Renewable and Sustainable Energy Reviews 57 (2016) 929–944

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Recent advances in humidification dehumidification (HDH) desalination processes: Improved designs and productivity

Adewale Giwa, Nawshad Akther, Amna Al Housani, Sabeera Haris, Shadi Wajih Hasan *

Department of Chemical and Environmental Engineering, Institute Center for Water and Environment (iWATER), Masdar Institute of Science and Technology, P.O. Box 54224, Abu Dhabi, United Arab Emirates

ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form
29 October 2015
Accepted 17 December 2015
Available online 7 January 2016

Keywords:
Humidification
Dehumidification
Renewable energy
Desalination
Water

ABSTRACT

One of the innovative methods for decentralized low-scale purification of water is the humidification dehumidification (HDH) desalination technology. Many research activities have been carried out recently with the aim of improving this technology. The economic and environmental benefits of the HDH technology are enormous including feasibility of being powered by sustainable energy sources such as solar and geothermal, ability to operate at low temperature, low maintenance requirements, and simple construction needs. The principal HDH components, latest research on HDH systems driven by renewable energy, and recent innovations on HDH design for sustainable water production are discussed in this paper. It is worth noting that the development of the key features and sustainability aspects of HDH desalination technology are still under research and more improvements are needed to optimize process performance parameters in terms of quantity of water produced, specific renewable energy required, and specific cost of water produced. However, HDH technology has been proven to be an inexpensive and reliable desalination system in terms of environmental friendliness for small scale applications.

Contents

* Corresponding author. Tel: +971 2 810 9237; fax: +971 2 810 9901.
E-mail addresses: agiwa@masdar.ac.ae (A. Giwa), nakther@masdar.ac.ae (N. Akther), aalhousani@masdar.ac.ae (A.A. Housani), sharis@masdar.ac.ae (S. Haris), swajih@masdar.ac.ae (S.W. Hasan).

http://dx.doi.org/10.1016/j.rser.2015.12.108
1364-0321/

1. Introduction

The surge in industrial activities and rising population in many parts of the world has been responsible for the consistent increase in the world's water demand. New sources of clean and safe water must be found in order to meet this demand. Sea or brackish water desalination offers a promising choice for water security since saline water is the only water source that could be termed as "unrestrained" (about 97% of the world's water resources is saline water). Nowadays, in many countries, desalination is a key water treatment approach for potable water production. Desalination is a treatment method that converts saline water to fresh water and concentrate. Many desalination processes have been devised but these processes can be classified into two broad types: membrane processes and thermal distillation.

The existing desalination plants are mainly large-scale. Huge energy and material requirements leading to high ecological footprints are some drawbacks of these plants. Also, large-scale plants are only affordable to the rich countries and unsuitable in many developing countries and remote locations. Many desalination plants today still consume a lot of fossil fuels for heat energy production in thermal distillation plants and electric energy requirement in membrane desalination plants. These fossil fuels release carbon dioxide and other greenhouse gases which pose serious threats to the environment. Recently, more research activities have been geared towards renewable energy-powered desalination technologies (most especially solar-powered desalination technologies) in order to mitigate the deleterious effects of fossil fuel-powered conventional desalination methods. Humidification dehumidification (HDH) desalination technology powered by a renewable energy source is one of these approaches. This technology conserves conventional energy [1], decreases environmental degradation [2], ensures that free natural energy resources are tapped and produces pure water from continuous processes with low maintenance needs [3–6].

HDH technology is a distillation technology that uses a carrier fluid such as air or water to obtain thermal energy from a heat source, which is then transferred to a humidifier for water evaporation from saline water and then to the dehumidifier for the condensation of the evaporated water to fresh water [6–9]. A simple form of HDH desalination process is made up of air or water heater, the evaporator (humidifier), and condenser (dehumidifier). Various heat sources such as solar thermal, solar PV, geothermal, wind, or their combinations can be the energy source for HDH desalination technology [10]. In the HDH system, thermal energy of air or the heat carrier medium is important because the capacity of the medium to vaporize pure water from saline water increases as the medium temperature rises [11]. A portion of the vapor absorbed can then be recovered from the humidified air by bringing it in contact with a cooling surface in the dehumidifier. Again, there is need to optimize the driving force of heat transfer or temperature gradient between the cooling system and humidified air at this stage in order to obtain optimum fresh water production. Saline water can also be used as the cooling water in a dehumidifier to recover latent heat from the heated air–water mixture, thereby ensuring that the salt water is preheated before being fed to the HDH system [12].

Therefore, the recent advances in HDH desalination technology in terms of improved designs and system productivity have been reviewed in this paper. The recently devised materials for the design of HDH components have been discussed in this review. In addition, the integration of HDH desalination technology with renewable energy sources such as solar and geothermal energy has been demonstrated. Recent innovative investigations, aimed at reducing the size of HDH system and ensuring energy efficiency for optimal system performance, have also been analyzed. Lastly, some research attempts that have been directed towards the enhancement of the scale of HDH systems and a comparative analysis of studies on HDH technology in terms of productivity and operating conditions have been reviewed in this paper. In general, this paper aims to present the current state of HDH desalination technology and recent improvements that might propel future interest and further upgrade of this technology.

2. Material requirement of HDH desalination technology

As mentioned in the Introduction, HDH desalination system is composed of humidifier, dehumidifier, and air/water heater. Pure water diffusion from saline water into air occurs in the humidifier and the humidity of air is increased in accordance with the difference in concentration between the water vapor in air and air–water interface. In other words, the mass transfer of vapor to air is influenced by water vapor partial pressure in air and pressure of vapor at the air–water interface [13]. In addition, the humidity of inlet air to the humidifier affects the operational performance of the humidifier. A numerical analysis of the performance of a humidifier with vertical parallel-plates channel has carried out by Kassim et al. [14]. The inlet air to the channel was maintained at constant velocity, humidity and temperature. One of the plates was kept dry and insulated from heat while the other was considered as wetted by film of water. It was discovered that the best working performances of the humidifier were recorded at low inlet air humidity. Several devices including packed bed, wetted walls and spray towers, and bubble columns have been tested for air humidification in the humidifier [15,16]. The same working principle is exhibited by these devices. An innovative design of solar film humidifier was also made by Saidi et al. [17] using an inclined plate of metal plane in the form of a parallelepiped. A wooden frame covered with glass was positioned on the plate in such a way that the exposure of the glass to solar radiation was maintained. A falling film was ensured on the plate with the aid of a porous tissue in such a way that the film was in direct contact with forced/natural air flow in ascending direction. Mass and thermal yields greater than 80% were reported.

Heat exchangers are required for the dehumidification part of HDH desalination system. Various types of heat transfer surfaces and materials have been tested as dehumidifiers. An important design requirement for dehumidification is to ensure that the heat transfer rate of the heat exchanger in the dehumidifier is appropriately determined under the specific conditions of operation. Flat plate [18,19] and finned-tube heat exchangers [20] are commonly used for dehumidification operations [21]. The most consistently used condenser is the condensation tower with coiled copper tube. This type of condenser has been theoretically and experimentally investigated by Amer et al. [22]. The condenser surface area can be increased with fins. In line with this, a dehumidifier consisting of three air coolers (connected to each other with tubes made of copper in series) and corrugated aluminum fins have been used successfully as dehumidifiers [23]. Research

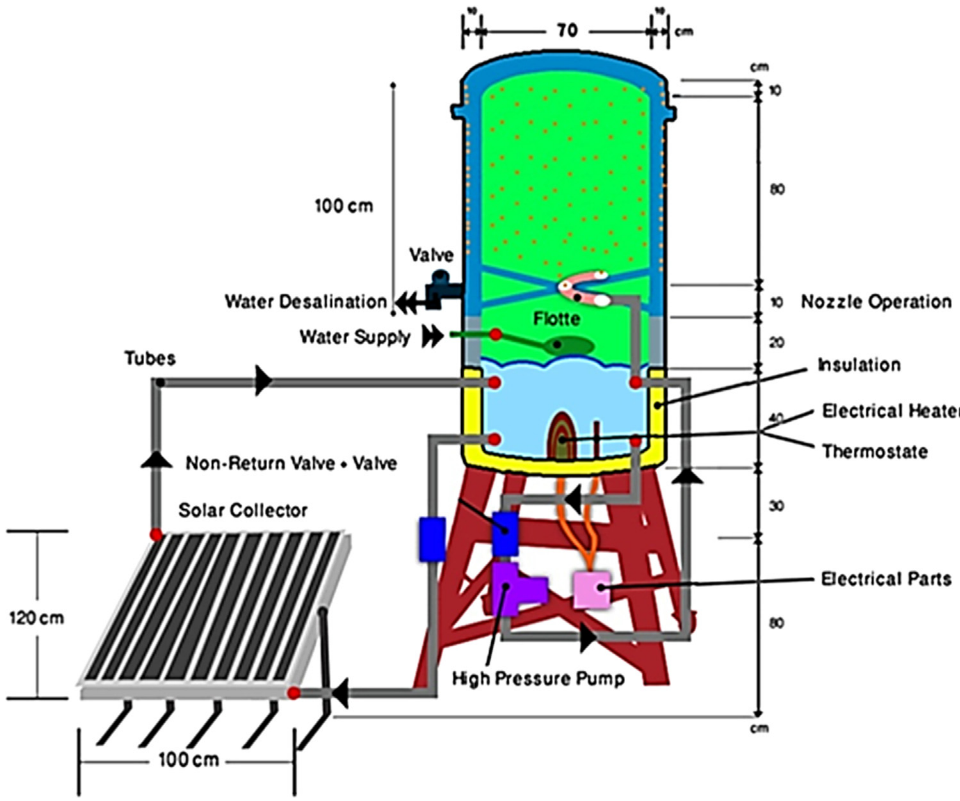

Fig. 1. HDH desalination via flat-plate solar collector [27].

work on bubble column dehumidification has also been carried out. Tow and Lienhard [24] developed a numerical model to predict the parallel flow effectiveness and heat flux of a bubble column dehumidifier and verified the results obtained with those obtained experimentally. The effects of the following controlling parameters were investigated: moist air temperature, coil length, sparger orifice size, bubble formation on coils and column liquid height. The column height was minimized to reduce the pressure drop in the gas side of the dehumidifier. It was observed that a decrease in the coil area, and an increase in the air flow rate and moist air temperature caused the effectiveness to decrease and heat flux to increase. Also, the column height and bubble formation on coils were found to have negligible impact on the effectiveness and heat flux. However, Tow and Lienhard [24] concluded that by using smaller coils than those used in their previous work, they were still able to obtain high parallel flow effectiveness.

The materials and devices used as heaters to provide thermal energy for the carrier medium is another important aspect of the HDH desalination system. Many devices including solar heated surfaces which increase the temperature of air or water (heat carrier) have been tested for this part. A water solar collector have been considered as the heater by Zhani et al. [25]. Copper sheet-and-tube absorber was used as the design material for this system [25]. A water solar collector device consisting of 6 collectors made of copper tubes for desalination has also been investigated [26]. Dayem [27] designed and experimentally tested a solar HDH desalination system under varying weather conditions. A 1.15 m^2 flat-plate solar collector was used as a heating source for the feed saline water (Fig. 1). It was observed that the HDH system could produce desalinated water at around 1.6 L/kW h of solar energy or 9 L/d for every quadratic meter of solar collector surface area. Additionally, experimental results showed that system performance was largely dependent on the feed water temperature and scaling was a significant problem. The water production cost was found to be USD0.5/L, which is comparatively high.

Water heating via solar water heater has a major importance on the production of pure water when compared with air heating using solar air heater because the heat capacity of water is higher than that of air [28]. On the other hand, air collectors are mostly flat plate absorbers consisting of large airflow channels. The air moves under or above the absorber plate through the air channel [29]. In some cases, double pass methods are used. An air-heated HDH system has also been incorporated with circular half-perforated inserts placed inside the air heater at angles of orientation of 45 – 180° [30]. Optimum water production of 0.82 kg/h was obtained when the flow rate of air was 21 kg/h and angle of orientation was 180°. From the economic analysis of the system, a payback period of the system was found to be 171 days. The performance of air heating solar collector can be enhanced by integrating a phase change material (PCM) with the collector. A system that incorporated a solar air heater with PCM for performance enhancement has been tested by Summers et al. [31]. In this system, constant temperature of outlet air from the collector was ensured by the incorporation of the PCM directly below the absorber plate. Results obtained from both two dimensional transient finite element modeling and experimental investigation when a layer of PCM was placed at 8 cm under the absorber plate indicated that there was a good prospect to achieve consistent temperature of the heated air outlet throughout the entire length of the day, with an average collector efficiency of 35%. Still, such a system is economically infeasible as a large-scale desalination system because collectors with huge areas would be needed for small heat outputs. Many other studies have evaluated air-heated HDH principle [32–34] and other studies have compared different configurations that gave minimum water cost and optimized performance for air-heated HDH desalination systems [35,36].

Moumouh et al. [37] reviewed various HDH desalination technologies using solar thermal energy as heat source for saline water and air and highlighted the various types of solar collectors, solar water heaters and solar air heaters that could be used in HDH desalination systems. They concluded from their review that the most efficient solar collectors for HDH desalination comprised of a thermosiphon solar water heater with a flat-plate collector and a storage tank, and a packed-bed solar air heater with a flat-plate collector.

Lately, a novel thermal energy source for HDH desalination was developed by Giwa et al. [13]. In this work, the heat absorbed by solar PV cells (which hinders the ability of PV panel to produce electricity) was recovered as a thermal energy source for HDH desalination process. Cooling air was made to pass through a gap at the back side of the PV panel. The heated air at the outlet of the PV gap was then used to desalinate seawater in the HDH setup. The life cycle analysis of the system was also carried out. 833 L/m^2 y of water and 278 kW h of electrical power were produced by this system. However, a disadvantage of this system is the fluctuation in daily water production as a result of varying solar irradiance which necessitates the use of a battery to store photovoltaic energy or the coupling of the system with other energy sources to prevent intermittency of electric power. Meanwhile, a dynamic model that is based on heat and mass transfer has been developed by Nematollahi et al. [38] to predict a solar desalination system consisting of a collector and humidifier. High exergy efficiency was obtained for the system through this model.

Meanwhile, it is worth noting that a holistic design improvement is needed in order to enhance the performance of HDH desalination system. This means that focusing on only one or two components might not yield the desired result; hence efforts must be directed towards all HDH system components and operating conditions in order to optimize the system performance. An attempt aimed at improving the performance of HDH desalination through a holistic approach has been carried out by Kabeel et al. [39]. The HDH system was designed using the principle of open-water and closed-air cycle. The effect of different wet surface areas of cellulose paper, which was used as a substratum for packing material in the humidifier unit, on the unit performance was studied. A modified design of dehumidifier made up of a circular cross sectional area and corrugated-type fins was also carried out to enhance the unit performance. Additionally, the influence of the following operating conditions on the performance of the HDH unit was investigated: natural convection, forced air circulations (up, down, and up–down), and temperature and mass flow rate of inlet water to the humidifier. The most favorable ratio of condenser inlet water to evaporator inlet water (C/H) was also determined. Experimental results showed that the main parameter influencing the performance of the HDH desalination unit was the wet humidifier surface area. Higher productivity was obtained when a 5 mm cellulose paper was used, as compared with a 7 mm-cellulose paper. The highest productivity was achieved when C/H was equal to 2. It was also observed that HDH unit performance was higher when air circulation was forced down. In addition, the modified dehumidifier design gave an effectiveness of about 0.71, which was higher than the conventional type with effectiveness of 0.49. Hence, the modified HDH unit design gave a better performance than the conventional type [36].

3. Renewable energy-powered HDH desalination

A key advantage of HDH desalination technology is its compatibility with renewable energy sources. HDH technology becomes even more beneficial when its applicability in remote locations with abundant renewable energy sources is considered. The classification of HDH systems into three categories was carried out by Narayan et.al [7]. The first classification entails the energy source used. Solar thermal, solar PV, geothermal, and hybrid energy combinations have been investigated as energy sources. The interesting aspect of this classification is that HDH desalination can be carried out using low-grade heat with the aim of environmental protection. The most commonly applied renewable energy in HDH desalination systems is solar energy [40]. Another classification of the HDH systems is based on the nature of the heated stream (whether air-heated or water-heated systems). System performance is highly influenced by the nature of heated stream, as different results would be obtained for system productivity when water or air is heated. An intensive research has been carried out on solar water heating devices whereas solar collectors for air heating have received relatively lower attention from researchers. The cycle configuration of HDH systems is the third classification. HDH desalination systems can be categorized into closed water-open air cycle and closed air-open water cycle [41]. In the closed water-open air cycle, air is heated, humidified, partly condensed, and released to an open cycle. On the other hand, in the closed air-open water cycle, air circulation between the humidifier and dehumidifier is ensured in a closed loop. Air circulated can be ensured by natural or forced convection (mechanical blowers). Productivity and costs of HDH desalination systems are hugely influenced by the type of cycle selected. Therefore, it is important to understand the relative benefits and shortcomings of both configurations for optimum performance efficiencies [42,43]. However, little focus has been directed towards the optimization of HDH cycles in published works; rather, a lot of research activities have been focused on the optimization of the different units of HDH desalination systems.

3.1. HDH systems powered by solar energy

To produce a sizeable quantity of fresh water, a huge amount of thermal and electric energy is required [44,45]. The most common energy sources in desalination plants nowadays are oil and natural gas. These sources are unsustainable because they emit poisonous greenhouse gases to the environment during combustion and would be depleted if the current rate of extraction is maintained [46]. However, the continued consumption of fossil fuels for desalination purposes can be curtailed through the use of renewable energy. In remote locations where the cost of energy transmission is high, desalination systems powered by renewable energy can now compete economically with fossil energy-powered systems. However, in other locations, conventional desalination plants still outperform the sustainable systems in terms of economic benefits. Meanwhile, as a result of declining costs of renewable energy sources in recent times, sustainable desalination systems are expected to compete favorably with conventional systems in the long run [47]. In solar thermal distillation, heat from the sun can be used to evaporate the salty water to obtain vapor and concentrate [48]. Then, fresh water can be obtained by the re-condensation of the vapor [49–52]. In recent years, studies have shown that the evaporation and condensation approach such as that adopted in solar HDH desalination systems can be considered as the most desired and optimal technique for small-capacity water desalting in terms of environmental friendliness and energy and cost requirements [13,53,54].

Results from a comprehensive examination of the principles and cost assessment of solar HDH desalination process by Al-Hallaj et al. [55] has shown that an increase in the overall desalination efficiency and cost effectiveness could be achieved from the combination of solar energy with HDH. The contribution of energy to total cost was only 0 – 10%. However, additional work on cost assessment is required so as to estimate the total system cost.

For small-scale applications in rural or remote locations, another study has indicated that brackish water desalination using solar HDH technology would be a cost-effective and economically viable approach [56]. A more recent work focused on the decrease of the cost of product water obtained from solar HDH system under certain process and geographical constraints through mathematical optimization [53]. An important conclusion from this study is that 7 – 28% cost reduction can be obtained. Also, recycling the humidifier outlet water into the dehumidifier will increase the system productivity and reduce the specific thermal energy consumed by HDH process but this would lead to an increase in production cost. The costs of water produced from HDH technology can also be reduced by combining a solar cooling plant with HDH desalination plant [57]. In a conventional solar cooling plant, the absorption chiller provides cooling energy and reject large amount of heat at low temperature to the environment. The low grade heat from a cooling plant has been used by Franchini et al. [57] to drive a single-effect HDH system based on closed air cycle Certain operating conditions such as feed flow rate and temperature and storage tank size were varied to obtain a 50 kW cooling capacity and improve the cooling system performance. Improvements in the performance of the system in terms of cooling and desalination were obtained by reducing the feed seawater temperature which can be made possible via heat rejection at higher temperature, increasing the flow rate of seawater, and increasing the temperature of heat source [57].

Meanwhile, a serious limitation of some solar HDH systems is their inability to work throughout the day because of the absence of solar irradiance during night periods. Because of this constraint, Yuan and Zhang [58] has developed a closed-air circulation solar HDH system that could operate all day. The efficiency of this system can be increased by optimization of air flow and adequate use of the latent heat of the circulated air. The system design and performance were investigated via a mathematical model. The effects of the area of collector, flow rate of seawater and cooling water, and system's dimensions on system productivity were also studied. The simulation results showed that reduction in fresh water production would result from an increase in the flow rate of feed water when the solar collector area was kept constant. In China, the productivity of this system could reach 5.2 kg/m^2 d in summer and 2.7 kg/m^2 d in winter. Another experimental investigation of solar HDH system presented in China [59] concluded that a solar irradiance of 550 W/m^2 could be used to produce 1200 L/d of water at a cost of RMB 19.2 Yuan/m^3.

Solar humidification based on air bubbling has been investigated by Zhang et al. [16]. Experimental analysis of the air bubbling humidification process has revealed that thermal energy of evaporating water in the humidifier is a strong determinant of the significant temporal changes of the water temperature and performance of the humidification process. Higher water temperature and humidification performance were reported when the total heat supplied was greater than that received by the evaporating water at the initial stage, although stability of heat transfer was observed as the process progressed. The study concluded that high humidification capacity or greater water evaporation was achieved in the humidifier when higher amount of heat was supplied to the air bubbling process. A prototype of solar HDH system based on air bubbling humidification for brackish water desalination has also been investigated by Ghazal et al. for its performance in North Cyprus [60]. This HDH system was modified to allow for a more compact design by replacing some of the components of a conventional HDH desalination system (solar air/water heater and evaporator) with a solar collector. Air moved into the humidification unit as bubbles through the water-filled solar collector (Fig. 2).

The effects of several parameters (water temperature, bubble regeneration, bubble coalescence, and increased radiation due to

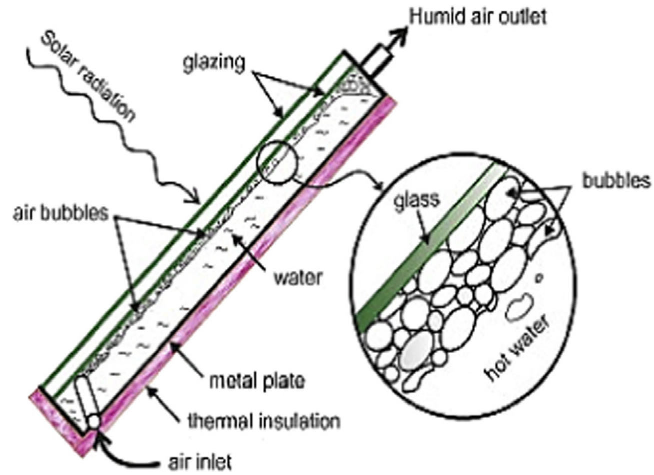

Fig. 2. Basic design of air bubbling through water-filled solar collector [60].

reflection) on system performance were studied. It was observed that humidification via direct contact bubbling can be efficiently used in solar HDH desalination system. Additionally, heat and mass transfer between air and water could be improved by increasing the air–water contact surface area through the use of inverted sieves to resize the air bubbles. Sieves also increased heat transfer by acting as solar absorbers, which further enhanced the vapor carrying capacity of air by increasing the air temperature. Moreover, increased radiation from reflection was observed, leading to an enhancement of the humidification process by 32% at air flow rate of 12.6 kg/h [60].

From the reviewed studies on solar HDH desalination systems, it is clear that different levels of system performance would be obtained when different configurations are used. To this end, Narayan et al. [7] has compared the performance of different types of solar HDH systems. The basis of comparison was the cycle configurations of these systems i.e. air and water heating cycles. The most energy-efficient solar HDH system was found to be the multi-effect closed-air open-water (CAOW) system with specific cost of USD 3–7/m^3 [18]. Although, this cost was more than that obtained in reverse osmosis, other benefits have been attributed to this HDH system for distributed small-scale applications. Simpler water pretreatment with minimal operation and maintenance are some advantages of this system for low-scale water desalination. It was concluded that there is need for more research in order to improve the HDH system efficiency and realize its full economic potential to produce fresh water [7]. A parabolic trough solar collector has also been used to propel and optimize water production from HDH system [61]. A test set-up was designed and theoretical modeling of the system was carried out in order to estimate the fresh water production from the system. It was observed that the designed system could be driven by parabolic trough solar collector and more fresh water was obtained as day time increased [61,62]. The summer season gave the highest system productivity because the highest solar irradiance and longest peak sun hours could be obtained in this season [61]. Energy balances solved via one-dimensional implicit finite difference approach with the aid of a computer program have also been used to obtain the thermal performance of a parabolic trough solar collector, with water and synthetic oil as the heat transfer fluids. A thermal efficiency of about 69.73 – 72.24% was reported [63].

The use of external reflector in solar HDH desalination system has also been tested for performance improvement. Elminshawy et al. [64] analytically and experimentally investigated the impact of using flat external reflector, immersion water heaters, induced atmospheric air, and the effect of weather condition on the performance of solar

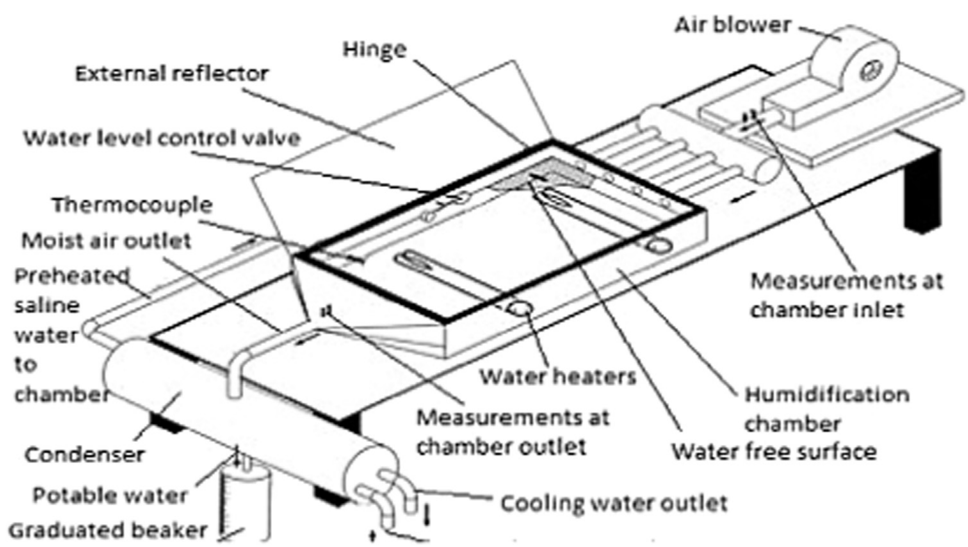

Fig. 3. HDH system with a humidifier coupled with flat external reflector and immersion water heaters [64].

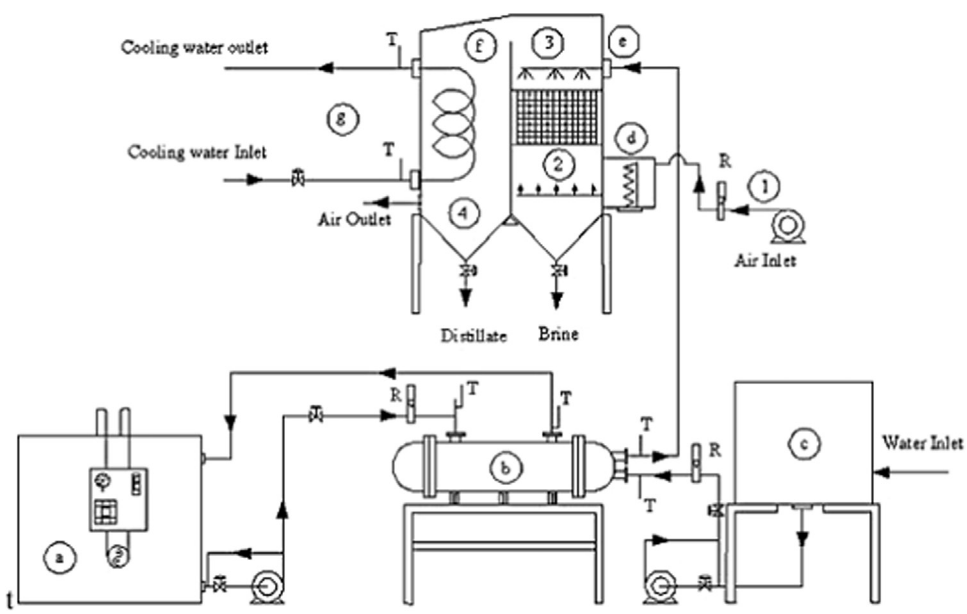

Fig. 4. HDH desalination system with a geothermal heat source [66]. (a) Geothermal heat source, (b) heat exchanger (c), water tank, (d) air preheater, (e) humidifier, (f) dehumidifier and (g) cooling water.

HDH system. The HDH system used in this study comprised of a modified solar still with an air blower at the inlet and a condenser at the outlet of the humidification chamber (Fig. 3).

The HDH system performance was inspected with and without reflector and water heaters. It was observed from experimental results that system productivity was significantly enhanced by the reflector and water heaters because these components improved the evaporation rate. The HDH system efficiency was found to increase with rise in solar radiation and the peak efficiency observed was 0.77. An economic analysis was used to estimate the cost of desalinated water produced from this HDH system. The specific cost of water production was obtained as USD 0.035 /L [64].

3.2. HDH systems powered by geothermal energy

Research has been carried out to check if geothermal energy can be used to power the HDH system. The use of geothermal energy to accomplish seawater desalination via HDH technology has been presented by Ghalavand et al. [65]. In this work, geothermal energy was used as the renewable energy source to heat up the seawater. Some investigated variables included the proportion of mass flow rate of seawater to that of air, difference in temperature of cooling water through the condenser, quantity of distillate produced, and temperature of geothermal heat source at heat exchanger inlet [66]. Experimental and theoretical analyses were carried out, and results obtained from a computer program were close to those obtained from the experimental study. It was observed that a ratio of 1.5–2.5 was the optimum ratio of the flow rate of seawater relative to that of air. However, an increase in the temperature of geothermal heat source and improvement of the difference in temperature of cooling water through the condenser would enhance the quantity of fresh water produced at this optimum ratio [66]. A facility used for experimental testing of seawater desalination using geothermal heat source is shown in Fig. 4. Heated water was fed to the humidifier top and brought in contact with air in the humidifier that was made up of packed bed [66].

4. Innovations in HDH design

Considerable amount of research work has been carried out to get the best design concepts for HDH desalination in order to maximize fresh water production, minimize energy consumption, and ensure economic scale-up of HDH systems. Recent innovations made in designing HDH desalination systems are analyzed in details in this section. The energy performance of thermal desalination processes is defined by Gained Output Ratio (GOR). GOR is fraction of latent heat of produced water to the thermal energy supplied to the process. GOR is the energy efficiency criterion of desalination systems which defines the level of heat recovery or thermal energy utilization [67]. In order to optimize the energy efficiency of HDH desalination, an exergy analysis of HDH desalination has been presented by Ashrafizadeh and Amidpour [68]. Factors affecting exergy losses were investigated using driving forces concept. A heat sink and source model was developed. It was observed that 80 – 90% of total loss is related to the heater section and no exergy losses occurred as a result of mass transfer across desalination systems. Meanwhile, exergy losses can be minimized and heat transfer rate across a HDH desalination system can be improved by using inserts and specialized packing materials in the system components. For instance, the effect of using three kinds of inserts in the air heater, spring insert in the dehumidifier and two kinds of packing materials in the humidifier on HDH desalination performance has been studied by Muthusamy and Srithar [69]. The inserts in the air heater were placed at different orientations, and the pitch ratio (PR) was varied in the air heater and in the dehumidifier to improve the heat transfer rate. The modified HDH system with the best performance involved short-length twisted tape inserts with PR 3 in the air heater, spring inserts with PR 3 in the dehumidifier, and gunny bag packing material in the humidifier. This modification increased the HDH productivity by 45% compared to a conventional system that has a productivity of 0.34 kg/h. A maximum distillate production rate of 11.223 kg/h m^2 was obtained. Furthermore, energy and exergy efficiencies of 44 and 38% were achieved, respectively due to better heat transfer rate. The sizes of the humidifier and dehumidifier also influence the heat transfer rate considerably. Sharqawy et al. has carried out a comparative study on air-heated and water-heated HDH cycles based on the sizes of HDH units, using thermodynamic mathematical modeling [70]. These sizes were found under various design conditions. A maximum GOR was obtained for each HDH cycle in accordance with the optimum mass flow rates. Additionally, the effectiveness of the humidifier and dehumidifier was improved by increasing their sizes, which resulted in higher GOR. Moreover, it was observed that GOR increased for the air-heated cycle and decreased for the water-heated cycle as the water temperature entering the humidifier increased. Although approximately identical GOR was obtained for the two configurations, it was observed that the air-heated cycle needed a smaller dehumidifier and a larger humidifier unlike the water-heated cycle. The air-heated cycle required more power for pumping air; whereas, the water-heated cycle required more power for pumping water. This comparison would help designers to make informed decision on the sizes of HDH components based on power needs and initial capital cost of these components [70].

4.1. Innovations in HDH to reduce the dehumidifier size

Dehumidifier or the condenser is one of the most important components in HDH system. To scale up the HDH desalination system, the size of dehumidifier would increase considerably. This can ultimately affect the whole design configuration and eventually, the cost of water production from the system. Recent innovations aimed at reducing the dehumidifier size include the use of direct contact HDH system in contrast to the conventional noncontact system and use of different types of carrier gases other than air.

4.1.1. Direct contact HDH process

Many challenges experienced with indirect contact condensers such as drop in hydraulic pressure, leakage of saline water, and pipe corrosion problems could be solved with direct contact HDH process [71]. Initial works had indicated that dehumidifier, rather than humidifier, has significant influence on the amount of fresh water produced. Early attention was directed towards the design and operation of dehumidifier in terms of sizing, material requirements, and operating conditions. An initial work had indicated that an improvement in dehumidifier design could help to enhance the productivity of HDH desalination system [72]. Countercurrent or co-current flows in packed beds or spray towers can be applied to ensure direct contact between humid air and cooling medium and allow greater thermal energy transfer without thermal resistance from the dehumidifier walls. Direct contact dehumidifier offered the advantage of minimum loss of humid air pressure as a result of high specific area of interface between the two streams that are directly in contact. Therefore, low heat transfer driving force and high heat transfer efficiency are the results of direct contact dehumidification [72]. Direct contact dehumidification is beneficial, most especially for small-scale water production from HDH desalination technology [73]. According to Dawoud et al. [74], this method is not complex; it is cheap and not prone to scaling; and it offers high rate of thermal energy transfer with low specific pressure drop.

Both humidification and dehumidification columns can be direct contact heat exchangers but the effect of direct contact dehumidification column on desalination performance is more prominent. The area of contact between air and water streams could be increased by using plastic rings in direct contact packed columns. Packed columns are direct contactors which are advantageous over indirect contact ones (stacked condensers and shell and tube exchangers). The use of packed beds increases the recovery of fresh water in the HDH process. Packed columns provide high area of heat transfer due to the high specific packing surface and ensure a decrease in heat transfer resistance. These benefits improve the recovery of energy which is expended in the humidifier and more efficient condensation in the dehumidification column [75]. In a direct contact humidification process, inlet air rather than inlet water is heated prior to entering the humidification column. This is because, in the conventional process, a rise in saline water temperature would increase the solubility of the different salts which can create operational difficulties [76]. Lowering the pressure drop in comparison with indirect heat exchangers leads to lower capital costs. However, some scales may still be formed around the packs which might add extra resistance to mass and heat transfer, specifically in the humidification column [77]. The main design features of a direct contact HDH process with three major segments: the heat source, humidifier and dehumidifier have been theoretically explained by Mehrgoo and Amidpour [10]. Two flow models for air circulation - natural and forced circulations - were considered to analyze and optimize the process. The parameters considered for this study were air flow rate, tube diameters ratio, and flow rate and temperature of both inlet saline water and fresh water, with the aim of increasing the water production rate. The genetic algorithm method and Lagrange multiplier methods were used for the optimization study. The study showed that the production rates are highly influenced by the temperatures of the heated water and cooling water. The columns' heat transfer areas and heat consumption decreased with an increase in inlet heated water temperature and increased considerably when the temperature of

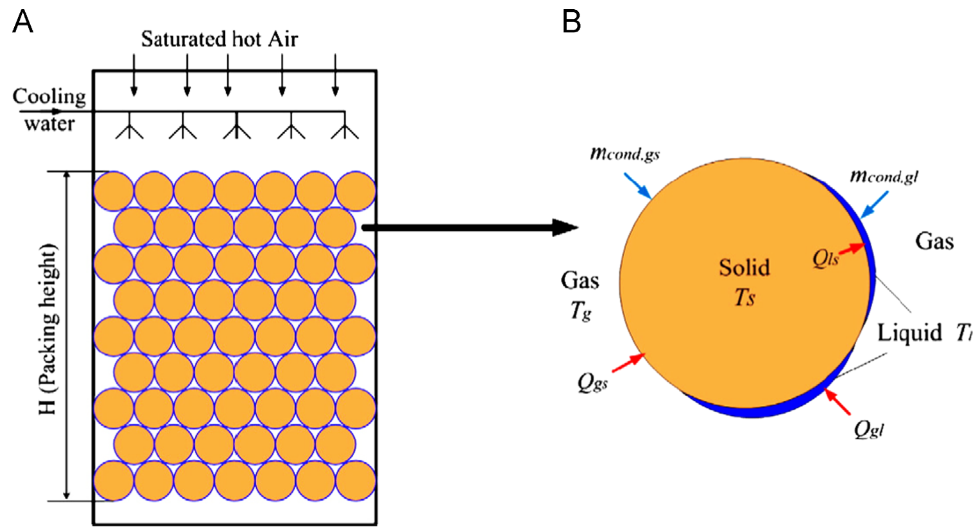

Fig. 5. Schematic of the PCM direct contact humidifier (a) packed bed and (b) schematic of one packing element showing mass and heat flow [78].

cooling water was increased. This approach was very promising because it was simple and based on physical and completely deterministic principles [10].

Eslamimanesh et al. [77] have also modeled a direct contact HDH desalination process theoretically. The process characteristics were modeled via a computer code using energy and mass balances where air was the carrier gas. The investigated modeling parameters included: temperatures of inlet air and recycled fresh water; flow rates of saline water, inlet air and recycled fresh water; and the ratio of flow rate of saline water to that of air. It was reported that the production of fresh water increased as the flow rates of recycled water and inlet air increased. Fresh water production was also enhanced by an increase in the temperature of air inlet to the humidifier or a decrease in the temperature of water inlet to the dehumidifier. In addition, improvements in fresh water production were observed when the recycle flow rates of saline water and fresh water in dehumidifier were increased. However, a decrease in system productivity was reported when the ratio of flow rates of water to air in the humidifier was increased. A direct contact dehumidifier consisting of packing medium made up of spherical phase change material (PCM) elements has also been shown to enhance the condensation rate in a dehumidifier (Fig. 5) [78]. This enhancement is as a result of the high heat capacity and melting temperature of the encapsulated PCM packing that is not too different from the lower limit of the range of the dehumidifier's operating temperature. A one-dimensional mass and heat transfer model was also created and optimized to explain the thermodynamic operation of the PCM elements and it was observed that agreement existed between the model and experimental data to a reasonable degree of accuracy. The system productivity was influenced by factors including the type, size and thermal properties of PCM packing; ratio of mass flow rate of air to water; and geometrical characteristics of dehumidifier. It was shown that small-sized inexpensive PCM packing with high heat conductivity would give the best results in terms of fresh water production.

The mass and heat transport across direct contact dehumidifier have also been modeled using countercurrent and co-current flow patterns in accordance with interpenetration continua approach with volume averaging method [79]. For this model, a HDH desalination plant with a direct contact condenser containing spherical PCM packing medium with co-current flow regime between cooling water and humid air was designed. The PCM packing was also compared with air capsules and it was observed that PCM packing resulted in- the production of more fresh water. For co-current flow pattern, water production rates were insignificantly affected by the processes involved in PCM melting. However, better mass and heat transport between water and air resulted from countercurrent flow when compared with co-current flow [79]. Another direct current HDH system whereby humid air was condensed through the spraying of cold water into a stream of the humid air has been developed by Niroomand et al. [71]. From this system, reduced productivity was obtained when the initial speed and diameter of sprayed droplets of water were increased. A decline in system productivity was also reported when the air flow rate was raised. However, fresh water production was enhanced from this system when the temperature and flow rate of cold water were reduced [71]. Similarly, Agboola and Egelioglu [80] investigated the impact of spray jets in a solar desalination unit with an absorption plate heater and observed that the use of two jets is more productive than the use of four or more jets. These authors also included a black wick on the thermal energy absorption plate and discovered that the system productivity was enhanced from 5.19 to 6.41 kg/m^2 through the addition of the wick in the summer season.

4.1.2. Carrier gases other than air

Carrier gases other than air have been evaluated in HDH desalination process in order to reduce the heat transfer resistance of the dehumidification stage [81]. A performance evaluation study has been carried out through modeling and simulation techniques, using carrier gases other than air [82]. The major parameters in this study were the coefficients of mass and heat transfer. The carrier gas properties and geometrical configuration of the HDH unit influenced these coefficients [82]. It was found that gases such as helium and hydrogen with lower molecular masses are preferred in order to ensure high rates of heat transfer whereas gases such as carbon dioxide with higher molecular masses are preferred in order to ensure high rates of mass transfer [81]. The highest fresh water production rate was obtained using carbon dioxide as the carrier gas under the same operating conditions. Additionally, using carbon dioxide as carrier gas for desalination helps to reduce the formation of calcium scale.

4.2. Innovations in HDH for minimizing energy utilization

This section summarizes the various HDH system modifications that have been investigated in order to decrease the amount of energy consumed.

4.2.1. Mechanical compression HDH

Various energy schemes have been evaluated for the HDH desalination process [83]. In the conventional HDH, a condenser is used as a dehumidifier to produce the fresh water. Recently, alternative schemes have been devised to promote energy efficiency such as the use of vapor compression, drying of desiccant air and membrane air for dehumidification purpose [83]. HDH process with vapor compression involves the compression of the humidified air to higher pressure to facilitate rise in air pressure and temperature [84]. Condensation of water vapor takes place when the compressed air is cooled by feed seawater. The necessity to compress a huge amount of air together with the water vapor, while using the mechanical vapor compression (MVC), is the main disadvantage of this approach as it dramatically influences the overall heat transfer coefficient. This might ultimately require higher power consumption larger than that required for the single-effect MVC or RO process, if it is not well managed [85].

Another energy-efficient design involves the use of a humidification desiccant absorption unit which incorporates either a solid desiccant (zeolite) or a liquid desiccant (lithium bromide solution) to remove fresh water from humid air [83]. The main benefits of this design are the high process efficiency and production of a huge amount of heat that can be utilized to preheat feed water [86]. However, the proposed design requires a large number of units compared with the conventional type; and the deficiency of practical experience in operation, design and maintenance of the desiccant absorption unit add to the shortcomings of this process. A membrane drying process that involves the passage of the compressed humidified air stream through a membrane unit has also been evaluated for enhanced dehumidification [83]. The membrane's selective properties lets the air humidity to permeate from the feed side to the permeate side. There are a number of industrial scale dehumidification membranes available for applications involving air drying. The compressed air is obtained from an air compressor driven by an electric motor. The major disadvantage of this process is the existence of a large amount of air in the air–water mixture, resulting in reduced process efficiency. As a result of this, larger sizes are required for the condensation or drying units. A novel exergy analysis of an evaporative air conditioning unit based on desiccant has also been carried out. The transport and destruction of exergy was investigated during experimentation and it was observed that the exergy efficiency of the system was 25 – 56% at 0 – 30 °C [87].

The decrease in HDH desalination system performance as a result of the uneven counter flow in a hollow fiber membrane module used for air humidification has been experimentally and theoretically studied by Li and Zhang [88]. The effect of three modules with different packing fractions on flow maldistribution was tested in this study. In addition, mass and heat transfer between water and air flow was analyzed. The humidification and sensible cooling efficiencies were also evaluated from the nonuniform velocities in the membrane module's fiber bundle. The experimental results indicated that flow maldistribution was significantly influenced by the packing fraction within the module, which then significantly decreased the humidification and sensible cooling efficiencies. Moreover, the humidification and sensible cooling efficiencies in the module were observed to decrease significantly with an increase in the nonuniformity of air flow. Nonuniformity in flow rate was found to decrease with higher packing density but at the cost of increased pressure drops within the module. Hence, a packing fraction of 0.3 was recommended [88]. A novel HDH desalination technology named "Humidification Compression" which is more advantageous in terms of providing high energy performance, high recovery rate, and so on when compared with the conventional HDH process, has also been developed recently as a mechanical compression HDH to solve the energy problems associated with conventional systems [65]. Another design involving a desalination unit operated by MVC pump that reclaimed most latent heat by sufficiently utilizing the heat from condenser has been proposed [89]. The unit comprised of three components: a solar collector, a HDH unit (humidifier, pre-condenser and evaporative condenser), and a heat pump (compressor, throttle, air condenser and evaporator). This study used the hydrokinetics method for the mathematical modeling of the desalination unit. The desalination unit produced 60 kg/d of freshwater with low electric power consumption of 500 W and has been validated to be an efficient desalination system for freshwater production, especially in remote area [89]. In traditional water-heated HDH, the thermal energy consumption is about 950 kJ/kg and the electrical energy consumption is about 5–18 kJ/kg with a GOR equivalent to 2. Whereas for a mechanical compression HDH, no thermal energy is consumed, the electrical energy consumption is about 160 kJ/kg, and a higher GOR value of 6 and above can be achieved [67]. Thus, mechanical compression HDH proved to be more energy-efficient when compared with traditional HDH.

Nada et al. proposed and carried out an experimental study on the performance of a hybrid HDH desalination and air conditioning system [90]. The system performance was tested by varying the following operating conditions: air inlet temperature, air flow rate, evaporator saturation temperature and specific humidity. The outcomes of varying these operating conditions on production rate of desalinated water, compressor work for every kilogram of desalinated water produced, mass transfer coefficient, refrigeration capacity, relative humidity of air and air temperature were observed in order to assess the system performance. Experimental results demonstrated an increase in desalinated water production rate, compressor work for every kilogram of desalinated water produced and refrigeration capacity with increasing mass flow rate and specific humidity of air. The relative humidity of air and supply air temperature were found to increase significantly with increasing desalinated water production rate [90].

4.2.2. Balancing the humidifier or the dehumidifier thermodynamically

The performance of HDH cycle can be enhanced by reducing the entropy generation of the system or by thermally balancing it. Some researchers have investigated the feasibility of thermodynamically balancing the humidifier and dehumidifier by the extraction of fluid from either water or air stream in one component, followed by its injection into the other [41]. The entropy generation when two streams are brought closer to each other can be reduced at a given location inside the unit by varying the rate of heat capacity of the streams [91]. Narayan et al. proposed the possibility of thermodynamically balancing the humidifier or the dehumidifier by using mass extraction and injection for minimizing the systems' energy consumption [92]. Investigation was conducted for discrete or continuous mass extraction and injection of air from humidifier to dehumidifier and vice versa. The system was modeled based on design component variables. Additionally, extraction profile was developed for 100% effective HDH for achieving thermodynamic reversibility in HDH system. A new parameter, known as modified heat capacity rate ratio (HCR), was also introduced for designing a HDH that is thermally balanced. When the value of HCR is 1, a thermodynamically-balanced position for a simultaneous mass and heat exchange component is represented. The impact of air or water extraction from one unit in a HDH system and its injection into the other to obtain a thermally-balanced HDH system with reduction in entropy generation has also been studied by other authors [93–95]. Chehayeb et al. [96] implemented mass and heat transfer models of a two-stage fixed-size HDH desalination system comprising of a packed-bed humidifier, a multi-tray bubble column dehumidifier and

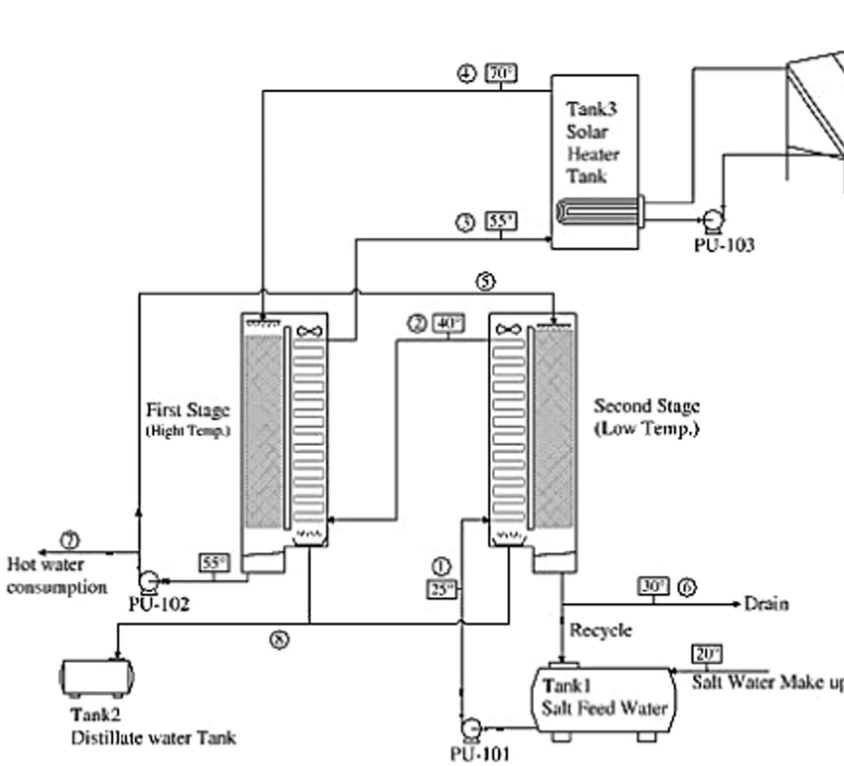

Fig. 6. Multi-stage HDH system with 2 stages [102].

a single stage air injection/extraction [96]. The influence of varying the mass flow rate ratio on the system performance, entropy generation, and mass and heat transfer driving forces was studied by modeling using MATLAB. Also, the impact on system performance of allocating available area amongst separate stages was observed. The study concluded that balancing a HDH system thermodynamically allows maximum water recovery and energy efficiency but minimum entropy generation per unit of produced desalinated water. This allows optimal use of the surface area available in mass and heat exchangers. Moreover, the effect of thermodynamically balancing the HDH system is greater on energy efficiency compared to water recovery. Furthermore, air or water should at all times be extracted from the humidifier to the dehumidifier so as to ensure an effective thermodynamically-balanced HDH system. The extraction location is an important criteria in order to obtain a thermodynamically-balance system because complete balancing is difficult to obtain in all locations. Therefore, HDH system performance can be enhanced by equal distribution of heat duty over the available surface area in mass and heat exchangers [96].

4.2.3. HDH with common heat transfer wall

In HDH desalination system with common heat transfer wall, moist air in the dehumidifier condenses on a common wall and releases heat, which passes through the common wall to the evaporator. Studies have been done on dewvaporation, which is an alternative to HDH desalination and this process couples the two main components into a single unit by partitioning them with a thin wall [67]. It has been observed that the common wall would enhance the net performance and GOR of the system by improving the heat recovery between the humidifier and the dehumidifier [67]. In the evaporation section, air comes in contact with the warm feed water film, which is formed by spraying water on the side of the common heat transfer wall. Water vaporizes into the air from the film more efficiently due to transmission of heat through the thin common wall from the condenser to the evaporator side. The warm humid air from the evaporator is injected with steam for further heating and humidification before it is sent to the condenser. As a result of the lower temperature on the evaporator side, hot humid air in the condenser side losses heat and condenses on the common wall's surface due to the net heat transfer from the condenser to the evaporator side [67].

The theoretical values obtained for GOR are as high as 9.5 for seawater and 16.8 for brackish water for this innovation. These values indicate the possibility of this system to compete with large-scale thermal desalination technologies like MED and MSF on the basis of energy consumption [97,98]. This type of HDH system has been investigated experimentally and economic analysis of the system has also been carried out [98]. The system has shown the best salt rejection obtained from HDH seawater desalination.

4.2.4. Multi stage air heated HDH

A novel scheme of HDH where air is heated in multiple stages has been studied to maximize the ratio of humidity at the humidifier exit [99]. In this system, a solar collector is used to heat the air, which is then sent to the humidifier for saturation. The humid air is heated and humidified further, repeating this process in stages of four or five. The advantage of this system is that water production can be increased by increasing the exit humidity of the air. The exit humidity increased from 4.5 to 9.3 wt% for a single-stage and a four stage system, respectively. Nevertheless, the GOR of the cycle can be increased only by 9% regardless of the increase in the humidity, from a thermodynamic perspective [8]. The multi-stage system can be designed to allow both series and parallel water flow [99]. Another innovative design is a two-stage multi-effect HDH desalination system, which does not only recycle the latent heat of condensation but is successful in recycling the residual heat in the brine [100]. A mathematical model using energy and mass balances has been developed for this design. It was observed from experimental results that the production rate of fresh water can reach up to 72.6 kg/h and the GOR of value 2.44

can be achieved from the two-stage multi-effect HDH, as latent heat and the residual heat in the brine are recycled.

A two-stage multi-effect HDH system where a solar evacuated tube collector is employed has also been designed by Hou [101]. Using pinch technology, two different temperature ranges were plotted and tested. The higher temperature and the lower temperature ranges tested were 60 – 80 °C and 30 – 60 °C, respectively. Based on the pinch chart, the rate of energy recovery can increase depending on the working temperature range. The two-stage solar multi-effect HDH desalination system has a greater rate of energy recovery than the one stage process and thus higher GOR [101]. Zamen et al. experimentally analyzed a two-stage technique for HDH process to enhance production of desalinated water from brackish water [102]. A schematic of the two-stage system is shown in Fig. 6. Two-stage process with a solar collector area of 80 m^2 was chosen for HDH pilot plant and it was found to be the optimum choice based on estimation of construction costs. The mathematical modeling of the process was also carried out and it was demonstrated that maximum enhancement occurred for the two-stage process based on process parameters: desalinated water production rate/area of solar collector and specific energy consumption. Improvements in process parameters were negligible when the number of stages was greater than two. The pilot plant was tested on hot and cold days, and the experimental results showed that the total water production in summer was twice more than that produced in winter. Additionally, it was observed that the two-stage process can minimize HDH system's specific thermal energy consumption and thus, reduce the unit's initial investment cost. Moreover, productivity of desalinated water can be enhanced up to 20% in the two-stage unit relative to the single-stage unit based on feed saline water flow rate [102].

The integration of multi-stage HDH with a cooling plant has also been carried out to maximize energy utilization factor (EUF) for the plant and process cycle based on thermodynamic study. Chiranjeevi and Srinivas [103] studied the thermodynamic simulation and analysis of a two-stage solar HDH desalination plant integrated with a cooling plant. Solar flat plate collector was chosen for the HDH desalination unit and concentrating collector was selected for the single-effect vapor absorption refrigeration (VAR) plant. The effect of the controlling parameters: humidifier effectiveness and efficiency, chilled water temperature and hot water temperature on the performance of the proposed integrated system was investigated. It was observed that large values of humidifier effectiveness and efficiency, exit temperature of VAR evaporator and hot water temperature increased the EUF. As a result of the cooling plant integration, the distillate/fresh water production rate was enhanced from 270 liter per hour (LPH) to 400 LPH per unit volume of air, where a total distillate production of 670 LPH was obtained from the integrated plant. The final EUF was 0.33 for plant and 0.58 for cycle [103].

4.3. HDH for larger scale systems

Instead of scaling up a HDH system as a stand-alone desalination plant, HDH can be coupled up with other well-established large-scale desalination technologies like RO (reverse osmosis) or SSF (single stage flashing), to increase the energy efficiency. Some research works which have been carried out to couple HDH with established desalination technologies and ensure large scale production of water are discussed in this section. Besides conducting an experimental study on the performance of a HDH water desalination unit integrated with an air conditioning system, Nada et al. analyzed the performance of different configurations of the proposed hybrid system based on their fresh water productivity and energy savings in hot arid regions [104]. Four HDH systems with different configurations comprising of heat recovery units and evaporative cooler were placed in different locations in addition to two other systems that were used as reference. An example of such configurations with an evaporative cooler is shown in Fig. 7. All the configurations were investigated and evaluated by varying the following operating conditions: temperature of space supply air, fresh air ratio and wet bulb temperature of outside air. The systems were

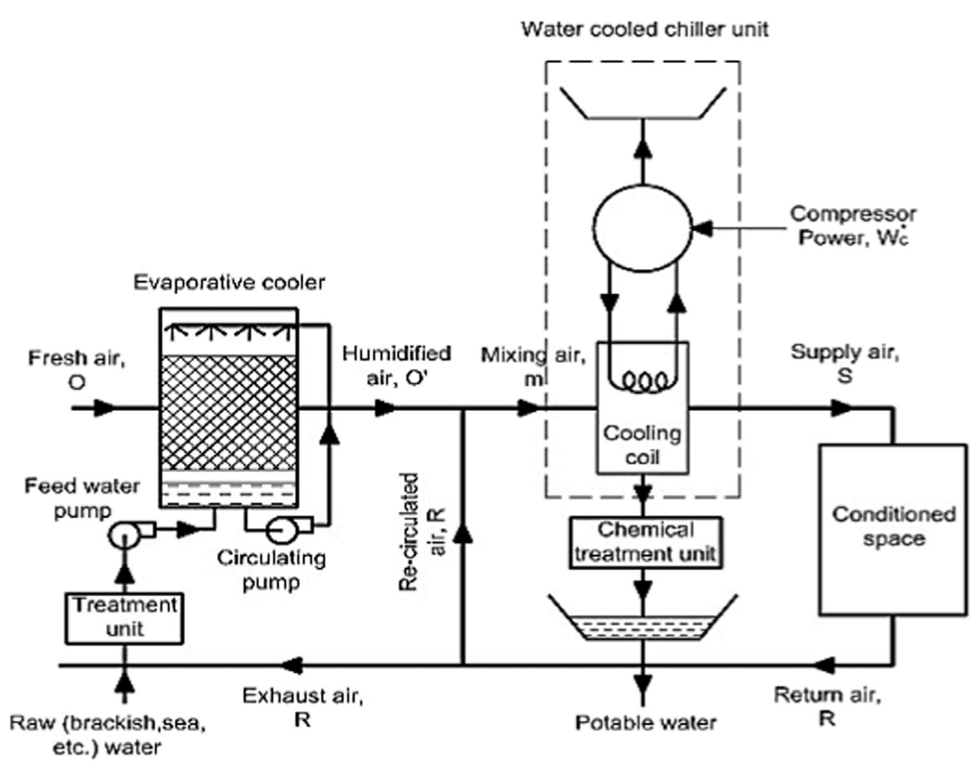

Fig. 7. HDH desalination integrated with air conditioning system [104].

compared and evaluated based on the following parameters: production rate of fresh water, refrigeration capacity, electrical power consumption of the compressor, total cost saving and power consumption savings. Generally, it was observed that the production rate of fresh water increased with increasing space supply air temperature, fresh air ratio and outside air wet bulb temperature. Power savings of all the system configurations increased effectively with: increasing supply air temperature, rising air supply ratio up to 0.7 after which the change is negligible, and decreasing outside air wet bulb temperature. For all the system configurations, the total cost saving increased with rising space supply air temperature, increasing fresh air ratio and decreasing outside air wet bulb temperature. In addition, numerical correlations for water production rate and total system energy utilization were developed based on the system input parameters [104].

HDH desalination system can also be integrated with a thermoelectric cooler for performance improvement. This type of integrated system has been experimentally investigated by Yıldırım et al. [105]. The performance of the pilot plant with open air/open water cycle was tested at various operating conditions in order to investigate the relation between thermoelectric and psychrometric phenomena. The influence of air flow velocity and feed water mass flow rate on the fresh water production rate and thermoelectric cooler unit's coefficient of performance (COP) value was studied. The maximum fresh water production rate obtained was 143.6 g/d and the highest thermoelectric cooler's COP value observed was 0.78. From this study, this possibility of integrating thermoelectric cooler with portable HDH desalination systems was ascertained. Varying the mass flow rate of water within a given range did not affect the daily water production. However, reduction in daily water production was observed as the air flow velocity was decreased. The COP value of the thermoelectric cooler increased with decreasing mass flow rate of feed water; but water production was found to be independent of COP value of the thermoelectric cooler. Additionally, low temperature of inlet water to the humidifier resulted in low production of fresh water. Therefore, it is important to incorporate heating equipment to the HDH system to enhance its performance. Moreover, the small condensation surface area of the dehumidifier may result in reduced productivity. However, increasing the surface area for condensation is a challenge for a portable system as this will increase the size and weight of the dehumidifier [105]. HDH and RO systems have also been combined using high-pressure steam as energy, in order to increase energy efficiency. It was reported by Narayan et al. [106] that the RO-HDH system had a GOR of 20 and its performance is similar to that of thermal desalination systems and considerably higher than that of conventional HDH desalination systems. Fig. 8 shows the process schematic of a HDH system coupled with RO. Using a steam supply, the humidified carrier gas at the exit of the humidification chamber is compressed with a thermal vapor compressor (TVC) and then condensed in the dehumidifier. Energy is recovered as work by expanding the dehumidified carrier gas. The recovered energy is then used to operate a RO unit for desalinating brine obtained from the humidifier [67].

A hybrid HDH-SSF (single stage flashing) system has also been demonstrated [12,35]. This system is dependent on the processes of air-heated HDH and water flashing evaporation. A solar HDH unit and SSF evaporation unit have been coupled in a HDH-SSF plant. Solar collector was used to heat air and feed water [35,36]. Economic analysis was conducted on the separated and hybrid modes to investigate the feasibility and economic benefits of the two modes [107]. The concept of total cost of ownership was adopted for the economic analysis and it was shown that the hybrid mode was better in terms of water production and process economics. An economic study of HDH pilot plant to evaluate the economic advantages of the process as compared to a standalone RO system for small-scale water production have also been carried out by [108]. Initial investment and operating costs, internal return rate on

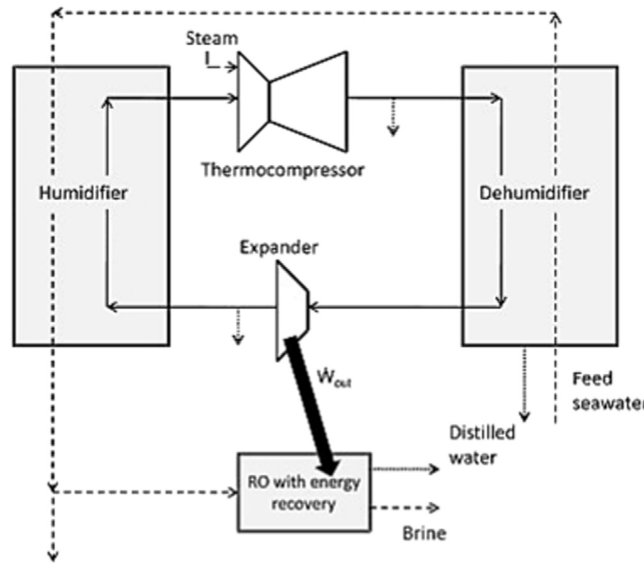

Fig. 8. HDH using thermal vapor compression hybridized with RO [106].

investment, total production cost and other economic indices were obtained using COMFAR III software. It was suggested that HDH process is a cheap and non-complex technology which can be used in the absence of membranes. However, RO was considered as suitable for domestic applications because of the lower environmental footprint of RO for large-scale production. In addition, it was observed that properties of fresh water such as TDS can be selected in accordance with the membrane in RO but the HDH process may need more precise control [108]. Therefore, HDH could be hybridized with RO in order to integrate the comparative advantages of both desalination technologies for large-scale applications. HDH system has also been hybridized with thermal energy recovered from the back plate of a PV panel for seawater desalination and electrical power production [13]. This thermal energy could have, otherwise, resulted in the reduction of the electrical efficiency of the PV panel if it is recovered for desalination. Also, HDH has been used for produced water treatment [109]. Several advances aimed at improving the quality of treated effluents from wastewater treatment units have been reported in recent times [110–113]. The integration of HDH with wastewater treatment to serve the dual purpose of desalination and water reuse would further add to the comparative benefits of HDH technology in terms of energy efficiency and cost competitiveness.

5. Productivity of HDH systems

Several research works on HDH systems have reported widely varying values of productivity. It is observed that the diverse product water yields, as reported by different authors, have been hugely affected by the configuration, schemes, properties of streams and carrier medium used in the HDH designs [114–118]. The flow rates of water and/or air have contributed massively to the differences in the reported performances of the HDH technology (Table 1). In order to clearly distinguish between the methods and innovations employed by some of the studies examined in this review, the different levels of productivity from recent studies have been presented in Table 1. This comparison will afford researchers and investors an opportunity to improve what has been done in the past or examine those designs with high potential for commercialization and economic viability.

Table 1
Different reported productivity values of HDH desalination systems.

Refs.	Maximum productivity	Operating conditions
Li et al. [119]	1000 L/d	Air flow rate = 140 m^3/h
Ben Halima and Gabssi [120]	2 kg/h	Air flow rate = 8 kg/h; Initial hot water temperature = 70 °C; Hot water level = 10 cm; Inlet air temperature = 26–31 °C.
El-Shazly et al. [121]	2 L/h	Water flow rate = 15 L/min; Air flow rate = 3.2 m^3/h.
Chang et al. [122]	63.6 kg/h	Water flow rate = 1000 kg/h; Air flow rate = 3.9 m/s; Water temperature in constant temperature water tank = 85 °C; Feed seawater flow rate = 1000 kg/h.
Kabeel and El-Said [35]	32.56 kg/d	Water flow rate = 4.5 kg/s; Air flow rate = 0.12 – 0.32 kg/s.
Yıldırım and Solmuş [28]	12 tons/y	Water flow rate = 0.01 kg/s; Air flow rate = 0.01 kg/s.
Mahmoud et al. [33]	60 L/m^2 h	Water flow rate = 27 L/h m^3
Ben Bacha [123]	20 kg/d	Water flow rate = 0.04 kg/s; Air flow rate = 0.01 kg/s.
Ashrafizadeh and Amidpour [68]	0.0059 kg/s	Water flow rate = 0.1607 kg/s; Air flow rate = 0.0959 kg/s
El-Agouz [124]	8.22 kg/h	Air flow rate = 14 kg/h; Operation time = 1.5 h; Seawater temperature in evaporator = 86 °C.
Wang et al. [56]	0.873 kg/m^2 d	Water flow rate = 1000 m^2/d
Hermosillo et al. [32]	1.45 kg/h	Water flow rate = 0.012–0.023 kg/s; Air flow rate = 0.004–0.0043 kg/s, Inlet seawater temperature of the condenser = 27.9 °C, Brine flow rate = 0.012 kg/s, Ambient temperature = 30.5 °C.
Farsad and Behzadmehr [42]	27 kg/h	Water flow rate = 0.4–1.4 kg/s, Air flow rate = 0.4–1.2 kg/s.
Amer et al. [22]	5.8 L/h	Wooden slates packing; Forced air circulation; Water mass flow rate = 2.8 kg/min; Water temperature at humidifier inlet = 85 °C.
Zhani and Ben Bacha [26]	21.75 kg/d	Solar radiation = 693 W/m^2; Ambient temperature = 32.75 °C; Air flow rate = 0.01 kg/s; Water flow rate = 0.04 kg/s; Inlet air temperature of air solar collector = 43.88 °C; Inlet water temperature of water solar collector = 37.54 °C; Inlet air temperature of the humidifier = 53.6 °C; Inlet water temperature of the humidifier = 44.69 °C; Inlet air temperature of the evaporation tower = 31.98 °C; Inlet air temperature of the condensation tower = 32.41 °C; Inlet water temperature of the condensation tower = 29 °C.
Muthusamy et al. [30]	0.82 kg/h	Air flow rate = 21 kg/h; Angle of orientation of the inserts = 180°; Pitch ratio = 3.
Kabeel et al. [39]	23.6 kg/h	Inlet water flow rate to the humidifier = 4 kg/min; Forced down air circulation; Inlet water temperature at humidifier = 90 °C; Equilateral triangle shaped cellulose paper packing of side length of 5 mm.
Kabeel and El-Said [36]	41.8 kg/d	Feed water flow rate of HDH = 1 kg/s; Air flow rate = 0.03 kg/s; Feed water flow rate of SSF = 0.085 kg/s; Cooling water flow rate of HDH = 0.1 kg/s; Cooling water flow rate of SSF = 0.045 kg/s; Cooling water inlet temperature of HDH and SSF = 20 °C; Brine pool height inside flashing chamber of SSF unit = 10 cm; Vacuum pressure inside flashing chamber of SSF unit = 0.04–0.07 bar; Supply water salinity = 3000 ppm.
Wang et al. [56]	0.873 kg/m^2 d	Air velocity = 5.9 m/s; Forced convection; Evaporative brackish water temperature = 64.3 °C; Performance time = 8 h; Photovoltaic panel area = 9.16 m^2.
Ghazal et al. [60]	0.75 kg/m^2 h	Average solar radiation intensity = 700 W/m^2; Air flow rate = 12.6 kg/h.
Yuan et al. [59]	1200 L/d	Average solar radiation intensity = 550 W/m^2; Solar air heater field = 100 m^2; Solar water collector area = 12 m^2.
Yuan and Zhang [58]	38 kg/d	Solar collector area = 10 m^2 ; Seawater flow rate = 200 kg/h; Cooling water flow rate = 200 kg/h.
Ghalavand et al. [65]	151 kg/h	Feed seawater flow rate = 1000 kg/h; Air flow rate = 450 kg/h; Inlet water temperature = 25 °C; Condenser temperature = 35 °C.
Gao et al. [89]	5.15 L/d	Air flow rate = 200 kg/h; Cooling seawater flow rate = 350 kg/h; Cooling inlet seawater temperature = 18 °C; Solar insolation density = 750 W/m^2.
Nada et al. [90]	4.74 kg/h	Inlet air temperature = 25 °C; Air outlet temperature = 22.71 °C.
Kang et al. [100]	72.6 kg/h	Ambient temperature = 16 °C; Saline water temperature in lower temperature condensation tower = 15 °C; Water flow rate in lower temperature condensation tower = 1000 kg/h.
Zamen et al. [102]	580 L/d	Solar collectors area = 80 m^2; TDS of salty feed water was greater than 4500 ppm.
Chiranjeevi and Srinivas [103]	670 L/h	Air flow rate = 1 m^3/s; Evaporator temperature = 6 °C; Maximum solar radiation delivered to solar concentrating collectors = 1000 kW; Heat output from solar concentrating collectors = 150 kW; Hot water flow rate from solar water heater 31,500 L/h; Thermic fluid flow rate from solar concentrating collector = 12,300 L/h; Chilled water flow rate from evaporator = 12,300 L/h; Solar concentrating collector area = 350 m^2; Flat plate collector area = 1050 m^2; Total area of collectors = 1400 m^2.
Orfi et al. [115]	27.8 L/m^2 d	Open system; Air flow rate = 0.05 kg/s; Ambient temperature = 33 °C; Seawater temperature = 27 °C; Wind velocity = 2.9 m/s; Solar intensity = 930 W/m^2; Sea water flow rate = 0.08 kg/s; Air collector surface area = 2 m^2; Water collector surface area = 2 m^2; Condenser surface area = 40 m^2; Evaporator surface area = 40 m^2.
Gang et al. [125]	22 kg/m^3 h	Heating temperature = 85 °C; Feed water rate = 2 t/h.

6. Concluding remarks

Various types and design improvements of HDH desalination system have been reviewed in details in this paper. It is found that the HDH desalination process is a promising technique for producing fresh water to meet localized water demand. The overall thermal energy needed to operate the HDH system can be obtained from renewable sources like solar and geothermal energy, as it is a low temperature process. However, most of the HDH systems in current and previous studies have been powered by solar energy. HDH is notable for its simple operation and low maintenance requirements.

As an alternative to the scale-up of HDH systems in stand-alone desalination plants, HDH can be developed for multistage operations or combined with other well-known high-throughput desalination technologies such as RO or SSF to ensure energy efficiency. HDH, when coupled with RO, gives a larger GOR and can be implemented on a large scale. HDH can also be coupled with other desalination technologies that use low-grade heat such as membrane distillation for improved overall thermal efficiency. The use of nanotechnology is rapidly developing and nanoparticles would play a key role in future desalination [126,127]. The use of nanomaterials in solar collection heating fluid has been tested [35,36,128]. The development of this area would open new opportunities for the enhancement of the thermal energy efficiency of solar heaters. In addition, the application of HDH for produced water and wastewater treatment can ensure the realization of water reuse and desalination [109,129]. However, more research and development activities should be directed towards the application of HDH technology for both saline and wastewater treatment because of its associated sustainable benefits. Some studies, which have already been carried out to integrate HDH with well-developed desalination technologies, have obtained high productivity of pure water.

The HDH might be a cost-effective and simple technology for future desalination needs. Mechanical compression-driven HDH is expected to have a greater potential due to low capital cost. However, thermodynamic balancing and other approaches should be adopted in order to minimize the cost of energy. The niche for such a system could be renewable energy-based, small-scale, decentralized water production. One of most desirable characteristics of HDH systems is that the feed water does not need to undergo special pretreatment unlike established thermal desalination systems. The HDH system driven by thermal vapor compression is also a promising technique that can be made economically feasible for large-scale applications in the future if a suitable and cost-effective method can be determined for producing medium pressure steam. As HDH desalination system is a tripartite configuration consisting of the heat source, humidifier, and dehumidifier, better results in terms of water productivity and energy efficiency can be further obtained when the design of each of these different units is optimized. Design optimization achievable through the advancement of the sizing/operation of the three major HDH components is perhaps a critical step in the commercialization of HDH desalination technology [55].

Research in improving the HDH desalination technology is still advancing. With the potential of HDH to use renewable energy instead of fossil fuel-power, it is likely that HDH might be the clean desalination technology of the future.

Acknowledgment

The authors would like to thank Masdar Institute of Science and Technology, Abu Dhabi, United Arab Emirates, for providing the platform where previous and current research on HDH systems and recent innovations in HDH design were obtained.

References

[1] Fath HES, Ghazy A. Solar desalination using humidification—dehumidification technology. Desalination 2002;142:119–33. http://dx.doi.org/10.1016/S0011-9164(01)00431-3.
[2] Ettouney RS, Fawzi NA, El-Rifai MA, Ettouney HM. Flue gas desulfurization and humidification dehumidification in power plants. Desalin Water Treat 2012;37:337–49. http://dx.doi.org/10.1080/19443994.2012.661290.
[3] Fath HES, El-Shall FM, Vogt G, Seibert U. A stand alone complex for the production of water, food, electrical power and salts for the sustainable development of small communities in remote areas. Desalination 2005;183:13–22. http://dx.doi.org/10.1016/j.desal.2005.03.028.
[4] Fath HES, Elsherbiny SM, Hassan AA, Rommel M, Wieghaus M, Koschikowski J, et al. PV and thermally driven small-scale, stand-alone solar desalination systems with very low maintenance needs. Desalination 2008;225:58–69. http://dx.doi.org/10.1016/j.desal.2006.11.029.
[5] Fath HES, Elsherbiny S, Ghazy A. A naturally circulated humidifying/dehumidifying solar still with a built-in passive condenser. Desalination 2004;169:129–49. http://dx.doi.org/10.1016/j.desal.2004.08.014.
[6] Giwa A. Salty groundwater treatment: Recovery of magnetic nano-particles. Int. Conf. Hydrol. Groundw. expo, Raleigh, North Carolina, USA: 2013.
[7] Narayan GP, Sharqawy MH, Summers EK, Lienhard JH, Zubair SM, Antar MA. The potential of solar-driven humidification-dehumidification desalination for small-scale decentralized water production. Renew Sustain Energy Rev 2010;14:1187–201. http://dx.doi.org/10.1016/j.rser.2009.11.014.
[8] Narayan GP, Sharqawy MH, JHL V, Zubair SM, Thermodynamic analysis of humidification dehumidification desalination cycles, Desalin Water Treat 16, (April 2010), 339–353, http://dx.doi.org/10.5004/dwt.2010.1078.
[9] Bourouni K, Chaibi MT, Tadrist L. Water desalination by humidification and dehumidification of air: State of the art. Desalination 2001;137:167–76. http://dx.doi.org/10.1016/S0011-9164(01)00215-6.
[10] Mehrgoo M, Amidpour M. Constructal design and optimization of a direct contact humidification-dehumidification desalination unit. Desalination 2012;293:69–77. http://dx.doi.org/10.1016/j.desal.2012.02.025.
[11] Hamed MH, Kabeel AE, Omara ZM, Sharshir SW. Mathematical and experimental investigation of a solar humidification–dehumidification desalination unit. Desalination 2015;358:9–17. http://dx.doi.org/10.1016/j.desal.2014.12.005.
[12] Kabeel AE, Hamed MH, Omara ZM, Sharshir SW. Water desalination using a humidification-dehumidification technique — A detailed review. Nat Resour 2013;04:286–305. http://dx.doi.org/10.4236/nr.2013.43036.
[13] Giwa A, Fath H, Hasan SW. Humidification–dehumidification desalination process driven by photovoltaic thermal energy recovery (PV-HDH) for small-scale sustainable water and power production. Desalination 2016;377:163–71. http://dx.doi.org/10.1016/j.desal.2015.09.018.
[14] Kassim MA, Benhamou B, Harmand S. Effect of air humidity at the entrance on heat and mass transfers in a humidifier intended for a desalination system. Appl Therm Eng 2011;31:1906–14. http://dx.doi.org/10.1016/j.applthermaleng.2011.01.047.
[15] Treybal RE. Mass Transfer Operations. NewYork, USA: McGraw-Hill; 1980.
[16] Zhang L, Chen W, Zhang H. Study on variation laws of parameters in air bubbling humidification process. Desalin Water Treat 2013.
[17] Saidi S, Ben Radhia R, Dhifaoui B, Ben Jabrallah S. Experimental study of the inclined solar film evaporator. Desalin Water Treat 2014:1–8. http://dx.doi.org/10.1080/19443994.2014.981415.
[18] Müller-Holst H, Engelhardt M, Herve M, Schölkopf W. Solarthermal seawater desalination systems for decentralised use. Renew Energy 1998;14:311–8. http://dx.doi.org/10.1016/S0960-1481(98)00083-4.
[19] Sievers M, Lienhard JH. Design of flat-plate dehumidifiers for humidification–dehumidification desalination systems. Heat Transf Eng 2013;34:543–61. http://dx.doi.org/10.1080/01457632.2013.730355.
[20] El-Agouz SA, Abugderah M. Experimental analysis of humidification process by air passing through seawater. Energy Convers Manag 2008;49:3698–703. http://dx.doi.org/10.1016/j.enconman.2008.06.033.
[21] Sievers M, JHL V. Design of plate-fin tube dehumidifiers for humidification–dehumidification desalination systems. Heat Transf Eng 2015:36. http://dx.doi.org/10.1080/01457632.2014.916153.
[22] Amer EH, Kotb H, Mostafa GH, El-Ghalban AR. Theoretical and experimental investigation of humidification-dehumidification desalination unit. Desalination 2009;249:949–59. http://dx.doi.org/10.1016/j.desal.2009.06.063.
[23] Yamali C, Solmus I. A solar desalination system using humidification-dehumidification process: experimental study and comparison with the theoretical results. Desalination 2008;220:538–51. http://dx.doi.org/10.1016/j.desal.2007.01.054.
[24] Tow EW, Lienhard JH. Experiments and modeling of bubble column dehumidifier performance. Int J Therm Sci 2014;80:65–75. http://dx.doi.org/10.1016/j.ijthermalsci.2014.01.018.
[25] Zhani K, Ben Bacha H, Damak T. Modeling and experimental validation of a humidification–dehumidification desalination unit solar part. Energy 2011;36:3159–69. http://dx.doi.org/10.1016/j.energy.2011.03.005.
[26] Zhani K, Ben Bacha H. Experimental investigation of a new solar desalination prototype using the humidification dehumidification principle. Renew Energy 2010;35:2610–7. http://dx.doi.org/10.1016/j.renene.2010.03.033.
[27] Abdel Dayem AM. Efficient solar desalination system using humidification/dehumidification process. J Sol Energy Eng 2014;136:041014. http://dx.doi.org/10.1115/1.4027725.
[28] Yıldırım C, Solmuş İ. A parametric study on a humidification–dehumidification (HDH) desalination unit powered by solar air and water heaters. Energy Convers Manag 2014;86:568–75. http://dx.doi.org/10.1016/j.enconman.2014.06.016.
[29] Ho CD, Yeh HM, Wang RC. Heat-transfer enhancement in double-pass flat-plate solar air heaters with recycle. Energy 2005;30:2796–817. http://dx.doi.org/10.1016/j.energy.2005.01.006.
[30] Muthusamy C, Gowtham M, Manickam S, Manjunathan M, Srithar K. Enhancement of productivity of humidification–dehumidification desalination using modified air heater. Desalin Water Treat 2014.
[31] Summers EK, Antar MA, Lienhard JH. Design and optimization of an air heating solar collector with integrated phase change material energy storage for use in humidification–dehumidification desalination. Sol Energy 2012;86:3417–29. http://dx.doi.org/10.1016/j.solener.2012.07.017.
[32] Hermosillo J-J, Arancibia-Bulnes CA, Estrada CA. Water desalination by air humidification: Mathematical model and experimental study. Sol Energy 2012;86:1070–6. http://dx.doi.org/10.1016/j.solener.2011.09.016.
[33] Mahmoud MS, Farrag TE, Mohamed WA. Experimental and theoretical model for water desalination by humidification – dehumidification (HDH). Procedia Environ Sci 2013;17:503–12. http://dx.doi.org/10.1016/j.proenv.2013.02.065.
[34] Fath HES. Thermal performance of a simple design solar air heater with built-in thermal energy storage system. Energy Convers Manag 1995;36:989–97. http://dx.doi.org/10.1016/0196-8904(94)00069-C.
[35] Kabeel AE, El-Said EMS. A hybrid solar desalination system of air humidification-dehumidification and water flashing evaporation. Part I. A numerical investigation. Desalination 2013;320:56–72. http://dx.doi.org/10.1016/j.desal.2013.04.016.
[36] Kabeel AE, El-Said EMS. A hybrid solar desalination system of air humidification, dehumidification and water flashing evaporation: part II. Experimental investigation. Desalination 2014;341:50–60. http://dx.doi.org/10.1016/j.desal.2014.02.035.
[37] Moumouh J, Tahiri M, Salouhi M. Solar thermal energy combined with humidification–dehumidification process for desalination brackish water: technical review. Int J Hydrog Energy 2014;39:15232–7. http://dx.doi.org/10.1016/j.ijhydene.2014.04.216.

[38] Nematollahi F, Rahimi A, Gheinani TT. Experimental and theoretical energy and exergy analysis for a solar desalination system. Desalination 2013;317:23–31. http://dx.doi.org/10.1016/j.desal.2013.02.021.
[39] Kabeel AE, Hamed MH, Omara ZM, Sharshir SW. Experimental study of a humidification-dehumidification solar technique by natural and forced air circulation. Energy 2014;68:218–28. http://dx.doi.org/10.1016/j.energy.2014.02.094.
[40] Al-Enezi G, Ettouney H, Fawzy N. Low temperature humidification dehumidification desalination process. Energy Convers Manag 2006;47:470–84. http://dx.doi.org/10.1016/j.enconman.2005.04.010.
[41] Narayan GP, Lienhard VJH, Zubair SM. Entropy generation minimization of combined heat and mass transfer devices. Int J Therm Sci 2010;49:2057–66. http://dx.doi.org/10.1016/j.ijthermalsci.2010.04.024.
[42] Farsad S, Behzadmehr A. Analysis of a solar desalination unit with humidification-dehumidification cycle using DoE method. Desalination 2011;278:70–6. http://dx.doi.org/10.1016/j.desal.2011.05.008.
[43] Narayan GP, Sharqawy MH, Lienhard VJH, Zubair SM. Thermodynamic analysis of humidification dehumidification desalination cycles. Desalin Water Treat 2010;16:339–53. http://dx.doi.org/10.5004/dwt.2010.1078.
[44] Mezher T, Fath H, Abbas Z, Khaled A. Techno-economic assessment and environmental impacts of desalination technologies. Desalination 2011;266:263–73. http://dx.doi.org/10.1016/j.desal.2010.08.035.
[45] Mabrouk A-NA, Nafey AS, Fath HES. Steam, electricity and water costs evaluation of power desalination co-generation plants. Desalin Water Treat 2012;22:56–64. http://dx.doi.org/10.5004/dwt.2010.1537.
[46] Abusharkh A, Giwa A, Hasan S. Wind and geothermal energy in desalination: A short review on progress and sustainable commercial processes. Ind Eng Manag 2015;04:175. http://dx.doi.org/10.4172/2169-0316.1000175.
[47] Yapp R. Solar energy and water: Solar powering desalination 2012. 〈〈http://www.renewableenergyworld.com/rea/news/article/2012/12/solar-energy-and-water-solar-powering-desalination〉〉 (accessed 20.06.15.).
[48] Fath HES, El-Sherbiny SM, Ghazy A. Transient analysis of a new humidification-dehumidification solar still. Desalination 2003;155:187–203. http://dx.doi.org/10.1016/S0011-9164(03)00296-0.
[49] Fath HES. Technical assessment of solar thermal energy storage technologies. Renew Energy 1998;14:35–40. http://dx.doi.org/10.1016/S0960-1481(98)00044-5.
[50] Fath HES. High performance of a simple design, two effects, solar distillation unit. Energy Convers Manag 1997;38:1895–905. http://dx.doi.org/10.1016/S0196-8904(96)00104-5.
[51] Fath HES, Abdelrahman K. Micro-climatic environmental conditions inside a greenhousewith a built-in solar distillation system. Desalination 2005;171:267–87. http://dx.doi.org/10.1016/j.desal.2004.05.007.
[52] Fath HES. Solar distillation: a promising alternative for water provision with free energy, simple technology and a clean environment. Desalination 1998;116:45–56. http://dx.doi.org/10.1016/S0011-9164(98)00056-3.
[53] Zamen M, Amidpour M, Soufari SM. Cost optimization of a solar humidification–dehumidification desalination unit using mathematical programming. Desalination 2009;239:92–9. http://dx.doi.org/10.1016/j.desal.2008.03.009.
[54] Abdelmoez W, Mahmoud MS, Farrag TE. Water desalination using humidification/dehumidification (HDH) technique powered by solar energy: a detailed review. Desalin Water Treat 2013;52:4622–40. http://dx.doi.org/10.1080/19443994.2013.804457.
[55] Al-Hallaj S, Parekh S, Farid MM, Selman JR. Solar desalination with humidification-dehumidification cycle: review of economics. Desalination 2006;195:169–86. http://dx.doi.org/10.1016/j.desal.2005.09.033.
[56] Wang J hong, Gao N yun, Deng Y, Li Y li. Solar power-driven humidification-dehumidification (HDH) process for desalination of brackish water. Desalination 2012;305:17–23. http://dx.doi.org/10.1016/j.desal.2012.08.008.
[57] Franchini G, Perdichizzi A, Picinardi A. HD desalination by heat rejected from solar cooling systems. EnergyCon 2010. 2010 IEEE Int Energy Conf Exhib 2010:63–8. http://dx.doi.org/10.1109/ENERGYCON.2010.5771759.
[58] Yuan G, Zhang H. Mathematical modeling of a closed circulation solar desalination unit with humidification–dehumidification. Desalination 2007;205:156–62. http://dx.doi.org/10.1016/j.desal.2006.03.550.
[59] Yuan G, Wang Z, Li H, Li X. Experimental study of a solar desalination system based on humidification–dehumidification process. Desalination 2011;277:92–8. http://dx.doi.org/10.1016/j.desal.2011.04.002.
[60] Ghazal MT, Atikol U, Egelioglu F. An experimental study of a solar humidifier for HDD systems. Energy Convers Manag 2014;82:250–8. http://dx.doi.org/10.1016/j.enconman.2014.03.019.
[61] Mohamed AMI, El-Minshawy NA. Theoretical investigation of solar humidification-dehumidification desalination system using parabolic trough concentrators. Energy Convers Manag 2011;52:3112–9. http://dx.doi.org/10.1016/j.enconman.2011.04.026.
[62] Al-Sulaiman FA, Zubair MI, Atif M, Gandhidasan P, Al-Dini SA, Antar MA. Humidification dehumidification desalination system using parabolic trough solar air collector. Appl Therm Eng 2015;75:809–16. http://dx.doi.org/10.1016/j.applthermaleng.2014.10.072.
[63] Marif Y, Benmoussa H, Bouguettaia H, Belhadj MM, Zerrouki M. Numerical simulation of solar parabolic trough collector performance in the Algeria Saharan region. Energy Convers Manag 2014;85:521–9. http://dx.doi.org/10.1016/j.enconman.2014.06.002.
[64] Elminshawy NAS, Siddiqui FR, Addas MF. Experimental and analytical study on productivity augmentation of a novel solar humidification–dehumidification (HDH) system. Desalination 2015;365:36–45. http://dx.doi.org/10.1016/j.desal.2015.02.019.
[65] Ghalavand Y, Hatamipour MS, Rahimi A. Humidification compression desalination. Desalination 2014;341:120–5. http://dx.doi.org/10.1016/j.desal.2014.02.039.
[66] Mohamed AMI, El-Minshawy NAS. Humidification–dehumidification desalination system driven by geothermal energy. Desalination 2009;249:602–8. http://dx.doi.org/10.1016/j.desal.2008.12.053.
[67] Narayan GP, Mcgovern RK, Thiel GP, Miller J a, JHL V. Status of humidification dehumidification desalination technology. Perth. IDA World Congr. Conv. Exhib. Cent 2011.
[68] Ashrafizadeh SA, Amidpour M. Exergy analysis of humidification-dehumidification desalination systems using driving forces concept. Desalination 2012;285:108–16. http://dx.doi.org/10.1016/j.desal.2011.09.041.
[69] Muthusamy C, Srithar K. Energy and exergy analysis for a humidification–dehumidification desalination system integrated with multiple inserts. Desalination 2015;367:49–59. http://dx.doi.org/10.1016/j.desal.2015.03.032.
[70] Sharqawy MH, Antar MA, Zubair SM, Elbashir AM. Optimum thermal design of humidification dehumidification desalination systems. Desalination 2014;349:10–21. http://dx.doi.org/10.1016/j.desal.2014.06.016.
[71] Niroomand N, Zamen M, Amidpour M. Theoretical investigation of using a direct contact dehumidifier in humidification–dehumidification desalination unit based on an open air cycle. Desalin Water Treat 2014;54:305–15. http://dx.doi.org/10.1080/19443994.2014.880157.
[72] Klausner JF, Li Y, Mei R. Evaporative heat and mass transfer for the diffusion driven desalination process. Heat Mass Transf 2005;42:528–36. http://dx.doi.org/10.1007/s00231-005-0649-2.
[73] Paso E. Zero discharge waste brine management for desalination plants. U.S. Department of the Interior Bureau of Reclamation Technical Service Center Water Treatment Engineering and Research Group Denver, CO, University of Texas at El Paso, El Paso, TX; 2002.
[74] Dawoud B, Zurigat YH, Klitzing B, Aldoss T, Theodoridis G. On the possible techniques to cool the condenser of seawater greenhouses. Desalination 2006;195:119–40. http://dx.doi.org/10.1016/j.desal.2005.09.038.
[75] Nawayseh NK, Farid MM, Omar AA, Sabirin A. Solar desalination based on humidification process—II. Computer simulation. Energy Convers Manag 1999;40:1441–61. http://dx.doi.org/10.1016/S0196-8904(99)00017-5.
[76] Speight JG. Lange's Handbook Of Chemistry. 16th ed. New York, NY: McGraw-Hill; 2005.
[77] Eslamimanesh A, Hatamipour MS. Mathematical modeling of a direct contact humidification–dehumidification desalination process. Desalination 2009;237:296–304. http://dx.doi.org/10.1016/j.desal.2008.01.023.
[78] Hu T, Hassabou AH, Spinnler M, Polifke W. Performance analysis and optimization of direct contact condensation in a PCM fixed bed regenerator. Desalination 2011;280:232–43. http://dx.doi.org/10.1016/j.desal.2011.07.008.
[79] Wang K, Hu T, Hassabou AH, Spinnler M, Polifke W. Analyzing and modeling the dynamic thermal behaviors of direct contact condensers packed with PCM spheres. Contin Mech Thermodyn 2012;25:23–41. http://dx.doi.org/10.1007/s00161-012-0246-9.
[80] Agboola OP, Egelioglu F. An empirical evaluation of an integrated inclined solar water desalination system with spray jets variation. Desalin Water Treat 2013;53:2875–81. http://dx.doi.org/10.1080/19443994.2013.874113.
[81] Abu Arabi MK, Reddy KV. Performance evaluation of desalination processes based on the humidification/dehumidification cycle with different carrier gases. Desalination 2003;156:281–93. http://dx.doi.org/10.1016/S0011-9164(03)00359-X.
[82] Al-Sahali M, Ettouney HM. Humidification dehumidification desalination process: Design and performance evaluation. Chem Eng J 2008;143:257–64. http://dx.doi.org/10.1016/j.cej.2008.04.030.
[83] Ettouney H. Design and analysis of humidification dehumidification desalination process. Desalination 2005;183:341–52. http://dx.doi.org/10.1016/j.desal.2005.03.039.
[84] Vlachogiannis M, Bontozoglou V, Georgalas C, Litinas G. Desalination by mechanical compression of humid air. Desalination 1999;122:35–42. http://dx.doi.org/10.1016/S0011-9164(99)00025-9.
[85] H.T. El-Dessouky H.M. Ettouney Fundamentals of Salt Water Desalination. 2002 doi: 10.1016/B978-044450810-2/50008-7.
[86] Yanniotis S, Pilavachi PA. Mathematical modeling and experimental validation of an absorption-driven multiple-effect evaporator. Chem Eng Technol 1996;19:448–55.
[87] Uçkan İ, Yılmaz T, Hürdoğan E, Büyükalaca O. Exergy analysis of a novel configuration of desiccant based evaporative air conditioning system. Energy Convers Manag 2014;84:524–32. http://dx.doi.org/10.1016/j.enconman.2014.05.006.
[88] Li Z-X, Zhang L-Z. Flow maldistribution and performance deteriorations in a counter flow hollow fiber membrane module for air humidification/dehumidification. Int J Heat Mass Transf 2014;74:421–30. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.03.047.
[89] Gao P, Zhang L, Zhang H. Performance analysis of a new type desalination unit of heat pump with humidification and dehumidification. Desalination 2008;220:531–7. http://dx.doi.org/10.1016/j.desal.2007.01.053.
[90] Nada SA, Elattar HF, Fouda A. Experimental study for hybrid humidification–dehumidification water desalination and air conditioning system. Desalination 2015;363:112–25. http://dx.doi.org/10.1016/j.desal.2015.01.032.
[91] Mistry KH, Lienhard JH, Zubair SM. Effect of entropy generation on the performance of humidification-dehumidification desalination cycles. Int J Therm Sci 2010;49:1837–47. http://dx.doi.org/10.1016/j.ijthermalsci.2010.05.002.

[92] Narayan GP, Chehayeb KM, McGovern RK, Thiel GP, Zubair SM, Lienhard VJH. Thermodynamic balancing of the humidification dehumidification desalination system by mass extraction and injection. Int J Heat Mass Transf 2013;57:756–70. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.10.068.
[93] Miller JA, Lienhard VJH. Impact of extraction on a humidification-dehumidification desalination system. Desalination 2013;313:87–96. http://dx.doi.org/10.1016/j.desal.2012.12.005.
[94] McGovern RK, Thiel GP, Prakash Narayan G, Zubair SM, Lienhard VJH. Performance limits of zero and single extraction humidification–dehumidification desalination systems. Appl Energy 2013;102:1081–90. http://dx.doi.org/10.1016/j.apenergy.2012.06.025.
[95] Chehayeb KM, Prakash Narayan G, Zubair SM, Lienhard JH. Use of multiple extractions and injections to thermodynamically balance the humidification dehumidification desalination system. Int J Heat Mass Transf 2014;68:422–34. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.09.025.
[96] Chehayeb KM, Narayan GP, Zubair SM, Lienhard JH. Thermodynamic balancing of a fixed-size two-stage humidification dehumidification desalination system. Desalination 2015;369:125–39. http://dx.doi.org/10.1016/j.desal.2015.04.021.
[97] Hamieh BM, Beckman JR, Ybarra MD. Brackish and seawater desalination using a 20 ft2 dewvaporation tower. Desalination 2001;140:217–26. http://dx.doi.org/10.1016/S0011-9164(01)00371-X.
[98] Hamieh BM, Beckman JR. Seawater desalination using dewvaporation technique: experimental and enhancement work with economic analysis. Desalination 2006;195:14–25. http://dx.doi.org/10.1016/j.desal.2005.09.035.
[99] Chafik E. A new type of seawater desalination plants using solar energy. Desalination 2003;156:333–48. http://dx.doi.org/10.1016/S0011-9164(03)00364-3.
[100] Kang H, Yang Y, Chang Z, Zheng H, Duan Z. Performance of a two-stage multi-effect desalination system based on humidification–dehumidification process. Desalination 2014;344:339–49. http://dx.doi.org/10.1016/j.desal.2014.04.004.
[101] Hou S. Two-stage solar multi-effect humidification dehumidification desalination process plotted from pinch analysis. Desalination 2008;222:572–8. http://dx.doi.org/10.1016/j.desal.2007.01.127.
[102] Zamen M, Soufari SM, Vahdat SA, Amidpour M, Zeinali MA, Izanloo H, et al. Experimental investigation of a two-stage solar humidification–dehumidification desalination process. Desalination 2014;332:1–6. http://dx.doi.org/10.1016/j.desal.2013.10.018.
[103] Chiranjeevi C, Srinivas T. Combined two stage desalination and cooling plant. Desalination 2014;345:56–63. http://dx.doi.org/10.1016/j.desal.2014.04.023.
[104] Nada SA, Elattar HF, Fouda A. Performance analysis of proposed hybrid air conditioning and humidification–dehumidification systems for energy saving and water production in hot and dry climatic regions. Energy Convers Manag 2015;96:208–27. http://dx.doi.org/10.1016/j.enconman.2015.02.082.
[105] Yıldırım C, Soylu SK, Atmaca İ, Solmuş İ. Experimental investigation of a portable desalination unit configured by a thermoelectric cooler. Energy Convers Manag 2014;85:140–5. http://dx.doi.org/10.1016/j.enconman.2014.05.071.
[106] Narayan GP, McGovern RK, Zubair SM, Lienhard JH. High-temperature-steam-driven, varied-pressure, humidification-dehumidification system coupled with reverse osmosis for energy-efficient seawater desalination. Energy 2012;37:482–93. http://dx.doi.org/10.1016/j.energy.2011.11.007.
[107] Kabeel AE, Elmaaty TA, El-Said EMS. Economic analysis of a small-scale hybrid air HDH-SSF (humidification and dehumidification-water flashing evaporation) desalination plant. Energy 2013;53:306–11. http://dx.doi.org/10.1016/j.energy.2013.02.042.
[108] Eslamimanesh A, Hatamipour MS. Economical study of a small-scale direct contact humidification-dehumidification desalination plant. Desalination 2010;250:203–7. http://dx.doi.org/10.1016/j.desal.2008.11.015.
[109] Li X. Experimental analysis of produced water desalination by a humidification-dehumidification process. Socorro, New Mexico: New Mexico Institute of Mining; 2009.
[110] Jamaly S, Giwa A, Hasan SW. Recent improvements in oily wastewater treatment: Progress, challenges, and future opportunities. J Environ Sci 2015;37:1–16. http://dx.doi.org/10.1016/j.jes.2015.04.011.
[111] Giwa A, Ahmed I, Hasan SW. Enhanced sludge properties and distribution study of sludge components in electrically-enhanced membrane bioreactor. J Environ Manag 2015;159:78–85. http://dx.doi.org/10.1016/j.jenvman.2015.05.035.
[112] Giwa A, Hasan SW. Numerical modeling of an electrically enhanced membrane bioreactor (MBER) treating medium-strength wastewater. J Environ Manag 2015;159:78–85. http://dx.doi.org/10.1016/j.jenvman.2015.08.031.
[113] Giwa A, Hasan SW. Theoretical investigation of the influence of operating conditions on the treatment performance of an electrically-induced membrane bioreactor. J Water Process Eng 2015;6:72–82. http://dx.doi.org/10.1016/j.jwpe.2015.03.004.
[114] Soufari SM, Zamen M, Amidpour M. Performance optimization of the humidification–dehumidification desalination process using mathematical programming. Desalination 2009;237:305–17. http://dx.doi.org/10.1016/j.desal.2008.01.024.
[115] Orfi J, Galanis N, Laplante M. Air humidification–dehumidification for a water desalination system using solar energy. Desalination 2007;203:471–81. http://dx.doi.org/10.1016/j.desal.2006.04.022.
[116] Parekh S, Farid MM, Selman JR, Al-Hallaj S. Solar desalination with a humidification-dehumidification technique - A comprehensive technical review. Desalination 2004;160:167–86. http://dx.doi.org/10.1016/S0011-9164(04)90007-0.
[117] Mistry KH, Mitsos A, Lienhard JH. Optimal operating conditions and configurations for humidification–dehumidification desalination cycles. Int J Therm Sci 2011;50:779–89. http://dx.doi.org/10.1016/j.ijthermalsci.2010.12.013.
[118] Farsad S, Behzadmehr A, Sarvari SMH. Numerical analysis of solar desalination using humidification—dehumidification cycle. Desalin Water Treat 2012;19:294–300. http://dx.doi.org/10.5004/dwt.2010.1487.
[119] Li X, Yuan G, Wang Z, Li H, Xu Z. Experimental study on a humidification and dehumidification desalination system of solar air heater with evacuated tubes. Desalination 2014;351:1–8. http://dx.doi.org/10.1016/j.desal.2014.07.008.
[120] Ben Halima H, Gabssi S. Water desalination using humidification process: Laboratory study. 2014 5th Int. Renew Energy Congr, IEEE 2014:1–4. http://dx.doi.org/10.1109/IREC.2014.6827001.
[121] El-Shazly AH, Al-Zahrani AA, Alhamed YA, Nosier SA. Productivity intensification of humidification-dehumidification desalination unit by using pulsed water flow regime. Desalination 2012;293:53–60. http://dx.doi.org/10.1016/j.desal.2012.02.023.
[122] Chang Z, Zheng H, Yang Y, Su Y, Duan Z. Experimental investigation of a novel multi-effect solar desalination system based on humidification–dehumidification process. Renew Energy 2014;69:253–9. http://dx.doi.org/10.1016/j.renene.2014.03.048.
[123] Ben Bacha H. Dynamic modeling and experimental validation of a water desalination prototype by solar energy using humidification dehumidification process. Desalination 2013;322:182–208. http://dx.doi.org/10.1016/j.desal.2013.05.011.
[124] El-Agouz SA. A new process of desalination by air passing through seawater based on humidification–dehumidification process. Energy 2010;35:5108–14. http://dx.doi.org/10.1016/j.energy.2010.08.005.
[125] Gang W, Zheng H, Kang H, Yang Y, Cheng P, Chang Z. Experimental investigation of a multi-effect isothermal heat with tandem solar desalination system based on humidification–dehumidification processes. Desalination 2016;378:100–7. http://dx.doi.org/10.1016/j.desal.2015.09.024.
[126] Daer S, Kharraz J, Giwa A, Hasan SW. Recent applications of nanomaterials in water desalination: a critical review and future opportunities. Desalination 2015;367:37–48. http://dx.doi.org/10.1016/j.desal.2015.03.030.
[127] Akther N, Sodiq A, Giwa A, Daer S, Arafat HA, Hasan SW. Recent advancements in forward osmosis desalination: a review. Chem Eng J 2015;281:502–22. http://dx.doi.org/10.1016/j.cej.2015.05.080.
[128] Mokhtari H, Ahmadisedigh H, Ebrahimi I. Comparative 4E analysis for solar desalinated water production by utilizing organic fluid and water. Desalination 2016;377:108–22. http://dx.doi.org/10.1016/j.desal.2015.09.014.
[129] Thiel GP, Tow EW, Banchik LD, Chung HW, Lienhard JH. Energy consumption in desalinating produced water from shale oil and gas extraction. Desalination 2015;366:94–112. http://dx.doi.org/10.1016/j.desal.2014.12.038.