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Water desalination using humidification/dehumidification (HDH) technique powered by solar energy: a detailed review

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ABSTRACT

Water and energy are two of the most important topics on the international environment and development agenda. The social and economic health of the modern world depends on sustainable supply of both energy and water. Many areas worldwide that suffer from fresh water shortage are increasingly dependent on desalination as a highly reliable and nonconventional source of fresh water. So, desalination market has greatly expanded in recent decades and expected to continue in the coming years. In the developing world, water scarcity led to the pressing need to develop inexpensive, decentralized small-scale desalination technologies that use renewable resources of energy. This study reviews one of the most promising of these technologies, humidification–dehumidification (HDH) desalination powered by solar energy. The different types of HDH cycle design and its constituents (humidifier, solar heaters, and dehumidifiers) have been investigated. The review also includes water sources, demand, availability of potable water and purification methods. It is concluded that HDH technology is a promise process for decentralized small-scale water production applications, but it needs additional research and development to enhance the system efficiency and economy.

Keywords: Water desalination; Humidification–dehumidification; Solar-driven

1. Introduction

World population growth rate especially in developing countries has brought many concerns such as poverty, pollution, health, and environmental problems. Currently, one-fourth of habitants in the world is deprived of sufficient pure water either by water quality or by geographical distribution [1]. Table 1 shows the distribution of world population since 1950 and predictions up to 2050. As observed, the world population is more concentrated in developing countries located in Africa and Asia. Therefore, water desalination technology is seems more necessary in these regions.

1.1. *Natural water resources*

Water is one of the most abundant resources on Earth, covering three-fourths of the planet's surface. About 97% of the Earth's water is salt water in the oceans and 3% is fresh water contained in the poles (in the form of ice), ground water, lakes, and rivers, which supply most of human and animal needs.

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Table 1
Distribution of world population since 1950 and predictions up to 2050 (millions) [1]

Year	USA	EU	Africa	Asia	Total
1950	158	296	221	1,377	2,522
1960	186	316	277	1,668	3,022
1970	210	341	357	2,101	3,696
1980	230	356	467	2,586	4,440
1990	254	365	615	3,114	5,266
2000	278	376	784	3,683	6,055
2010	298	376	973	4,136	6,795
2020	317	371	1,187	4,545	7,502
2030	333	362	1,406	4,877	8,112
2040	343	349	1,595	5,118	8,577
2050	349	332	1,766	5,268	8,909

Nearly, 70% from this tiny 3% of the world's fresh water is frozen in glaciers, permanent snow cover, ice and permafrost. Thirty percent of all fresh water is underground, most of it in deep, hard-to-reach aquifers. Lakes and rivers together contain just a little more than 0.25% of all fresh water; lakes contain most of it [2,3]. Table 2 gives a summary for the distribution of various water resources across the globe. The global daily average of rainfall is $2(10^{11})$ m^3, and this amount is poorly distributed across the globe.

1.2. *Consumption and the lacks*

The Millennium development goals set by the United Nations highlight the critical need of impoverished and developing regions of the world to achieve self-sustenance in potable water supply [4]. Human has been dependent on rivers, lakes, and underground water reservoirs for fresh water requirements in domestic life, agriculture, and industry. About 70% of total water consumption is used by agriculture, 20% is used by the industry, and only 10% of the water consumed worldwide is used for household needs [2]. However, rapid industrial growth and the worldwide population explosion have resulted in a large escalation of demand for fresh water, both for the household needs and for crops to produce adequate quantities of food. Added to this is the problem of pollution of rivers and lakes by industrial wastes and the large amounts of sewage discharged. In total, water demand doubles every 20 years, so the water emergency situation is certainly very alarming [2,3].

Table 2
Distribution of various water resources across the globe

Resource	Volume (km^3)	Percent of total water	Percent of fresh water
Atmospheric water	12,900	0.001	0.01
Glaciers	24,064,000	1.72	68.7
Ground ice	300,000	0.021	0.86
Rivers	2,120	0.0002	0.006
Lakes	176,400	0.013	0.26
Marshes	11,470	0.0008	0.03
Soil moisture	16,500	0.0012	0.05
Aquifers	10,530,000	0.75	30.1
Lithosphere	23,400,000	1.68	
Oceans	1,338,000,000	95.81	
Total	1,396,543,390		

1.3. *The need for desalination*

The only solutions for the escalation of fresh water demand are seas and oceans that nearly is an inexhaustible sources of water. Their main drawback, however, is their high salinity. Therefore, it would be attractive to tackle the water-shortage problem with desalination of this water.

Desalinize in general means to remove salt from seawater or generally saline water. According to World Health Organization (WHO), the permissible limit of salinity in water is 500 parts per million (ppm) and for special cases up to 1,000 ppm, while most of the water available on Earth has salinity up to 10,000 ppm, and seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts [2,3]. Excess water salinity causes the problem of taste, stomach problems, and laxative effects. The purpose of a desalination system is to clean or purify brackish water or seawater and supply water with total dissolved solids within the permissible limit of 500 ppm or less. This is accomplished by several desalination techniques that may be classified into conventional and nonconventional methods.

However, conventional desalination technologies are usually large-scale, technology-intensive systems most suitable for the energy-rich and economically advanced regions of the world. They also cause environmental hazards because they are fossil–fuel-driven and also because of the problem of brine disposal. In the following sections, these conventional desalination technologies are introduced and their drawbacks are discussed.

Egypt is relatively modest in its water resources. Egypt's Nile water quota is put at 5.5 billion m^3, which represents 79.3% of the country's water resources and covers around 95% of its current needs.

Now, the current water desalination production in Egypt is $0.06 \times 10^9\,m^3$ which is targeted to be raised to $0.14 \times 10^9\,m^3$ by 2017 especially by using the low-cost techniques.

2. Desalination technologies

2.1. Conventional desalination technologies

Desalination of seawater or brackish water is generally performed by either of two main processes: by evaporation or by use of a semi-permeable membrane to separate fresh water from a concentrate. The most important of these technologies are listed in Table 3. In the phase-change or thermal processes, the distillation of seawater is achieved by utilizing a heat source. The heat source may be obtained from a conventional fossil/fuel, nuclear energy or from a nonconventional source like solar energy or geothermal energy. In the membrane processes, electricity is used either for driving high-pressure pumps or for establishing electric fields to separate the ions.

The most important commercial desalination processes [5] based on thermal energy are multistage flash (MSF) distillation, multiple effect distillation (MED), and vapor compression (VC), in which compression may be accomplished thermally (TVC) or mechanically (MVC). The MSF and MED processes consist of many serial stages at successively decreasing temperature and pressure. The MSF process is based on the generation of vapor from seawater or brine due to a sudden pressure reduction (flashing) when seawater enters an evacuated chamber. The process is repeated stage-by-stage at successively decreasing pressures. Condensation of vapor is accomplished by regenerative heating of the feed water. This process requires an external steam supply, normally at a temperature around 100°C. The maximum operating temperature is limited by scale formation, and thus, the thermodynamic performance of the process is also limited. For the MED system, water vapor is generated by heating the seawater at a given pressure in each of a series of cascading chambers. The steam generated in one stage, or "effect" is used to heat the brine in the next stage, which is at a lower pressure. The thermal performance of these systems is proportional to the number of stages, with capital cost limiting the number of stages to be used. In TVC and MVC systems, after vapor is generated from the saline solution, it is thermally or mechanically compressed and then condensed to generate potable water.

Table 3
Desalination processes

Thermal processes (phase-change)	Membrane processes
(1) Multistage flash (MSF)	(1) Reverse osmosis (RO)
(2) Multiple effect distillation (MED)	(2) Electrodialysis (ED)
(3) Vapor compression (VC)	(3) Nanofiltration
(4) Solar stills	
(5) Freezing	

The second important class of industrial desalination processes uses membrane technologies. These are principally reverse osmosis (RO) and electrodialysis (ED). The former requires power to drive a pump that increases the pressure of the feed water to the desired value. The required pressure depends on the salt concentration of the feed. The pumps are normally electrically driven [6]. The ED process also requires electricity to produce migration of ions through suitable ion-exchange membranes [7]. Both RO and ED are useful for brackish water desalination; however, RO is also competitive with MSF distillation processes for large-scale seawater desalination.

The MSF process represents more than 90% of the thermal desalination processes, while RO process represents more than 80% of membrane processes for water production. MSF plants typically have capacities ranging from 100,000 to almost $1,000,000\,m^3/day$ [8]. The largest RO plant currently in operation is the Ashkelon plant, at $330,000\,m^3/day$ [9]. Other approaches to desalination include processes like the ion-exchange process, liquid–liquid extraction, and the gas hydrate process. Most of these approaches are not generally used unless when there is a requirement to produce high purity (total dissolved solids < 10 ppm) water for specialized applications.

Another interesting process that has garnered much attention recently is the forward osmosis process [10]. In this process, a carrier solution is used to create a higher osmotic pressure than that of seawater. As a result the water in seawater flows through the membrane to the carrier solution by osmosis. This water is then separated from the diluted carrier solution to produce pure water and a concentrated solution which is sent back to the osmosis cell. This technology is yet to be proven commercially.

2.2. Limitations of conventional technologies

Conventional processes like MSF and RO require large amounts of energy in the form of thermal energy (for MSF) or electric power (for RO). Most desalination plants using these technologies are fossil–fuel-driven. This results in a large carbon footprint for the desalination plant, and sensitivity to the price and availability of oil. To avoid these issues, desalination technologies based on renewable energy are highly desirable.

Solar energy is the most abundantly available energy resource on earth. Solar desalination systems are classified into two main categories: direct and indirect systems. As their name implies, direct systems use solar energy to produce distillate directly using the solar collector, whereas in indirect systems, two sub-systems are employed (one for solar power generation and one for desalination). Various solar desalination plants in pilot and commercial stages of development were reviewed by [11].

In concept, solar energy-based MSF and MED systems are similar to conventional thermal desalination systems. The main difference is that in the former, solar energy collection devices are used. Some proposals use centralized, concentrating solar power at a high receiver temperature to generate electricity and water in atypical large-scale coproduction scheme [12]. These solar energy collectors are not yet commercially realized. It should be noted that at lower operating temperatures, solar collectors have higher collection efficiency, owing to reduced losses, and also, can be designed to use less expensive materials. Moreover, owing to their fossil-fuel dependence, conventional desalination techniques are less applicable for decentralized water production. Decentralized water production is important for regions which have neither the infrastructure nor the economic resources to run MSF or RO plants and which are sufficiently distant from large-scale production facilities that pipeline distribution is prohibitive. Many such regions are found in the developing world in regions of high incidence of solar radiation. The importance of decentralizing water supply was reviewed in detail by [13].

For small-scale applications (from 5 to $100\,\mathrm{m}^3$/day water production), the cost of water production systems is much higher than for large-scale systems. For RO systems, which are currently the most economical desalination systems, the cost of water production can go up to US\$ 3/m^3 [14] for plants of smaller capacity. Also, RO plants require expert labor for operation and maintenance purposes. This a clear disadvantage for small-scale applications in less developed areas, particularly when compared to the HDH system.

3. Humidification–dehumidification (HDH) technology

The Sun, which drives the water cycle, Fig. 1, heats water in oceans and seas. Water evaporates as water vapor into the air. Ice and snow can sublimate directly into water vapor. Evapotranspiration is water transpired from plants and evaporated from the soil. Rising air currents take the vapor up into the atmosphere where cooler temperatures cause it to condense into clouds. Air currents move water vapor around the globe, cloud particles collide, grow, and fall out of the upper atmospheric layers as precipitation. Some precipitation falls as snow or hail, sleet and can accumulate as ice caps and glaciers, which can store frozen water for thousands of years. Most water falls back into the oceans or onto land as rain, where the water flows over the ground as surface runoff. A portion of runoff enters rivers in valleys in the landscape, with stream flow moving water toward the oceans. Runoff and groundwater are stored as freshwater in lakes. Not all runoff flows into rivers, much of it soaks into the ground as infiltration. Some water infiltrates deep into the ground and replenishes aquifers, which store freshwater for long periods of time. Some infiltration stays close to the land surface and can seep back into surface-water bodies (and the ocean) as groundwater discharge. Some groundwater finds openings in the land surface and comes out as freshwater springs. Over time, the water returns to the ocean, where our water cycle started. The imitation version of this cycle is called the humidification–dehumidification desalination (HDH) cycle.

The HDH cycle has received much attention in recent years, and many researchers have investigated the intricacies of this technology. It should be noted here that the predecessor of the HDH cycle is the simple solar still. Several researchers [15–17] have reviewed the numerous works on the solar still, and hence, it is important to understand the disadvantages of the solar still concept. The basic design of a solar still desalination is shown in Fig. 2.

The most prohibitive drawback of a solar still is its low efficiency (gained-output-ratio less than 0.5) which is primarily the result of the immediate loss of the latent heat of condensation through the glass cover of the still. Some designs recover and reuse the heat of condensation, increasing the efficiency of the still. These designs (called multieffect stills) achieve some increase in the efficiency of the still but the overall performance is still relatively low. The main drawback of the solar still is that the various functional processes (solar absorption, evaporation, condensation, and heat recovery) all occur within a

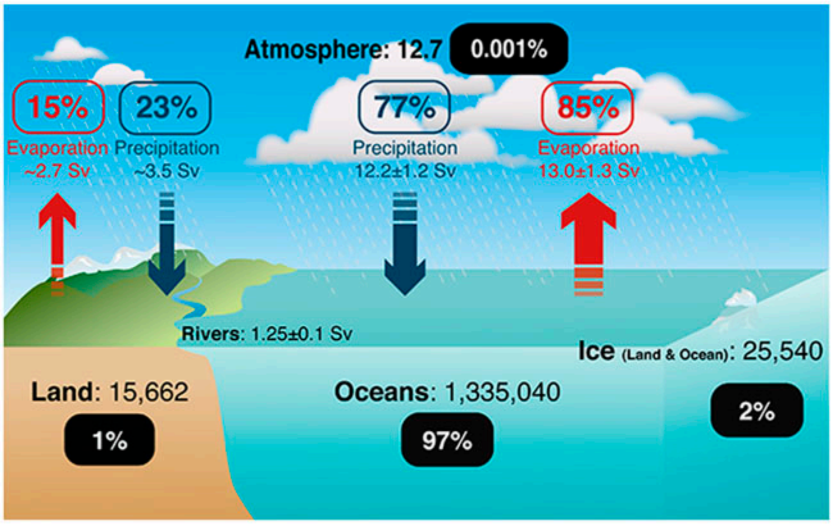

Fig. 1. Rain water cycle (natural humidification–dehumidification desalination (HDH) cycle).

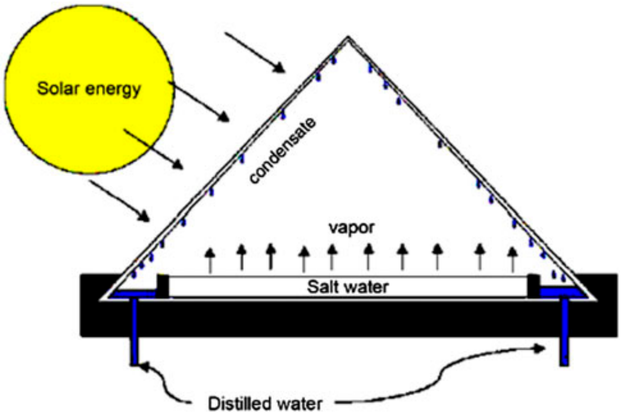

Fig. 2. The basic design of a solar still desalination.

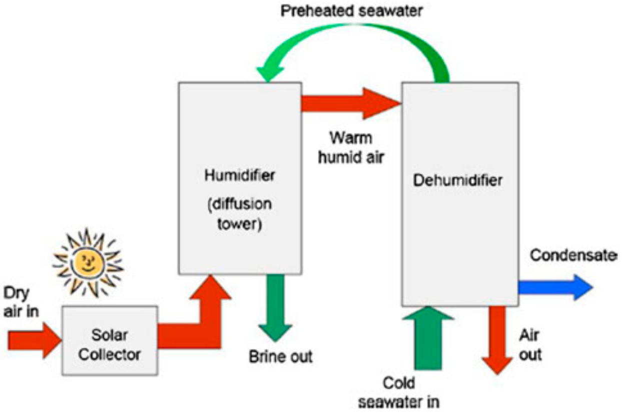

Fig. 3. The basic design of HDH process.

single component. By separating these functions into distinct components as shown in Fig. 3, thermal inefficiencies may be reduced and overall performance improves. This separation of functions is the essential characteristic of the HDH system. For example, the recovery of the latent heat of condensation, in the HDH process, is affected in a separate heat exchanger (the dehumidifier) wherein the seawater, for example, can be preheated. The module for solar collection can be optimized almost independently of the humidification or condensation component. The HDH process, thus, promises higher productivity due to the separation of the basic processes.

4. Evaluation of HDH performance

The performance of desalination process using HDH techniques is evaluated by different ways, parameters, these parameters are defined as follow:

4.1. Gained-output-ratio (GOR)

The ratio of the latent heat of evaporation of the distillate produced to the total heat input absorbed by the solar collector(s). This parameter is, essentially, the efficiency of water production and an index of the amount of the heat recovery effected in the system. This parameter does not account for the solar collector efficiency as it just takes into account the heat obtained in the solar collector. For the HDH systems to have thermal performance comparable with MSF or MED, a GOR of at least 8 (corresponding to energy consumption rates of 300 kJ/kg) should be achieved.

4.2. Specific water production

The amount of water produced per m^2 of solar collector area per day. This parameter is an index of the solar energy efficiency of the HDH cycle. This parameter is of great importance as the majority of the capital cost of the HDH system is the solar collector cost: 40–45% for air-heated systems [18] and 20–35% for water-heated systems [14].

4.3. Recovery ratio (RR)

It is the ratio of the amount of water produced per kg of feed. This parameter is also called the extraction efficiency [19]. This is, generally, found to be much lower for the HDH system than conventional systems. The advantage of a low RR is that complex brine pretreatment process or brine disposal processes may not be required for this system.

4.4. Energy reuse factor (f)

It is the ratio of energy recovered from the heated fluid to the energy supplied to the heated fluid [20]. This is another index of heat recovery of the system.

The unit product cost of fresh water differs when it is produced from different plant capacities. Table 4 shows the unit product cost of water produced from plants of different type, capacity, and source of energy. Product unit prices generally take into account all relevant costs originating from direct capital, indirect capital, and annual operating costs.

5. Theory of humidification–dehumidification

Generally, the heat transfer and diffusion of vapor through the gas at the interface between the gas and the liquid control the interaction between unsaturated gas and liquid [24]. In Fig. 4, distances measured perpendicular to the interface are plotted as abscissas, temperatures, and humilities as ordinates. The broken arrows represent the diffusion of the vapor through the gas phase, and full arrows represent the heat transfer (both latent and sensible) through gas and liquid phases. In the humidification process, the temperature of the liquid is higher than that of the gas as shown in Fig. 4(a), here both T_i and H_i are greater than T_y and H, thus the heat transfer, vapor diffusion, and the direction of temperature and humidity gradients initiate from liquid to vapor. Once evaporation of liquid commences, the liquid starts to cool. The humidity and temperature of the gas near the interface decrease as the gas move away from the interface. The temperature drop $T_x - T_i$ through the liquid phase must be sufficient to give a heat transfer rate high enough to account for both sensible and latent heats and consequently water could vaporize continuously.

Conditions at one point in dehumidification process are shown in Fig. 4(b), here H is greater than H_i, and therefore vapor must diffuse to the interface. Since T_i and H_i represent saturated gas, T_y must be greater than T_i; otherwise, the bulk of the gas would be supersaturated with vapor. These reasons lead to the conclusion that vapor can be removed from unsaturated gas by direct contact with sufficiently cold liquids without bringing the bulk of gas to saturation. At any time, the water is exiting from its surface as vapor. Meanwhile, the vapor condenses to water from the air. If the humidity increases, the amount of vapor

Table 4
Production rate, energy consumption, and the cost for different desalination technologies in cases of conventional and renewable energy sources

Source of energy	Type	Production rate, (m^3/d)	Energy consumption, (kWh/m^3)	Cost, (\$/m^3)	Reporting year
Conventional [21]	MVC	21,955	4.36	0.174	2002
	MSF	26876.4	23–27	0.292	2008
	MED	37816.3	1	0.409	2008
	RO	113.6	0.83–3.43	0.898	2008
	RO	4012.5		0.75	
	RO	37475.6		0.413	
	RO	113562.4		0.208	
Renewable [22,23]	RO, Wind	19.2	15	4.4–7.3	2003
	RO, PV	5-7.5	2.45	6.25	1995
	RO, PV	0.8	4.3–4.6	7.8	2006
	HDD	0.25–1.7	32.7	6.4–6.7	2010
	Solar MSF	10	81–106	3–4.5	1983
	Solar MED	72	60.8–75.4	2.86	2004
	Solar ED	2.8	0.82	16	1986

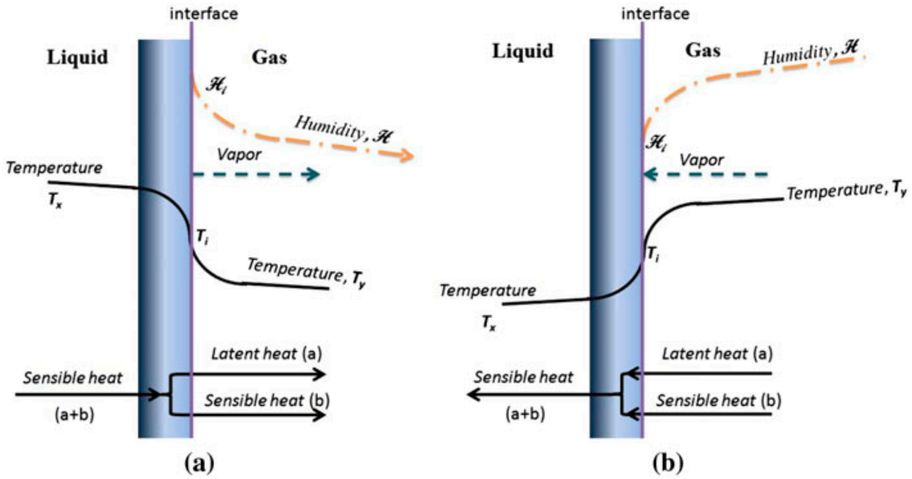

Fig. 4. (a) Conditions in variable temperature humidifier and (b) conditions in dehumidifier [25].

coming back to water increases. Such evaporation and condensation through water surface balance at the humidity of 100%.

6. Classification of HDH systems

HDH systems are classified under three broad categories. One is based on the form of energy used such as solar, thermal, geothermal, or hybrid systems. This classification brings out the most promising merit of the HDH concept: the promise of water production by use of low-grade energy, especially from renewable resources.

The second classification of HDH processes is based on the cycle configuration (Fig. 5). As the name suggests, a closed air, open water (CAOW) cycle is one in which the air is heated, humidified and partially dehumidified and circulated in a closed loop between the humidifier and the dehumidifier while, a closed water, open air (CWOA) cycle air exit from the dehumidifier and let out to atmosphere. The air in these systems can be circulated by either natural convection or mechanical blowers.

The third classification of the HDH systems is based on the type of heating used: water- or air-heating systems. The performance of the system depends greatly on whether the air or water is heated. It is of pivotal importance to understand the relative technical advantages of each of these cycles and choose the one that is best in terms of efficiency and cost of water production. In the published literature, not much attention has been paid to optimization of the cycle itself as compared to the optimization of the three subsystems. Further, a few investigators [26–28] have studied the cost of the HDH cycles and found that the cost of water production is high. This high cost may be brought down to more reasonable levels by using a source of renewable energy for heating water and air as well as understanding and optimizing the overall cycle.

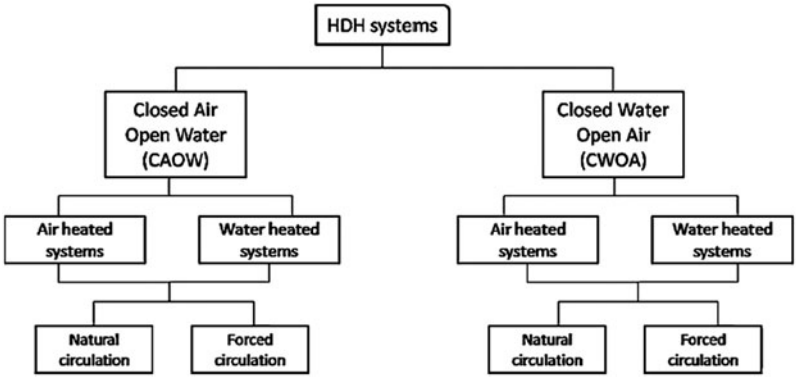

Fig. 5. Classification of typical HDH processes (based on cycle configuration).

6.1. Closed air, open water, water-heated (CAOW-WH) systems

A typical CAOW system is shown in Fig. 6. The humidifier is irrigated with hot water and the air stream is heated and humidified using the energy from the hot water stream. The humidified air is then fed to the dehumidifier and is cooled in a compact heat exchanger using seawater as the coolant. The seawater gets preheated in the process and is further heated in a solar heater before it irrigates the humidifier. The dehumidified air stream from the dehumidifier is then circulated back to the humidifier. Fig. 7 line A–B represents this process on the psychometric chart.

There are several works in the literature on this type of cycle. The important features of the system studied and the main observations from these studies are tabulated in Table 5. Some common conclusions can be drawn from this table. Almost all the investigators have observed that the performance is maximized at a particular value of the water flow rate. There is also an almost unanimous consensus that natural circulation of air yields better efficiency than forced circulation of air for the closed-air water-heated cycle. However, it is not possible to ascertain the exact advantage in performance (for natural circulation) from the data available in literature.

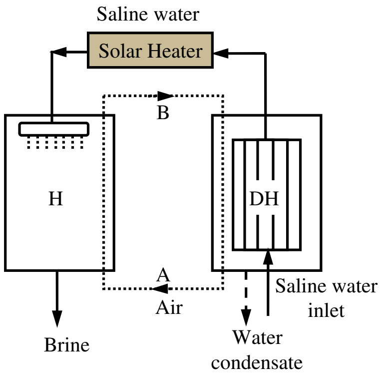

Fig. 6. Closed air, open water, water-heated (CAOW-WH) system.

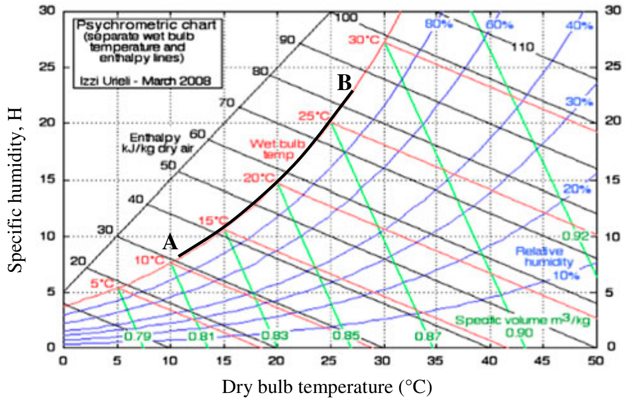

Fig. 7. Psychometric chart for closed air, open water, water-heated (CAOW-WH) system.

6.2. Closed air, open water, air-heated (CAOW-AH) systems

Air heating in humidification/dehumidification process could enhance the humidification step. Another configuration of HDH by CAOW system that has attracted much interest is the air-heated system. Table 6 represents some of previous works related to this class. These systems are of two types-single and multistage systems, Fig. 8 is a schematic diagram of a single-stage system. The air is heated in a solar collector to a higher temperature and sent to a humidifier. This heating process is represented by the constant humidity line A–B in the psychometric chart (Fig. 9). In the humidifier, the air is cooled and saturated. This process is represented by the line B–C. It is then dehumidified and cooled in the process C–A represented on the saturation line. A major disadvantage of this cycle is that the absolute humidity of air that can be achieved at these temperatures is very low (<6% by weight). This impedes the water productivity of the cycle.

Multistage heating and humidification cycle (Fig. 10) is reported by Chafik [18] to overcome the disadvantage of single-stage system. The process is represented on psychometric chart, Fig. 11, air after getting heated in the solar collector (line A–B) and humidified in the evaporator (line B–C) is fed to another solar collector for further heating (line C–D) and then to another humidifier (line D–E) and then fed to s third solar heater for further heating (line E–F) and then to another humidifier (line F–G) to attain a higher value of absolute humidity. Many such stages can be arranged to attain absolute humidity values of 15% and beyond. Point H in the figure represents the high temperature that has to be reached in a single-stage cycle to attain the same humidity as a three-stage cycle. This higher temperature has substantial disadvantages for the solar collectors. However, from an energy efficiency point of view, there is not much of an advantage to multistaging, as the higher water production comes with a higher energy input as compared to single-stage systems.

Also, from the various studies in the literature summarized in Table 6, we observe that the air-heated systems have higher energy consumption than water-heated systems. This is because air heats up the water

Table 5
Summary of various previous works on closed air, open water, water-heated (CAOW-WH) cycles in HDH

Reference	Unit description	Observation and conclusion
[29]	• Solar collector (tubeless flat-plate type of 2 m^2 area) has been used to heat the water to 50–70 ℃ and air is circulated by both natural and forced convection to compare the performance of both of these modes • Humidifier, a cooling tower with wooden surface, had a surface area 87 m^2/m^3 for the bench unit and 14 m^2/m^3 for the pilot unit • Condenser area 0.6m^2 for bench unit and 8m^2 for the pilot unit	• The authors noted that results show that the water flow rate has an optimum value at which the performance of the plant peaks • They found that at low top temperatures forced circulation of air was advantageous and at higher to temperatures natural circulation gives better performance
[30]	• Solar collector used for heating water (6 m^2 area) • There is a water storage tank which runs with a minimum temperature constraint • Cooling water provided using brackish water from a well • The packed bed type-used—Thorn trees • Dehumidifier made of polypropylene plates	• A daily water production of 19 L was reported • Without thermal storage 16% more solar collector area was reported to be required to produce the same amount of distillate • The authors also stated that the water temperature at inlet of humidifier, the air and water flow rate along with the humidifier packing material play a vital role in the performance of the plant
[31]	• 1.9 m^2 solar collector to heat the water • Air was in forced circulation • Wooden shaving packing was used for the humidifier • Multipass shell and tube heat exchanger used for dehumidification	• 12 L/m^2 production was achieved • The authors report the effect of air velocity on the production is complicated and cannot be stated simply • The water flow rate was observed to have an optimum value
[32]	• System has a thermal storage of 5 L capacity and hence has longer hours of operations • Solar collector area (used to heat water) is about 2 m^2 • Air moves around due to natural convection only • The latent is recovered partially	• The authors conclude that the water temperature at the inlet of the humidifier is very important to the performance of the cycle • They also observe that the heat loss from the distillation column (containing both the humidifier and the dehumidifier) is important in assessing the performance accurately
[33]	• This system is unique in that it uses a dual heating scheme with separate heaters for both air and water • Humidifier is a packed bed type with canvas as the packing material • Air cooled dehumidifier is used and hence there is no latent heat recovery in this system	• The authors reported a maximum production of 1.2 L/h and about 9 L/day • Higher air mass flow gave less productivity because increasing air flow reduced the inlet temperature to humidifier
[34]	• Three units constructed in Jordan and Malaysia • Different configurations of condenser and humidifier were studied and mass and heat-transfer coefficients were developed • Solar collector heats up the water to 70–80 ℃ • Air circulated by both natural and forced draft • Humidifier with vertical/ inclined wooden slates packing • Heat recovered in condenser by preheating the feed water	• The authors observed that the water flow rate has a major effect on the wetting area of the packing • They also note that natural circulation yields better results than forced circulation • The heat/mass transfer coefficient calculated were used to simulate performance and the authors report that the water production was up to 5 kg/h

(Continued)

Table 5 (*Continued*)

Reference	Unit description	Observation and conclusion
[14]	• Closed-air open-water cycle with natural draft circulation for the air • Thermal storage tank of 2m^3 size to facilitate 24 h operation • 38 m^2 collector field size heats water up to 80–90 ℃ • Latent heat recovered to heat the water to 75 ℃	• The authors report a GOR of 3–4.5 and daily water production of 500 L for a pilot plant in Tunisia • There is a 50% reduction in cost of water produced because of the continuous operation provided by the thermal storage device
[20,35–37]	• A unique HDH cycle with a direct contact packed bed dehumidifier was used in this study • The system uses waste heat to heat water to 60 ℃ • Uses a part of the water produced in the dehumidifier as coolant and recovers the heat from this coolant in a separate heat exchanger	• The authors demonstrated that this process can yield a fresh water production efficiency of 8% with an energy consumption of 0.56 kWh/kg of fresh water production based on a feed water temperature of only 60 ℃ • It should be noted that the efficiency is the same as the RR • Also the energy consumption does not include the solar energy consumed
[38]	• 1,700 m^2 solar pond (which acts as the heat storage tank) provides heated seawater to be purified • Forced air circulation • Latent heat recovered in the condenser to pre-heat seawater going to the humidifier	• Performance results not reported • Air flow rate seems to have a major impact on the production of water but surprisingly, water flow rate does not affect the performance
[39]	• Two-stage solar multi-effect humidification dehumidification desalination process plotted from pinch analysis • The solar evacuated tube collector is employed to heat the saline water • The water higher temperature range is from 60 to 80 ℃, and the lower is from 30 to 60 ℃ • The mass flow rates of dry air in the two stage desalination units are one of the parameters to be studied	• The study shows that the two-stage solar multi-effect humidification–dehumidification desalination process has a higher energy recovery rate than the one stage. • In an extreme case, the minimum temperature difference at pinches are 1 ℃, the energy recovery rate could reach 0.836. If using multistage, the energy recover rate would be higher, and that leads a higher GOR
[40]	• In this proposed system, we operate the humidifier and dehumidifier at different pressures • the pressure differential is maintained using a thermal vapor compressor (TVC) and an expander • The recovered work is used in a RO unit to desalinate the brine from the humidifier	• It has been found that recovering energy given by steam in the TVC as work in an expansion process leads to a more efficient system than using a isenthalpic throttling process. However, the use of an efficient expander leads to the majority of the water being produced in the RO unit coupled to it • For minimum specific energy consumption of the HDH-TVC-RO system, use of an efficient TVC and high pressure (Pst = 10 to 30 bar) steam are most important

in the humidifier, and this energy is not subsequently recovered from the water, unlike in the water-heated cycle in which the water stream is cooled in the humidifier. It should be noted that the CAOW air-heated systems have not been studied so far in literature and hence will not be dealt with in this study.

6.3. Multi-effect closed air, open water, water-heated (CAOW-WH) system

To enhance heat recovery, Muller-Holst [14] proposed the concept of multi-effect HDH. Figs. 12 and 13 illustrate an example of this system. Air from the humidifier is extracted at various points and supplied to the dehumidifier at corresponding points. This enables continuous temperature stratification resulting in small temperature gap to keep the process running. This in turn results in a higher heat recovery from the dehumidifier. In fact, most of the energy needed for the humidification process is regained from the dehumidifier bringing down the energy demand to a reported value of 120 kWh/m^3. This system is being commercially manufactured and marketed by a commercial water management company, Tinox GmbH. This is, perhaps, the first instance in which the HDH concept has been commercialized.

Table 6
Summary of some previous works on closed air, open water, air-heated (CAOW-AH) cycles in HDH

References	Unit description	Observation and conclusion
[18,27]	• Solar collectors (fourfold web-plate, or FFWP, design) of 2.08m^2 area heat air to 50–80 ℃ • Multistage system that breaks up the humidification and heating in multiple stagesPad humidifier with corrugated cellulose material • 3 separate heat recovery stages • Forced circulation of air	• The author reported that the built system is too costly and the solar air heaters constitute 40% of the total cost • Also he observed that the system can be further improved by minimizing the pressure drop through the evaporator and the dehumidifiers
[26]	• 5 heating and humidification stages • First two stages are made of 9 FFWP type collector of each 4.98m^2 area. The other collectors are all classical commercial ones with a 45m^2 area for the third and fourth stage and 27m^2 area for the final stage. Air temperature reaches a maximum of 90 ℃ • Air is forced-circulated • All other equipment is the same as used by Chafik [18]	• Maximum production of water was 516 L/day • Plant tested for a period of 6 months • Major dilation is reported to have occurred on the polycarbonate solar collectors • The water production cost for this system is (for a 450–500 L/day production capacity) 28.65$/m^3 which is high • 37% of the cost is that of the solar collector field
[41]	• FFWP collectors (with top air temperature of 90 ℃) were studied • Polycarbonate covers and the blackened aluminum strips make up the solar collector • Aluminum foil and polyurethane for insulation	• Variation of performance with respect to variation in wind velocity, inlet air temperature and humidity, solar irradiation and air mass flow rate was studied • Endurance test of the polycarbonate material showed it could not withstand the peak temperatures of summer and it melted. Hence, a blower is necessary • Minimum wind velocity gave maximum collector efficiency
[42]	• The experimental setup used in this work uses a solar heater for both air and water (has 2m^2 collector surface area) • There is a heat recovery unit to preheat seawater • The authors have used an evaporator with the heated water wetting the horizontal surface and the capillaries wetting the vertical plates and air moving in from different directions and spongy material used as the packing	• The authors report that there is an optimum mass flow rate of air to mass flow rate of water that gives the maximum humidification • This ratio varies for different ambient conditions
[43]	• A single-stage double-pass flat-plate solar collector heats the water • A pad humidifier is used and the dehumidifier used is a finned tube heat exchanger • Also a tubular solar water heater was used for some cases • The authors also used a 0.5 m^3 water storage tank • Heat is not recovered	• The plant produced 4 kg/day maximum • Increase in air flow rate had no effect on performance • An increase in mass flow rate of water increased the productivity • When the solar water heater was turned on the production went up to 10 kg/day maximum primarily because of the ability to operate it for more time
[44]	• The unit was conventional HD consist of two vertical ducts connected from top to bottom to form a closed loop circulation humidifier includes packing material, either plastic rings or structured packing external heat source was used for heating both air (10-85 ℃) and water (65–95 ℃)	• They found that inlet cold and hot water temperatures have significant effect on the top and bottom temperatures of columns and absolute humidity of air • The optimal configuration of HD system is consequently temperature-dependent
[45]	• Theoretical analysis based on the second law of thermodynamics for estimating the minimum work required for air dehumidification process to produce potable water in a humidification/dehumidification (HD) desalination cycle	• The estimated value of minimum work is independent of the devices involved in the process • For the same humid air temperature, the work required for dehumidification process increases with relative humidity

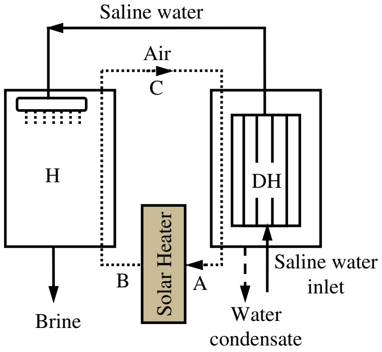

Fig. 8. Closed air, open water, air-heated (CAOW-AH) system.

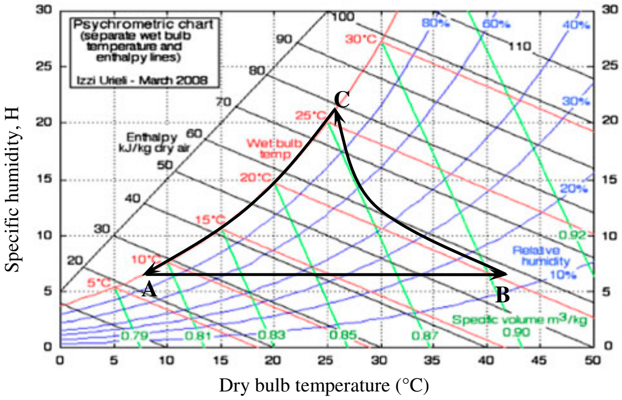

Fig. 9. Psychometric chart for closed air, open water, air-heated (CAOW-AH) system.

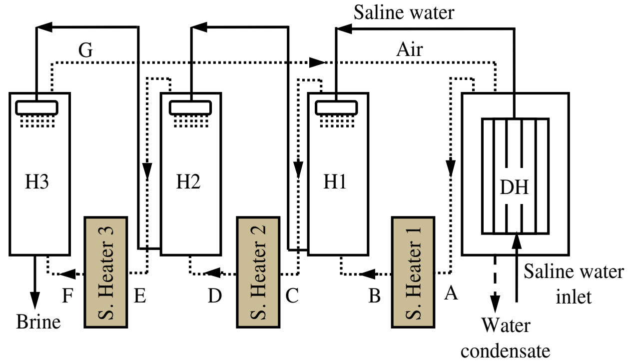

Fig. 10. Closed air, open water, multistage air-heated (CAOW-AH) system.

6.4. Closed water, open air, water-heated (CWOA-WH) systems

A typical CWOA system is shown in Fig. 14. In this system, the air is heated and humidified in the humidifier using the hot water from the solar collector and then is dehumidified using outlet water from the humidifier. The water, after being preheated in the dehumidifier, enters the solar collector, thus working in a closed loop. The dehumidified air is released to

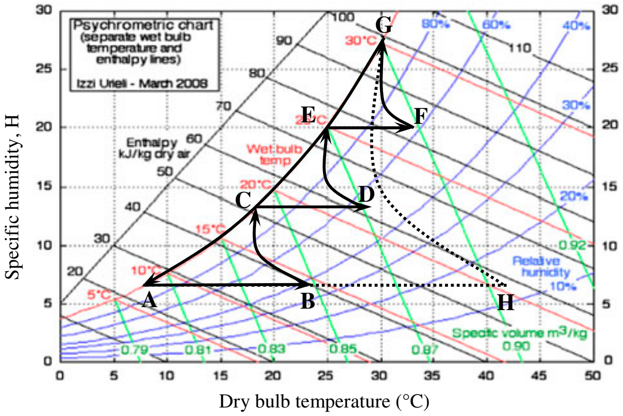

Fig. 11. Psychometric chart for closed air, open water, multistages air-heated (CAOW-AH) system.

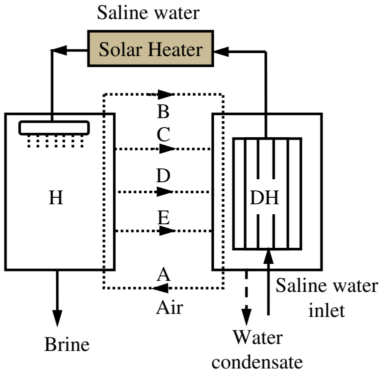

Fig. 12. Multi-effect closed air, open water, water-heated (CAOW-WH) system.

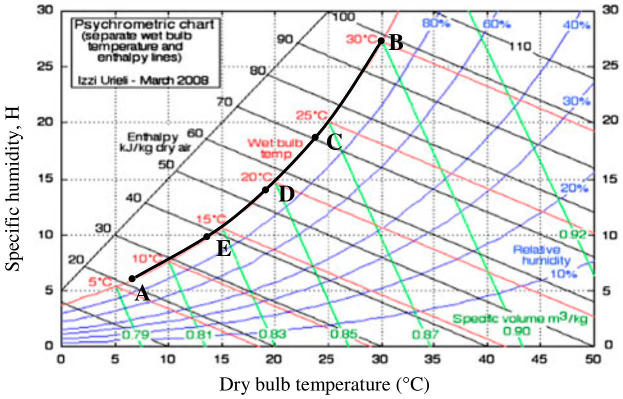

Fig. 13. Psychometric chart for multi-effect closed air, open water, water-heated (CAOW-WH) system.

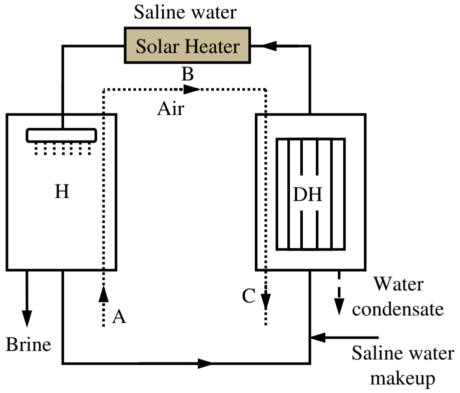

Fig. 14. A typical closed water, open air, water-heated (CWOA-WH) system.

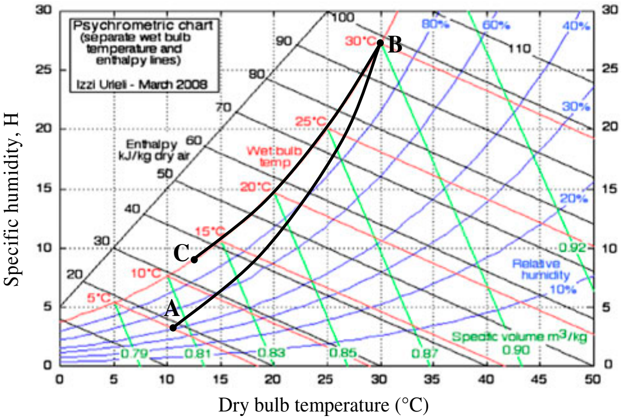

Fig. 15. Psychometric chart for closed water, open air, water-heated (CWOA-WH) system.

ambient. The humidification process is shown in the psychometric chart (Fig. 15) by line A–B. Air entering at ambient conditions is saturated to a point B (in the humidifier), and then, the saturated air follows a line B–C (in the dehumidifier). The air is dehumidified along the saturation line. A relatively small number of works in the literature consider this type of cycle and may be take into account for highly humidity areas, Table 7.

One of disadvantages of CWOA is that when the humidification process does not cool the water sufficiently the coolant water temperature to the inlet of the dehumidifier goes up. This limits the dehumidification of the humid air resulting in a

Table 7
Summary of some previous works on closed water, open air, water-heated (CWOA-WH) cycles in HDH

Reference	Unit description	Observation and conclusion
[46]	• Solar collector designed to heat air to 90 ℃ • Forced circulation of air • Cooling water circuit for the condenser • Heater for preheating water to 35–45 ℃ • Plastic packing was used in the humidifier	• The authors have studied the variation of production in kg/day and heat and mass transfer coefficients with respect to variation in cooling water temperature, hot water supply temperature, air flow rate, and water flow rate • They conclude that the highest production rates are obtained at high hot water temperature, low cooling water temperature, high air flow rate, and low hot water flow rate • The variation in parameters the authors have considered is very limited, and hence, these conclusions are true only in that range
[47,48]	• Honeycomb paper used as humidifier packing material • Forced convention for the air circulation • Condenser is fin tube type which also helps recover the latent heat by preheating seawater	• It was found that the performance of the system was strongly dependent on the temperature of inlet salt water to the humidifier, the mass flow rate of salt water, and the mass flow rate of the process air • The authors report that there is an optimal air velocity for a given top temperature of water • The top water temperature has a strong effect on the production of fresh water
[49]	• The system has a packed tower (with 50 mm ceramic Raschig rings) dehumidifier • The first system to use direct contact condenser in a HDH technology • The performance parameters are calculated numerically	• The authors report the GOR for their system as 0.8 which shows that heat recovery is limited • Based on an economic analysis, they conclude that the HDH Process has significant potential for small capacity desalination plants as low as 10 m^3/day

reduced water production compared with the open-water cycle. However, when efficient humidifiers at optimal operating conditions are used, the water may be potentially cooled to temperature below the ambient temperature (up to the limit of the ambient wet-bulb temperature). Under those conditions, the closed-water system is more productive than the open-water system.

7. Recent trends in humidification/dehumidification technique

7.1. Preheating of air

We observe that most studies in the literature consider cycles that heat the air before the humidifier (in single- or multistage), which causes the heat recovery to be reduced since the air gets cooled in the humidifier. If the heater is placed after the humidifier, saturated air from the humidifier is heated and sent to the dehumidifier. Seawater gets heavily preheated in the dehumidifier and the air in turn is heated and humidified in the humidifier [50].

There are two advantages to this cycle: (1) the condensation process occurs in a higher temperature range than the evaporation process, and hence, heat is recovered efficiently; and (2) the enthalpy curves for humid air are such that a large temperature rise can be achieved easily for this cycle. This can be observed from the psychometric chart shown in Fig. 16. Even for water-heated cycles, the humidification process occurs at higher air temperatures than the dehumidification process and the heat recovery is affected by that as well. Thus, the proposed cycle should have better heat recovery than all the systems presented in the literature.

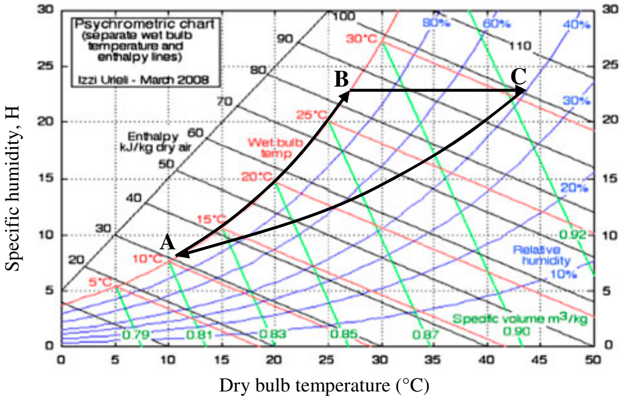

Fig. 16. Psychometric chart for preheating closed air, open water (CAOW) system.

7.2. Evacuated HDH system

It can be observed that all the HDH systems in the literature operate at atmospheric pressures only. The humidity ratios are much higher at pressures lower than atmospheric pressure [51]. This is expected to increase the water production many times for the HDH cycle [50]. For example, at a dry bulb temperature of 60°C, the humidity ratio at 50 kPa is 150% higher than at atmospheric pressure in case of fresh water where, accurate seawater properties should be used for thermodynamic analysis of HDH cycles. As the differences between fresh water and seawater thermophysical properties may lead to errors in the performance evaluation of the cycle under investigation.

7.3. Utilization of Fresnel lenses for preheating saline water

The Fresnel lens (FL) is a flat optical solar concentrator; the surface is made up of many small concentric grooves. Each groove is approximated by a flat surface that reflects the curvature at that position of the conventional lens, so each groove behaves like an individual prism. The high power density achieved with a FL installation is adequate for many applications such as traffic signals, theatre focus, slide projectors, rear windows of cars, photographic flash, etc. FL can act as collimators, collectors, condensers, field lenses, magnifiers, for imaging, thermometry, and solar energy collection. The advantages of the Fresnel installation make it a serious alternative to some conventional techniques used in this field [52].

In order to increase the efficiency of humidification process, heating the feed water is necessary to boost mass transfer and fortify evaporation. The FL solar collector concentrates the incident solar radiation in a spot. If we direct this spot to heat the steel pipe, then the saline water will be heated to the experiment starting temperature. The theoretical prediction of the water temperature coming out from the FL system is calculated with the aid of energy balance around FL-heating system. A mathematical model that describes the dynamic energy performance of the Fresnel lens solar collector is first developed. Eq. (1) represents the relation between the sun and earth geometry and their relation with the solar intensity concentration, where F is the length power, $F = f/d_{\text{lens}}$, f is the focal length (m), d_{lens} is the diameter of the FL (m), L is the length from sun to earth (m), r_{sun} is the radius of sun (m), I_{spot} is the spot intensity (W/m^2), and I_0 is the incidence solar intensity.

$$F^2 I_{\text{spot}} = \left(\frac{L}{r_{\text{sun}}}\right)^2 I_0 \qquad (1)$$

Zhai et al. [53] investigated the utilization of concentrating solar collector based on linear Fresnel lens experimentally. They concluded that this type of solar collector acquired higher thermal efficiency at a relatively high-temperature level than the commonly used flat-plate or evacuated tube solar collectors. Experimental results showed that the thermal efficiency is about 50% when the conversion temperature (water) is 90°C. The test shows that the indication of lost energy is $0.578\,\mathrm{W/m^2\,K}$, which is much smaller than that of commonly used evacuated tube solar collector without concentrating.

7.4. Atomization of hot water in air stream

The rate of evaporation of water from solution depends on the geometry of contact between water and air. In the case of spherical water droplets sprayed in air stream, the rate of evaporation depends on the particle diameter is calculated according to Eq. (2), [25].

$$k_c = \frac{2D_{\mathrm{AB}}}{D_{\mathrm{wd}}} \tag{2}$$

It is notable that decreasing droplet diameter will increase the mass transfer coefficient, k_c, and accordingly the rate of evaporation will increase. Therefore, the recommended way for efficient evaporation is to produce very fine droplets, which fly very fast through dry air. We can estimate the condition by boundary layer theory. The rate of mass transfer (N_A) for flow of air across water droplets is obtained by Eq. (3).

$$N_A = k_c(C_{A1} - C_{A2}) = k_G(P_{A1} - P_{A2}) \tag{3}$$

The mass transfer coefficient, k_c, can be obtained from an empirical equation of Reynolds number, Re, ranged from 1 to 480,000, and Schmidt number, Sc, from 0.6 to 2.7 according to Eq. (4), [25].

$$\mathrm{Sh} = 2 + 0.552\,\mathrm{Re}^{0.53}\mathrm{Sc}^{0.33} \tag{4}$$

The rate of evaporation per unit time, m, can be calculated using N_A as:

$$\begin{aligned} m &= N_A \cdot M_{\mathrm{wt}} \cdot \frac{A_{\mathrm{wd}}}{V_{\mathrm{wd}} \cdot \rho_w} \\ &= N_A \cdot M_{\mathrm{wt}} \cdot \frac{4\pi R_{\mathrm{wd}}^2}{(4/3)\pi R_{\mathrm{wd}}^3 \cdot \rho_w} \\ &= N_A \cdot M_{\mathrm{wt}} \frac{3}{R_{\mathrm{wd}} \cdot \rho_w} \end{aligned} \tag{5}$$

From this formula, it is evident that if water droplet of 0.001 m radius flies with speed 10 m/s, it completely evaporates within one second. Thus, spraying water in air stream enhances the area of contact between water in the air stream.

Spraying water in air stream using open water, closed air, water-heated (OWOA-WH) system have been investigated by Mahmoud [54]. The scheme of his system was to increase the humidification rate by increasing the surface area for the purpose of efficient contact between water and air, which can be accomplished by atomizing saline water within the air stream, thus the rate of fresh water production increases. A mathematical modeling for spraying hot water in air stream for humidification process have been accomplished by Mahmoud et al. [55].

8. Phase dispersion techniques

The common need to disperse a liquid into a gas has spawned a large variety of mechanical devices [56]. The different designs emphasize different advantages such as freedom from plugging, pattern of spray, small droplet size, uniformity of spray, high turndown ratio, and low power consumption. The conversion of bulk liquid into a dispersion of small droplets ranging in size from submicron to several hundred microns (micrometers) in diameter is of importance in many industrial processes such as spray combustion, spray drying, evaporative cooling, spray coating, and drop spraying and has many other applications in medicine, meteorology, and printing. Numerous spray devices have been developed which are generally designated as *atomizers, applicators, sprayers,* or *nozzles.*

A spray is generally considered as a system of droplets immersed in a gaseous continuous phase. Sprays may be produced in various ways. Most practical devices achieve atomization by creating a high velocity between the liquid and the surrounding gas (usually air). All forms of pressure nozzles accomplish this by discharging the liquid at high velocity into quiescent or relatively slow-moving air. Rotary atomizers employ a similar principle, the liquid being ejected at high velocity from the rim of a rotating cup or disc. An alternative method of achieving a high relative velocity between liquid and air is to expose slow-moving liquid into a high-velocity stream of air. Devices based on this approach are usually termed air-assist, air blast or, more generally, twin-fluid atomizers.

Most practical atomizers are of the pressure, rotary, or twin-fluid type. However, many other forms of atomizers have been developed that are useful in

Table 8
Summary of advantages and disadvantages of the different type atomizers

Types of atomizer	Design features	Advantages	Disadvantages
Pressure	• Flow $\sqrt{\alpha(\Delta P/\rho_l)}$. Only source of energy is from fluid being atomized	• Simplicity and low cost	• Limited tolerance for solids; uncertain spray with high-viscosity liquids; susceptible to erosion • Need for special designs (e.g., bypass) to achieve turndown
(1) Hollow cone	• Liquid leaves as conical sheet as a result of centrifugal motion of liquid. Air core extends into nozzle	• High atomization efficiency	• Concentrated spray pattern at cone boundaries
(a) Whirl chamber	• Centrifugal motion developed by tangential inlet in chamber upstream of orifice	• Minimum opportunity for plugging	
(b) Grooved core	• Centrifugal motion developed by inserts in chamber	• Smaller spray angle than 1*a* and ability to handle flows smaller than 1*a*	
(2) Solid cone	• Similar to hollow cone but with insert to provide even distribution	• More uniform spatial pattern than hollow cone	• Coarser drops for comparable flows and pressure drops. Failure to yield same pattern with different fluids
(3) Fan (flat) spray	• Liquid leaves as a flat sheet or flattened ellipse	• Flat pattern is useful for coating surfaces and for injection into streams	• Small clearances
(a) Oval or rectangular orifice. Numerous variants on cavity and groove exist	• Combination of cavity and orifice produces two streams that impinge within the nozzle		
(b) Deflector	• Liquid from plain circular orifice impinges on curved deflector	• Minimal plugging	• Coarser drops
(c) Impinging jets	• Two jets collide outside nozzle and produce a sheet perpendicular to their plane	• Different liquids are isolated until they mix outside of orifice. Can produce a flat circular sheet when jets impinge at 180˚	• Extreme care needed to align jets
(4) Nozzles with wider range of turndown			
(a) Spill (bypass)	• A portion of the liquid is re-circulated after going through the swirl chamber	• Achieves uniform hollow cone atomization pattern with very high turndown (50:1)	• Waste of energy in bypass stream

(*Continued*)

Table 8 (*Continued*)

Types of atomizer	Design features	Advantages	Disadvantages
(b) Poppet	• Conical sheet is developed by flow between orifice and poppet • Increased pressure causes poppet to move out and increase flow area	• Simplest control over broad range	• Added piping for spill flow • Difficult to maintain proper clearances
Two-fluid	• Gas impinges coaxially and supplies energy for breakup	• High velocities can be achieved at lower pressures because the gas is the high-velocity stream. Liquid flow passages can be large, and hence plugging can be minimized	• Because gas is also accelerated, efficiency is inherently lower than pressure nozzles
Sonic	• Gas generates an intense sound field into which liquid is directed	• Similar to two-fluid but with greater tolerance for solids	• Similar to two-fluid
Rotary wheels disks and cups	• Liquid is fed to a rotating surface and spreads in a uniform film. Flat disks, disks with vanes, and bowl shaped cups are used. Liquid is thrown out at 90° to the axis	• The velocity that determines drop size is independent of flow. Hence, these can handle a wide range of rates. They can also tolerate very viscous materials as well as slurries. Can achieve very high capacity in a single unit; does not require a high-pressure pump	• Mechanical complexity of rotating equipment. Radial discharge
Ultrasound	• Liquid is fed over a surface vibrating at a frequency > 20 kHz	• Fine atomization, small size, and low injection velocity	• Low flow rate and need for ultrasound generator

special applications. These include "electrostatic" devices in which the driving force for atomization is intense electrical pressure, and "ultrasonic" types in which the liquid to be atomized is fed through or over a transducer which vibrates at ultrasonic frequencies to produce the short wavelengths required for the production of small droplets. Both electrical and ultrasonic atomizers are capable of achieving fine atomization, but the low liquid flow rates normally associated with these devices have tended to curtail their range of practical application. Most atomizers fall into three categories: (1) pressure nozzles (hydraulic), (2) two-fluid nozzles (pneumatic), and (3) rotary devices (spinning cups, disks, or vaned wheels). A summary of the advantages/disadvantages of the different type units are represented in Table 8.

These share certain features such as relatively low efficiency and low cost relative to most process equipment. The energy required to produce the increase in area is typically less than 0.1% of the total energy consumption. This is because atomization is a secondary process resulting from high interfacial shear or turbulence. As droplet sizes decrease, this efficiency drops lower. Other types are available that use sonic energy (from gas streams), ultrasonic energy (electronic), and electrostatic energy, but they are less commonly used in process industries.

9. Conclusion

The use of renewable energies for desalination appears nowadays as a reasonable and technically attractive option toward the emerging and stressing energy and water problems. For low-density population areas worldwide, there are lacks of fresh water as well as electrical power grid connections. Therefore, the cheap fresh water may be produced from brackish, sea and oceans water by using solar panels, wind turbines and other emerging renewable energy technologies in order to reduce the carbon footprint of commercial desalination processes. Recent developments in indirect solar desalination have focused on HDH as a clean and economical operation. Different configurations of solar humidification–dehumidification desalination systems have been reviewed in detail in this paper. The HDH system has some advantages for small-scale decentralized water production. These advantages include much simpler brine pretreatment and disposal requirements and simplified operation and maintenance. From the present review, it is found that among all HDH systems, the multi-effect CAOW water-heated system is the most energy efficient. Methods to further improve the performance of the HDH cycle have also been proposed in this study. These methods include preheating of air using solar collector in the cycles of water heating, other way by misting (atomization) the hot water during the humidification step. Further research needs to be carried out to realize the full potential of these ideas and the HDH concept in general.

Acknowledgement

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Nomenclature

A_{wd} — surface area of water drop, m^2
C_{A1} — concentration of A at point 1, $\mathrm{kg/m^3}$
C_{A2} — concentration of A at point 2, $\mathrm{kg/m^3}$
D_{AB} — diffusion coefficient, $\mathrm{m^2/s}$
D_{wd} — diameter of water drop, m
M_{wt} — molecular weight, kg/kg-mol
F — the length power, m
f — the focal length, m
H_i — humidity at interface
H — humidity at bulk
I_o — incidence solar intensity, $\mathrm{W/m^2}$
I_{spot} — spot intensity, $(\mathrm{W/m^2})$
k_c — mass transfer coefficient, m/s
k_G — mass transfer coefficient for gases, kg-mol/ $(\mathrm{s\,m^2\,Pa})$
L — the length from sun to earth, $(1.5 \times 10^{11}\ \mathrm{m})$
N_A — rate of mass transfer, $\mathrm{kg/m^2\,s}$
P_{A1} — partial pressure of gas at point 1, Pa
P_{A2} — partial pressure of gas at point 2, Pa
Re — Reynolds number, (–)
R_{wd} — radius of water drop, m
Sc — Schmidt number, (–)
Sh — Sherwood number, (–)
T_i — temperature at interface, ℃
T_x — temperature of liquid at bulk, ℃
T_y — temperature of gas at bulk, ℃
V_{wd} — volume of water drop, m^3
ρ_w — water density, $\mathrm{kg/m^3}$

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