0.95, the SEC decreases 50% (from 1,200 to about 800 kWh/m^3)

The effect of the freshwater temperature on the gain output ratio at various dehumidifier effectiveness has been presented in Figure 12. As the inlet freshwater temperature decreases, the GOR increases. This is because the heat transfer rate between the hot air and cold freshwater will increase, which will increase the mass transfer rate between the two streams and cause more dehumidification. Therefore, having a lower temperature of freshwater leads to more water production and, as a result, by definition, will increase the GOR. As the dehumidification effectiveness increases, the GOR increases as shown in Figure 12. The increase in dehumidifier performance, which leads to better system performance, is primarily due to the better vapor condensation process in the dehumidification tower. The better the dehumidification process, the more water will be produced, resulting in an increase in the GOR.

Figure 13 shows the SEC changes with respect to the two parameters of freshwater temperature and dehumidifier effectiveness. As can be seen, the SEC decreases with increasing dehumidifier effectiveness and decreasing freshwater temperature. Also, according to Equation (28) for SEC, the produced freshwater and the SEC are inversely related. So, with decreasing freshwater temperature, freshwater production increases, and as a result, energy consumption decreases. In other words, as the temperature decreases, the SEC decreases significantly, which is very important in terms of the overall energy consumption of the system. As shown in the figure, the slope of the curve decreases at the lower inlet freshwater temperature. This means that the dependence of the energy consumption on the freshwater temperature decreases at the lower temperatures. Also, increasing the dehumidifier effectiveness causes better performance of the system and reduces the SEC.

Figure 14 shows the effect of air flow rate on the GOR and the SEC. As the air flow rate increases, the GOR increases and the SEC decreases. With an increasing air flow rate, the work of the blower increases, and this is due to the increase in energy consumption, but the growth rate of the water production is higher, and according to Equation (28), the SEC decreases. This also affects the GOR and increases it with an increasing air flow rate.

Figure 15 shows the GOR and SEC changes with the dehumidifier heat capacity ratio (HCR_d). It was found that the entropy production in a mass–heat exchanger (for efficiency and input conditions) is minimized when $HCR_d = 1$ (equilibrium

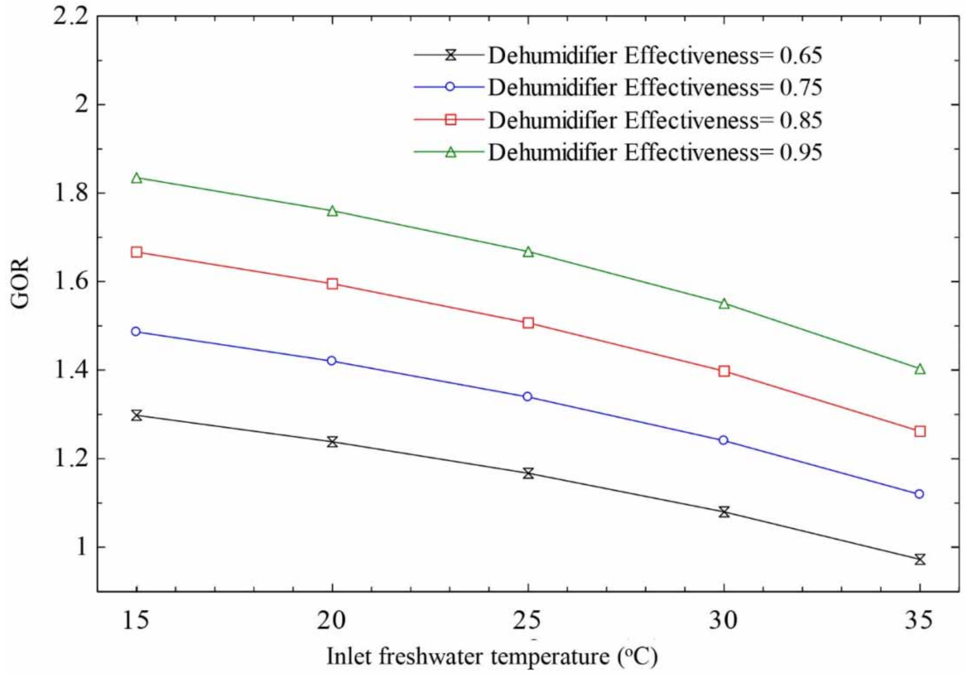


Figure 12 | GOR of the HDH system vs. inlet freshwater temperature and dehumidifier effectiveness.

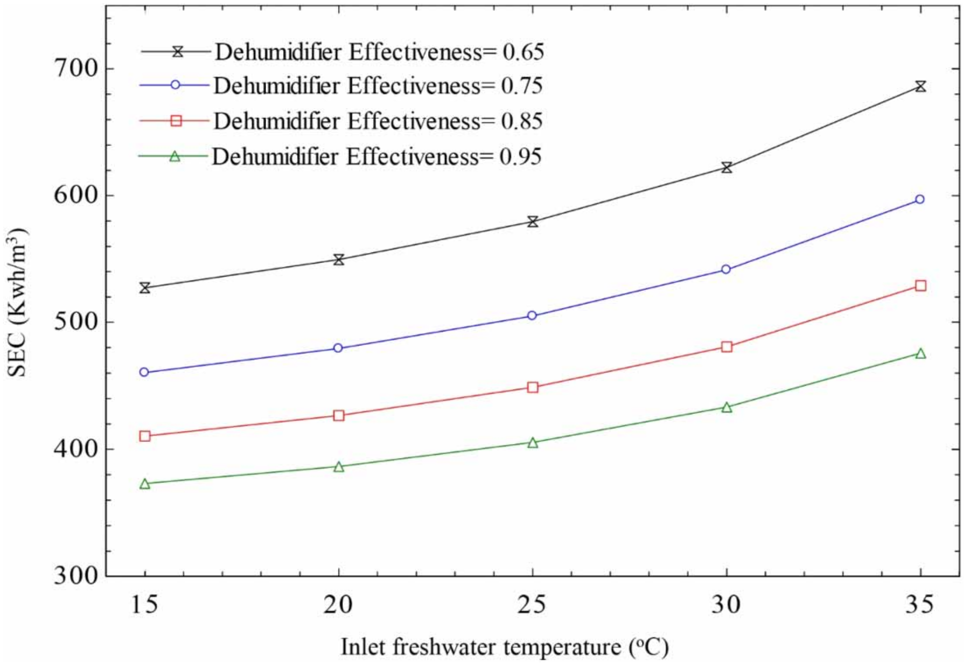


Figure 13 | SEC of the HDH system vs. inlet freshwater temperature and dehumidifier effectiveness.

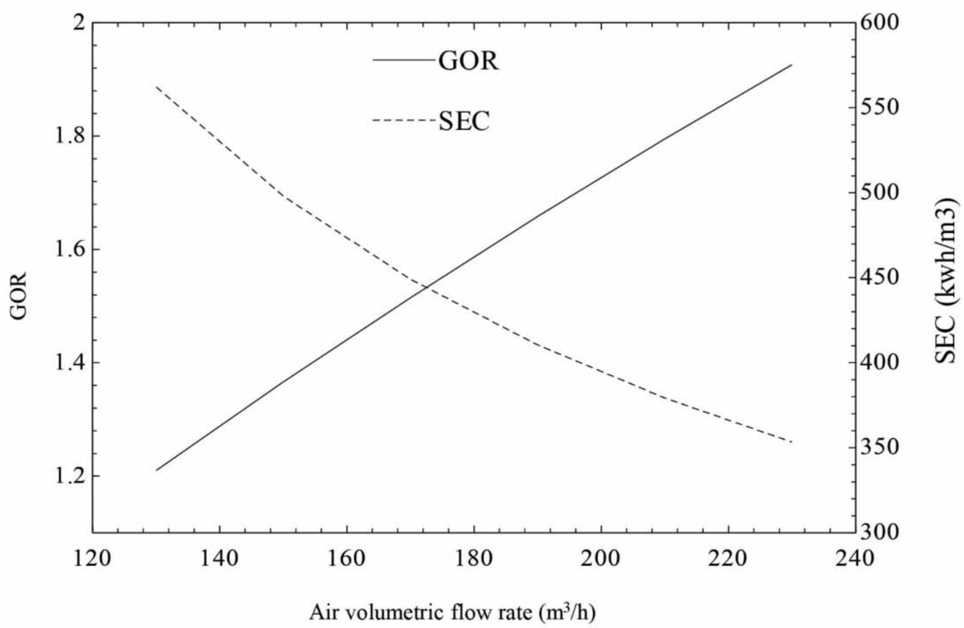


Figure 14 | The effect of the air flow on the GOR and SEC.

condition). As can be seen in $HCR_d = 1$, the GOR reaches a maximum value. The maximum value occurs under equilibrium conditions for dehumidification. Therefore, in the present system, the maximum GOR can reach 3.3 in ideal conditions. In the actual condition of the device, the GOR value is from 0.5 to 2.9, from which it can be concluded that with the improvement of the process and operational changes, engineering measures can still be taken to improve the device. Also, in Figure 15, the SEC parameter was examined, which also reaches its minimum value in the conditions of dehumidification equilibrium.

Recently, various configurations of the HDH desalination system have been presented. One of the important features is hybrid technologies integrated with HDH desalination. Hybrid technologies such as heat pump, vacuum, heat recovery,

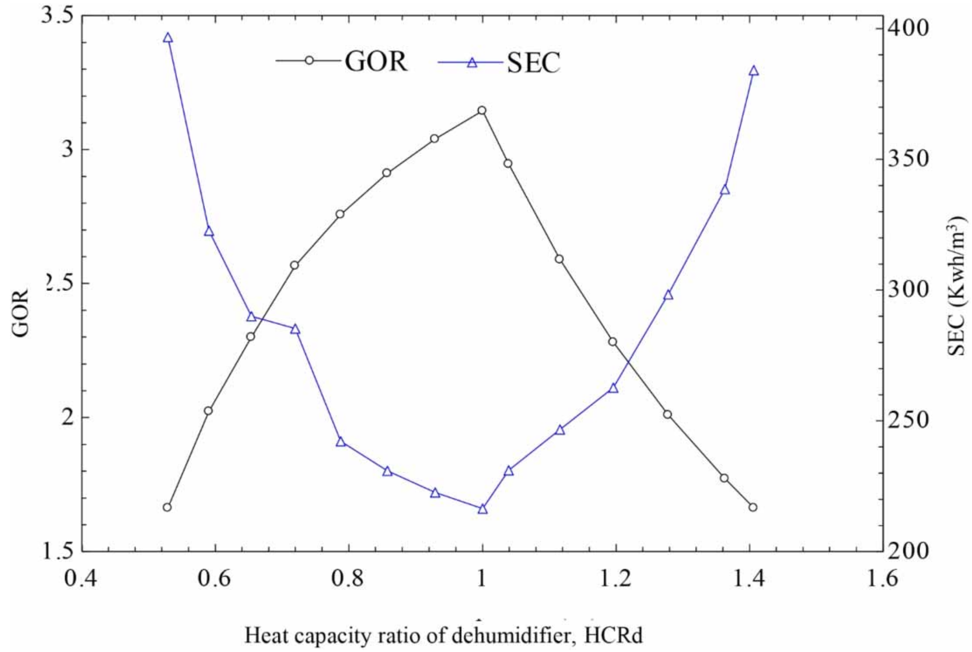


Figure 15 | The GOR and SEC changes with the dehumidifier heat capacity ratio (HCR_d).

solar chimney, solar still, turbulators and others are used to improve HDH system performance. Table 1 shows the GOR and water production of some hybrid HDH devices. The present contact direct dehumidifier HDH system has 300 L/day (12.5 kg/h) and the GOR = 3.3, which is considerable with these hybrid technologies. Certainly, if this device is hybridized with such technologies, it will have a higher performance.

Figure 16 compares the present device with the Niroomand *et al.* (2015) device. Both devices use a direct contact dehumidification system. This figure shows the effect of freshwater temperature on water production. As can be seen in the constant inlet seawater temperature of 60 °C, to change the freshwater temperature from 10 to 25 °C, the water production in the present study is always higher than that in the Niroomand *et al.* (2015) study.

CONCLUSION

In the present study, a dehumidifier–dehumidifier desalination system with a direct contact dehumidifier was analyzed. The main results of the present study are:

- The inlet seawater temperature to the humidification tower has the most and the ambient air temperature has the least effect on the amount of water produced.

Table 1 | Comparison between GOR and freshwater production of hybrid technologies with the present HDH device

System	GOR	Freshwater production
HDH + heat pump (Xu *et al.* 2018)	1.24	12.75 kg/h
HDH + vacuum (Rahimi-Ahar *et al.* 2018)	3.43	1.07 L/h·m^2
HDH + heat recovery (three-stage recovery cycle) (Wu *et al.* 2017a, 2017b)	2.65	–
HDH + solar chimney (Abdullah *et al.* 2020)	7.3	62 L/day
HDH + turbulators (Fouda *et al.* 2018)	1.63	350 kg/day
Present device	3.3	12.5 kg/h

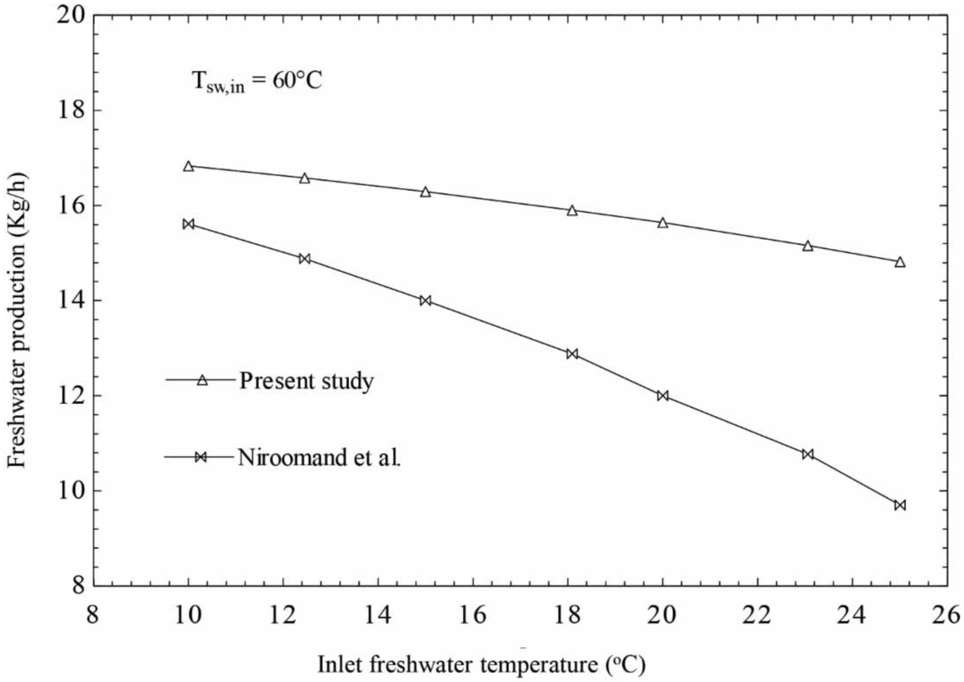


Figure 16 | Comparison between freshwater production of the present HDH device with Niromand *et al.*'s work (Niroomand *et al.* 2015).

- Increasing parameters such as seawater temperature, humidifier and dehumidifier effectiveness, and air flow rate increases the GOR and decreases the SEC, while increasing freshwater temperature and heat input to the system decreases the GOR and increases the SEC.
- The GOR range is from 0.5 to 2.9 depending on different operating conditions.
- The maximum GOR value in this system is 3.3, which is obtained in dehumidifying equilibrium conditions.
- The maximum freshwater production in the experiments is 300 L/day.

ACKNOWLEDGEMENTS

The authors wish to thanks the University of Hormozgan for sponsoring the project under grant no. 12666.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 26 October 2021; accepted in revised form 28 December 2021. Available online 4 February 2022