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REVIEW

A comprehensive review on solar thermal desalination systems based on humidification-dehumidification approach

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Abstract

Fresh water scarcity is turning into a serious and worrying challenge to the sustainable growth of human being. This issue highlights the necessity of seawater desalination techniques. There are various desalination technologies available and among them solar thermal humidification-dehumidification (HDH) desalination was reported as the most efficient technology for small-to-medium scale applications. In this review, firstly the basic principle of solar thermal HDH desalination system is discussed. The effect of different packing materials used in humidifier, different designs of dehumidifier and various types of solar water & air heating system on system performance has been discussed. It is observed that the polypropylene & porous plastic balls are the best packing material for humidifier. Similarly, in dehumidifier, the fin-tube type heat exchanger along with saline water as working medium is best choice of researchers, but the flow of saline water inside the tube of heat exchanger increases fouling problem, which further increases the cost of freshwater production by 5%. In case of heat source, the solar water heater outperformed the solar air heater due to higher heat capacity of water. The optimized operating & design parameters of the system, i.e., flow rate and temperature of saline water & process air are also reported. Finally, various performance parameters, thermal and economic analysis of solar HDH desalination system is reported along with major research finding and recommendations.

Keywords Dehumidifier · Humidifier · Packing material · Solar air heater · Solar water heater

List of symbols

$\dot{M}_w$	Freshwater production rate (kg/s)
E_{rf}	Energy reuse factor
L_v	Latent heat of evaporation (kJ/kg)
$V_{D,in}$	Vapor load at inlet of dehumidifier
E_{Input}	Input energy (kW)
$V_{D,out}$	Vapor load at outlet of dehumidifier
GOR	Gained output ratio
$V_{H,out}$	Vapor load at outlet of humidifier
M_{FR}	Mass flow rate ratio
S_{gen}	Specific entropy generation (kJ/kgK)
$\dot{w}_{sw}$	Saline water flow rate (kg/s)
$\ddot{S}_{gen}$	Entropy generation rate of each component (kW/K)
$\dot{w}_a$	Air flow rate (kg/s)
m	Interest rate
R_r	Recovery ratio
j	Lifetime
R_d	Running days
t	Operation time (sec)
Me	Merkel number
$C_{p,w}$	Specific heat of water (kJ/kgK)
ε_{DH}	Dehumidifier effectiveness
R	Heat capacity
A_{DH}	Dehumidifier area (m^2)
U	Overall heat transfer coefficient (W/m^2K)
NTU	Number of transfer unit
V_{pm}	Volume of packing material (m^3)
H	Height of packing material (m)
T_w	Water temperature (°C)
E	Energy required (kW)
E_{output}	Output energy (kW)
I	Solar intensity (W/m^2)
A_c	Area of solar collector (m^2)
T_a	Ambient temperature (°C)
T_s	Sun temperature (°C)
ϵ_{input}	Input exergy (kW)
ϵ_{output}	Output exergy (kW)

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η_e Energy efficiency
η_ε Exergy efficiency

Introduction

A crucial resource for meeting humans' daily fundamental needs is water. Most of the water available on earth is saline water in sea. Only a fraction (about 2.5%) of the total water available on earth is fresh water. The major part (about 70%) of it is in the form of ice at the poles. The remaining part of it (about 30%) is not directly accessible. It means that about 1% of the total fresh water available on earth is accessible, which is not uniformly distributed (Tiwari et al. 2022a, b). In the coming decades, there will undoubtedly be an increase in the global need for freshwater. Populations that are expanding quickly will lead to higher demand among house hold consumers, farmers, and industries. According to the report presented by the world resources institute (WRI), out of 167 countries, 33 countries such as Iran, Iraq, China, Australia, and India will face huge water crises by 2040 (Andrew Maddocks 2021) as shown in Fig. 1. Since, these countries have costal boundaries, and saline seawater is easily available. So, the desalination of seawater is possible solution for producing freshwater. Desalination is the technique which is used for removing salts from saline seawater to produced freshwater. Most of the desalination systems are based on reverse osmosis (RO) which are used for large scale application (Kasaeian et al. 2019). This technique uses fossil fuels for their operation which results in emission of greenhouse gases. Also, it is observed from Fig. 1 that, the earlier said countries are located in between tropic of cancer and tropic of capricorn. The region between tropic of cancer and tropic of capricorn receives good amount of solar energy. As a result, using solar energy for desalination of seawater is a possible solution to minimize the emission of greenhouse gases. Based on the use of solar energy, solar thermal desalination is classified into two categories, i.e., direct desalination and indirect desalination as shown in Fig. 2. The solar still is the simplest technique for desalinating saline water. But it has several disadvantages like low productivity, vapor leakage, salt deposition on the basin, and condensation of water vapors (Tiwari et al. 2022a, b). Among the other desalination technology, multi-stage flash (MSF) and multi-effect desalination (MED) are used for large-scale applications which requires large space. Also, the freshwater needs to be transported, which requires huge amount of cost. On the other-hand, the humidification-dehumidification (HDH) technique is used for medium-scale desalination systems. The HDH technique has several advantages such as simple construction, low maintenance, and operational cost, use of low-grade energy, and use with different solar collectors (Kasaeian et al. 2019). These advantages make the HDH desalination system the most prominent technology which eliminates the use of fossil fuels to produces freshwater. So, HDH is the possible technology which can supply demand of freshwater required for medium scale application. However,

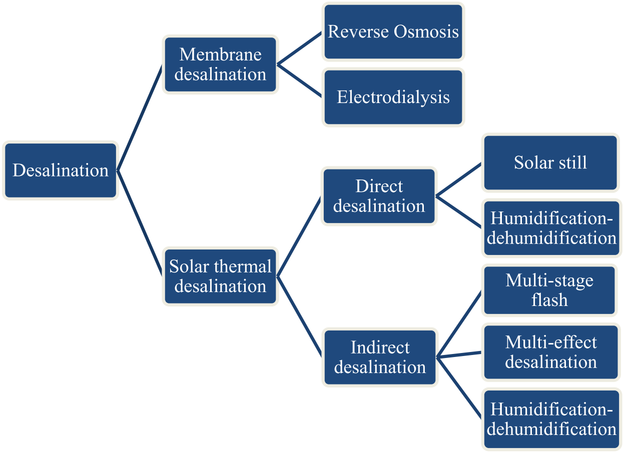
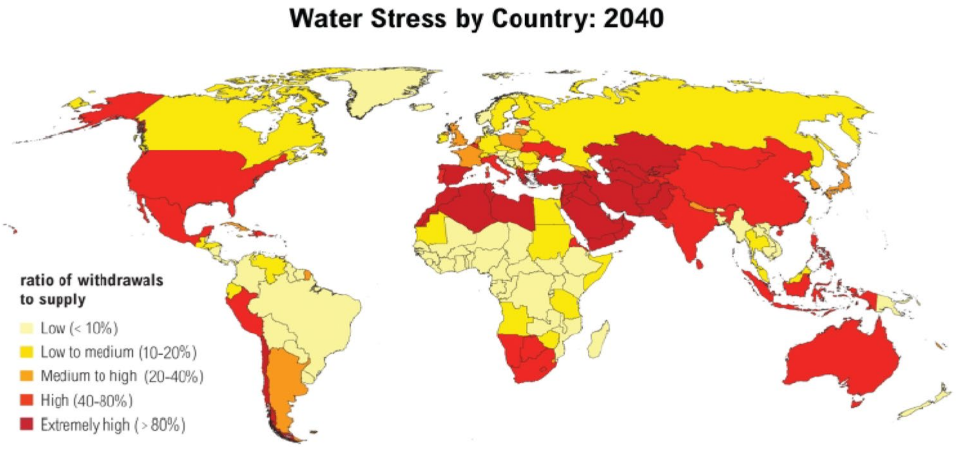


Fig. 2 Classifications of desalination technology

Fig. 1 Report on global water stress (Andrew Maddocks et al 2021)



in the rural areas, the demand of fresh water is on small-medium scale, but even then, the supply has always been a constraint. Because of this reason, the rural society had to portion their significant economics towards freshwater. Therefore, to cater this region with a continuous fresh water supply, HDH technology can be a feasible solution. Moreover, integration of solar energy to this technology will make this system self-sustainable and reliable. Some advantages and limitations of various desalination techniques are shown in Table 1.

In the present paper, the recent developments in the field of solar thermal HDH desalination systems are discussed. Various experimental and numerical research on different components of HDH is thoroughly explored. The optimized design of humidifier and dehumidifier are discussed. Also, the thermal and economic analysis of the solar driven HDH desalination system is presented. This strategy is used so that the findings will be more effectively arranged and the research gaps in the field will be well explored. On the basis of system performance, the impact of various parameters such as flow rates and temperatures of the working fluid, recirculation of brine, ambient temperature, humidifier, and dehumidifier design, is explored. Also, the comparison of different HDH desalination systems is discussed. At the end of the paper, the potential promising research areas are identified and suggested.

Review methodology

The methodology adopted for review paper is:

- The recent review papers are studied to know the basic principle of desalination system, classification of desalination system, working principle of conventional solar

Table 1 Advantages and limitations of various desalination techniques

Desalination Techniques	Advantages	Limitations
MED	Mild working temperature range (Raluy et al. 2006) Less thermal energy (Chandrashekara & Yadav, 2017) Good quality of portable water (.Chandrashekara & Yadav, 2017) (Tarpani et al. 2019) No need for a pre-water treatment process (Tiwari et al. 2022a, b) Low emission (Raluy et al. 2006)	High initial cost (Chandrashekara & Yadav, 2017) High electrical energy required (Tiwari et al. 2022a, b) Large space is required (Tarpani et al. 2019) Additional device required to maintain vacuum (Tiwari et al. 2022a, b)
MSF	Applicable for large-scale application (M. T. Ali et al. 2011) Good quality of portable water (Khawaji et al. 2008) No need for a pre-water treatment process (Raluy et al. 2006) Less environmental impact (Mezher et al. 2011)	A large amount of energy is required (Hoffman 1992) High working temperature range (Mezher et al. 2011) High cost of system (Mezher et al. 2011) Bulky system (Tarpani et al. 2019)
ED	Low working temperature range (Alkhudhiri et al. 2012) Less weight & non-corrosive system (use plastic material) (Alkhudhiri et al. 2012) Suitable for both; renewable & non-renewable energy sources (Sharon & Reddy 2015) Easy operation (Kasaeian et al. 2019)	Low efficiency (Koschikowski et al. 2003) High cost of a membrane (Qtaishat & Banat 2013) Large space required for membrane (driving force is low) (Sharon & Reddy 2015) Wetting of membrane (Sharon & Reddy 2015)
RO	Easy & flexible working (Khawaji et al. 2008) The cost of operation & maintenance is less (Kasaeian et al. 2019) The capacity of the system is high (Hoffman 1992) Applicable for groundwater (Raluy et al. 2006)	A large amount of brine (Gautam et al. 2017) more environmental impact (Al-Karaghouli et al. 2009) High cost due to use of battery (Kasaeian et al. 2019) An additional pump is required due to high working pressure (Raluy et al. 2006) Pre-treatment of water is required (Raluy et al. 2006)
Solar still	Less operational & maintenance cost (Al-Sahali & Ettouney 2008) Eco-friendly system (Dsilva Winfred Rufuss et al. 2016) Good quality of portable water (Eltawil & Zhengming 2009) Ease in operation and simple to use & construction (Koschikowski et al. 2003)	Low productivity (Tiwari et al. 2022a, b) Vapor leakage is high (Kumar et al. 2022) Low efficiency (Sharon & Reddy 2015) Not used for large-scale applications (Orfi et al. 2004) Condensation problem (Tiwari et al. 2022a, b)
HDH	Less operation & maintenance costs (Rahimi-Ahar et al. 2020) Easy & flexible system operation (Dave et al. 2021) Capable to use any type of energy (renewable, geothermal) (Baniasad Askari & Shahsavar 2021) Applicable for any capacity (small, medium, and high) (Zubair et al. 2017), Easy to couple with other processes (He et al. 2018)	The investment cost is high (Narayan et al. 2010a, b) Due to fouling, thermal efficiency is low (Deniz & Çınar 2016) High cost of produced water due to costly packing material (Ali et al. 2022) Higher carbon footprint (Abdelaziz et al. 2022)

thermal HDH desalination system, classification of HDH desalination system.

- The research articles related to solar thermal HDH desalination system are reviewed based on the type of heat source, humidifier & dehumidifier, packing material used.
- The theoretical articles related to design of humidifier and dehumidifier are reviewed to know the optimized size of humidifier and dehumidifier.
- Articles available related to the economic analysis of solar thermal HDH desalination system are reviewed to know the procedure to estimate the cost of fresh water.
- This review considers articles from last 20 years to show the advancements in HDH desalination technology.

Humidification-dehumidification (HDH) desalination systems

The HDH desalination system consists of a heat source, humidifier and dehumidifier, as shown in Fig. 3. In a humidifier, the hot saline water is sprayed, which comes in contact with the process air to increase the temperature and moisture content in the process air and the process air becomes hot and humid. Then the hot and humid process air passes through the dehumidifier where it condenses with the help of cold feed saline water and produces freshwater. The HDH desalination system is classified based on the circulation cycle of air & water and the type of heating system used, as shown in Fig. 4. Several researchers have done work to enhance the performance of the HDH desalination system using a different configuration, heat source, and air or water heating system. So, this section covers the various research done on different components of HDH desalination system, namely humidifier, dehumidifier and heat source. Also, at the end of this section advancement in the field of HDH is discussed.

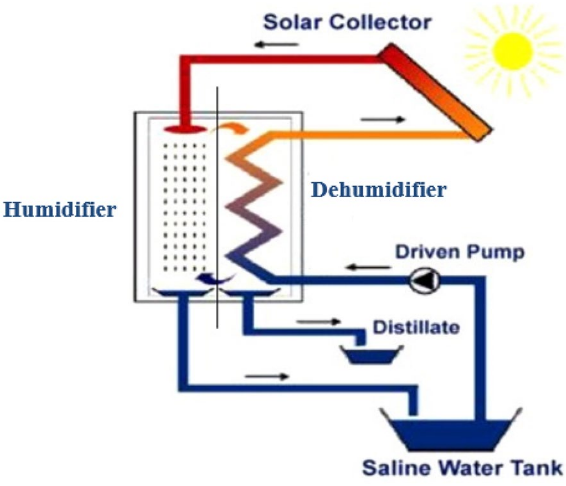


Fig. 3 Simple HDH desalination system (Tiwari et al. 2022a, b) with permission from springer nature

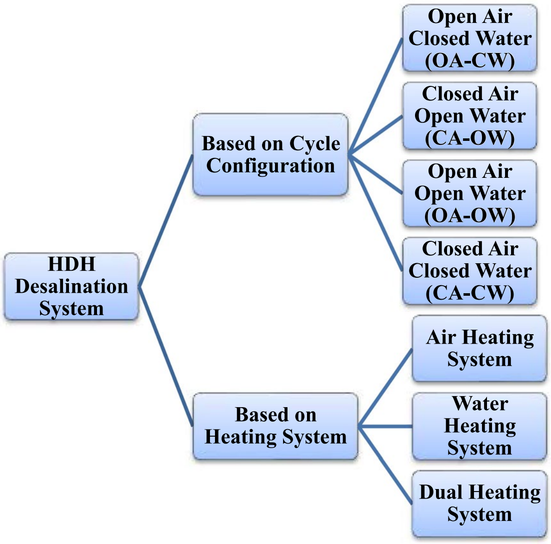


Fig. 4 Classifications of HDH desalination system

Humidifier & packing materials

The water production rate as well as overall efficiency of the HDH system can be increased by increasing evaporation rate inside the humidifier (Mohamed et al. 2021a, b). The evaporation rate directly depends on the contact time and contact area of sprayed water and air in the humidifier. So, to increase the contact area and contact time, the packing materials are used. (Hamed et al. 2015) examined the solar HDH system experimentally. The performance of the system was evaluated in two different ways, i.e., one by spraying hot water in the humidifier and other with using preheated water in the humidifier. The galvanized steel sheet having 1.5 mm thickness was used for humidifier (0.5 × 0.8 m) with 2 m of height. To drain out the salt deposited at the bottom of the humidifier, its bottom portion was gradually slope. The packing material was cellulous pads (honey comb structure of 80 × 50 × 10 cm^3) having 12 number of pads. The humidifier performance was enhanced by increasing the water temperature at the inlet of the humidifier. The quantity of freshwater produced by the system was 0.022 m^3/day at a cost of 57.8 \$/m^3. (Behnam & Shafii 2016) experimentally investigated the performance of solar HDH desalination system using evacuated tube collector (ETC) with heat pipe (HP) and bubble column humidifier, as shown in Fig. 5. The use of bubble column humidifier results in higher contact area and better mixing of water & air for effective heat & mass transfer. The acrylic plastic sheet having 3 mm thickness

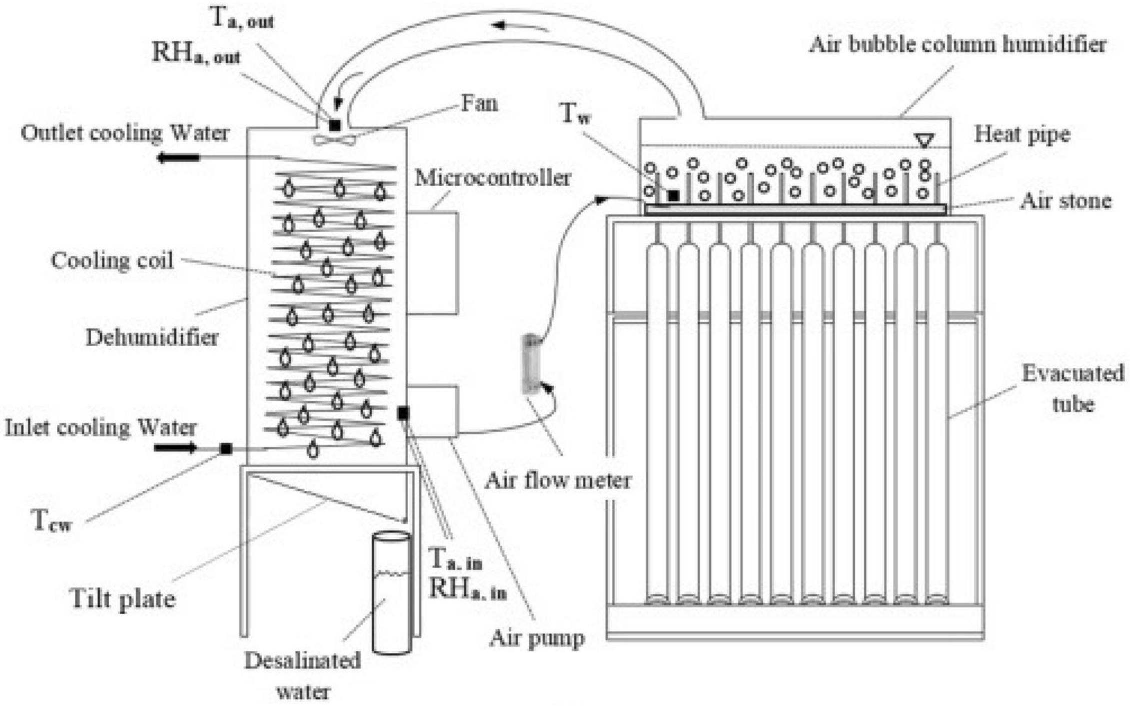


Fig. 5 Schematic of HDH system using bubble humidifier (Behnam & Shafii 2016) with permission from Elsevier

was used for humidifier (0.9 × 0.15 m) with 0.3 m of height. The results indicate that using oil in the space between ETC and heat pipe increases the productivity and efficiency of the system. Also, increasing the flow rate of air, increases the productivity of the system. The productivity of system at flow rate of air (4, 6, & 8 kg/min) was 0.00188, 0.001895, & 0.001945 m^3/day, respectively. The maximum daily productivity and efficiency of the system was 6.275 kg/m^2 and 65%, respectively, and the cost of produced water was 28 \$/m^3.

(Gang et al. 2016) experimentally investigated the performance of multi-effect HDH desalination system. The porous ball humidifier was used which increases the evaporation rate by increasing the contact surface area and contact time between air and water in the humidifier. The performance ratio (PR) of the system was 2.65 at 85 °C of water temperature. Also, as the temperature of water was increased from 60 to 90 °C with flow rate of water as 2000 kg/h, the productivity of the system was increased by 207.13%. It was observed that productivity of the system was improved by increasing the flow rate of water and air. The maximum productivity of the system was 22 kg/m^3/h. (Srithar & Rajaseenivasan 2017) experimentally investigated the performance of solar HDH system using bubble column humidifier. The system consists of solar air heater, humidifier (bubble column) and dehumidifier (shell and tube heat exchanger). The sheet of mild steel having 2 mm thickness was used to manufactured the humidifier (0.5 × 0.5 m) having 0.2 & 0.29 m of height at lower & higher side which 10° of inclination. The results indicate that at 8 cm of water depth in the humidifier, the optimum performance of the system was obtained. Also, the performance of solar air heater and humidifier was enhanced by increasing the flow rate of air. The highest humidifier efficiency obtained was 91.7%. The maximum productivity of the system was 0.02062 m^3/day with overall efficiency of 78.6%. (Aref et al. 2021) experimentally investigated the HDH desalination system using pulsating heat pipe as heat source. The experiment was performed using bubble basin type of humidifier as shown in Fig. 6, and results were compared with bubble column type of humidifier. The bubble basin type was manufactured using galvanized sheet of 0.003 m thickness having 0.4 × 0.4 m cross section and 0.15 & 0.35 m height on lower and higher side, respectively. Also, 0.02 m thick insulation of PVC was done on the outer area of bubble basin humidifier to minimize the heat losses. The latent heat of condensation was recovered by circulating the air in closed loop. The productivity of system was maximum using bubble basin humidifier due to greater surface area with daily productivity of 0.0087 m^3/day.

(Thanaiah et al. 2021) experimentally investigated the HDH desalination system using different packing materials. The experiments were performed using polypropylene and paddy grass packing materials, as shown in Fig. 7. The melting temperature & density of polypropylene was 130 to 171 °C & 0.855 g/cm^3, respectively. Whereas, the diameter & length of paddy grass was 0.005 m & 0.4 m, respectively, having 157.07 m^2/m^3 of packing density and

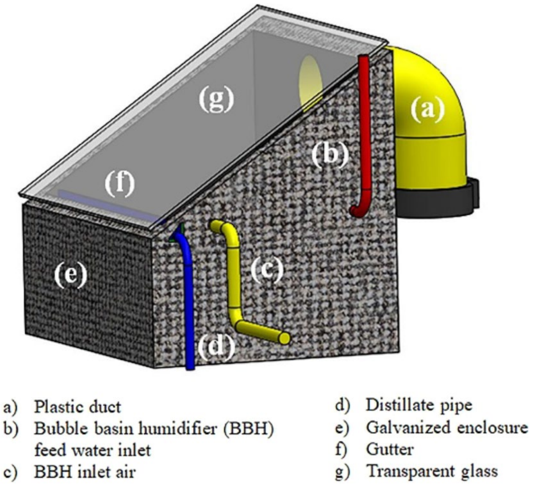


Fig. 6 Image of bubble basin humidifier (Aref et al. 2021) with permission from Elsevier

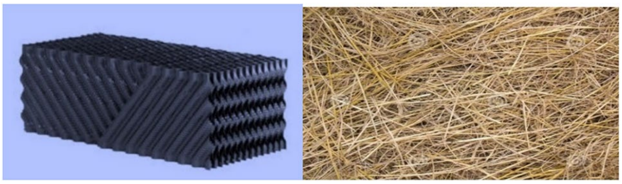


Fig. 7 Image of packing materials (polypropylene and paddy grass) (Thanaiah et al. 2021) with permission from Elsevier

Fig. 8 Image of humidifier (Thanaiah et al. 2021) with permission from Elsevier

10.05 m^2 of surface area. The cross section of humidifier was 0.4 × 0.4 m with 1 m height and the material was mild steel as shown in Fig. 8. The air enters from the bottom section of the humidifier, whereas it exits from the top section and enters the dehumidifier. The flow rate of air & water was taken same (0.01 & 0.040 kg/s, respectively) for both the packing materials. It was observed that paddy grass packing material performed better and produced maximum amount of freshwater with low cost per liter. The yield of the system with polypropylene and paddy grass packing material was 0.01104 and 0.01752 m^3/day, respectively.

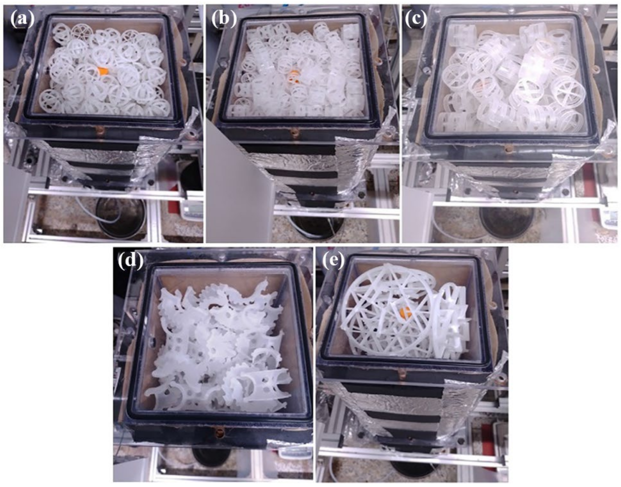


Fig. 9 Image of packing materials **a** tri-pack rings, **b** small pall rings, **c** large pall rings, **d** super intalox saddle rings, **e** snowflakes rings (Santosh et al. 2022) with permission from Elsevier

A novel packing material (fine & coarse grain foam, aspen pads and papers) was experimentally investigated to increase the evaporation rate (Abdel Dayem & AlZahrani 2022). The surface area of aspen pads was 500 m^2/m^3. The specific humidity for fine grain foam was maximum than as compared to the other packing materials. The gained output ratio (GOR) of 4.23 and productivity of 0.025 m^3/day was obtained at 80 kg/h flow rate and 60 °C temperature of water. (Hussain Soomro et al. 2022) experimentally investigated the HDH desalination system with different packing materials in the humidifier. The specific surface area of hackettes, saddles and snowflakes were 280 m^2/m^3, 169 m^2/m^3, and 138 m^2/m^3, respectively. The performance of the system was evaluated at same temperature in terms of GOR and productivity for each packing materials, namely hackettes, saddles and snowflakes. The experiments were performed at different mass flow rate of air (20.17–27.36 kg/h) and water (6.12–18 kg/h). The hackettes packing material have better performance than as compared to the other two packing material with maximum productivity and GOR of 0.64 kg/h (at 80 °C) and 1.45 (at 50 °C), respectively, with coefficient of mass transfer of 0.00331 kg/m^2s. (Santosh et al. 2022) experimentally investigated the use of low-grade waste heat in close air-open water HDH desalination system. In the humidifier, different packing materials (tri-pack rings, pall rings, saddle rings and snowflake rings, as shown in Fig. 9) were used to evaluate the effect of surface area on the system performance. The maximum yield of the system was 0.001398 m^3/h with 16 mm pall rings as packing material at optimized flow rate of air & water of 3.5 kg/min & 0.9 kg/min, respectively. The temperature of air & water at the inlet of humidifier were 70 & 55 °C, respectively. The water quality test indicates that using low-grade waste heat in HDH system, the percentage of the ions and salts present in seawater was reduced to certain amount which makes freshwater drinkable. (Alrbai et al. 2022a) experimentally investigated the performance of HDH desalination system using fogging nozzle. The performance of system was examined using two different sizes of water droplets in fogging nozzle (20 and 30 microns). The small size droplets and large contact area increases the evaporation and condensation rate. The fogging nozzle of 20 microns size had optimum performance with minimum exergy destruction and GOR of 3.4, which was obtained at mass flow rate ratio of 0.78.

It is observed that the packing materials inside humidifier increases the surface area and contact time between air & saline water, which results in increasing of evaporation rate. Also, the effectiveness of humidifier was improved by increasing the contact area which can be done by reducing the size of water droplets inside the humidifier, which is achieved by using small diameter of nozzle. The bubble basin humidifiers are more effective and dependable for desalinating highly saline water and have a longer lifespan. Further, the different types of packing materials are shown in Table 2.

Dehumidifier

The hot & humid air from the humidifier is condensed in dehumidifier. The dehumidifier consists of heat exchanger through which cooling medium is flowing and absorb the heat of humidified air to produce freshwater. The exit air from the dehumidifier is reuse or exhaust into surrounding. To enhance the effectiveness of dehumidifier and performance of solar thermal HDH desalination system, different types of heat exchanger are used such as shell and tube heat exchanger, fin-tube heat changer, and plate type heat exchanger. This section covers the various research done on dehumidifier to enhance the performance of desalination system. (Li & Zhang 2016) uses fin and tube heat exchanger in dehumidifier to enhanced the performance of solar membrane HDH desalination system. The system consists of evacuated tube collector, water storage tank, humidifier (hollow fiber membrane) and dehumidifier (fin and tube heat exchanger). The material for dehumidifier was stainless steel (grade-316L). The number of tubes were 42 having outer diameter of 9.52 mm with fins (aluminum) on their outer surface. The arrangement of tubes is shown in Fig. 10a. In dehumidifier, the bottom section was provided small angle to collect the produced freshwater. The results indicate that, for dehumidifier the specific water production rate was 0.003097 $m^3/h/m^2$ with effectiveness of 0.927. It was reported that around 92% of total energy required by the system was provided by solar energy. It was observed that at 180 L/h & 15 m^3/h of saline water & air flow rate, the production rate of the system was more than 0.01527 m^3/day of freshwater.

Table 2 Different types of packing materials

References	Packing material	Specific surface area (m^2/m^3)
Hamed et al., (2015), Lawal et al., (2020), Mohamed et al., (2020)	Cellulose pads	400
Thanaiah et al., (2021)	Paddy grass	157
Kaunga (2022), Rahimi-Ahar et al., (2018)	Rasching rings	440
Hussain Soomro et al., (2022)	Hackettes Saddles Snowflakes	280 169 138
Abdel Dayem & AlZahrani, (2022)	Aspen pads Foam	500 –
Chang et al., (2014), Wu et al., (2017a, b)	Porous plastic ball	–
Nafey et al., (2004)	Canvas packing	–
Abdullah et al., (2018)	Thorn tree’s	–
Santosh et al., (2022)	Tri-pack rings Pall rings	–
Dehghani et al., (2019), W. He et al., (2019a, b)	Polypropylene	226
He et al., (2019a, b)	Sulzer Mellapak 250 Y	–
Li & Zhang, (2016)	Porous fiber membrane	–
Muthusamy & Srithar, (2015)	Gunny bag & saw dust	–

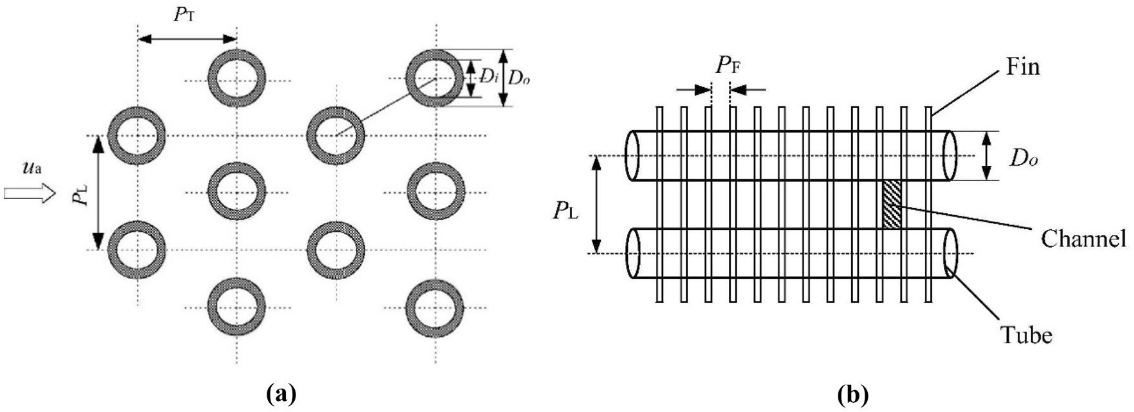


Fig. 10 Schematic of dehumidifier **a** arrangement of tubes **b** air flow path (Li & Zhang 2016) with permission from Elsevier

(Kabeel et al. 2018) experimentally investigated a hybrid system which consists of solar HDH desalination system integrated with indirect evaporative cooler. The condensation process was done in two stages using two flat finned and tube type heat exchangers (0.4 × 0.38 × 0.1 m) in dehumidifier. The maximum productivity of the hybrid system was 0.03865 m^3/day at 70 m^3/h of air flow rate. The productivity and coefficient of performance (COP) increases by increasing the flow rate of air. It was observed that, the productivity was increased from 0.03578 to 0.04721 m^3/h & COP was increased from 1.78 to 2.256 which was obtained by increasing the flow rate of air from 60 to 90 m^3/h. (Zhang et al. 2018) experimentally investigated the HDH desalination system incorporated with heat pump. The open-air cycle was used with condensation of water vapors in two stages. The 1st dehumidifier was fabricated using galvanized sheet of steel having square shape of cross-sectional dimension 0.36 × 0.36 m and 0.67 m of length. The gross area for heat transfer was 28 m^2 for 1st stage dehumidifier. While, the 2nd dehumidifier had same cross-sectional dimension with the length & gross area for heat transfer of 0.21 m & 21 m^2, respectively. In 1st stage dehumidifier, seawater was used as cooling medium, which was sprayed in humidifier after passing through the plate type heat exchanger. For 2nd stage dehumidifier, chilled water was used for condensing the outlet air from 1st dehumidifier. It was observed that temperature of seawater had significant effect on the productivity of the system. Also, the increase in flow rate of air results in higher yield from the system. The maximum productivity of the system was 0.02226 m^3/h with cost of water as 51 \$/m^3. (Rahimi-Ahar et al. 2018) experimentally investigated a solar vacuum HDH system. The system consists of solar water heater (SWH), solar air heater (SAH), vacuum pump, humidifier and double-pipe heat exchanger dehumidifier with closed-air and open-water cycle. The area of double-pipe heat exchanger was 1.58 m^2. The operating condition used while experiments was 10 to 35 °C of water temperature at inlet of dehumidifier and 10–30 kg/h of flow rate of water at inlet of dehumidifier. In dehumidifier, the saline water was preheated by hot & humid air and then feed to the SWH. The preheating of saline water results in improvement of system performance. The maximum productivity and GOR of the system were 0.00107 $m^3/h/m^2$ and 3.43, respectively, and the cost of produced water as 4.1 \$/m^3. (Thanaiah et al. 2021) used V-shaped dehumidifier consisting of baffle plates as shown in Fig. 11. The dehumidifier was fabricated using mild steel sheet of 1 mm thickness. The dimension of dehumidifier was 0.8 m length with 0.2 × 0.2 m cross section. To enhanced the condensation rate, six baffle plates (0.15 m length & 3 mm thickness) having 0.16 m of gap between two successive baffle plates were used. It was observed that the productivity of the system was enhanced by 60% using baffle plates inside dehumidifier. The maximum productivity of 0.073 m^3/h was obtained at cold-water flow rate of 0.05 kg/s.

(El-Said et al. 2022) experimentally investigated the HDH desalination system coupled with cooling system. The cooling system (vapor compression system) plays the role of dehumidifier. The evaporator of vapor compression system (placed inside dehumidifier) was used for condensing the hot & humid air. The size of dehumidifier was 0.6 × 0.4 × 0.4 m and made up of galvanized steel sheet. The flow rate of air had significantly affected the performance of HDH system.

Fig. 11 Image of dehumidifier with baffle plates (Thanaiah et al. 2021) with permission from Elsevier

The maximum productivity was obtained at 0.01156 kg/s flow rate of air. Beyond 0.01156 kg/s of air flow rate, the residence time of humid air in the dehumidifier was decreases which reduced the productivity of the system. The water productivity was 0.00612 m^3/day with GOR of 1.24. The energy & exergy efficiency of the system was 26.73 & 1.57%, respectively.

It is observed that the working fluid for condensing air in the dehumidifier was seawater which results in fouling inside the heat exchanger. To eliminate fouling, different working medium can be used such as thermic fluid and nanofluids. Other possible solution is the use of air-to-air heat exchanger which reduces fouling inside heat exchanger and cost of the system.

Heat source

There is various heat source available such as electric heater, waste heat, heat pump, geothermal energy, biomass and solar energy. This paper focus on solar energy-based desalination system for desalinating seawater. (Yamali & Solmus 2008) used the double-pass flat plate collector (FPC) for air heating. The HDH system consists of double-pass solar air heater (SAH) using FPC, humidifier with packing material, water storage tank and dehumidifier. The principle of HDH system was CW-CA cycle. The FPC-SAH was inclined at 30° angle with south facing having dimension of $1 \times 0.5 \times 0.1$ m. The SAH was coated with matt black dye. It was observed that using double-pass FPC-SAH enhanced the productivity of the system by 15%. This was occurred due to higher temperature of air supplied by SAH. (Zhani & Ben Bacha 2010) used the FPC for air and water heating and investigated the thermal performance of HDH desalination system. The system consists of FP-SAH, FP-SWH, humidifier, evaporation tower and dehumidifier. The area of SAH & SWH was 16 & 12 m^2, respectively. The maximum temperature of water and air at the outlet of SWH and SAH was near about 90 and 70 °C, respectively. It was observed that the SWH was more efficient as compared to the SAH. The productivity of the system was 0.02 m^3/day with payback time of 6776 days. (Mahmoud 2011) tested the HDH desalination system using parabolic trough collector (PTC). The PTC was able to increase the temperature of 25 L saline water from 35 to 70 °C in 3 h. The highest productivity of the system was 0.00265 m^3/h, which was obtained at 85 °C temperature of saline water. Also, around 45 kWh/m^3 of energy was consumed by the system to produced freshwater, which was higher than as compared to the RO based desalination system. To reduce this energy consumption, PV panels can be used. (Antar & Sharqawy 2013) uses solar energy to investigated the performance of HDH desalination system experimentally. The system consists of ETC-SAH, humidifier, dehumidifier, pump and fan. The CA-CW cycle was used in the HDH system. The two set of evacuated tubes SAH was connected in series to increase the temperature of air. A decrease in temperature of hot air occurs when hot air from solar collectors flows through lengthy pipe connections and fittings because of the pressure drop and heat loss. Because there is little temperature difference between the hot air and the water sprayed, the humidification process is ineffective. The results indicated that the productivity of two-stage system (0.006 m^3/day) was higher than as compared to one-stage system (0.0035 m^3/day). (Khalifa Zhani 2013) performed an experiment on HDH system using solar

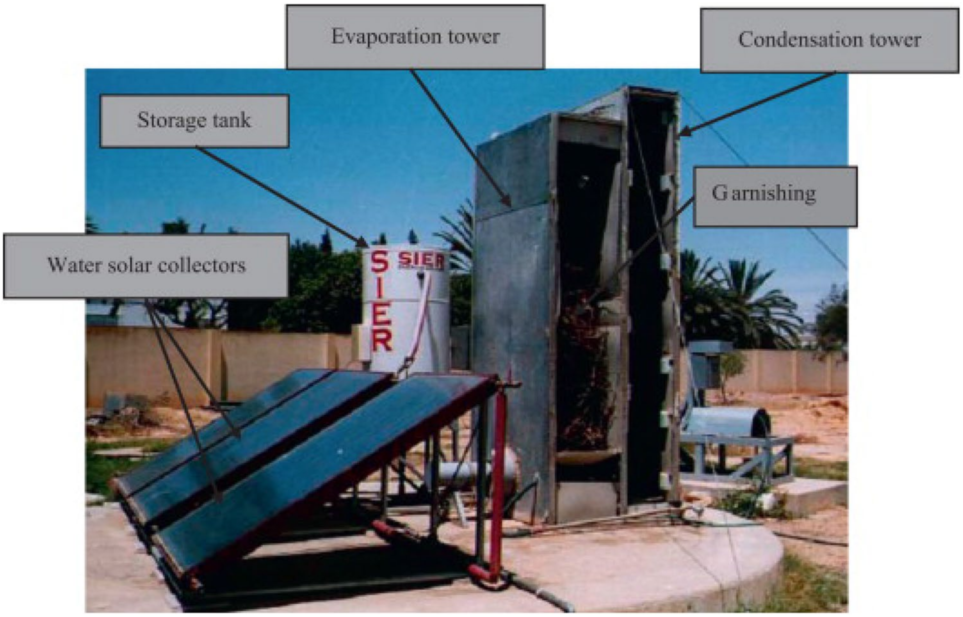


Fig. 12 Image of HDH using flat plate SWH (Khalifa Zhani 2013) with permission from Elsevier

energy as shown in Fig. 12. The water sprayed in the humidifier was heated by using flat plate (FP)-SWH. The area of FP-SWH was 7.20 m^2. It consists of an absorber plate in which copper tubes were uniformly placed. To enhance the absorptivity, black paint was used on upper surface of copper tubes. It was observed that increasing the flow rate of water increases the efficiency of FP-SWH. The optimum value of water flow rate was 0.4 kg/s, up-to which the efficiency of SWH was increases and beyond this value it starts decreasing. Also, the efficiency of SWH was decreases by increasing the temperature of water at flow rate of water 0.1 kg/s.

(Kabeel & El-Said 2013) studied the performance of hybrid HDH system using flash evaporator. The flat plate collector (FPC) was used for water and air heating. The total aperture area of SWH & SAH was 7 & 1.415 m^2, respectively. The mass flow rate of water and air in SWH & SAH was 0.014 and 0.3 kg/s, respectively. It was observed that aperture area of SWH and SAH had significant effects on the productivity of system. Increasing the aperture area increases the amount of heat absorbed, which increase the productivity of the system. It was noted that increasing the area of SAH was much efficient as compared to the increasing the area of SWH. The efficiency of SWH and SAH was 55 and 56%, respectively, and the maximum amount of freshwater produced by the system was 0.0418 m^3/day. (Rajaseenivasan & Srithar 2017b) experimentally investigated the performance of HDH desalination system coupled with dual purpose solar collector (DPSC), as shown in Fig. 13. The DPSC was used to heat air and water simultaneously. The shape of DPSC was rectangular having dimensions of $0.95 \times 0.75 \times 0.12$ m with 10° inclination angle. The turbulators (convex and concave type) were used to create turbulence in air, which increases the temperature of air and moisture carrying capacity of air. The increase in specific humidity of air increases the condensation rate, which results in higher productivity of the system. The maximum productivity of the system was obtained using concave turbulators (0.01523 m^3/day) with cost of water as 25.7 \$/m^3. The system's overall efficiency was 68%.

(Xiao et al. 2021) uses Fresnel lens solar collector (FLSC) to heat the seawater inside the humidifier. The effective length and breadth of FLSC was 1.0 and 1.3 m, respectively (effective area of 1.3 m^2). The diameter of cylindrical surface and focal length was 2.11 and 1.11 m, respectively, with optical efficiency of 90%. The bubble column humidifier and dehumidifier were used. The maximum yield of HDH desalination system was 1.24 kg/h/m^2 with thermal efficiency of 69%, which was obtained at 980 W/m^2 of solar radiation. (Mohamed et al. 2021a) experimentally studied the performance of solar HDH desalination system using closed air loop. SWH using evacuated tubes was used to increase the temperature of seawater, which results in enhancement in yield of the system. It was observed that with every 10 °C increase in water temperature, the yield of system was increased on an average by 69%. The yield and GOR of the HDH system were 0.00699 m^3/h and 0.81, respectively, at maximum water temperature of 70 °C.

It is observed that FPC was extensively used for air and water heating system. The efficiency and working temperature range of FPC is low. So, for air heating, ETC can be used which helps in achieving higher temperature of air and higher productivity from the desalination system. Also, to run the system continuously, sensible and latent heat storage medium can be used, which results in higher productivity and low cost per liter. It is noted that the closed cycle configuration enhances the performance of the HDH desalination system by reducing the required input energy to heat the feed water. Also, the performance of the HDH desalination system is higher with the use of hot water as compared to the use of hot air because of the greater heat capacity of water compared to the air.

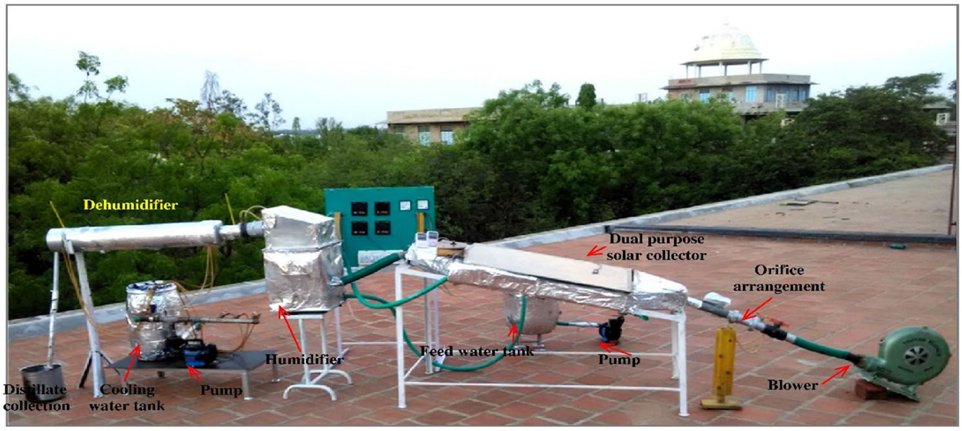


Fig. 13 Image of HDH system coupled with DPSC (Rajaseenivasan & Srithar 2017b) with permission from Elsevier

Advancements in HDH desalination system

In the above section, various research in the field of humidifier, dehumidifier and heat source for solar thermal HDH desalination system (STHDH) is discussed. With the aim to enhance the performance of solar thermal HDH desalination system, many researchers have done research on integration of STHDH desalination system with other system (such as heat pump, solar still, dryer and air conditioning system). This section covers the advancement in the field of STHDH desalination system.

- Solar thermal HDH desalination system integrated with solar still

(Abdullah et al. 2018) experimentally investigated the HDH system coupled with six wick solar still, as shown in figure 14. The effective area of each solar still was 0.5 m^2. The brine of humidifier was used as feed water in wick solar still. Different packing materials (aspen pads & thorn trees) were used at different flow rate of water (1, 2, 3 & 4 kg/s). It was observed that aspen pads at water flow rate of 4 kg/s produce maximum amount of freshwater having GOR of 4.5. Also, by increasing the flow rate of water from 2 to 4 kg/s, the GOR of system was enhanced by 11.76%. It was observed that the productivity of the combined system was 0.12 m^3/day, which was much higher than as compared to the simple HDH desalination system. (Sharshir et al. 2016a, b) experimentally investigated the performance of hybrid desalination system which consists of HDH system coupled with four solar stills. The drain water of HDH system was feeded to the solar still to prevent the loss of energy available with the drain water. The reuse of drain water, enhances the GOR by 50% and the efficiency of solar still by 90%. The maximum productivity of hybrid system was 0.0663 m^3/day with cost of freshwater as 34 \$/m^3. (Farshchi Tabrizi et al. 2016) experimentally investigated the performance of HDH desalination system integrated with cascade solar still. The solar still produced freshwater as well as hot water. The hot water generated by cascade solar still was sprayed in humidifier. The efficiency and productivity of the combined system was increased from 9 to 20% and 28 to 141%, respectively, at saline water flow rate of 0.04–0.15 L/min. The maximum productivity of integrated system was 0.0054 m^3/day with efficiency of 39% at minimum flow rate.

- Solar thermal HDH desalination system integrated with heat pump

(Ayati et al. 2020) experimentally investigated the performance of two vacuum HDH desalination systems incorporated with heat pump. In the first setup, compressor and throttle valve was used to obtain the vacuum in the humidifier, whereas in the second setup, liquid ring vacuum pump was utilized for obtaining vacuum in the humidifier. The power consumption of heat pump was 3.2 kW and the refrigerant used in heat pump was R22. It was observed that incorporating the heat pump with vacuum HDH system enhanced the productivity by 25% at 43 kPa of humidifier pressure. On the other hand, power consumption of the system was also increased by 9%. The maximum productivity of the combined system was 0.00112 m^3/h at 43 kPa of humidifier pressure and 90 °C temperature of saline water. (Lawal et al. 2020) experimentally investigated the open air-open water HDH desalination system coupled with heat pump, as shown in Fig. 15. The evaporator of heat pump helps in the dehumidification process whereas condenser helps in the humidification process.

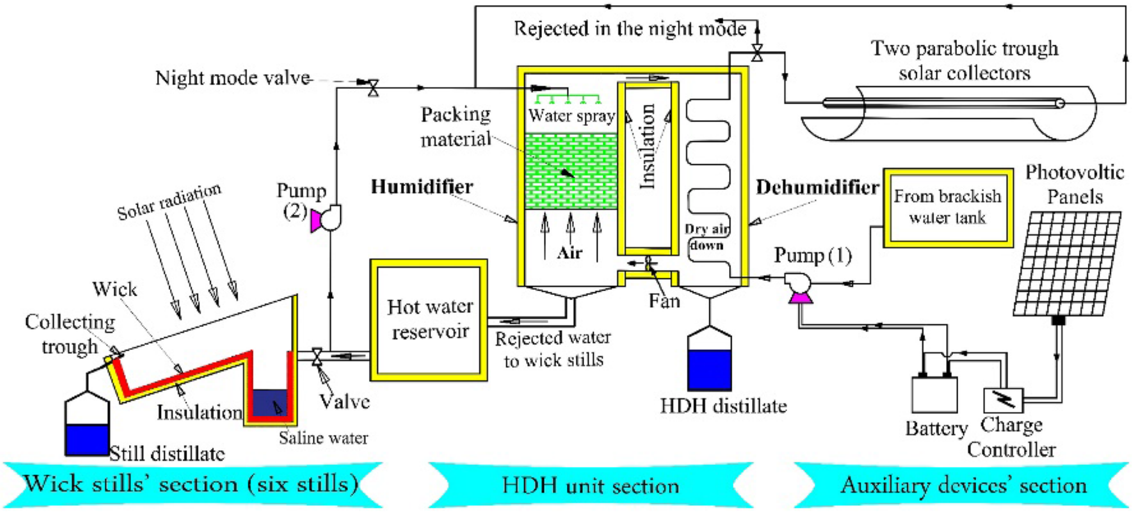


Fig. 14 Schematic diagram of HDH system coupled with wick solar still (Abdullah et al. 2018) with permission from Elsevier

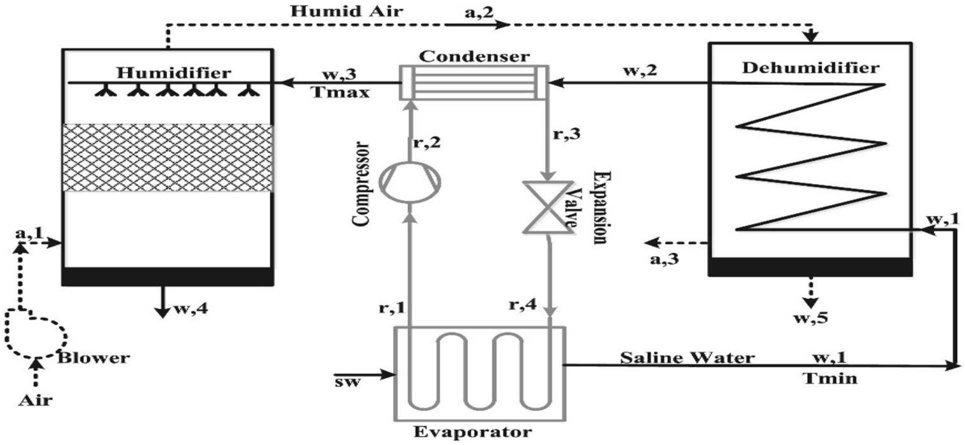


Fig. 15 Schematic diagram of HDH system combined with heat pump (Lawal et al. 2020) with permission from Elsevier

The cross section of humidifier was 0.3 × 0.37 m having 1.1 m of height. The packing material was cellulose pads having 8.1 m^2 of wetted surface area. The dehumidifier consists of fin-tube heat exchanger with cross section of dehumidifier as 0.3 × 0.39 m and 1.1 m of height. The refrigerant used in heat pump was R-134a. The important factors which affected the productivity of the desalination system were ratio of flow rate of seawater & air and temperature of seawater. At seawater temperature of 23.5 °C and air flow rate of 0.105 kg/s, the productivity was 0.0076 m^3/h. It was observed that increasing the temperature of seawater from 23.5 to 31.8 °C, the productivity was enhanced by 21.94%. The maximum GOR and recovery ratio was 2.72 and 2.56, respectively. (Anand et al. 2022) experimentally investigated the HDH system incorporated with modified heat pump for producing freshwater as well as for cooling. The modified condenser of heat pump was utilized as a humidifier and the evaporator as a dehumidifier which eliminates the heat source and heat exchanger of the conventional HDH system. By keeping air flow rate fixed and by increasing the flow rate of saline water, the GOR and cooling rate of the system increases. The maximum productivity of the system was 0.00294 m^3/h with GOR of 1.30.

- Solar thermal HDH desalination system integrated with drying system

(Kabeel & Abdelgaied 2018) coupled the two-stage drying system with HDH desalination system. It consists of drying unit, blower, SAH, humidifier, dehumidifier (2-stage), SWH. The air (cool and humid) from 2nd stage dryer was feed to the humidifier and then from humidifier, hot and humid air was condensed in two stages of dehumidifier. The flow rate of cooling water and saline water was 6 L/min and 4.5 L/min, respectively. It was observed that at 60 m^3/h of air flow rate, the productivity and moisture removal rate of 1st dryer & 2nd stage dryer were 0.03354 m^3/day and 5.634 & 4.044 kg/day, respectively. Also, increasing the flow rate of air from 50 to 75 m^3/h, the productivity and GOR of the system was enhanced by 43 and 29%, respectively.

- Modified solar thermal HDH desalination system

(E. S. Ali et al. 2021) experimentally investigated the HDH desalination system coupled with adsorption cycle and ejectors. The waste energy of silica gel from adsorption cycle was utilized by HDH desalination system which improved the performance of the overall system. The use of waste heat increases the productivity of HDH system by 80%. The productivity of proposed system obtained was 83.1 m^3 per ton with GOR and cost of freshwater as 2.7 and 1.49 \$/m^3, respectively. (Rahimi-Ahar & Hatamipour 2021) experimentally investigated the performance of solar driven multi stage HDH desalination system. The humidifier and dehumidifier of conventional HDH system was modified which gives better results as compared to the other HDH desalination system. The results showed that by increasing the temperature of water and by decreasing the humidifier pressure, the performance of desalination system can be improved. The maximum yield was 0.0018 m^3/h with cost of 0.002 \$/m^3. (Al-Otoom & Al-Khalaileh 2020) experimentally investigated the HDH desalination system using rotating belt and hygroscopic solutions. The hygroscopic solutions ($CaCl_2$ and Kaolin) were used to increase the contact surface area and evaporation rate. It was observed that kaolin solution had better performance which results in three-time higher evaporation rate with thermal efficiency of 61%. The productivity of system was 0.032 m^3/day using kaolin solution.

The research done by various researcher has been assessed & discussed in this section. It is observed that, integrating other system enhance the productivity and GOR of the solar thermal HDH desalination system. But integrating heat pump with STHDH desalination system increase the power consumption, which can be minimize

Table 3 Comparison of various HDH desalination systems

References	Heat source	Cycle	Packing material	Productivity (Kg/h)	GOR	Remarks
Narayan et al. (2010a)	Electric heater	CA-OW	–	29.16	2.6	To obtain the higher GOR of HDH system without air extraction in between the stage, the system should be operated at a higher top temperature of brine
Kabeel et al., (2014)	Solar energy	CA-OW	Cellulose paper	23.6	–	The maximum performance was achieved in the case of forced circulation of air. The optimum thickness of packing material was 5 mm to obtain higher productivity
Li et al., (2014)	Solar energy	OA-CW	Cellulose paper	41.67	-	The productivity was enhanced by using a higher temperature and humidity ratio of air at the outlet of SAH. Increasing the temperature of sprayed water increases the temperature & moisture carrying capacity of air which enhanced the performance of the system
Zamen et al., (2014)	Solar energy	CA-OW	Cellulose paper	1.03	–	Multi-staging enhanced the productivity by 40% as compared to the single-stage system. By controlling the quality of water at the inlet & outlet, the system was able to be used in arid regions also
Hamed et al., (2015)	Solar energy	CA-OW	Cellulose paper	5.5	2.2	Increasing the temperature of sprayed water enhanced the productivity of the desalination system. The maximum productivity was obtained with preheating of feed water
Muthusamy & Srithar, (2015)	Electric heater	OA-CW	Gunny bag & saw dust	0.67	–	The maximum energy & exergy efficiency was 44% & 38%, respectively. The use of inserts in air heaters enhanced productivity by 45%
Giwa et al., (2016)	Solar energy	CA-OW	–	2.28	–	The use of PV panels in the HDH desalination system minimizes the environmental impact by 83.6% which was achieved by utilizing the heat recovery from the PV panel
Li & Zhang, (2016)	Solar energy	OA-CW	Porous fiber membrane	1.17	–	Solar energy provides around 92% of the energy required by the HDH desalination system. The polyvinyl alcohol & polyvinylidene fluoride layer were used to prevent the packing material from pollutant gases
Elminshawy et al., (2016)	Solar & geothermal energy	OA-CW	–	8	1.58	By increasing the flow rate of water in the geothermal tank, the absolute humidity was enhanced by 46%. The productivity and GOR of the combined system were enhanced by increasing the temperature of water in the geothermal tank
Rajaseenivasan et al., (2016)	Solar energy	OA-CW	–	2.99	3.3	The efficiency of the humidifier and overall system was 92% and 78%, respectively, by using turbulator in the SAH. Increasing the temperature of air increases the humidity ratio of air resulting in more condensation of hot & humid air

Table 3 (continued)

References	Heat source	Cycle	Packing material	Productivity (Kg/h)	GOR	Remarks
Rajaseenivasan & Srithar, (2017a)	Biomass	OA-CW	–	6.1	1.00	The performance of the humidifier was mainly affected by the temperature of sprayed water. The GOR of the system was lower than the solar HDH system but the productivity was higher due to the use of air preheaters
Wu et al., (2017a, b)	Electric heater	–	Plastic balls	182	2.65	Due to the use of regeneration more latent heat of condensation was utilized which enhanced the GOR of the system
Zubair et al., (2017)	Solar energy	CA-OW	–	4.00	1.60	The optimum flow rate ratio and temperature at the outlet of the collector were 1.8 and 60 °C, respectively
Wu et al., (2017a, b)	Solar energy	CA-CW	Porous plastic balls	182.47	2.65	The use of latent heat of condensation and excess energy of feed water enhanced the performance of the desalination system
Shafii et al., (2018)	Heat pump	OA-CW	Cellulose pads	2.79	2.08	The GOR of the system was enhanced by increasing the flow rate & humidity ratio of air entering in the dehumidifier. Increasing the temperature of ambient air reduces the GOR of the system
Rahimi-Ahar et al., (2018)	Solar energy	CA-OW	Ceramic Rashing ring	2.2	1.28	The integration of vacuum pumps with HDH helps in achieving higher productivity and GOR of the system
Zubair et al., (2018)	Electric heater	OA-CW	Cellulose pads	–	0.71	The GOR of the system increases by increasing the mass flow rate ratio and effectiveness of the components. The re-circulation of brine enhanced the performance of the HDH desalination system
He et al., (2019a, b)	Waste heat	CA-OW	Polypropylene	289.32	3.06	The effectiveness of the humidifier was increased by reducing the enthalpy change between the inlet & outlet of the humidifier. The waste heat recovery load and flow rate of air decreases by decreasing the sprayed water temperature
Dehghani et al., (2019)	Electric heater	OA-CW	Polypropylene	4.9	0.65	The re-circulation of brine increases the total recovery ratio of the desalination system. Direct contact dehumidifier removed the corrosion problem in seawater desalination
W. He et al., (2019a, b)	Heat pump	OA-OW	Sulzer Mellapak 250 Y	89.27	4.17	The productivity was increased by 8.78 kg/h and the effectiveness of the humidifier by 12.5%. The performance was enhanced by using lower temperature difference for the evaporator & condenser
Huang et al., (2020)	Electric heater	OA-CW	–	–	3.41	Productivity & energy efficiency decreases with an increase in the level of salinity. The maximum energy efficiency was obtained when the salinity level was below 15%

Table 3 (continued)

References	Heat source	Cycle	Packing material	Productivity (Kg/h)	GOR	Remarks
Mohamed et al., (2020)	Solar energy	OA-CW	Cellulose paper	2.45	–	The GOR & yield increases by increasing the temperature of feed water beyond 50 °C. The yield & condensing rate increases by increasing the flow rate of feed water
Pourafshar et al., (2020)	Solar energy	CA-OW	–	1.14	–	The increase in the rate of evaporation is achieved by increasing the flow rate of seawater. For the region where seawater was easily available, the recommended flow rate and the condensing temperature were 0.15 kg/s and 25 °C, respectively
Wang et al., (2020)	Solar energy	OA-OW	–	4.9	0.51	The preheating of regenerated air enhanced the efficiency of electrical energy and obtained COP was 0.411. The combined system efficiency & heat capacity was 65% and 3.39 kWh, respectively
Weifeng et al., (2022)	Solar energy	CA-OW	–	57.38	1.56	The combined system (PV/T & HDH) was able to produce a good amount of freshwater & electricity
Abdelaziz et al., (2022)	Solar energy	OA-CW	–	0.702	1.54	The productivity increases by spraying very fine size of water and by decreasing the height of the water. The flow rate of air had a significant influence on the performance of the system
Alrbai, Hayajneh, Al-Dahidi, et al., (2022a, b, c)	Solar energy	CA-OW	–	3.8	3.41	The use of 10 μm size of nozzle results in better performance of the system

by using PV panels. Further, the comparison between heat source, cycle, packing material used, productivity & GOR of the available research is shown in table 3.

Optimization & design of solar HDH desalination system

The optimization & design approach helps in the prediction of system optimum performance parameters. Various research was done on optimizing the solar thermal HDH desalination system. In optimization & design, the most important part is the size of humidifier and dehumidifier. This section covers the design procedure of humidifier and dehumidifier. The current designing is based on Merkel method (Elzayed et al. 2020). Further, the optimized size and working parameters of humidifier and dehumidifier are shown in Table 4.

Humidifier

The humidifier is divided into three zone namely, spray zone, packing zone, and rain zone. From these different zones, packing zone is the most important section because it consists of packing material, which helps in evaporation of water. The height and volume of packing material is an important parameter, which needs to be optimized. Both the height and volume are the function of Merkel number. Generally, in the designing of humidifier, spray zone and rain zone are taken as 10% of packing zone. The assumptions for designing of humidifier are (Elzayed et al. 2020):

- The losses from the humidifier to the surrounding are neglected.
- The Lewis factor is taken as 1.
- The variation of pressure throughout is neglected.
- Steady-state condition.

Table 4 Summary of size and working parameters of solar thermal HDH desalination system

References	Humidifier			Dehumidifier	
	Cross-sectional area (m^2)	Seawater flowrate (m^3 /h)	Process air flow rate (m^3 /h)	Cross-sectional area (m^2)	Cooling water flowrate (m^3 /h)
Soufari et al., (2009)	0.134	0.25		0.126	0.25
Kabeel & El-Said, (2013)	0.16	14.4	1.08	0.1	1.44
Zamen et al., (2014)	0.5	1.4	–	30	–
Elminshawy et al., (2015)	1.2	0.18	345.6	–	–
Sharshir et al., (2016a, b)	0.4	0.15	–	0.125	0.15
Giwa et al., (2016)	-	0.0036	0.004	–	0.0036
Fouda et al., (2016)	-	0.54	0.54	–	0.54
Campos et al., (2017)	0.093	0.036	0.154	0.093	0.036
Kabeel et al., (2017)	0.135	0.077	130	0.135	0.077
Fouda et al., (2018)	–	0.54	0.54	–	0.54
Xu et al., (2019)	0.16	0.9	300	0.16	0.3
Faegh & Shafii, (2020)	0.0385	0.9	83.8	0.04	–
Mohamed et al., (2020)	0.48	0.24	0.0486	10.24	0.24
Shalaby et al., (2021)	0.25	0.36	0.000144	0.28	0.18
Memon et al., (2022)	0.0256	0.108	0.072	0.0256	0.144

The Merkel number is the dimensionless number which helps in calculating the performance of humidifier and is given as (Elzayed et al. 2020):

$$\mathrm{Me} = C_{p,w} \int_{T_{w,\mathrm{out}}}^{T_{w,\mathrm{in}}} \frac{dT_w}{h_{a,w} - h_a} \tag{1}$$

where, $h_{a,w}$ is the enthalpy of saturated air at temperature of inlet seawater and is given as:

$$h_{a,w} = \left(\delta_1 \left(\delta_2 - T_w\right)^{-1} - \delta_3\right)^{\delta_4} \tag{2}$$

And, h_a is the enthalpy of saturated air and is given as:

$$h_a = h_{a,\mathrm{in}} + C_{p,w} M_{\mathrm{FR}} \left(T_w - T_{w,\mathrm{out}}\right) \tag{3}$$

The height (H) of the packing material is given as:

$$H = \left(\frac{Me}{A_1 M_{FR}^{A_2}}\right)^{1/A_3} \tag{4}$$

where $A_1, A_2, and A_3$ are the constant which depends on the packing material type.

The volume of packing material (V_{pm}) used in the humidifier is given as:

$$V_{\mathrm{pm}} = 0.214 \times \dot{w}_{\mathrm{sw}} \times \mathrm{Me}^{1.58} \times M_{\mathrm{FR}}^{1.232} \tag{5}$$

Dehumidifier

The design method used for calculating the area of dehumidifier is ε – NTU method and the cross-flow type heat exchanger with no mixing of working fluid is adopted. The effectiveness of dehumidifier depends on number of transfer unit (NTU) and ratio of heat capacity (R) which is given as (Elzayed et al. 2020):

$$\varepsilon_{\mathrm{DH}} = 1 - \exp^{-(1+R)\mathrm{NTU}\left[I_0\left(2\mathrm{NTU}\sqrt{R}\right) + \sqrt{R} I_1\left(2\mathrm{NTU}\sqrt{R}\right) - \frac{1-R}{R} \sum_{i=2}^{inf} R^{i/2} I_i\left(2\mathrm{NTU}\sqrt{R}\right)\right]} \tag{6}$$

The ratio of heat capacity is the ratio of minimum heat capacity to the maximum heat capacity of both the working fluids and is given as:

$$R = \frac{\left[\dot{w}_{\mathrm{sw}} C_{p,\mathrm{sw}}, \dot{w}_a C_{p,a}\right]_{\mathrm{min}}}{\left[\dot{w}_{\mathrm{sw}} C_{p,\mathrm{sw}}, \dot{w}_a C_{p,a}\right]_{\mathrm{max}}} \tag{7}$$

NTU helps in determining the size of heat exchanger which is given as:

$$\mathrm{NTU} = \frac{U \times A_{\mathrm{DH}}}{R_{\mathrm{min}}} \tag{8}$$

Generally, the value of overall heat transfer coefficient (U) lies in between 5–100 W/m^{2}K (Elzayed et al. 2020). Equations (6), (7), and (8) are used to calculate the area of dehumidifier.

Analysis of solar thermal HDH desalination system

To properly assess the viability of the solar desalination system, the performance is typically assessed using a variety of criteria, like energy & exergy efficiency, GOR, and the cost of generated water. This section covers the analysis of solar thermal HDH desalination system based on energy & exergy efficiency, performance parameters and economic analysis.

Energy & exergy analysis

The thermal analysis of solar thermal HDH desalination system is depending on energy & exergy efficiency of the system. The following assumptions are taken for thermal analysis (Deniz & Çınar 2016):

- No leakage of air from the humidifier, dehumidifier and solar air heater.
- The temperature of water in dehumidifier is constant.
- Specific heat capacity of spray water is constant.

The energy input of the system is:

$$E_{\text{input}} = IA_c + E_{\text{pump}} + E_{\text{blower}} \tag{9}$$

The energy output of the system is:

$$E_{\text{output}} = \dot{M}_w \times L_v \tag{10}$$

The energy efficiency of system is:

$$\eta_e = \frac{\dot{M}_w \times L_v}{\text{IA}_c + E_{\text{pump}} + E_{\text{blower}}} \tag{11}$$

An estimate of the system's maximum usable energy output under the current environmental circumstances is provided by exergy efficiency. The exergy input of the solar HDH desalination system is given as (Kumar & Mehla 2022):

$$\varepsilon_{\text{input}} = \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \times I \times A_c \tag{12}$$

The exergy output of system is:

$$\varepsilon_{\text{output}} = \dot{M}_w \times L_v \times \left[1 - \frac{T_a}{T_{\text{fw}}}\right] \tag{13}$$

The exergy efficiency of system is:

$$\eta_\varepsilon = \frac{\dot{M}_{\text{fw}} \times L_v \times \left[1 - \frac{T_a}{T_{\text{fw}}}\right]}{\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \times I \times A_c} \tag{14}$$

Performance parameters

Some indicative measures, including GOR, specific freshwater production, recovery ratio, the mass flow rate ratio of air & water, energy reuse factor, and specific entropy generation, are used to evaluate the performance of the solar thermal HDH-based desalination system. The expression and definition of performance parameters are shown in Table 5.

Economic analysis

Economic feasibility is a crucial aspect of making decisions for any system. This seems to be particularly true in technologies that need a lot of investment, such as desalination systems. Therefore, economic evaluation is a crucial aspect for the practical feasibility of the desalination system based on HDH. (Voivontas et al. 1999) presented a procedure to evaluate the cost of freshwater produced from the desalination system using renewable energy sources (RES). The annual cost of the desalination system depends upon investment cost, operational & maintenance (O&M) cost, and the annual income. The economic analysis of the HDH desalination system on small scale was compared with the economic analysis of the RO system (Eslamimanesh & Hatamipour 2010). The use of renewable energy makes the HDH desalination system more economically feasible than as compared to the RO system. It was recommended that during economic analysis, the capacity of the system, packing material quantity, and fouling resistance were considered. It was observed that by increasing the capacity of the system, the cost of freshwater production reduces. The quantity of packing material affects the fixed cost of the system but by increasing the quantity of packing material, the heat & mass transfer between air and water increases which results in more freshwater from the system. The use of saline water in the heat exchanger causes fouling inside the heat exchanger, which increases the cost of freshwater production by 5%. (Kabeel et al. 2013) uses the total cost of ownership (TCO) concept to evaluate the cost of a hybrid desalination system (HDH combined with flash evaporation system). The TCO consists of fixed cost, operational & maintenance cost, cost of energy produced from PV panels, and income from produced freshwater. The cost of freshwater produced was minimized by different methods such as, by increasing the life of the system, which was achieved by proper selection of materials and by proper maintenance. (Rahimi-Ahar et al. 2020) present the procedure for economic analysis of solar thermal HDH desalination system which is shown in Table 6.

The economic analysis of solar thermal HDH desalination systems presented in this section are assessed and addressed. The cost of freshwater obtained from various

Table 5 Expression & definition of performance parameters

References	Parameters	Expression	Definition
Mistry et al., (2011)	Gained output ratio (GOR)	$GOR = \frac{\dot{M}_w \times L_v}{E_{Input}}$	The important metrics used to assess the HDH desalination system performance is the gained output ratio (GOR). It is defined as ratio of product of quantity of freshwater produced and latent heat of vaporization to the total energy input to the desalination system
Siddiqui et al., (2017)	Mass flow rate ratio (M_{FR})	$M_{FR} = \frac{\dot{w_{sw}}}{\dot{w}_a}$	The performance of HDH desalination system is significantly impacted by the ratio of mass flow rate (M_{FR}), which is defined as the ratio of the mass flow rate of feed water to the mass flow rate of entering air to the system
Chafik, (2003)	Specific freshwater production (S_{FW})	–	It is the daily amount of freshwater generation per square meter of the collector. It helps to examine how effectively the HDH desalination system uses solar energy to generate freshwater
Sharqawy et al., (2014)	Recovery ratio (R_r)	$R_r = \frac{\dot{M}_w}{\dot{w_{sw}}}$	The recovery ratio is measured as the ratio of quantity of freshwater produced from the system to the quantity of feed water to the system. The recovery ratio of desalination system is enhanced by reducing salinity of water and by using multi-staging in desalination system
Hamieh & Beckman, (2006)	Energy reuse factor (E_{rf})	$E_{rf} = \frac{V_{D,in} - V_{D,out}}{V_{D,in} - V_{H,out}}$	Many researches have been done for recovery of heat to reduce the cost of energy. The energy reuse factor is defined as the ratio of amount of useful heat absorb from the working fluid to the total energy of the working fluid. From the literature, the optimum value of E_{rf} is in the range of 6 to 12 (Narayan et al. 2010a, b)
Mistry et al., (2010)	Specific entropy generation (S_{gen})	$S_{\mathrm{gen}} = \frac{\sum(\ddot{S}_{\mathrm{gen}})_{\mathrm{components}}}{\dot{M}_w}$	The specific entropy generation is defined as the ratio of entropy generation rate of each component in HDH desalination system to the total freshwater produced from the system

Table 6 Equations to calculate the cost per liter of the solar thermal HDH desalination system (Rahimi-Ahar et al. 2020)

Cost	Expression	Unit
Annual cost (A_C)	$F_{YC} + M_{YC} + R_{YC} - S_{YC}$	\$
First-year cost (F_{YC})	$I_C \times C_{RF}$	\$
Capital recovery factor (C_{RF})	$\frac{m(m+1)^j}{(m+1)^j - 1}$	–
Maintenance cost (M_{YC})	$F_{YC} \times 0.15$	\$
Yearly running cost (R_{YC})	$E_R \times e_c$	\$
Energy required (E_R)	$R_d \left(\sum P_e\right) t$	kWh
Cost of electricity	e_c	\$/kWh
Yearly salvage cost (S_{YC})	$S_C \times S_{FF}$	\$
Salvage cost (S_C)	$I_C \times 0.2$	\$
Sinking fund factor (S_{FF})	$m / \left\{(m+1)^j - 1\right\}$	–
Initial cost (I_C)	$\sum_{i=1}^{n} C_e$	\$
Yearly productivity (P_Y)	$R_d \times \dot{m}_{fw}$	L
Cost per liter (C_{PL})	$\frac{A_C}{P_Y}$	\$/L

Table 7 Cost of freshwater produced from various HDH desalination systems

References	Cost (\$/m^3)
Yuan et al., (2011)	2.8
Behnam & Shafii, (2016)	28
Deniz & Çınar, (2016)	98.1
Zubair et al., (2017)	32–38
Ahmed et al., (2017)	10
He et al., (2018)	20
He et al., (2019a, b)	8.04
Zhao et al., (2019)	3.86
Faegh & Shafii, (2020)	19
Mohamed et al., (2020)	47
Dave et al., (2021)	7–35
Baniasad Askari & Shahsavar, (2021)	5.33
Mohamed et al. (2021b)	12
Xiao et al., (2021)	27
Ali et al., (2021)	1.49
Rahimi-Ahar & Hatamipour, (2021)	2
Alrbai et al. (2022b)	54.3

HDH desalination system is shown in Table 7. It is observed that, the cost of freshwater is in the range of 0.015–0.04 ($/m^3), which is reasonably low and makes the HDH desalination system for the practical application. Also, to reduce the cost of HDH desalination system, it might be integrated with solar energy.

Conclusion and recommendations

Continuous depletion of freshwater and rapid increase in population of human being results in scarcity of freshwater. The seriousness of this significant issue demands the desalination of seawater. The high carbon emissions, energy demands, and inefficient existing desalination systems force us to find an alternative desalination system that can run on renewable energy sources. In this review, the ideas, effect of various components, design & operating parameters, and categories of the HDH desalination system is thoroughly covered. The conclusion and recommendation are listed below:

- The productivity of solar thermal HDH desalination system can be increased by increasing the evaporation rate, which is achieved by increasing the contact time and contact area of air and sprayed water inside humidifier. To increase the contact time and contact area, packing materials are used. The different types of packing materials were used till now are cellulose pads, tri-pack rings, pall rings, saddle rings and snowflake rings, polypropylene, porous plastic balls, and thorn tree, etc. The polypropylene and porous plastic balls are found as most efficient packing materials. The use of plastic balls increases the pressure drop inside humidifier so the honey comb structure porous plastic can be used. As, use of plastic can impact environment so eco-friendly materials like porous clay and jute can be used in humidifier.
- The size of humidifier can be reduced with increase in temperature of process air and saline water. The evaporation rate of saline water inside humidifier can be improved by increasing contact area between process air and saline water, which can be done by reducing the size of water droplets. The nozzle with small diameter can produce small size of water droplets.
- In dehumidifier, the temperature of working medium (saline water) inside the heat exchanger should be low to increase the condensation rate.
- So, it is recommended to use indirect evaporative cooler, which can maintain the temperature of saline water as low as wet bulb temperature of ambient air.
- For dehumidifier, the fin-tube type heat exchanger along with saline water as working medium is first choice of researchers, but the use of saline water inside the tube of heat exchanger increases fouling problem, which further increases the cost of freshwater production by 5%.
- It is recommended to use different working medium such as thermic fluid or nanofluid in heat exchanger of dehumidifier, which eliminates the problem of fouling and increases the life of heat exchanger. Also, air-to-air heat exchanger along with direct evaporative cooler can be used for dehumidifier.
- The solar water heater and solar air heater were mostly used as heat source by researchers. It is observed that, the performance of solar thermal HDH system is higher, when solar water heater is used as heat source as compared to solar air heater. This is because water has high specific heat capacity as compared to air. But use of saline water in solar water heater might cause the problem of salt deposition, which is difficult to remove.
- It is recommended to prefer air heating system as a heat source to increase the life of the system. Further, for air heating, mostly flat plate collector was used. The use of evacuated tube collector in air heating system can be a possible way to increase the performance and efficiency of the system. It is recommended to use heat storage unit along with solar collector, which can help in continuous operation of system and can increase the productivity of the system.
- The integration of solar still, heat pump, dryer, and air conditioning system with solar thermal HDH desalination system increases the performance of the overall system, but it makes the system complicated.
- It is recommended to use multi-staging of humidification & dehumidification process to increase the performance of the system.
- It is observed that the cost of freshwater produced by solar thermal HDH desalination system is in the range of 0.015–0.04 ($/L), which is reasonably low. So, the solar thermal HDH desalination system can be used for practical applications. The cost of freshwater can be reduced by increasing the area of solar collector, which helps in absorbing more solar radiation and produce more freshwater. Also, proper maintenance of the system can also help to minimize the cost of freshwater.
- The performance of solar thermal HDH desalination system was reported in terms of GOR, recovery ratio, productivity, and mass flow rate ratio.
- It is recommended to focus on exergy and environmental analysis of these system. The exergy analysis helps us to understand the amount of energy destruction in different components of the system. The environmental analysis helps us to understand the carbon layout of the system. So, more research is needed in the field of exergy and environmental analysis of solar thermal HDH desalination system.

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Declarations

Competing interests The authors declare no competing interests.

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