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A Review Study of Experimental and Theoretical Humidification Dehumidification Solar Desalination Technology

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Abstract

Most of the desalination technologies consume a huge quantity of energy resulting from petroleum products in the form of heat or electrical energy. Solar desalination is a promisingly sustainable freshwater production technology. Solar desalination humidification dehumidification process showed the best approach as it is of the highest overall energy efficiency. In this review paper, a detailed study of the previous work is performed on solar humidification dehumidification desalination techniques experimentally and theoretically. Also in this review, different types of HDH systems were mentioned. The review showed that the humidification dehumidification desalination systems are suitable for decentralized demand. On the other hand, capacity of HDH units is not as large as conventional methods or small as solar stills. Finally, this study threw light on the scope of the parameters which have a considerable influence on increasing the freshwater output of the HDH systems as feed water flow rate, air flow rate, and design of the evaporator, condenser, and packing material. A brief economical study and a comparison of the costs per liter are performed for various humidification dehumidification desalination systems presented in this study.

Keywords

Humidification, Dehumidification, Desalination, Experimental Study, Theoretical Study, Solar Energy, HDH

1. Introduction

The lack of the fresh water, shortage of energy, and climate change are the most intimating concerns for humanity as it brought many problems like health, pollution, and ecological issues, especially in Middle East and Egypt. In addition to global warming, population growth and economic development create a worldwide gap between freshwater supply and demand. At the beginning of this new century, the challenge of providing adequate supplies of fresh water may indeed become the world's most serious problem. According to 2030 Water Research Group report (2009), the predicted demand of the potable water by 2030 is to be 6900-billion m^3. The fresh water supply is of 4200 billion m^3, which is further down the potable water demand. More than 70 percent of the surface of our Earth is covered with water. Salt water represents 97 percent of the Earth's total water, just 3 percent left as fresh water. Almost 70 percent of that fresh water is frozen in the icecaps of Antarctica and Greenland. Most of the rest is present as soil moisture or is found in deep underground aquifers as groundwater that is not accessible to human use. According to World Bank, more than 41.5 percent of the worldwide countries suffer from water deficiency, which affect the resources of these countries. Moreover, 40% of the inhabitance exists in dry, remote regions which have no supplies for fresh water. Water shortage in countries is either physically or economically. Weak infrastructure and lack of investment lead to economic fresh water scarcity. When the water needs are greater than the population, it is called physical scarcity. The sun showers Earth every day with multiple thousand times the amount of energy that we use. Most of the needed energy in the world can be provided directly from solar power. The annual amount of solar radiation on earth's surface is about {1 × 1018 KWh}, which can be given by {500,000 billion petroleum tank}. In terms of intensity, the spatial distribution of total solar radiation worldwide is divided into four large belts around the earth. The most desirable belt lies between 15˚N and 35˚N latitudes. It is interesting to notice that between latitudes 35˚N and 35˚S, the majority of Africa and the Middle East countries fall inside the most desirable regions. After general overview on the coming era water stress and scarcity, also the abundance of solar energy in the Middle East, the idea of desalination can be the answer to the world's water resource problems. In specific words, Solar Desalination is the simplest way of solving the problem. A great effort was made to find suitable solution for this water crisis. Desalination technologies were the perfect solution of this inadequacy.

Therefore, the aim of the present paper is to include a thorough analysis of numerous experimental and theoretical developments conducted for performance enhancement of HDH systems. The current study offers a thorough analysis that focuses mainly on the qualified use of clean and renewable solar energy by means of various specified solar technologies adopted for the heating of heat transfer fluids (water, air and both) in any HDH system. Further, the effect of various HDH components systems such as humidifier material and design, dehumidifier design, and effect of preheating (both water and air) on the system performance and yield are also discussed. A special focus has been given on Economics which plays a key role in the design and selection of optimum process parameters and materials for any maximum yield HDH system. In addition, a detailed comparison of different cost analysis investigation studies has been outlined with scope for further development.

2. Technical Description

Desalination is a process of water treatment which separates salts from brine water to produce distilled water with low total dissolved solids (TDS) as shown in Table 1. The use of this process has significant advantages as it opens up a variety of resources of raw water, ranging from the ocean itself to brackish waters located on-island or underground.

3. Different Methods of Desalination

Numerous methods of desalination processes presented. The main processes are divided into two categories; the thermal and the membrane methods as shown in Figure 1. The thermal method simulates natural processes of distillation. Multi Stage Flash (MSF), Multi Effect Distillation, Vapor Compression (VC) distillation and Humidification Dehumidification (HDH) are the most reliable techniques in thermal process. The main idea of membrane process is refining the salty sea water using a membrane. The salty water is derived through the membrane using electrical power. Electro-dialysis (ED) and Reverse Osmosis (RO) are the main techniques used in membrane method.

4. Humidification Dehumidification Desalination (HDH)

The main idea of the HDH desalination technology based on imitate the hydrological cycle. The oceans are being heated by sun rays; Evaporation of salty water takes place which is converted to create the clouds. The clouds are then converted to rainfall. This is the main steps of HDH technique as shown in Figure 2.

Humidification Dehumidification desalination process is one of the most important technologies especially in MENA regions as it can be integrated with different renewable energies especially the solar energy. In humidification dehumidification cycle, the air is humidified in the humidification section using sprayers which spraying the salty water on the air till it becomes totally saturated. The sprayed sea water is heated using solar energy. Then it flows naturally or forced to the dehumidification section. The water content in the humid air starts to precipitate on the condenser. The condensed water on the condenser is collected as distilled water. The heat energy released from the condensation process is mainly moved to the cold sea water used in condenser. The sea water comes out of the condenser can be used as a feed back for the sprayers after passing through a solar collector to raise its temperature. The theory of desalination technology presented by Muller *et al.* [1] is illustrated in Figure 3.

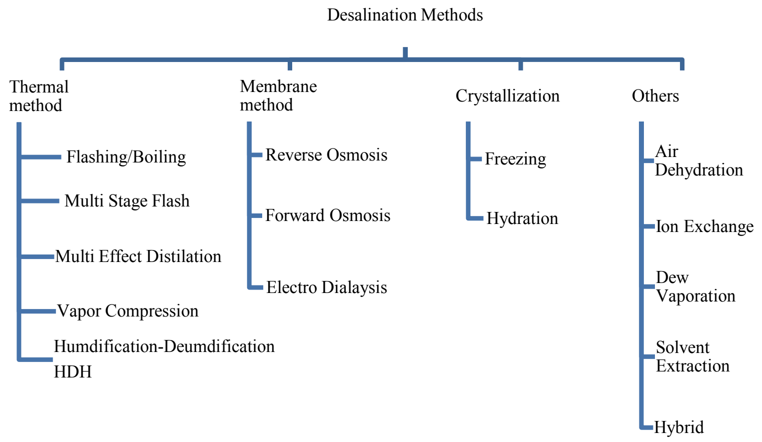

Figure 1. Classification of desalination technologies.

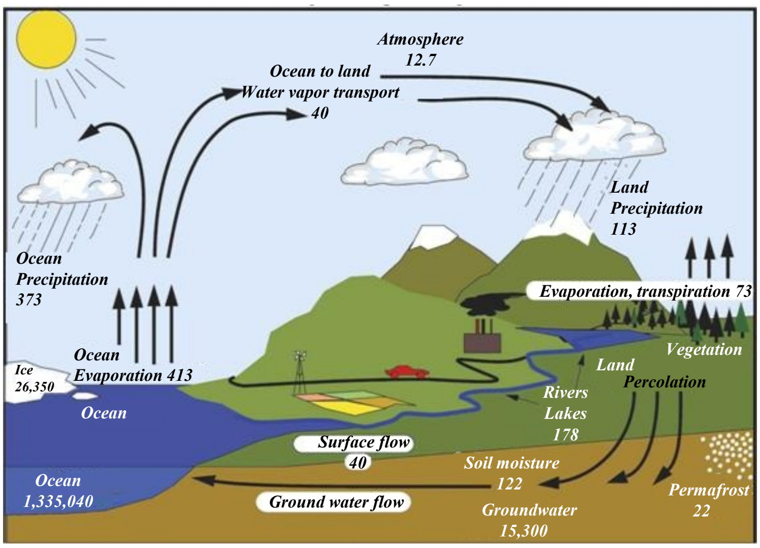

Figure 2. Natural hydrological cycle.

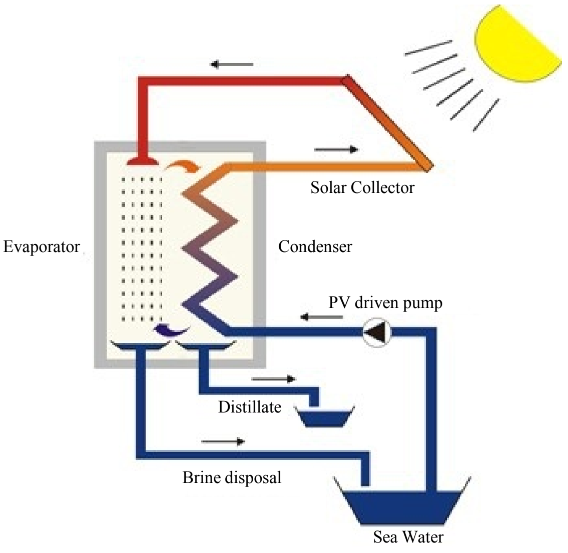

Figure 3. Illustration of HDH system.

Table 1. Classification of Natural water according to their Total Dissolved Solids (TDS).

Type of water	TDS value (mg/l)
Sweet waters	0 - 1000
Brackish waters	1000 - 5000
Moderately saline waters	5000 - 10,000
Severely saline waters	10,000 - 30,000
Seawater	More than 30,000

During the closing decade, a number of HDH systems had been conducted and tested. K. Bouronni *et al.* show a detailed research of the desalination unit based at the HDH technology [2]. In this unit, the air is heated during the circulation and humidified by the water received either from a flat-plate solar collector or using an electrical heater. Reliance of the HDH mechanism on feed water and airflow values was also studied in [3] and the ideal values were identified. They suggested that; system with the forced flow of air is optimal for solar desalination on a small scale. Their system achieved 12 l/m^{2}d productivity, which is three times that of a traditional system.

5. HDH Systems Categorization

The humidification dehumidification approach is classified according to medium of heat transfer, mechanism of the flow and cycle design. They are commonly arranged into Closed Water Open Air (CWOA), Closed Air Open Water (CAOW) and open-air open-water as illustrated in **Figure 4**.

5.1. Closed Air Open Water (CAOW)

In CAOW, the air circulates in a closed loop between the humidification chamber and the dehumidification chamber whereas the water is not recycled through the dehumidification chamber but discharged or partially recirculated in the humidification chamber in order to recuperate heat as shown in **Figure 5**. This process design is therefore correlated with the need for large quantities of cooling water, which at the same time acts as hot feed.

Al-Hallaj *et al.* [4] conducted an experiment with a flat plate solar collector of 2 m^2 in size. The water is heated to 50˚C - 70˚C. Also, air circulates through both natural and forced convection as shown in **Figure 6**. The authors found that forced air circulation was beneficial at low temperatures and that natural circulation gives better efficiency at higher temperatures.

Nawayseh *et al.* [5] described a simulation model as shown in **Figure 7**. Numerous simplifications are done to recognize the attributes of optimizations. The researchers conducted a comparison between their experimental outcomes from a CAWH HD configuration with natural and forced convection, described by M.M. Farid *et al.* [3]. In a subsequent publication by Nawayseh *et al.* [6], they used empirical heat and mass transfer correlations conducted by S. Al-Hallaj *et al.* [4] and adjusted by correlations derived from experimental investigations.

$$LCp_w\left(T_2-T_1\right)+0.5U_{loss}A_{unit}\left(\frac{T_5-T_6}{2}-T_{amb}\right)=G\left(H_6-H_5\right) \tag{1}$$

$$LCp_w\left(T_2-T_1\right)=U_{cond}A_{cond}\left[\frac{\left(T_6-T_2\right)-\left(T_5-T_1\right)}{\ln\dfrac{T_6-T_2}{T_5-T_1}}\right] \tag{2}$$

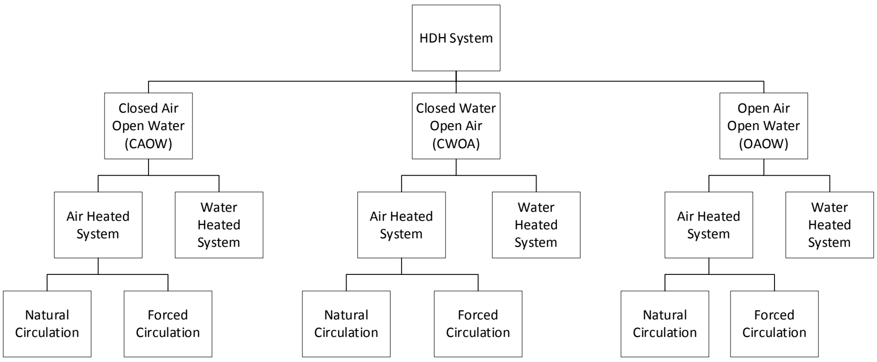

Figure 4. Classification of HDH system.

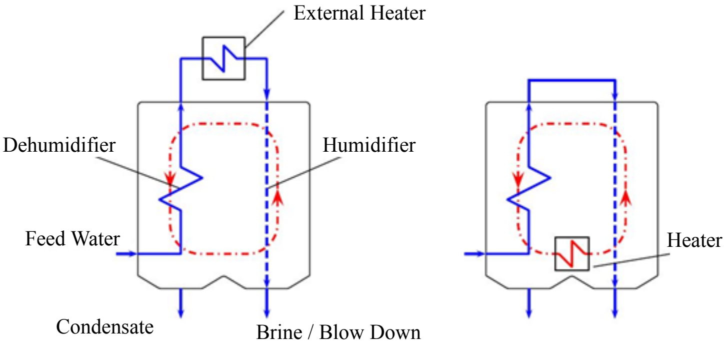

Figure 5. (a)Closed-Air Open-Water Heated (CAOW) HDH system (b) Closed-Air Open Water-Air Heated (CAOW) HDH system.

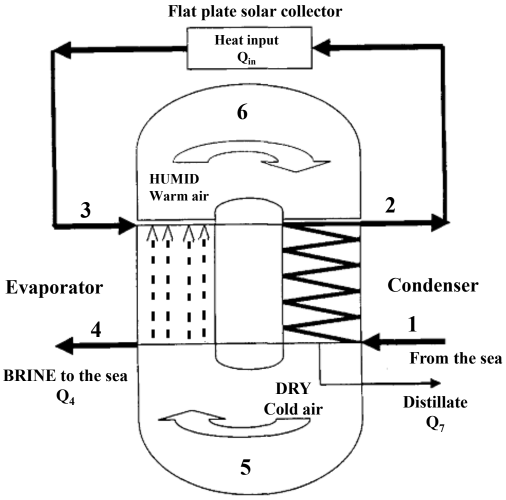

Figure 6. Schematic diagram of Al-Hallaj *et al.* unit [4].

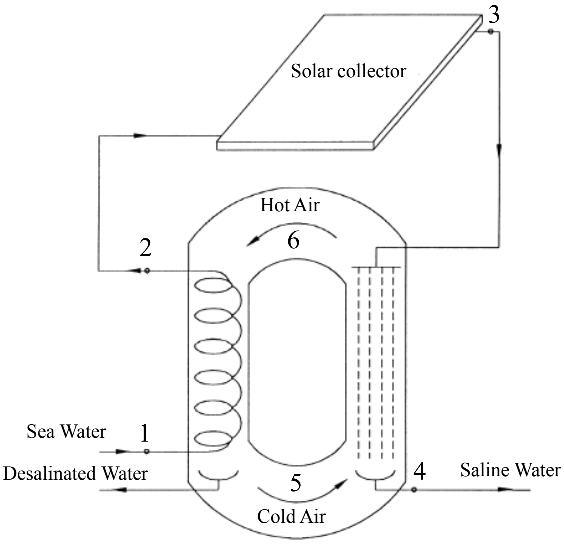

Figure 7. Schematic diagram of Nawayseh *et al.* configuration [5].

$$LCp_3\left(T_3-T_4\right)-U_{loss}A_{unit}\left(\frac{T_5-T_6}{2}-T_{amb}\right)=G\left(H_6-H_5\right) \tag{3}$$

$$KaV\left[\frac{\left(H_3-H_6\right)-\left(H_4-H_5\right)}{\ln\dfrac{H_3-H_6}{H_4-H_5}}\right]=G\left(H_6-H_5\right) \tag{4}$$

$$\begin{aligned}I_TA_{col}\eta_{col}=&\frac{M_{unit}C_{unit}}{\Delta t}\left[\left(\frac{T_5+T_6}{2}\right)_{i+1}-\left(\frac{T_5+T_6}{2}\right)_i\right]\\&+U_{loss}A_{unit}\left(\frac{T_5+T_6}{2}-T_{amb}\right)+LCp_w\left(T_4-T_1\right)\end{aligned} \tag{5}$$

Nawayseh and Farid [7] [8] used the earlier conclusions to conduct a simulation method to examine the effect of various parameters. A CAWH HD system introduced using free and forced convection method. Experimental results show the effect of feed water flow rates in increasing efficiency of the collector however it decreases the rates of vaporization. The conducted model based mainly on mass and heat balances for the humidifier, dehumidifier and the heater. The study stated that free convection is better than forced convection. Energy and mass balances for the humidifier, dehumidifier, and external heater were analyzed together with the approximate effectiveness of the components and relative humidity at the exit of each part by Narayan *et al.* [9]. Modeling an HDH cycle using governing equations with many approximations, Soufari *et al.* [10] achieved heat balance for the humidifier and dehumidifier interface among water and air. The water to air mass flow ratio for a system with forced convection has been highlighted to reach optimal performance. Specific energy consumption is minimized when the brine is recycled between humidifier and dehumidifier. A heat and mass transfer equations were developed by Bacha *et al.* [11] for steady state operation. More researches followed for HD units integrated with solar energy by [12]. The advantage is to enhance the daily fresh water production according to the area of solar collector. Chafik *et al.* [13] noted that Scale forming and corrosion are drastically reduced when heated air is used instead of heated water. However low air heat capacity and low air heat transfer coefficient result in low fresh water output and large heat exchanger surfaces used.

5.2. Closed Water Open Air (CWOA)

In CWOA, Water circulates in a closed system and air is released into the environment as shown in **Figure 8**. In such systems the water is generally heated. It is used to enhance the recovery of the saltwater through the cycle and ensure a maximum use of the saltwater to generate freshwater. Therefore the system would require less water for cooling. Awfully few literatures have been documented based on this process configuration. One downside of the CWOA is that it quickly raises the temperature of cooling water in the dehumidification chamber. It limits the dehumidification of humid air and reduces the output of freshwater compared to the CAOW method.

Studies for OAWH HDH configurations were conducted and system output evaluated by Khedr [14] and Dai *et al.* [15]. A number of experiments were carried out to notice the ideal air mass flow rate for a constant water mass flow rate to maximize fresh water productivity. Kolb [16] reports that by using low air mass flow rate the efficiency of the collector is 20% higher.

5.3. Open Air Open Water (OAOW)

In this system, both the air and the water streams follow separate path through the humidifier and dehumidifier. There is water-heated system in which the heater is located in the path of water between the humidifier and dehumidifier; Also, there is Air-heated system in which the heater is located between the humidifier and the dehumidifier in the air path as shown in **Figure 9**.

Mistry *et al.* [17] optimize the performance of HDH cycle based on maximum gained output ratio as shown in **Figure 10**. Gain output ratio has been observed to decrease with rising temperature difference between two ends of each component of the system.

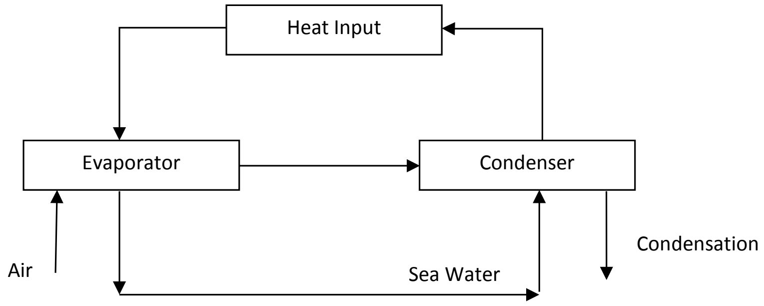

Figure 8. Closed-Water Open-Air Heated (CWOA) HDH system.

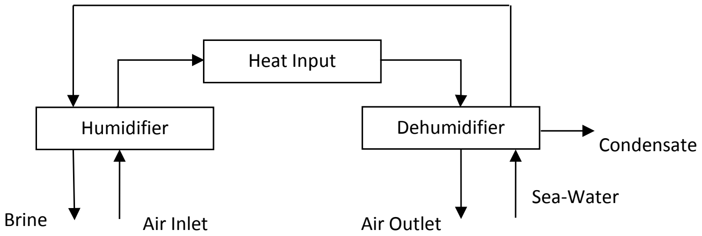

Figure 9. Open-Air Open-Water Heated (OAOW) HDH system.

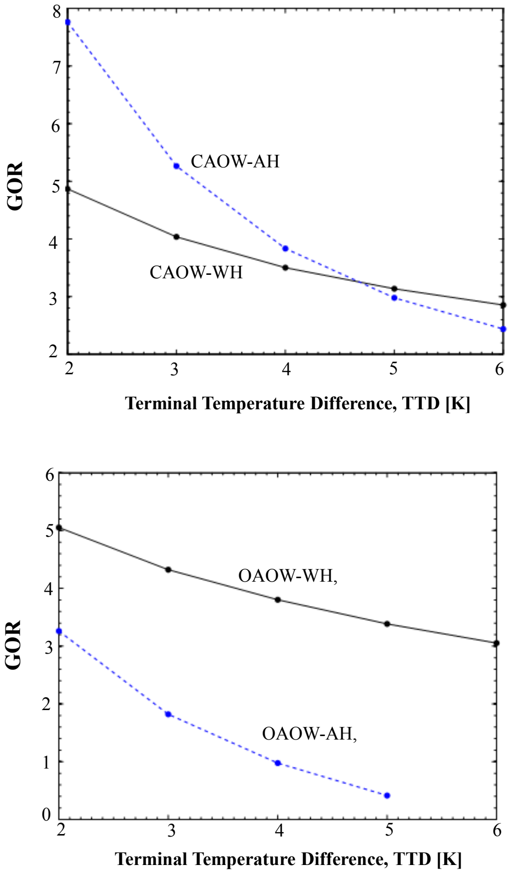

Figure 10. GOR versus TTD for CAOW & OAOW [17].

6. Major Components in the HDH System

Humidification dehumidification system main components include air heater, water heater, humidifier and dehumidifier. The related work to the above-mentioned components reviewed individually as well as combined with HDH system.

Dai *et al.* [18] conducted a mathematical model of a solar desalination system and experimentally validated by analyzing the effect of temperature and mass flow rate of air, feed water and cooling water in the solar desalination unit. It was noticed that the inlet temperature and relative humidity improve the productivity. Mousa *et al.* [19] assessed the efficiency of desalination processes with various carrier gasses, based on the HDH theory to absorb water vapour from feed water such as hydrogen, helium, neon, nitrogen, oxygen, argon and carbon dioxide through modeling and simulation techniques. The properties of the used gases have an influence on the heat and mass transfer coefficients. In desalination systems, Carbon dioxide was observed to be preferred as a carrier gas.

Orfi *et al.* [20] conducted experimental as shown in **Figure 11** and theoretical analysis of water desalination system using solar energy and a general mathematical model dependent on air and water heat and mass balances was presented. It was found that distilled water output depended on the rate of water's ratio to the rate of air mass flow.

Ettouney [21] reviewed four different layouts of HDH systems such as humidification vapour compression, conventional HDH process, desiccant system and humidification membrane drying as shown in **Figure 12**.

Al-Enezi *et al.* [22] highlighted the impact of operational parameters such as temperature and flow rate of feed water, air and cooling water on the HDH desalination system and proved that productivity strongly depended on hot water temperature, increased by increasing air mass flow rate and decreased with the temperature of cooling water.

Yamali & Solmus [23] proposed a Mathematical model-based computer simulation program of solar water desalination system shown in which was established using MATLAB Code. It was observed that the double pass solar air heater showed considerable enhancement of productivity than single pass air heater in solar HDH desalination system.

Hou & Zhang [24] investigated the hybrid humidification dehumidification desalination solar system working with solar still. It was found that system performance was strongly dependent on the inlet salt-water temperature and mass flow rate, as well as process air. Gain-output ratio improved by 2 - 3 by recycling the discharged water. Mohamed & Minshawy [25] tested the geothermal energy for water heating in HDH desalination system and inferred from the analysis that the optimum ratio between sea water and air mass flow rate should be within 1.5 and 2.5 for maximizing the productivity in HDH desalination system.

A theoretical and experimental investigation was carried out at various operating conditions of humidification dehumidification desalination system with several packing materials by Amer *et al.* [26]. Zhani & Bacha [27] conducted an economic analysis and empirical study on the solar humidification-dehumidification and found that the ambient air temperature had negligible impacts on system performance compared to other parameters.

Eslamimanes & Hatamipour [28] made an experimental analysis and economical study of humidification–dehumidification desalination (HDH). The observational data showed that the unit's thermal efficiency relied on solar radiation, and the temperature of the ambient air had negligible effects on it. Summers *et al.* [29] presented the comparative study of different design adopted in solar air heater of HDH desalination system such as roughness absorber plate, multiple pass and multiple glazing layers.

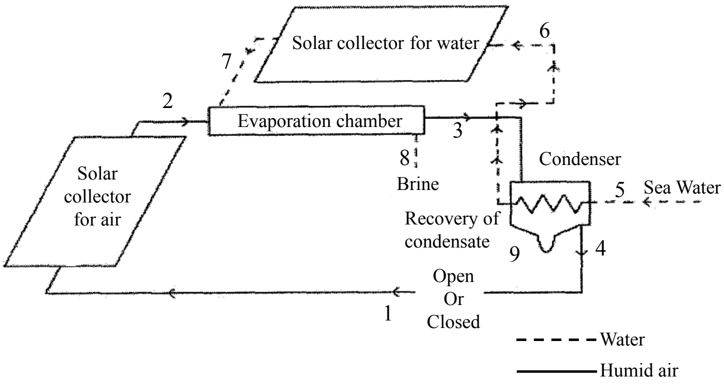

Figure 11. Schematic diagram of desalination system by orfi *et al.* [20].

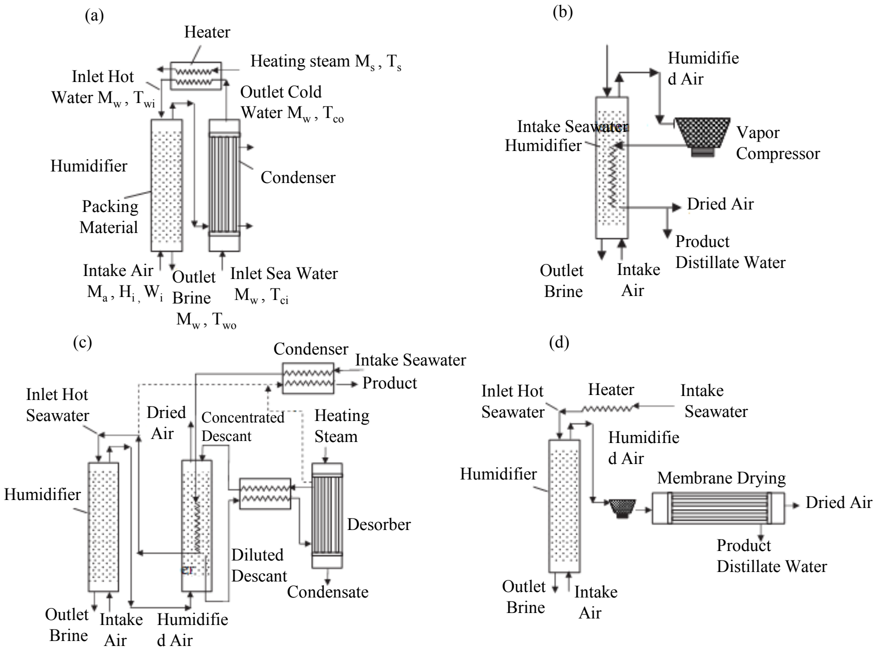

Figure 12. (a) Conventional humidification-dehumidification desalination process; (b) Humidification vapor-compression; (c) Humidification desiccant absorption; (d) Humidification and membrane drying.

Abdelrahman *et al.* [30] developed an HDH desalination unit with water heated cycle, cross-flow with brine recirculation. The authors investigate the effect of mass ratio (MR) at different hot water temperature on Gain output ratio (GOR), Recovery ratio (RR), humidifier, and dehumidifier effectiveness. The study showed that the freshwater productivity, recovery ratio, and effectiveness of the dehumidifier are the maximum as the temperature increases.

Chehayeb *et al.* [31] provided a mathematical model for a humidification dehumidification unit composed of a packed bed humidifier and a column dehumidifier with multi-tray bubbles. The impact of the mass flow rate ratio on fixed-size system performance was also evaluated. Moustafa *et al.* [32] investigated experimentally OAOW HDH desalination unit coupled with a Heat pump. Results showed that the system average fresh water was found to be 8.64 l/h. The condensate rate also improves with the water-to-air ratio increasing. The optimum temperature of inlet cooling water to the heat exchanger is 15˚C.

Yamali *et al.* [33] studied the influence of different conditions on the outcomes of solar HDH as a prototype in Ankara's climate. An experimental research composed of different components designed and constructed. The authors concluded the system efficiency is increased by 15% by using a double pass solar heater.

Khabazi *et al.* [34] studied the influence of moisturized air heating at different elevations on accumulated freshwater productivity of the HDH-based solar desalination plant. The authors concluded that the conducted study could yield up to 6% higher efficiency with respect to the traditional one. Also, hot weather can increase the efficiency by 8%.

Elatter *et al.* [35] conducted parametric and experimental studies in integration of air conditioning with solar HDH system. The productivity, energy consumption, coefficient of performance was studied at different operating conditions.

Srithar *et al.* [36] performed studies in a coolant-integrated HDH desalination unit, including an energy recovery stage where condenser and evaporator waste heat is used for the desalination process. The effects of air and water flow rates were studied, Also the influence of different shapes of turbulator were studied. They mentioned that conventional refrigerator COP was reported as 2.6 and improved to 4.61 by combining the HDH system with water flow rate of 544 kg/h and airflow rate of 30 kg/h. Nevertheless, the COP of the new refrigerator set-up is up to 7.6 with turbulator in the dehumidifier and gunny bag covering the condenser, which is 2.09 times higher than the traditional refrigerator.

Hamed *et al.* [37] investigate the performance and productivity theoretically and experimentally for a solar HDH desalination unit. Comparisons between experimental and theoretical results were conducted. The results show that the average productivity of humidification dehumidification system is 22 liter per day, the estimated cost per liter of product freshwater for humidification dehumidification is 0.0578$, and the productivity of the unit enhanced with raising the inlet water temperature to the humidifier.

Li *et al.* [38] construct a solar energy driven and membrane-based air humidification dehumidification desalination (MHDD) system. Also, they built a mathematical model and validate it by experimental data. Different parameters and its effect on the performance of the model are studied. Li *et al.* conclude that, Humidifier, dehumidifier, and solar heater play significant roles throughout the system.

Q. Chen *et al.* [39] conducted a desalination spray assisted desalination rig. The system is investigated experimentally and numerically. The system operates in ambient conditions. It is noted that in February desalination unit achieves the highest production rate of 8.97 $\text{l}\cdot\text{day}^{-1}$ powered by a 2 m^2 solar thermal collector. Study reveals that the productivity rate is inversely proportional to the concentrations of the feed, whereas the reuse of a small amount of the hot saltwater enhances the thermal efficiency and freshwater production.

Li *et al.* [40] has constructed a solar desalination system with multi effect heat recovery using all glass evacuated tube absorber as heat collector. The study stated that 4.23 kg/m^2 is the product of distilled water on the sunny day while 3.03 kg/m^2 on the cloudy day without power consumption.

Kabeel *et al.* [41] investigate experimentally an HDH desalination unit combined with reheater two stage indirect solar dryer. The study stated that a two-stage drying unit with reheating results in enhancing the average removal of humidity content by 71.78 percent relative to the drying unit with single stage.

Mahdizade *et al.* [42] conducted a theoretical analysis with SOAOW configuration on water-heated, air-heated and dual-heated HDH desalination systems to determine the influences of design parameters and operating conditions on system performance. The study stated that the ambient temperature has more effect on the performance of the system than the ambient relative humidity. The findings also reveal that when the ambient temperature is high, there is a better output in the close air loop. Since condensation of freshwater in dehumidifier and the mass transfer between air and water in humidifier, effectiveness depends on moisture and temperature. Effectiveness of humidifier and dehumidifier is defined as in Equation (6). Gained output ratio (GOR) is commonly used to get the performance of HDH system as in the following equations:

$$\varepsilon = \frac{\Delta H}{\min\left(\Delta H_{\max,w} \Delta H_{\max,a}\right)} \tag{6}$$

$$\text{GOR} = \frac{\dot{m}_{pw} h_{fg}}{\dot{Q}_{in}} \tag{7}$$

$$\dot{Q}_{in} = \dot{m}_h \left(h_{ht,out} - h_{ht,in}\right) \tag{8}$$

Marale *et al.* [43] conduct an experiment on two stage humidification dehumidification cooling and desalination plant by varying the flow rate of hot water at various inlet temperatures and air flow rate. The experimental outcomes stated that the performance of dehumidifier is the main component which has significant effect on fresh water production and air cooling. Computational fluid dynamics (CFD) code is used to perform a numerical simulation analysis on the dehumidifier. The main parameters that affect the dehumidifier efficiency are the temperature of chilled water, the temperature of humid air, and volume fraction. The advantage of two stage humidification dehumidification systems increasing the production of freshwater as well as air cooling for utilize of air conditioning.

Amir *et al.* [44] developed a two effect HDH solar desalination system using hybrid solar still coupled with solar concentrator and two thermally cooled photovoltaic panels. The results showed that increasing of basin height and the air mass flow rate results in decreasing of system productivity. Freshwater production significantly increased as photovoltaic panels integrated along with solar concentrator at high concentration ratio.

Capocelia *et al.* [45] presented and analyzed a new process including a multiple extraction humidification-dehumidification with vapour adsorption (HDHA) and brine recirculation. Analysis and simulation showed the lower the moisture entering the humidifier, the higher the HDHA thermodynamic performance; the more extractions, the lower the carbon footprint (GOR up to 10). Furthermore, mathematical model and the process scheme of the adsorption system coupled with the HDH are analyzed in the study.

The performance of a humidifier of an HDH compression system was studied and analyzed by Ghalavand *et al.* [46]. The performance was predicted by conducting a mathematical model. Also, the study showed that the effect of variations in the inlet temperature of the water on system performance is greater than that of variations in inlet air. Jamil *et al.* [47] conducted an exergy economic study of HDH desalination unit running under traditional open air open water OAOW, a modified closed-water open-air CWOA, combined HDH-RO under three different types including a simple HDH-RO, HDH-RO with Pelton turbine, and HDH-RO with a pressure exchanger.

A mathematical model of humidification dehumidification desalination system with waste heat recovery is built by He *et al.* [48], and then a simulation for the corresponding thermodynamic and economic outcomes presented. Also, the effect of the sprinkling temperature of seawater on thermo-economic performance is also studied. Through the simulation and analysis, it is observed that freshwater productivity improves always with the increase of the air mass flow rate. As the temperature of the sea-water spray decreased the cost of water production also decreased. A competitive cost of one-kilogram freshwater with 0.02$ concerning solar-driven humidification dehumidification desalination unit conducted by Zubair *et al.* [49] with 0.038$ which refers to the advantage of the HDH desalination systems driven by waste heat.

Xing *et al.* [49] developed and verified experimentally a thermodynamic and pressure drop models of the humidification dehumidification (HDH). The experimental outcomes revealed that the increase of air and liquid mass flow rate as well as the liquid top temperature increases the pressure drop in the system. Furthermore, Xing *et al.* performed a numerical optimization to obtain the minimum specific exergy consumption.

Lawal *et al.* [50] investigate experimentally a new coupled humidification dehumidification desalination system with heat pump system. A significant influence of mass flow rate ratios and feed water temperature whereas chilled water does not affect the integrated system.

Dawood *et al.* [51] presents experimentally a solar HDH desalination unit. The researchers used an ultrasonic technique as an efficient method of humidification. Mass flow rate of water and air was found to have a significant effect. The authors studied effect of heating the water before spraying in humidifier over different flow rates.

Gabrielli *et al.* [52] investigate theoretically an HDH process design and operation combined with solar photovoltaic-thermal (PVT) modules for the simultaneous generation of clean water and electricity. The optimal design of the system is studied for different range of ambient conditions. Giwa *et al.* [53] investigates an air-cooled photovoltaic system built into a humidification dehumidification desalination system with ambient seawater flow. The authors developed a model of the physical and thermodynamic properties involved in the recovery of PV. Also they determined the impact of this recovery on freshwater production throughout different environmental conditions. The study showed that environmental impacts decreased by 83.6% on using PV-HDH system than that of using PV-Reverse Osmosis (PV-RO) system. The integrated PV-HDH desalination technology is also promising and is expected to play a key role in the water desalination sector.

7. Comparison of Economic Cost versus Productivity

Economics play a vital role especially in the improvement of desalination technologies. Consequently, huge financial studies are done in this field. In the coming part, different cost analysis investigation studies in the field of humidification dehumidification desalination are reviewed and evaluated as shown in **Table 2**.

Voivontas *et al.* [54] represent an economical study of desalination plants integrated with renewable energy as shown in **Figure 13**.

Economical and thermodynamic considerations in designing solar desalination plants are investigated by Goosen *et al.* [55]. Moreover the researchers showed that the operation and maintenance costs of condenser and pump are the main effective parameters in economic analysis of HDD systems. Enhancement for both economic and thermodynamic efficiencies could be done by integrating HDD systems to waste heat recovery and regeneration cycles.

Shatat *et al.* [56] stated that the cost of freshwater productivity from solar-powered desalination systems is about 11 $\$/m^3$, these study were conducted for desalination systems coupled with solar energy in dry and semi-dry remote regions. The author stated that desalination productivity cost decreases with increasing lifetime of the desalination plant. Furthermore, the freshwater cost reduced as the system capacity increased. In this study, plant life-time, area of solar collector, and interest rate are the parameters being investigated from an economic point of view. The solar desalination plant payback period as well as annual useful energy as a function of solar collector area is shown in **Figure 14**. The graph refers that as collector area increases the annual useful energy increases also, but the payback period significantly decreases.

8. Conclusion

A condensed review of solar humidification dehumidification desalination technology is conducted. Also different desalination systems related to this theory have

Table 2. Comparison between different HDH systems.

Author	Year	Ref.	Study category	System description	Productivity	Cost per unit
Kabeel *et al.*	(2013)	[57]	Theoretical	HDH-FE	96 l·day^{-1}	0.0086 US$/l for hybrid 0.0097 US$/l for separate
Zubair *et al.*	(2017)	[58]	Theoretical	CAOW WH	16,430 - 19,445 kg/year	From 0.0032 US$/l to 0.0038 US$/l
Jamil *et al.*	(2018)	[47]	Theoretical	Hybrid HDH ROD	-	0.00013 US$/l
Kabeel *et al.*	(2015)	[37]	Experimental & Theoretical	Solar HDH	22 l/day	57.8 US$/m^3
Deniz *et al.*	(2016)	[59]	Experimental & Theoretical	OACW A/WH Solar HDH	1.1173 l/h	98.1 US$/m^3
Rostamzadeh *et al.*	(2018)	[60]	Theoretical	Heat pump	38.84 kg·h^{-1}	2217 - 7130 US$/m^3
Y. Zhang *et al.*	(2019)	[61]	Theoretical	Heat pump	42.55 l·h^{-1}	41.2 US$/m^3
W.F. He *et al.*	(2019)	[62]	Theoretical	Heat pump	71.56 l·h^{-1}	18 US$/m^3
Y. Zhang *et al.*	(2018)	[63]	Experimental	Heat pump	22.26 kg·h^{-1}	51 US$/m^3
Lawal *et al.*	(2020)	[50]	Experimental	Heat pump	287.8 l·day^{-1}	10.68 US$/m^3
M. Faegh *et al.*	(2019)	[64]	Theoretical	Heat pump	287.8 l·day^{-1}	14 US$/m^3
Okati *et al.*	(2018)	[65]	Theoretical	OAOW	264.8 l·day^{-1}	0.0276 US$/l
He *et al.*	(2018)	[66]	Theoretical	CAOW	84.6 kg·h^{-1}	6.2 - 13.41 US$/kg·h
Wu *et al.*	(2017)	[67]	Experimental & Theoretical	CAOW	0.182 m^3·h^{-1}	0.0025 US$/l
Narayan *et al.*	(2013)	[68]	Experimental	CAOW	700 kg/day	-
El-Agouz *et al.*	(2014)	[69]	Experimental	-	9 kg·m^{-2}	0.029 US$/l
Dayem *et al.*	(2014)	[70]	Experimental	-	9 kg/m^2 day	0.5 US$/l
Rajaseenivasan *et al.*	(2017)	[71]	Experimental	OAOW	6.1 kg·h^{-1}	0.0133 US$/kg
Elminshawy *et al.*	(2016)	[72]	Experimental & Theoretical	OAOW	104 kg·m^{-2}	0.003 US$/l
Rahimi-Ahar *et al.*	(2018)	[73]	Theoretical	CAOW	2 - 2.2 kg·h^{-1}	0.002 - 0.041 US$/l
El-Agouz *et al.*	(2018)	[74]	Theoretical	OAOW A/W H	0.46 kg$_w$/kg$_a$	-
Zubair *et al.*	(2018)	[75]	Experimental & Theoretical	OAOW OACW	-	4.10 - 6.55 US$/m^3 0.79 - 2.25 US$/m^3
He *et al.*	(2018)	[48]	Theoretical	CAOW	99.05 kg·h^{-1}	0.02 US$/kg
Tariq *et al.*	(2018)	[76]	Theoretical	OACW-WH	21 kg·day^{-1}	0.03 US$/l
Rahimi-Ahar *et al.*	(2018)	[77]	Experimental	CAOW A/W H	1.07 kg·h^{-1}·m^{-2}	0.0041 US$/l
El-Agouz	(2010)	[78]	Experimental & Theoretical	OACW WH	8.22 kg·h^{-1}	0.115 US$/l
Behnam *et al.*	(2016)	[79]	Experimental	CACW WH	6.275 kg·day^{-1}·m^{-2}	0.028 US$/l
Elminshawy *et al.*	(2015)	[80]	Experimental & Theoretical	OACW WH	30.3 kg·day^{-1}·m^{-2}	0.035 US$/l
Zhani *et al.*	(2010)	[27]	Experimental	CAOW AH/WH	20 kg·day^{-1}	0.08 €/l
Ahmed *et al.*	(2017)	[81]	Experimental	OACW A/WH	15 kg·h^{-1}	0.01 US$/l
Rajaseenivasan *et al.*	(2017)	[82]	Experimental	OACW AH/WH	15.23 kg/day·m^2	0.0257 US$/kg
Wang *et al.*	(2012)	[83]	Experimental	CAOW WH	0.873 kg/day·m^2	0.0218 US$/kg
Xu *et al.*	(2019)	[84]	Theoretical	CACW WH	0.14 kg/h	8.59 US$/m^3

Continued

Ariyanfar *et al.*	(2016)	[85]	Experimental	CAOW WH	326.52 kg/h	0.86 US$/m^3
sayyaadi *et al.*	(2018)	[86]	Theoretical	CAOW AH/WH	970 kg/h	0.66 US$/m^3
Ayati *et al.*	(2019)	[87]	Theoretical	HDH HDH-HP HC-HP VPHDH-HP	1.05 kg·h^{-1} 1.34 kg·h^{-1} 1.35 kg·h^{-1} 1.83 kg·h^{-1}	3.4 US$/m^3 3.42 US$/m^3 5.12 US$/m^3 4.68 US$/m^3
Elsafi	(2017)	[88]	Theoretical	HDH-CPVT AH	33 l/day	0.01 US$/l
Rajaseenivasan *et al.*	(2016)	[89]	Experimental	HDH SAH HDH SAH /Turbulators HDH DPC/Turbulators	16.32 kg/day·m^2 20.61 kg/day·m^2 23.92 kg/day·m^2	0.032 US$/l 0.026 US$/l 0.019 US$/l
Muthusamy *et al.*	(2017)	[90]	Experimental	HDH AH	6.8 l/day	1.25 US$/l
Yuan *et al.*	(2011)	[91]	Experimental	HDH-EVT WH	1200 l/day	0.0029 US$/l
Sharshir *et al.*	(2016)	[92]	Experimental	HDH-Solar Still EVT WH	7480 l/year	0.034 US$/l
Xu *et al.*	(2018)	[93]	Experimental	HDH SAHPD	12.75 kg·h^{-1}	0.030 - 0.042 US$/l
Xu *et al.*	(2019)	[94]	Experimental	HDH SAHPD	17.45 kg/h	0.025 - 0.03 US$/l
Shafii *et al.*	(2018)	[95]	Experimental	HDH AH	2.79 kg/h	0.0114 US$/l
M. Faegh *et al.*	(2019)	[96]	Theoretical	HDH WH	0.91 kg·h^{-1}	0.014 US$/l
Kabeel *et al.*	(2013)	[97]	Theoretical	HDH-FE	96 l/day 88 l/day 77 l/day 89 l/day	0.01253 US$/l 0.01308 US$/l 0.01771 US$/l 0.01423 US$/l
B. Habeebullah	(2010)	[98]	Experimental	HDH HP	2.23 m^3/day	13.5 US$/ m^3
Ali *et al.*	(2019)	[51]	Experimental	HDH WH	42 kg/day	0.0144 US$/l
Farsad *et al.*	(2011)	[99]	Theoretical	HDH AH/WH	22 l/day	0.0578 US$/l
El-Said *et al.*	(2016)	[100]	Theoretical	MSH SSF	112.5 kg/day	6.43 US$/ m^3
Abdel-Hady *et al.*	(2018)	[101]	Experimental	-	5.424 l/h	0.043 US$/l

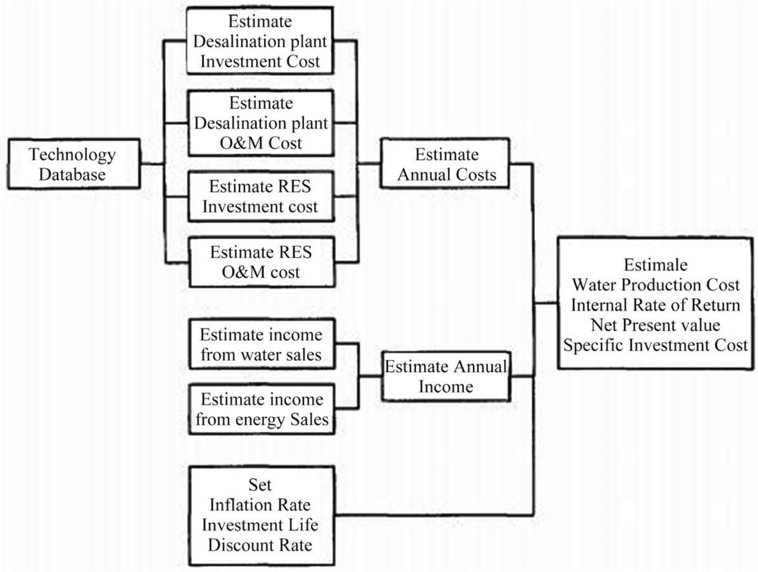

Figure 13. Financial analysis algorithm for a RES driven desalination plant by Voivontas *et al.* [54].

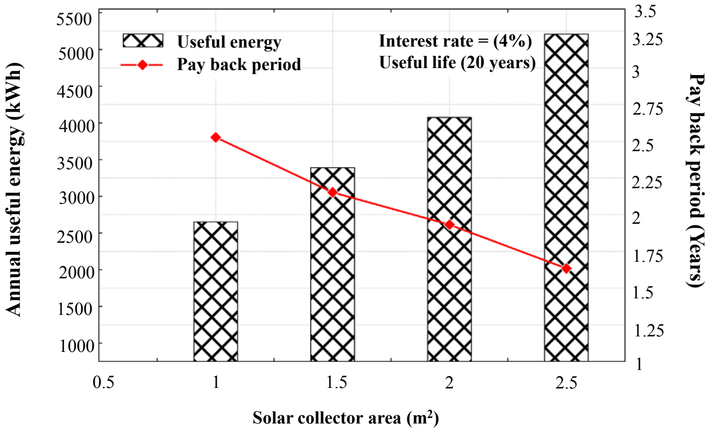

Figure 14. Desalination system payback period and annual useful energy as a function of solar collector area by Shatat *et al.* [56].

been introduced in this paper. A detailed study of other desalination techniques based on HDH basics will help to improve the performance of existing HDH solar power systems. The review in this paper showed that HDH is suitable for the productivity of freshwater when the request is decentralized. Also the review showed the parameters which has a significant effect on humidification dehumidification systems performance which are surface area of evaporator, surface area of condenser. Additionally, the unit needs to be optimized by adjusting its component size to achieve the effect of optimum feed water and airflow levels.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

AH	Air Heating	-
CFD	Computational Fluid Dynamics	-
COP	Coefficient Of Performance	-
CPL	Cost Per Liter	*$*
CAWH	Closed Air Water Heated	-
CAOW	Closed Air Open Water	-
CWOA	Closed Water Open Air	-
DPC	Dual Purpose Collector	-
ED	Electrodialysis	-
EVT	Evacuated Tubes	-
FE	Flashing Evaporation	-
GOR	Gain Output Ratio	-
HDH	Humidification Dehumidification	-
HDHA	Humidification Dehumidification with Adsorption system	-
HP	Heat Pump	-
MENA	Middle East and North Africa	-
MHDD	Membrane Humidification Dehumidification Desalination	-
MR	Mass Ratio	-
MSF	Multi Stage Flash	-
MED	Multi Effect Distillation	-
MSH	Multi Stage Humidification	-
OAOW	Open Air Open Water	-
OAWH	Open Air Water Heated	-
OACW	Open Air Closed Water	-
PV	Photovoltaic	-
PVT	Photovoltaic Thermal	-
RO	Reverse Osmosis	-
RR	Recovery Ratio	-
SAH	Solar Air Heater	-
SAHPD	Solar Assisted Heat Pump Desalination	-
SSF	Single Stage Flash	-
TDS	Total Dissolved Solids	mg/l
VC	Vapor Compression	-
VPHDH	Variable Pressure Humidification Dehumidification	-
WH	Water Heating	-