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Water desalination by humidification–dehumidification technology with performance evaluation using exergy analysis

Wael Abdelmoez*, Eman A. Ashour, Noha M. Sayed

Department of Chemical Engineering, Faculty of Engineering, Minia University, 61516 Minia, Egypt, Tel. +20 100 0859791, Fax +20 86 2346674, email: drengwael2003@yahoo.com (W. Abdelmoez), emanalyashour@yahoo.com (E.A. Ashour), noha.mohammed63@yahoo.com (N.M. Sayed)

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ABSTRACT

Water desalination by humidification-dehumidification technology (HDT) has been reviewed in detail in this research. Firstly, the principles of water desalination and different types of desalination processes which included HDT were presented as; HDT is considered as one of the most suitable methods for a small-scale water desalination system, since it could be powered by low energy grade such as solar and geothermal energies. In addition HDH (humidification-dehumidification) system could be manufactured easily. In the recent work, a detailed description of HDT components such as humidifier, dehumidifier, heating sources, and air supply mechanism were explained and discussed. Finally, thermodynamic analysis of HDT especially exergy analysis was investigated. The exergy analysis aims to optimize the usable energy efficiency in HDH system in order to improve its performance.

Keywords: Exergy; Exergy analysis; Humidification-dehumidification; Desalination

1. Introduction

The scarcity of freshwater increases by the day along with the population growth. Accordingly, it is important to find an improved potable water resource. It is well known that saline water in the seas and the oceans - which represents 97.5% of the total quantity of water on the earth - could be considered a great source of water needed to resolve the water scarcity problem. Water desalination could be carried out through thermal, mechanical, electrochemical, and membrane filtration technologies. Amongst the thermal processes, humidification-dehumidification (HD) technology is considered the most promising emerging technology. The HD technology is developed based on the same principle of the traditional solar stills where humidification, dehumidification, and heating are carried out in a single unit while heat lost during condensation is not recovered. As a result, the process has significantly low efficiency. In 1950, good efforts were exerted by the US Office of Saline Water (OSW) to improve multiple-effects of solar stills. The system was improved through separating each process in an individual unit and this development caused the HD technology (HDT) to advance rapidly. The first HD system powered by solar energy was built in Puerto Peñasco, Sonora, Mexico in 1964 [1]. The recent work demonstrates the various studies that were conducted in the field of HDT in order to improve its efficiency. In order to select the most impactful parameters on the humidification phase, the performance of several types of humidifiers in addition to their testing and operation at different conditions were demonstrated in this review. These humidifiers include spray towers, packed bed, wetted wall, and bubbler column. Furthermore, different types of dehumidifiers were introduced such as shell and tube, flat-plate, and finned tube heat exchangers. The results of numerous studies were analyzed to reach the optimal design of an HDH unit with plausible potable water production and low energy consumption [2]. HDT systems were investigated from the energy point of view and the exergetic efficiency

*Corresponding author.

of HDT system was determined. Finally, for the first time, the performance was optimized based on exergy analysis in order to enhance the efficiency of the system.

2. Overview of desalination processes

Desalination is a process in which salt is removed from saline water at the expense of energy. Over 70% of earth is water and about 97.5% of the total quantity of water is found in oceans and seas as saline water. As for the remaining water, only 30% of the freshwater is accessible for human beings meanwhile, 2.5% of the freshwater are confined as polar ice and ground water [3]. Consequently, we need to exploit the large percentage of saline water through removing the salt content via desalination technologies. There are different methods of desalination which can be classified into two categories.

- Thermal processes (phase change).
- Membrane processes (single phase).

Traditional methods of desalination processes such as RO and MSF require a huge amount of electrical energy (RO) and thermal energy (MSF). These technologies utilize the burning of fossil fuel as a heating source which produces a large amount of CO_2 emissions. Accordingly, the incorporation of renewable energy sources is vital in order to avoid this issue. One of the desalination technologies that operates using renewable energy such as solar energy is humidification-dehumidification technology (HDT). HDT is classified under thermal desalination processes where thermal energy is used for desalting saline water. It is also considered one of the most promising methods of water desalination since it imitates the natural water cycle as shown in Fig. 2. In this method, water evaporates from oceans and seas due to the sun then condenses into freshwater as a result of the dehumidification process. HDT process is an innovative technology with plenty of application as its flexible, easily constructed, requires low maintenance, has low capital cost, and ability to use a low grade of energy. Furthermore, it is considered a highly convenient process for decentralized water systems production. This production is also important for remote areas that have

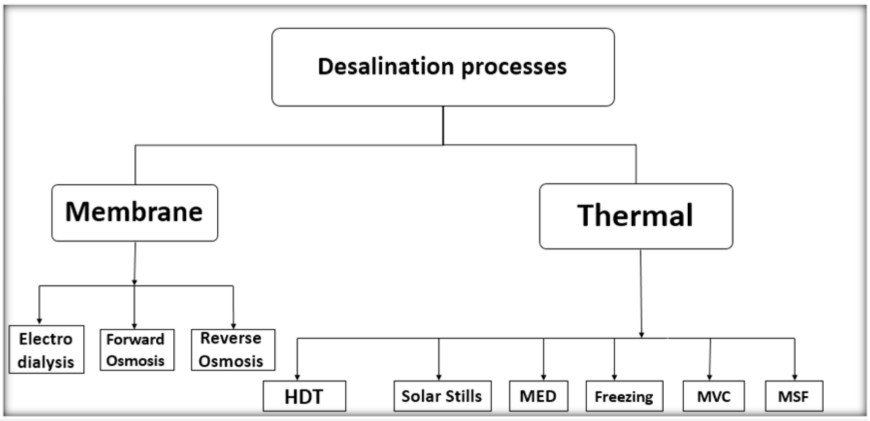

Fig. 1. Humidification-dehumidification (HD) desalination processes.

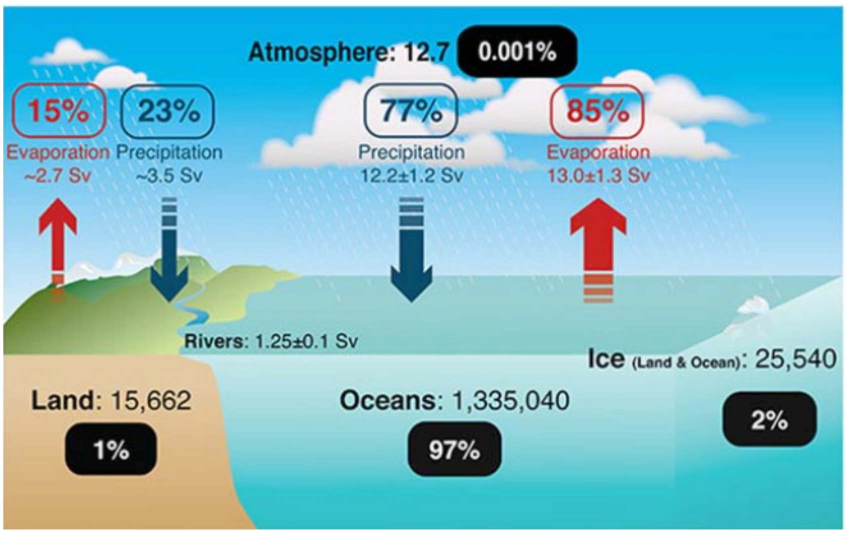

Fig. 2. Natural water cycle [4].

no infrastructure or economic resources. HDT is developed from solar stills which have many disadvantages such as low energy efficiency (Gain-Output Ratio (GOR) = 0.5) because the latent heat of condensation cannot be recovered [4]. In order to overcome these drawbacks, multi-effect stills technique is used to recover the latent heat of condensation and increase the efficiency of the process, however, the overall efficiency of the system is still considered quite low. In solar stills heating systems, both evaporation and condensation occur in a single unit which causes the system to be inefficient. Thus, in order to improve the performance of the system each process should be separated in an individual unit. This procedure is considered the main characteristic of HDT.

HDT system is composed of three main parts; humidifier, dehumidifier, and a heating source. Saline water is evaporated at the expense of thermal energy then air holds the water vapor molecules formed as shown in Fig. 3. This process is called humidification and it occurs in the humidifier (evaporator). Air's ability to hold water vapor increases with increasing the temperature of the medium. For example, 1 kg of dry air can carry 0.5 kg more of water vapor due to the increase of its temperature from 30 to 80°C. In the dehumidifier (heat exchanger), humid air is contacted with cold saline water which results in the condensation of freshwater. Amount of freshwater produced increases with increasing condensation rate through decreasing the saline feed water temperature.

Parameters used for HDT performance evaluation are summarized in Table 1. These parameters are the most important indicators use to estimate the efficiency of the

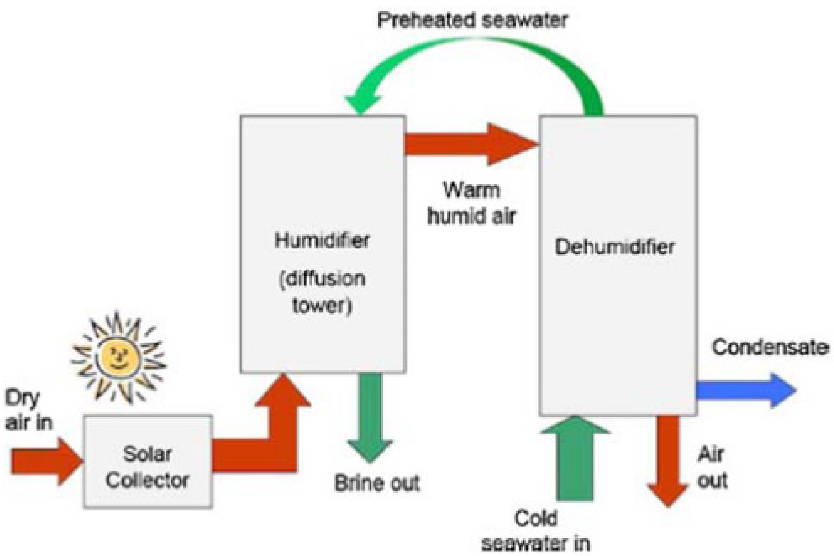

Fig. 3. Humidification-dehumidification cycle [4].

Table 1
Performance parameters and their equations

Parameter	Definition	Equation
1. Humidification process efficiency	Is a percentage of air humidity increasing comparing with the maximum increasing at a saturated temperature of air.	$\eta_H = \frac{(\omega_{out} - \omega_{in})}{(\omega_{\text{sat.air}} - \omega_{\text{in}})} * 100$
2. Humidifier or dehumidifier effectiveness	Is the ratio between actual change of air or water enthalpy to the maximum change in the humidifier or dehumidifier.	$\epsilon_h = \frac{\Delta \text{h}_a}{\Delta \text{h}_a^{ideal}}$
3. Thermal efficiency of desalination process	Is the ratio between heat outputs to heat inputs (supplied to the system).	$\eta_d = \frac{(m_w L_{w,vap}) * 100}{(Q_{in} + W_c)}$
4. Heat capacity ratio	Is the ratio between maximum enthalpy change of cold fluid to the maximum enthalpy change of hot fluid in the dehumidifier.	$HCR = \frac{\Delta \text{H}_{\text{max},cold}}{\Delta \text{H}_{\text{max},hot}}$
5. Gained output ratio (GOR)	This parameter measures the amount of heat which can be reused .Is the ratio between heat outputs from the system with freshwater to the heat input with the inlet saline water in the humidifier.	$GOR = \frac{m_{pw} h_{fg}}{Q_{in}}$
6. Recovery ratio (RR)	Measures the productivity of the HDH system, is the ratio between the produced freshwater to feed input water.	$RR = \frac{m_{mp}}{m_w}$

HDH system. The performance could be viewed through different points of view. Firstly, through thermodynamics point of view which is discussed in details in this article and secondly through the productivity point of view. Other parameters are further discussed such as humidification process efficiency that compares actual air humidity with the maximum amount of water vapor that can actually be held by air at saturation. This parameter directly indicates freshwater productivity as when the amount of water vapor in the air increases to the maximum value, the freshwater productivity is maximized as well. Another discussed parameter is the humidifier effectiveness that is a thermodynamic parameter that dictates indicates the ratio between the change of air enthalpy in the humidifier and maximum enthalpy change of air. The thermal efficiency of desalination process measures the amount of heat output compared with the amount of heat input. Heat capacity ratio (HCR) measures the ratio between the maximum enthalpy of cold fluid to the maximum enthalpy of hot fluid in the dehumidifier. Gained-output ratio (GOR) is a ratio between heat outputs with freshwater to heat input in the humidifier therefore, GOR specifies the amount of heat that can be recovered. Recovery ratio (RR) is a parameter which measures the amount of freshwater produced as it is the ratio between produced freshwater amounts to feed input water.

3. Main constituents of HDH systems

As previously mentioned in the abstract section, HDH systems are composed mainly of humidifiers, dehumidifiers, and heating source. The humidifier is used for loading the dry air with water and its main aim is the extraction of the maximum amount of water vapor. Hence, humidification is considered as the main process of HDT during which freshwater is separated from salt. The dehumidifier is the second step of the desalination process where cooling of hot humid air occurs via indirect contact with cold saline water. Saline water and air are heated before humidification process by air heaters and solar water heaters in order to enhance the performance of the system.

3.1. The Humidifier

Humidifier or evaporator is a device where contact between unsaturated air and sprayed hot water occurs to increase the amount of water vapor contained by the air that is called air humidity. In the humidifier, mass transfer occurs due to the concentration gradient between amount of water vapor in air and air-water interface. In addition, heat transfer takes place due to the temperature difference between air and water vapor that acts as driving force.

3.1.1. Types of humidifiers

There are many types of humidifier columns that can be used in HD system including spray towers, bubble towers, wetted – wall towers, and packed bed towers. Various studies carried out with different types of humidifiers are introduced in the following section.

3.1.1.1. Packed-bed humidifier

In the packed bed tower, saline water is sprayed over packing materials. Packing materials are used for increasing contact surface area and time of contact between air and water. Packed beds operate as a direct contractor to enhance both mass and heat transfer between air and water due to its high specific surface area of packing. Several studies were carried out to increase packed-bed humidifier efficiency using different types and structures of packing materials such as plastic materials which is used by Yamali et al. [6] in a pad humidifier. Plastic materials with various structures were used by different researchers. Plastic materials in form of rings were used by Morteza Mehrgoo et al. [7], A.H. El-Shazly et al. [8], and Al-Sahali et al. [9] while honeycomb structure materials were used by Yuan et al. [10]. In addition, Li et al. [11] and Sharshir et al. [12] used a plastic material in the form of corrugated cellulosic sheets. Textile was also used as a packing material by Zhani et al. [13]. Moreover, Muthusamy et al. [14] used gunny bags as a packing material. Gao et al. [15] investigated the performance of a HDH unit powered by a mechanical vapor compression pump. They used a packed bed humidifier (450, 450, 300 mm) called alveolate humidifier which contains a honeycomb paper packing material with a large evaporation surface area. Firstly, air was heated in a solar air heater and thrusted through the humidifier via a blower. Afterwards, hot humid air was cooled by indirect contact with cold saline water and then further cooling was conducted in an evaporative condenser of the heat pump is performed for obtaining freshwater. There are two advantages of this unit, using heat pump condenser and evaporator as a cooling and heating source respectively which gives a concise structure of the system. The second advantage is the usage of solar energy as a heating source which is environmental friendly and cost-effective. A mathematical model was developed for the new desalination unit in order to study mass and heat transfer in the packed humidifier.

The influence of many parameters was discussed such as mass flow rate of air and water and their temperatures. It was notable that freshwater production rate is increased by increasing solar insolation and vice versa. Maximum freshwater production (4700 ml) was reached when the air flow rate was 200 kg/h. Freshwater yield was increased by increasing the mass flow rate of saline water (cooling water). Furthermore, it was found that freshwater rate increases by decreasing temperature of cooling water. Plastic packing materials were utilized by El-Shazly et al. [16]. The most effective parameters which affect the efficiency of the solar humidification-dehumidification unit using packed-bed of screens as a humidifier were investigated. The proposed HDH system is mainly composed of a humidifier, dehumidifier and flat-plate solar collector for heating saline water. The packed-bed humidifier which used in the experiments was consisted of plastic screens with a bed length (20–50 cm) and 1 mm screen thickness. Hot saline water that came from the solar collector entered a sprayer at the top of the humidifier and air is passed through the packing from the bottom of the humidifier for air humidification performing. There were three objectives for the paper, the first was to investigate of HDT performance using external heating source for heating instead of the solar collector. The second objective was defining the most effective factors that affected the solar collector efficiency and the third objective was to study the HDT performance at different operating conditions. Results indicated that freshwater productivity is increased with increasing temperature of inlet saline water temperature, its flow rate, and thickness of packing materials. Results showed that solar collector performance is enhanced by increasing its angle up to 45°. Results also indicated that HDT productivity is increased by increasing inlet water flow rate up to 5 L/min and the optimum packed column thickness was 40 cm above this value, productivity is decreased. It was found that brine recycling to the solar collectors enhancing the productivity up to 214% comparing with HDT productivity without recycling.

Another study was carried out using plastic materials by Chiranjeevi et al. [17] to improve humidification process performance. A new two-stage HD (humidification-dehumidification) pilot plant with the cooling plant was designed. Experimental and mathematical analyses were carried out for the modified system which was composed of two stages of humidification-dehumidification to increase the production of freshwater. Two packed-bed humidifiers in the presence of two layers of plastic materials were used in order to enhance humidification capacity of the outlet air. Three dehumidifier units were used for humid air cooling to produce freshwater as a product of HDT. Effect of various parameters was studied such as inlet saline water flow rate and its temperature in the humidifier. It was found that air temperature is increased in the preheater by increasing the mass flow rate of saline water. So, saline water flow rate played an important role in exit air properties. Results showed that inlet conditions of dehumidifier are influenced by exit humidifier conditions. It was noticed that temperature drop in the dehumidifier is increased by increasing temperature in the humidifier. Freshwater yield is enhanced by adding the second stage of HD unit.

In order to investigate plastic materials performance, El-Shazly et al. [18] performed a developmental study to enhance humidification efficiency by using three layers of plastic material. They investigated the performance of a fixed bed (packed bed) humidifier on water desalination system by HD technology. The packed humidifier was composed of three layers of plastic Raschig rings, column height 200 cm, 40 cm distance between each layer, 10 cm height of each layer, and 30 cm column diameter. Packing materials are fixed in the column by using perforated plates. Air is forced by a blower in the column where humidification process occurs. Various factors have been examined to select the optimum conditions and knowing the most effective parameters. Packing material height has an effective role in humidification process efficiency as by increasing packing height, amount of produced freshwater is decreased. Freshwater productivity is enhanced by increasing the distance between packing layers up to 5 cm. The productivity of HDT is increased by increasing of packing materials diameter but up to limit (1.27 cm) above this limit, productivity is decreased. For studying the effect of the type of packing materials Rajaseenivasan et al. [19] used a new packing material which is jute cloth to elaborate the contact between air and hot saline water. They have investigated experimentally the performance of HDH water desalination system using a dual purpose solar collector. The dual-purpose solar collector is used for heating both air and saline water before entering the humidifier. Tested HDH cycle consists of the dual purpose solar collector which is designed as a rectangular box (0.95*0.75*0.12 m) with using 2 mm absorber plate made of mild steel sheet as shown in Fig. 4. The collector consists of two passes, one of air and the other pass for water where both of them are heated. Packed-bed humidifier which is constructed from mild steel with 0.09 m^2 surface area using a jute cloth to increase contact surface area and time of contact between air and water which enhancing heat and mass transfer. Shell and tube heat exchanger is used as a dehumidifier where humid air is cooled to get freshwater. Various parameters were studied such as mass flow rate of air and water. It was found that performance of HDH system and its capacity were enhanced with increasing mass flow rate of air and water. Cost of produced freshwater was found to be 0.0257$/kg for the proposed system.

Thiel et al. [20] used packed bed humidifier in which water is sprayed over packing materials to enhance mass transfer rate and to investigate the effect of mass extraction/injection on HDT performance. A packed humidifier similar to cooling tower was used. Dry air is passed through the packing materials from the humidifier bottom and hot water is sprayed from the humidifier top. The effect of mass extraction/injection of air and water on HDT performance was studied to enhance energetic efficiency. In the dehumidifier, a portion of water was extracted and injected to a certain point in the humidifier. Extraction point temperature in the dehumidifier should be the same temperature of the injection point in the humidifier to minimize irreversibilities which resulting from mixing of two streams with different temperatures. In the humidifier, air was extracted and injected to the dehumidifier. Extraction/injection of air and water mass flow rates which minimize entropy generation were performed in order to increase GOR of the system. A mathematical model for humidifier and dehumidifier was developed and numerical implementation also provided. Results showed that a single water extraction from a dehumidifier to humidifier increases GOR up to 10%. It

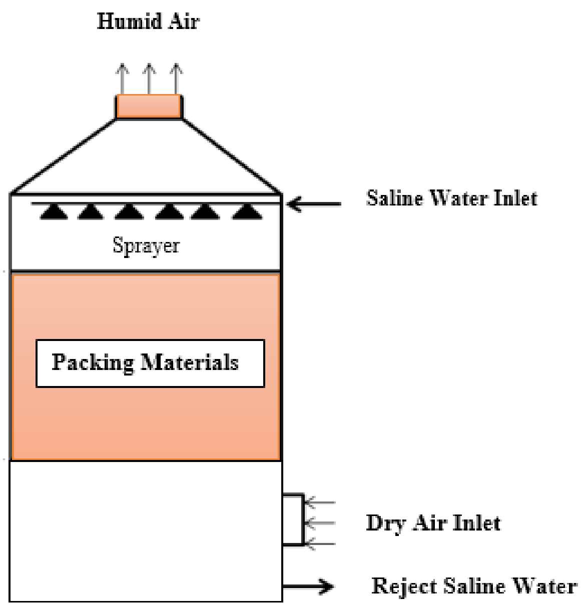

Fig. 4. Schematic diagram of packed bed humidifier.

was proved that the direction of extraction/injection from the dehumidifier to humidifier is better than the opposite direction. The optimal extraction flow rate was found as 40% of the total cycle flow rate. Increasing of system size decreases the heat input and increases GOR and water production rate but, this effect is limited when one component size only is increased.

Chehayeb et al. [21] utilized packed bed humidifier in HDH system which is the same as cooling tower used in power plant. They have studied the effect of operating parameters such as water-to-air mass flow rate ratio and top and bottom temperature on HDH efficiency. A solution algorithm for heat and mass transfer models of HDH system which composed of packed bed humidifier and multi-tray dehumidifier was presented. Results proved that maximization of energy efficiency and water production of HDT occur when HCR equal to 1. The top temperature (temperature in heat source) has a larger effect than the bottom temperature on HDT performance.

Sharqawy et al. [22] presented a thermodynamic model of the air-heated cycle and water-heated of HDH water desalination system (Fig. 5). First law of thermodynamics was applied to each component on the two cycles. The water-heated cycle where feed saline water is heated by the solar collector. In the air-heated cycle, air is heated before entering the dehumidifier to increase the system performance. For the two cycles, water enters the humidifier at a temperature higher than the air temperature this enhance air humidifying capacity rather than cold water with hot air. Results approved that GOR of the system is maximized at an optimum value of mass flow rates ratio of water and air for each cycle. Recovery ratio which measures the productivity of the system is improved by increasing effectiveness of the dehumidifier and humidifier. It was found that for the water-heated cycle the optimum mass flow rate ratio was greater than 1. In addition, recovery ratio (RR) was enhanced by increasing effectiveness of humidifier and dehumidifier. For air heated cycle, the optimum mass flow rate ratio was less than 1 and GOR of the system was enhanced by increasing the temperature of water.

Zubaira et al. [23] studied the performance of HDH water desalination system with using solar evacuated tubes for saline water heating and packed column humidifier also was used. They investigated the performance of the system in different locations in Saudi Arabia in order to select the best location where solar intensity is high. Cost analysis of HDT system was performed in each selected location and calculating of freshwater production rate also was provided. A mathematical model which described HDH system performance into two parts, evacuated tubes solar collector and HDH cycle were provided. Effect of various parameters on HDT efficiency was studied such as ambient temperature, location, and solar radiation. Results indicated GOR of HDH system is increased with decreasing inlet air flow rate. Water production rate was doubled when the effectiveness of humidifier and dehumidifier is increased from 0.85 to 0.95. A comparison between results of this study and literature was represented and it was found that the relation between GOR and relative humidity was the same relation in the literature too. They recommended that air-water mass flow rates ratio should be 1.8 and outlet temperature of saline water from solar collector should be 60°C. Sharurah was found to be the location where highest freshwater production rate was obtained in Saudi Arabia in compared with other locations. The total capital cost was found $12,400 and cost per liter of freshwater was between $0.032–0.03.

3.1.1.2. Spray tower humidifier

In the spray tower humidifier, water is sprayed from the top of the column into fine droplets and the air is injected from the bottom which comes in counter current contact with the falling hot water droplets. The efficiency of this tower is low as low exit air humidity or low water hold up so, various studies were carried out to improve its efficiency. A spray column humidifier is used by Ben Amara et al. [24] to investigate experimentally the parameters which affect the performance of multiple effect HDH system. The stud-

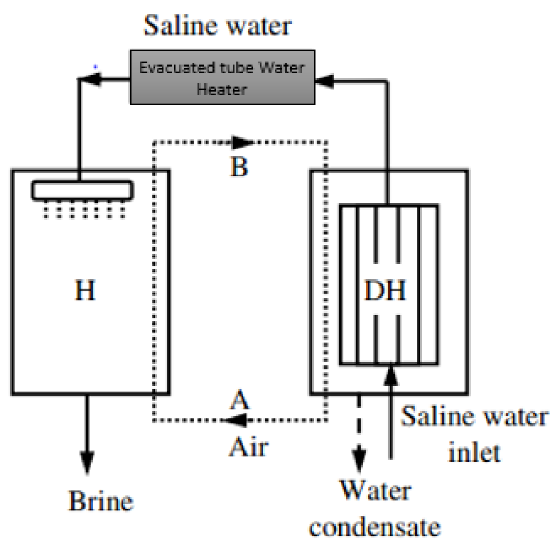

Fig. 5. Schematic of water heated HDH system [4].

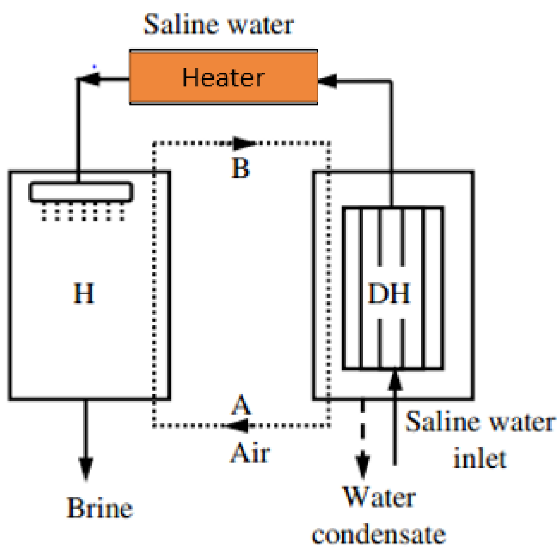

Fig. 6. Scheme of a HD desalination unit using spray humidifier [4].

ied operating parameters were humidity of inlet air in the humidifier, water-air mass ratio, and inlet air temperature in the humidifier. Results indicated the optimum ratio of water-air mass flow rate ratio was 45% and number of heating-humidification stages equal to 5. Four different configurations of HDH system were tested by Franchini et al. [25] using a spray tower as a humidifier in the first and second configurations. In addition, a recuperative heat exchanger is used in the second configuration where discharged air from the dehumidifier is preheated by indirect contact with the discharged brine. In the first configuration, HDH system has been tested for different operating conditions; saline feed water temperature was (45–55°C) and seawater-air flow rate ratio was (0.5–1.5). It was found that freshwater production rate is increased by increasing inlet water temperature in the humidifier because of a huge amount of water vapor extracted by the air stream. It is recommended that optimum water-air flow rate ratio is 1 which improves system performance at inlet seawater temperature (55°C). Results showed that using the heat exchanger in the second configuration is allowed to save 10% of thermal heat input. In the third configuration, authors used packed bed tower which increased efficiency by 20% compared with the first two configurations.

As mentioned in the previous section, using spray tower humidifier in humidification shows a low efficiency. In addition, solar stills performance also very low, consequently a hybrid system of solar still and HDT desalination using spray humidifier is proposed by Ghazy et al. [26] in order to make an efficient design. The hybrid system is designed for increasing the production rate of freshwater and improving the efficiency of solar still by minimizing heat losses. Performance of combined system was analyzed for recovering heat losses occur in the conventional solar still. A comparison between the new hybrid system and the conventional solar still at the same conditions was carried out. A spray humidifier column where hot air is humidified after heating in the solar still is used. The hot humid air was cooled by passing around tubes of cupper which contains cold saline water. A comparison between the new hybrid system and the conventional solar stills showed that combined HDT-solar still has a higher temperature of saline water than in the conventional stills. Various methods were performed for increasing the production rate of conventional stills; one of them was decreasing of saline water level in the still basin. Results indicated the thermal performance of combined HDT and solar still was 1.5 times of the conventional method. An additional development study was performed by S.W. Sharshir et al. [27] to enhance the efficiency of the hybrid system. The proposed system is composed of two parts; the first part is HDH unit with using spray column as a humidifier and the second part is the conventional solar stills. Saline water is heated in the solar collector and sprayed into fine droplets at the top of the spray humidifier; the air is supplied by a fan and passed through the bottom of the humidifier. The feed of solar stills is the rejected hot water from the humidifier. Four solar stills with 1 m^2 surface were used. Results showed that freshwater production rate is increased by increasing water temperature in the humidifier. The performance and the productivity of the system were enhanced by increasing insulation thickness of solar stills and the optimum insulation thickness was 0.03 m. GOR of HDT is increased by 50% due to reusing of dismissed warm water. In addition, the efficiency of a single solar still in the hybrid system is improved by 90%. It was found that freshwater production rate of conventional solar still, single solar still in the hybrid system, four solar stills, and the hybrid system were 3.2, 10.5, 42, 24.3 and 66.3 kg/d, respectively. Cost per liter of distilled water of conventional solar still, humidification-dehumidification, and the hybrid system were \$0.049, \$0.058 and \$0.034, respectively.

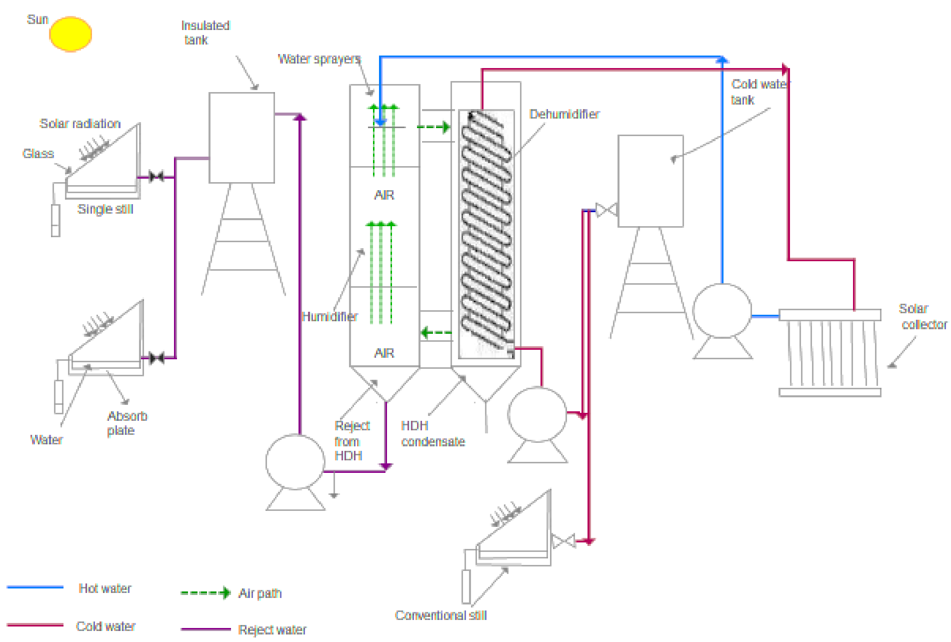

Fig. 7. HDH and solar stills hybrid system.

3.1.1.3. Bubbler humidifier

Bubbler humidifier is a new technique for air humidification where the air is dispersed into hot water through a perforated plate or sparger. Mass and heat transfer is enhanced by making the air in fine bubbles which increase the contact surface area between air and hot water. In addition, the bubbling of air into water increases the outlet air humidity. This type of tower is used to improve the humidification performance due to higher heat and mass transfer between air and hot water. El Agouz et al. [28] have studied the behavior of hot humid air in a single stage HD using the bubbler humidifier. They investigated experimentally and theoretically the operating parameters of the HDH system. An evaporator chamber (humidifier) was used for air humidification process by passing air bubbles through 44 holes located at the top side of a copper pipe. Many factors effects have been studied such as water temperature, brackish water level, and air flow rate. Results indicated that the productivity of freshwater is increased at T_w (water temperature) equal to 60, 70, 80°C with increasing inlet air flow rate expect at 50°C the productivity is decreased. The productivity of HDH system is improved by increasing number of air bubbles and density distribution which enhances air-water contact consequently, humidity of exit air is increased. Maximum freshwater production was found to be 8.22 kg/h at 86°C and mass flow rate of air equal to 14 kg/h. A cost analysis of HDT unit has been performed and showed that at air flow rates from 4.2–14 kg/h, freshwater production cost was found about 0.08 $/kg at 50°C, 0.052 $/kg at 60°C, 0.057 $/kg at 70°C, and 0.095 $/kg at 80°C. Cost of freshwater production was very high as the high cost of the compressor and the capital cost of desalination process but the cost will be reduced when the system is commercialized.

Zhang et al. [29] designed a new technique of solar HDH desalination system by using air bubbling humidification. Saline water is heated by solar seawater heater and the air is preheated by solar air heater. Heated air is passed through holes on sieve plate for contacting hot saline water in the bubbler humidifier then humid air is passed through a heat transfer pipes in the dehumidifier for hot air cooling and freshwater condensing by indirect contact between humid air and sprayed cold saline water. Bubbler humidifier with 500 mm height, 200 mm sieve plate diameter, and 1 mm diameter of the hole was examined (Fig. 8). Different parameters effects have been studied such as air flow rate, air and water temperatures, and water level height. Results showed that pressure drop of inlet air and blower power consumption were increased with increasing air flow rates. It was found that air humidity in the humidifier is increased by increasing water height consequently, resistance to air passing through the sieve is increased and power consumption of the blower also increased. It was found that when saline water temperature is 80°C, GOR of the improved system is 2.3. Cost of freshwater production is decreased from 66 to 12 Yuan/t when inlet water temperature is increased from 40°C to 80°C. For enhancing humidification performance and decrease the cost of freshwater, the temperature of air and water should be increased.

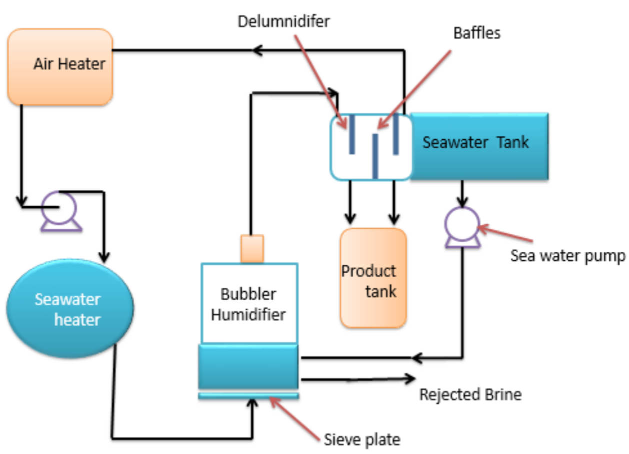

Fig. 8. Improved HDH system.

The performance of a bubbler humidifier with varying number of opening holes was evaluated by Zhang et al. [30] in which air is passed through single-stage sieve plate. Humidification system consists of the blower, air heater, bubbler, and humidifier column. Electrical heaters were used for air and water heating. Many parameters were studied for obtaining the most effective parameters in the humidification performance. Air flow rates, temperatures in the humidifier, water level, different sieve holes, and sieve diameter were varied with fixing the other parameters. Experiments proved that humidification process is enhanced with increasing the temperature of air and water as humidification load of air is increased by 80%. Results indicated air pressure drop and blower power consumption were decreased by increasing sieve hole diameter and number of open holes. Relative humidity of air in the outlet of the humidifier was found to be 100% if the air mass flow rate is increased.

Instead of varying number of holes to improve the performance of bubbler humidifier, Ghazal et al. [31] came with a new compact design of humidification process. They have performed an experimental study of solar bubbler humidifier where gas (air) is dispersed into a column filled with liquid (saline water). Camarasa et al. [32] and Pohorecki et al. [33] proved that mass and heat transfer rate is enhanced by decreasing the diameter of air bubbles. Accordingly, inverted sieves were used for resizing air bubbles easily that improves heat and mass transfer. It was aimed to combine air heating, water heating, and humidification process in one compact unit as it is shown in Fig. 9. The compact humidifier was manufactured from a galvanized metal sheet at the bottom and was covered by a glass sheet from the top. The chamber between the glass and the metal sheet is filled with saline water. A pipe with 2 mm diameter holes and 500 mm length was used for air bubbles generation. Three configurations of humidifier were proposed; the first configuration, air is passed through sieve holes which immersed in the water at the bottom of the humidifier. In the second configuration, a black painted and inverted stainless steel sieve plates were introduced which act as absorber and air bubbles generators. Resulting in increasing of air temperature, therefore, increasing its vapor capacity. The third configuration in which 1 m^2 reflective mirror was added so as to reflect extra solar energy. Results showed that in the second and third configurations

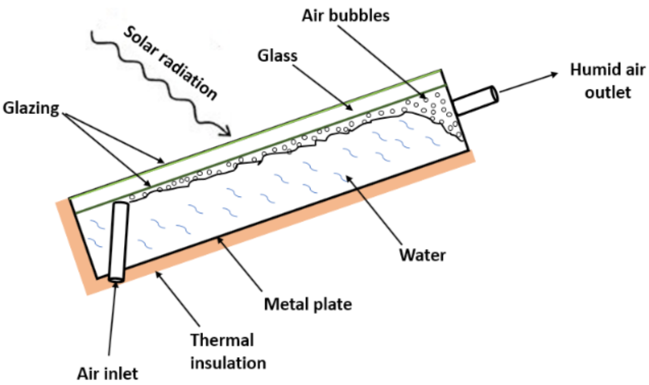

Fig. 9. Compact humidifier.

air temperature at each hour of the experiment reaches the same value of water temperature which enhances humidifier effectiveness. Results proved the efficiency of the humidifier reached to 95–100%. Higher vapor content was obtained in configurations 2, 3 as higher air bubbles temperature and smaller bubbles diameter, in addition, using a reflecting mirror which enhances the humidification performance. Configuration 2 has better performance because of higher bubbles formation. The average effectiveness of the humidification process is enhanced by adding the reflective mirror from 75 to 90% in the third configuration. It was found that when the solar radiation intensity was 700 W/m^2 and air mass flow rate 12.6 kg/h; water evaporated amount was 0.75 kg/h. Cost of the proposed system was calculated to be $280.

Abd-ur-Rehman et al. [34] developed an analytical model for bubbler humidifier to improve HDH system performance. Bubbler humidifier is designed to increase heat and mass transfer between hot water and air which is distributed through a perforated plate or sparger as it is shown in Fig. 10. Heat and mass transfer occurs simultaneously when air bubbles propagate through hot saline water in addition air bubbles increase the contact surface area between liquid and gas phase. The mathematical model which constructed can be used to predict the mass and heat transfer without introducing any adjustable parameters. The effect of air inlet velocity, water column height, and perforated plate hole diameter on heat and mass transfer were studied. Results indicated heat and mass transfer coefficient was improved by increasing inlet air velocity. Total heat flux is lightly decreased by increasing water column height and air bubble diameters. It was found that bubbler column performance is enhanced by increasing the temperature difference between air and water stream.

Khalil et al. [35] used different types of bubbler humidifier with different holes diameter as it is shown in Fig. 11. The system is composed of two loops; the first is the closed saline water cycle where saline water is heated by solar water heater then hot saline water is passed through bubbler column humidifier. The second loop is an open-air cycle where the air is injected into 1200 holes with different size 1, 3, and 5 mm. The influence of different parameters such as sieve plates hole size (hole diameter), inlet water temperature, water level in the humidifier, and air mass flow rate were studied. Bubbler column humidifier is a suitable solution for air humidification where air bubbles were

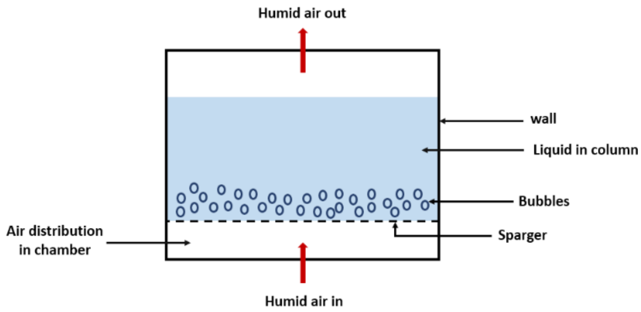

Fig. 10. Bubbler humidifier.

dispersed through the hot saline water to increase the area of contact between air and water for increasing air humidity as well as freshwater productivity. Bubbler column humidifier has many advantages such as effective mass and heat transfer, high contact surface area between air bubbles and hot saline water. A shell and tube heat exchanger was used as a dehumidifier. Shell is made of steel with 400×400 mm dimensions and 900 mm height. Results indicated productivity of the system is increased by increasing amount of water extracted by air bubbles. It was found that humidity of air is increased by decreasing sieve hole diameter. It is observed the best hole diameter is 1 mm which gave a high performance but, 5 mm diameter gave the lowest productivity as when size of hole decreased, the number of bubbles is increased consequently, contact surface area and time of contact between air bubbles and hot water were increased which enhanced the productivity of the system. Results showed that GOR of the system was 0.53, the daily production rate of freshwater was 21 kg, and system efficiency was 63% when inlet saline water was 62°C.

3.2. Dehumidifier

Dehumidifiers (condensers) are heat exchangers which are used for transferring the thermal energy from hot fluid to the cold one. Heat which exchanges in the heat exchanger could be latent heat or sensible heat or both. There are different designs of heat exchangers where two fluids are brought into contact; this contact may be direct or indirect form. In direct contact heat exchangers; two fluids interchanged energy in the absence of a separating wall such as cooling towers. This cooling technique is used for resolving many problems such as corrosion due to saline water contact, pressure drop, and leakage of seawater [36]. Indirect contact heat exchangers in which the two fluids are separated by a solid wall to prevent mixing such as regenerators that recover heat from cycling through heat sinks. Dehumidifiers are the second part of HDH water desalination system where hot humid air and cold saline feed water are brought into contact to produce condensing freshwater.

3.2.1. Different types of dehumidifiers

There are many types of dehumidifier systems including bubbler column, flat-plate and fin-tube dehumidifier. Different types are discussed in details in the following sections.

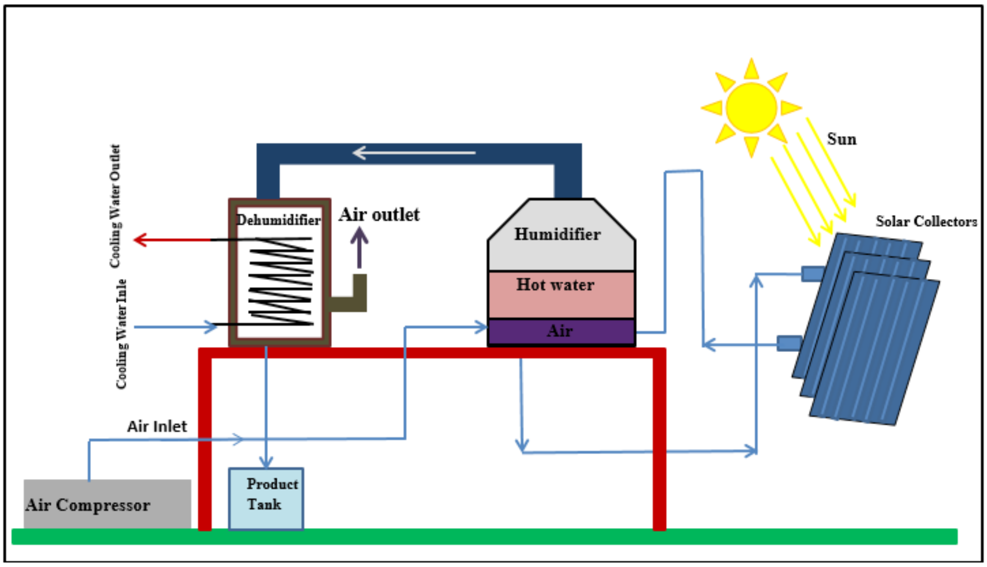

Fig. 11. HDH schematic diagram.

3.2.1.1. Bubbler dehumidifier

Bubbler column dehumidifier is a new technique for performing dehumidification process where humid air in the form of fine bubbles is cooled by indirect contact with saline water. Several studies were carried out in order to enhance condensation process performance. An innovative design of bubbler dehumidifiers was used by Tow et al. [37]. In the bubbler dehumidifiers, hot humid air is passed through a perforated plate (sparger) into a column of freshwater which is cooled by contacting with the cold saline water through a small coil. Bubbler dehumidifiers have many advantages such as enhancing heat transfer between hot humid air and feed saline water. In addition, bubbler dehumidifier is considered as an inexpensive unit than the conventional fin-tube heat exchanger that needs a large amount of copper or metals. Bubbler dehumidifier is used to overcome the high resistance to water vapor diffusion due to the non-condensable gases by using a large surface area of bubbles. An analytical model of heat and mass exchange was developed that used for the bubbler dehumidifier or humidifier. In order to improve HDT efficiency and decrease capital cost, various studies are performed for using an efficient dehumidifier configurations. Tow et al. [38] tested a bubble column dehumidifier that shown in Fig. 12 by using a smaller cooling coil length than those used in the previous study. Dehumidifier which was used in the experiments is 28 cm square and 36 cm high. In the bubble column dehumidifier, saline water is passed through coils that were made from 9.5 mm outer diameter copper tubes and humid air is distributed through a sparger which had 64 holes each 2.83 mm diameter. By indirect contact between bubbles of hot humid air and cold saline water, condensation of freshwater from air was obtained. Different parameters were varied to enhance the performance of the bubbler dehumidifier such as column liquid height, inlet moist air temperature, and cooling coil size. Results indicated bubble column dehumidifier effectiveness was enhanced and its value approaching 1 with increasing coil surface area. Heat flux and heat transfer rate per unit coil area were increased by decreasing the size of cooling coil. Heat flux was increased with increasing the temperature of inlet humid air as when inlet air temperature is increased that mean a high water vapor concentration in air and high air enthalpy. Effectiveness of bubble dehumidifier was decreased with increasing inlet moist air temperature as heat transfer coefficient of coils is near constant so, effectiveness is decreased. It was found that the critical liquid column height was below 4 cm when 2.83 mm orifice diameter was used.

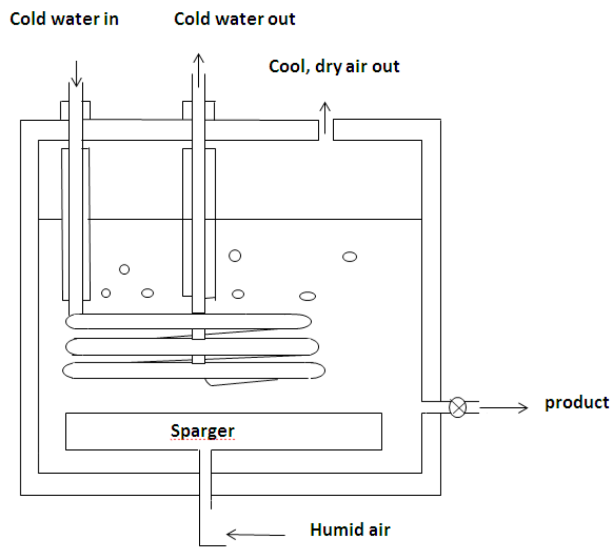

Fig. 12. Schematic diagram of the experimental bubble column dehumidifier.

A numerical model of heat and mass transfer was used by Chahayeb et al. [39] to evaluate HDH performance under varying feed salinity. A multi-tray bubble column dehumidifier was used to increase heat transfer rate between air bubbles and water by increasing air-water interface surface. The model of heat and mass transfer between air bubbles and feed water in a multi-tray dehumidifier was developed by Tow and Lienhard [40]. They assumed a perfect mixing in the dehumidifier so, exit air has the same temperature of the dehumidifier column. Results showed that for the single stage and two stage HDT systems, the best performance was obtained when modified HCR (heat capacity ratio) equal to 1. For the single stage, GOR was not affected by the feed salinity variation. It was found that GOR for 200 ppt is lower than 0 ppt. For two-stage HDT, the performance of the system was decreased with increasing feed salinity. In a single stage system, recovery ratio (RR) is not affected by feed salinity as it remains constant. For two-stage, RR was decreased from 8.3 to 7.9% when feed salinity was increased (0–200 ppt). Results indicated HDT performance was decreased slightly by increasing feed salinity because of decreasing of the vapor pressure of saline water that decreases the amount of water vapor extracted by air. It was found that when feed salinity increased from 0 to 200 ppt, optimum water to air mass flow rate ratio increased from 4.2 to 4.8. The effect of feed salinity on HDT performance was found to be neglected so, it is a very important advantage of HDT as the system is suitable for treating saline water with varying feed salinity.

3.2.1.2. Flat-plate dehumidifier

The flat-plate heat exchanger is used as a dehumidifier for hot humid air cooling in HDH system. It is composed of consecutive thin plates. Gaskets are used for separating between plates and make the system to be closed toward to the environment. Cooling of air is achieved by indirect contact with cold saline water. Flat plate heat exchangers were used by Sievers et al. [41] as a dehumidifier in HDH system. Thin plates were made of polyethylene. Feed saline water is distributed through the plates from the bottom and contacting with the humidified air which is passed through the top of the plates. The effect of using polypropylene as a construction material instead of a metal material on the flat-plate heat exchanger performance was studied. Fouling problem which results from depositing of suspended or dissolved salts also was discussed. A pretreatment of seawater was recommended for resolving this problem before using it in the dehumidifier. Fouling resistance is depending on different variables such as properties of dehumidifier surface, the velocity of seawater flow, and the temperature. A mathematical model was designed for a detailed analysis of the dehumidifier. Simulation of plate heat exchangers indicated fouling factor of saline water has the low efficiency due to their high thermal performance. It was found that polypropylene has a low thermal conductivity which causes 17% lower heat flow in comparison with titanium alloy plates with the same heat exchanger geometry.

3.2.1.3. Plate-fin tube dehumidifier

Plate-fin tube heat exchanger is used in air dehumidification process in HDH system and it is considered as one of the most common type for cooling air in HDH or HVAC (heating, ventilation and air conditioning) systems. This type is composed of numbers of tubes and plates. Hot air is passed through plates around the tubes where seawater is distributed into the tubes. Sievers et al. [42] studied water desalination by HDT using a plate-fin tube heat exchanger for dehumidification process. This type of dehumidifiers was composed of number of finned tubes which embedded in plates. Air is passed through the plates and saline water flows in the tubes. Fins were used to enhance heat exchanger performance as increasing area of heat transfer between hot humid air and cold saline water or to increase turbulence.

Dimensions of air cooling (dehumidifier) were; outside diameters 8, 10, 12.5,16, 20, 25 mm, longitudinal and transverse tube spacing (15–75 mm), fin spacing from (1.4–6.4 mm), fin thickness (0.127–0.203 mm). A numerical model of dehumidifiers was developed by using segment-by-segment method. The model of plate-fin tube heat exchanger was performed to indicate the effect of different geometric parameters on heat exchanger efficiency. Seawater pretreatment was carried out to prevent the fouling problem through the tubes. It is recommended that fouling resistance is 0.09 m^2 K/KW for a seawater temperature up to 50°C. Results showed that seawater pressure drop is increased by using shorter tubes. Heat flow from air flow direction was increased by increasing temperature difference between air and seawater. It was found that; air heat transfer coefficient was enhanced by 8% depending on the condensation production.

4. Thermodynamic analysis of HDH

The major drawback of HDH system is the low usable energy efficiency. Consequently, various thermodynamic analyses especially exergy analysis were carried out to elaborate HDH efficiency. Conventional thermodynamic analysis is based on first law of thermodynamics (FLT) that represents the concept of energy conservation and calculates energy efficiency of the system. However, energy efficiency cannot be considered as an accurate measure of system performance as the deviation between actual and ideal efficiency is not provided. Accordingly, exergy analysis overcomes the limitations of conventional energy analysis. Exergy analysis is a thermodynamic technique based on second law of thermodynamics (SLT) which is considered as a tool used for enhancing and optimizing designs and analyses. This analysis provides the deviation of actual performance of process and ideal one. It indicates the types, sources, and locations of energy losses [43].

4.1. Exergy concept

The first law of thermodynamics indicates that energy is not destroyed but can be transferred from one form to another. It determines the amount of energy in the system but no cares about the quality of using these amounts. Energy balance which is made by this law introduces that amount of energy enters the system equal to the amount out of the system at steady state. However, this balance gives no information about the direction of energy flow, quality or efficiency of energy and lost or destroyed amount of energy. So, FLT has many limitations which lead to the second law of thermodynamic concept that defines the direction of energy from higher temperature to lower one and clarifies the energy quality of the system is called exergy. So, the first law of thermodynamics uses energy balance for analysis of thermal systems but, the second law of thermodynamic uses exergy balance for analysis of these systems [44].

But before starting the use of exergy analysis we must firstly be introduced to some important terminologies which are used intensively in exergy analysis of desalination systems:-

- Exergy is the maximum utilization of energy in the system or the maximum theoretical work obtainable from an overall system consists of a system and an environment when a system state is higher than the dead state. Exergy can be classified into two types, thermomechanical and chemical exergy. The thermomechanical exergy can be defined as the maximum amount of work that can be obtained from the system when the temperature (T) and pressure (P) of the system differ from the temperature (T_o) and pressure (P_o) of the environment. The chemical exergy can be defined as the maximum theoretical work that can be obtained from the system when the concentration (W) of each component in the system differs from its concentration (W_o) in the environment at environment temperature and pressure [45].
- Dead state is a state in which system is in equilibrium with the environment, means that exergy which can be obtainable from the system equal to zero as the system and the environment have the same temperature and pressure, no potential for developing work.
- Entropy is a measure of the amount of molecules disorder in the system due to heat transfer from or to the system. When the system temperature is high this produces high entropy and vice versa. It measures the deviation of the process from the reversible process and evaluates irreversibilities which are created in the system.
- Exergy destruction is the amount of exergy which is lost due to irreversibilities, entropy generation, and dissipation of the energy from the system to the surrounding.
- Exergetic efficiency; there are three definitions of exergetic efficiency found in the literature. These are rational exergetic, conventional (simple) exergetic, and utilizable exergy coefficient. The simple definition is the ratio between outputs of exergy flows to the inputs of exergy flows. The rational exergetic efficiency is the ratio between the desired outputs exergy to the consumed exergy. Utilizable exergy coefficient is considered as an improved form of traditional efficiency as it extracted the transformed components from the input and output stream. [46]
- Exergy analysis is the analysis which aims to the effective use of nonrenewable energy resources such as natural gas, coal, and oil. This analysis calculates the amount of energy lost and indicates the locations where energy or exergy destruction due to entropy generation. Exergy analysis shows the locations of the energy degradation which leads to system improvement (more efficient system) as it is shown in Fig. 13.
- Pinch technology provides a systematic approach for design and targeting of thermal, chemical processes ,and utilities which associated with them [47]. The objective of this technology is to generate heat integration scheme in the process and offers energy target for the design which is the minimum amount of energy demand for thermal processes. Exergy analysis is combined with pinch technology in order to provide effective promising modifications.

4.2. Exergy analysis of different desalination techniques

Exergy analysis is an important tool used for analysis, improvement, design, and assessment of thermal systems. This analysis was performed for different water desalination technologies such as RO, MED, MSF which is discussed in this section. In order to improve RO performance and identifying the common causes of irreversibilities, an exergetic analysis is carried out for RO plant with 7250 m^3/d potable water production and 500 ppm [48]. The system was composed of low-pressure pumps where saline feed water is withdrawn, and then it is separated into process water and blend water. Saline process water is passed through a static mixer where HCl and antiscalant were added to prevent RO membrane deterioration. After that, saline water entered the cartridge filter for removing suspended solids then passed through RO membrane by a high-pressure pump. In RO desalination unit, saline water is separated into permeate (freshwater) and brine

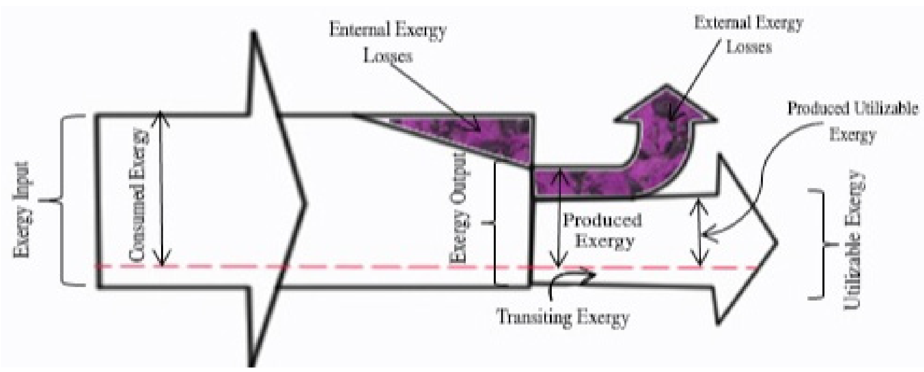

Fig. 13. Exergy analysis description.

(rejected water) which is discharged by two throttling valves. An exergy analysis of this unit is performed and showed that 80.8% of the exergy which entering the system is supplied by a high-pressure pump and the rest is supplied by a low-pressure pump. Exergy destruction which occurred in the membrane, static mixer, filter, and throttling valves were due to pressure drops through them. It was found that the largest exergy destruction occurred in RO membrane and it is complied with Romero-Ternero et al. [49] . They have found that 80% of exergy destruction occurs in RO unit, high-pressure pump, and valves but Aljundi et al. [50] found that highest exergy destruction occurs in throttling valves (58.8%). An alternative design was proposed to decrease irreversibilities occurs in the system caused by throttling valves. Throttling valves were replaced by pressure exchangers which transfer pressure energy from high-pressure stream to a low-pressure stream, these modifications save 94% of exergy losses and increase second law efficiency from 4.3 to 4.9%. Eshoul et al. [51] used pressure exchanger and found that exergy efficiency increased to 77% and exergy destruction decreased to 53%. Esposto et al. [52] studied the performance of RO desalination unit powered by photovoltaic (PV) panels and found that the overall exergetic efficiency of the system was 11.2% because of lowering of PV exergetic efficiency to15% and exergy is destructed and reached to 80% of the inlet exergy.

Sadri et al. [53] investigated the performance of RO desalination unit and simulated using exergy analysis. Influence of various operating parameters such as temperature and pressure of feed saline water were studied. Results indicated exergetic efficiency is increased and exergy destruction is decreased with increasing pressure. It was found that brine stream has the highest exergy destruction value. Results of optimization indicated that exergetic efficiency and freshwater production were improved by increasing membrane area.

Gude et al. [54] carried out an exergy analysis of desalination process at a temperature near ambient temperature and low pressure. Desalination of saline water occurs by evaporation at the low temperature near ambient temperature and at low pressure. Condensation process is performed to obtain freshwater. An exergy analysis of desalination process at low pressure is presented in order to define the most suitable operating parameters for decreasing exergy destruction. Results showed that the highest exergy destruction occurred in the condenser due to the dissipation of energy to the environment. It was found that overall exergetic efficiency was about 0.78%.

Gnaneswar [55] identified the locations where exergy destruction occurred in the desalination processes such as MSF, MED, and RO. Importance of second law analysis or exergy analysis was discussed. The study focused on exergy analysis of desalination processes for identifying further improvements which can be performed in the system. Mass, energy, and exergy balance equations for the control volume system were also provided. It was found that the major part where exergy destruction occurred was the condenser because of dissipation of heat to the environment. Using of high exergy sources in order to produce a higher performance product was recommended. An exergy analysis of MSF was carried out by Nafiz [56]. They have found that the highest exergy destruction occurred in MSF unit (77.7%) and second law efficiency was found 4.2%.

4.3. Exergy analysis of HDH system

Exergy analysis approach was performed for water desalination using HDT system in order to enhance its performance by identifying the locations where exergy destruction occurs. Exergy analysis provides the causes and common sources of exergy losses. An exergy analysis of solar multi-effect HDT desalination process was performed by Hou et al. [57] by using pinch technology. HD system was composed of two main parts; the first part was the wooden packed humidifier where hot saline water is sprayed and came into contact with air which is introduced by a fan. The second part is the condenser (dehumidifier). As usual, seawater is fed to the dehumidifier for preheating and recovered latent heat of condensation then it is further preheated in a flat-plate solar collector. After that hot saline water is sprayed into the packed bed humidifier for air humidification process then, air is cooled in the condenser by transferring heat to the cold saline water and producing freshwater. Exergy analysis was carried out on solar multi-effect HDT desalination process or on any thermal system for design, optimize and analysis of the system. The results indicated that exergy efficiency of HDT and the solar collector is low so, HDT system needs more improvements to increase the recovery rate of exergy. It was found that solar collector exergy loss was 4.77% and dehumidifier exergy destruction was 5.7%.

Elhaj et al. [46] have carried out an exergy analysis of HDT water desalination system to measure its performance with varying operating conditions such as saline water inlet and outlet temperature, cold air outlet temperature, air to saline water mass flow rate ratio, and feed salinity. It was aimed to measure exergy destruction and exergetic efficiency of each component of HDT system. The system which is used in this analysis as usual consists of humidifier (evaporator), dehumidifier (condenser) and solar collector. A computer programming using visual basic has been executed for determining exergy losses which occurred due to irreversibilities in the humidifier and dehumidifier. In addition, predicting the exergetic efficiency of HDH system. The results showed that humidifier and dehumidifier exergy efficiencies were enhanced by increasing air to saline water mass flow rate ratio. It was recommended that air exit temperature should be decreased and saline water inlet temperature should be increased to improve humidifier exergetic efficiency. Mass flow rate of cooling water or saline water flow rate has an important influence on dehumidifier exergy destruction as by increasing this value exergy destruction is increased as heat transfer to the environment is increased.

A novel hybrid water desalination system which is composed of HDT and RO has been analyzed by Al Sulaiman et al. [58] using exergy analysis. The proposed hybrid system has many merits when it is compared to other conventional desalination processes. It has higher GOR and low electricity requirements comparing to constant pressure HDH system. The hybrid system consists of two cycles. The first cycle is the humid air cycle where air enters the humidifier for air humidification then, it is passed through

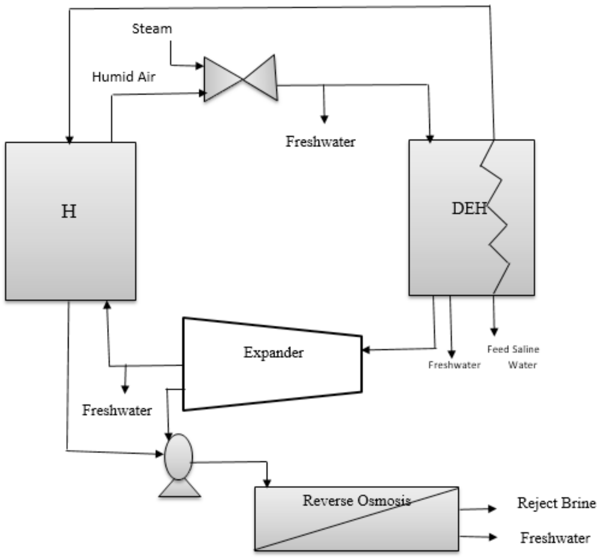

Fig. 14. Schematic diagram of HDH-TVC-RO desalination system.

thermal vapor compressor (TVC) where it is compressed with high-pressure steam. After that compressed humid air is cooled in the dehumidifier for freshwater production. Cold air enters expander which produces power that used for pump running in RO subsystem. Temperature and pressure of air were lowered, and then it is recycled to the humidifier and repeated the loop again. The second cycle is the saline water cycle where cooling of humid air is performed by an indirect contact with seawater in the dehumidifier. After that humidification step occurs by extraction of water vapor using air in the humidifier. Discharged brine was pumped to the RO for freshwater production. Performance parameters such as overall exergetic efficiency, exergy destruction, and specific exergy lost were examined. Different performance parameters were studied such as steam pressure and it was found that overall exergy efficiency is decreased by increasing steam pressure as energy which entering the system is increased. Results showed that produced water mass flow rate is increased from 6 to 8.8 kg/s when pressure of the system is increased from 1000 to 10000 kPa. The specific exergy destruction of the humidifier is decreased from 24 kJ/kg at 1000 kPa to 14 kJ/kg at 10000 kPa.

Muthusamy et al. [59] investigated an experimental analysis of HDH system to enhance system performance by adding inserts in the air heater, humidifier, and dehumidifier. It aimed to obtain maximum system performance and comparing HDT efficiency with using two different types of packing materials in the humidifier. HDH system is usually composed of air and water heater, humidifier chamber, air blower, and dehumidifier. Air heater is made of galvanized iron pipe with 500 mm length, 33 mm diameter, and 1.5 mm thickness and covered by asbestos rope for insulation and reduced energy losses to the environment. A humidifier with PVC material of construction was used with 152 mm diameter and 800 mm height. A shell and tube heat exchanger was used as a dehumidifier which is composed of one shell and 5 tubes with 13 mm diameter, 1000 mm length, and 152 mm shell outer diameter. As usual, air is supplied by a blower to air heater for increasing air temperature and water vapor content. Hot air is passed through the humidifier from the bottom and contacting with hot saline water which is heated in the water heater for air humidification. In the humidifier chamber, air is humidified and its humidity is increased then moist air is passed through the inner tube of the dehumidifier where hot air lost latent heat of vaporization to the cold saline water which is passed around the tubes or in the shell. Condensing freshwater is collected in the distillate tank. Due to the enhancement of HDH system some of modifications were performed in the system components. In the air heater, twisted tape, cut-out conical inserts, and half perforated circular inserts were added to increase heat transfer rate to the air as by increasing air temperature consequently, its ability of carrying water vapor is increased. In the humidifier, packing materials were used such as gunny bag and sawdust to increase area and time of contact between hot air and hot saline water which improves the system productivity. As well as in the dehumidifier, spring inserts were added to the inner tubes of a shell and inner tubes of the heat exchanger to enhance heat transfer between hot air and cold saline water which enhance condensation rate. Results showed heat transfer coefficient is increased by increasing Reynolds number which decreases the boundary layer due to inserts addition in the air heater and dehumidifier. Exit air temperature is increased by 40% with the addition of the twisted tape inserts in the air heater comparing with air heater without inserts. Results indicated that mass transfer coefficient is increased by increasing air mass flow rate. This study compared the usage of two different types of packing materials and proved the gunny material has high water retaining capacity and gave higher mass transfer coefficient for all air mass flow rates. Water retaining capacity of sawdust was good but it restricted air flow. One of the main aims was to perform an exergy analysis of HDH system and this analysis showed that exergy efficiency is enhanced by increasing Reynolds number. Air and water temperature were increased by using inserts in air heater. Resulting in, improving exergy efficiency of air heater and humidifier. The maximum exergetic efficiency was obtained when twisted tape is added to air heater and gunny material in the humidifier. The modified HDH system productivity was 0.670 kg/h with first law efficiency 44% and second law efficiency 38% comparing with the conventional HDH system productivity 0.340 kg/h with first law efficiency 20% and second law efficiency 15%. So, HDH system productivity increased by 45%.

Exergy, energy, economic and environmental analyses of the solar desalination system with HDT were performed by Deniz et al. [60] using data obtained from the experimental studies. A novel HDT desalination system was tested with actual conditions using solar energy as a heat source. HDH system is tested using solar energy as the heat source and photovoltaic (PV) for electrical energy. HDH unit is composed of humidifier and dehumidifier which are made of 1mm thick steel sheet and insulated with polystyrene. Pipes that used for water and air circulation is made of polyethylene and polyvinyl chloride (PVC) and insulated with the thermoflex material. Two sprays were used in the humidifier with 10 mm thickness cellulosic pad for increasing air humidification load. The finned heat exchanger used as a dehumidifier. Three stages of analyses were performed; energy, exergy and economic analyses. Many tests were performed to study the influence of the inlet and outlet temperatures of air and water, mass flow rates of air and water. An inverse relationship between temperature and relative humidity of air was noticed. Overall energy and exergy efficiencies were found between 4.1–31.54% and 0.03–1.867%, respectively. Cost of HDT was 0.098 US$/L which is decreased with increasing HDT efficiency. Results proved that HD unit productivity is improved with increasing air and water temperature that entered the humidifier. The maximum freshwater production rate was 1117.3 g/h

Chiranjeevi et al. [61] carried out an exergy analysis of a two-stage dehumidifier which represented an essential part of HDT system. Second law efficiency and irreversibility loss were calculated for the two-stage dehumidifier. HDT system consists of two main units. The first unit is the humidification unit where the air is humidified with water vapor which is produced from heating of saline water using solar energy as a heat source. Packing materials were used in the humidifier to enhance contact between hot air and hot water. The second unit is the dehumidification unit where humid air is dehumidified and cooled by an indirect contact between hot humid air and cold saline water. The system contains two-stage humidifier and two-stage dehumidifier. It was focused on exergy analysis of two-stage dehumidifier. In addition, irreversibility loss and second law efficiency were determined. In the first stage dehumidifier, humid air is cooled using an indirect contact with normal cooling water. In the second stage dehumidifier, hot air dehumidified using chilled water that is produced by vapor absorption refrigeration cycle using solar energy as a heat source. The relation between irreversibility loss, varying of cooling water temperature, and changing the mass flow rate of cooling water were studied. Results indicated that irreversibility loss is decreased by increasing water temperature, but up to a limit range of temperatures above this range, irreversibility loss is increased. Exergy efficiency of the first stage dehumidifier is studied with varying cooling water flow rates at different temperatures. It was observed that maximum exergy efficiency was obtained when the temperature of cooling water was (25–32.5°C) and high mass flow rate of cooling water. At a certain range of temperatures, second law efficiency is increased with increasing mass flow rate of cooling water because irreversibility is decreased. The optimum mass flow rate of cooling water was 500 L/h which gave a maximum exergy efficiency at 25°C. Variation of temperatures and mass flow rates of chilled water which used in the second stage dehumidifier were studied with the variation of exergy efficiency, second law efficiency, and irreversibility loss. Irreversibility loss is decreased with increasing cooling water flow rates. At a low cooling water mass flow rate, irreversibility loss is decreased with increasing water temperature. At high flow rates of cooling water, irreversibility loss is decreased by increasing water temperature but, up to a certain limit of temperatures. By increasing chilled water mass flow rates, dehumidifier exergy efficiency is increased because irreversibility loss is decreased. At a constant chilled water mass flow rate, second law efficiency is increased and irreversibility loss is decreased by increasing chilled water temperature. The optimum temperature of cooling was from 25 to 30°C to enhance exergy efficiency, second law efficiency, and decreased irreversibility loss.

Ashrafizadeh et al. [62] performed a new method for exergy analysis of HDT system. This method differs from conventional methods for exergy analyses which are called the stream wise method that are interested in exergy of input stream and exergy output stream. Advantages of this analysis are defining the locations where exergy destruction occurs in HDH system. In addition, calculating exergy losses caused by different kinds of irreversibilities in the system and performing an exergy analysis for each component in HDH system. The main objective of exergy analysis is to identify the locations where exergy losses occur to enhance and improve HDT performance. An exergy analysis of humidifier, dehumidifier, and the heater was carried out for defining causes of exergy losses in each unit. A mathematical model was developed for determining many parameters effects on exergy losses and making a comparison between the outputs of the model with the references. Results indicated that for water-heated closed air-open water (CAOW) HDH system, the major exergy losses source was found in the heater so, for improving HDT efficiency, heater efficiency should be enhanced. Similarly for air-heated closed air-open water cycle, the largest exergy destruction resources were found in the heater. For water-heated CAOW system, exergy losses in the humidifier were decreased by increasing air outlet temperature and GOR (gained-output ratio) was increased by increasing air outlet temperature. In the dehumidifier, exergy losses were decreased by increasing water outlet temperature on heated air CAOW cycle and under the same conditions, GOR of the dehumidifier was increased by increasing water outlet temperature. The maximum temperature of the HDH system (temperature outlet of air or water) has an important role in decreasing exergy losses. So, exergy losses are decreased by increasing the maximum outlet temperature also GOR is increased by this increase. Air-heated system gave a higher performance than water-heated system. Other factors were studied to determine their effect on exergy loss such as inlet water temperature factor. It was found that total exergy losses were decreased by increasing water inlet temperature but, up to limit as above this limit exergy losses is increased. It was observed that GOR is increased with increasing inlet water temperature but at a certain value GOR is decreased with increasing inlet water temperature. The optimum inlet water temperature was found to be (30–35°C).

Muthusamy et al. [63] presented an exergy analysis of water desalination by humidification dehumidification technology in order to provide the improvements for energy saving potential in the system and increasing HDT productivity with decreasing the power input of the system. Different modifications were performed in HDT components for enhancing its performance and making it as an efficient desalination technology from the thermodynamic point of view. HDT is composed of air heater which is made of iron pipe (1000 mm length, 38 mm diameter), water heater, humidifier, and dehumidifier. Air is supplied by a blower to air heater then, it is passed through a humidifier column which is made of plastic pipe (152 mm diameter-800 mm height). Water heater is made of iron where cold saline water is heated then, it is sprayed at the top of the humidifier column for air humidification. Two types of dehumidifiers were used in order to select the more efficient one; the first type was double pipe dehumidifier which made of aluminum (1000 mm long, 32 mm diameter). The second type was shell and tube dehumidifier that is composed of one shell and five tubes. Air heater modifications were added for enhancing heat transfer such as half perforated circular inserts. Three types of packing materials such as sawdust, leaves, gunny bag and plastic cylinder were used in the humidifier. Spring inserts were added to the shell and tube dehumidifier for enhancing heat transfer rate between cold saline water and humid air. The optimum mass flow rate of saline water in the humidifier was 42 kg/h and 110 kg/h in the dehumidifier which gave the maximum productivity of HDH system. Heat transfer coefficient is enhanced by adding inserts in the dehumidifier that increased Reynolds number and enlarging turbulences which enhanced heat transfer rate. Gunny bag materials were found to be the best packing materials compared with saw dust. Exergetic efficiency of air heater is increased with decreasing of pitch ratio and increasing of an angle of orientation of circular inserts. Maximum exergetic efficiency was found in the air heater, humidifier, and dehumidifier but minimum exergetic efficiency was in the water heater. The productivity of modified HDH system was increased by 50% compared with the conventional system by using the same energy input. Second law and first law efficiencies for modified HDH system were 38% and 44% respectively compared with the conventional HDH system which was 15% and 20%.

Mistry et al. [64] performed irreversibilities analysis of water desalination by HDT for defining the potential improvements in the system. First objective was applying entropy generation analysis for minimizing entropy generation and identifying further improvements of HDH components. Second objective was defining of operating conditions which should take it into account for HDT designing. Authors found that GOR and entropy generation were affected by water-air mass flow rate ratio at a constant top temperature with changing component effectiveness. Optimal configurations of air heated and water heated cycle for entropy generation minimization and increasing GOR were discussed. It was found that GOR is not a function of entropy generation as it is based on mass flow rate ratio. It was observed that there was not a direct relation between exergy analysis and GOR. For any cycle, effectiveness of humidifier or dehumidifier would be limited by minimum temperature pinch of HDH system.

Alhazmy et al. [65] investigated a theoretical analysis according to second law of thermodynamics of HDT system in order to estimate the minimum work required for dehumidification process for producing freshwater. Air dehumidification cycle consists of two path; isothermal dehumidification path then sensible cooling dehumidification path. Dehumidification process is assumed to be a separation process of an ideal air-water vapor mixture. Minimum work of dehumidification process is defined as, the work required to carry out the reversible process path. The minimum work necessary for dehumidification process is increased by increasing inlet temperature at a certain inlet relative humidity because of increasing of vapor content of air. Minimum work is increased by 6.7% when inlet temperature is increased by (10°C). At a certain dry bulb temperature, minimum work is increased by 1.7%. Authors provided contours of minimum work plotted on psychometric chart which help designers to estimate the minimum work for air-dehumidification process.

Mistry et al. [66] discussed entropy analysis and second law efficiency of desalination technologies for explanation of irreversibilities causes. Entropy generation sources in many desalination techniques such as HDT, RO, MEF systems were presented. The model which was developed by Mistry [67] was used with additional equations for calculating of entropy generation caused by change of temperature and chemical composition. The model was designed by considering all components of HDH system (humidifier, dehumidifier and water heater) as black boxes and the selected operating conditions were provided. It was found that RO technology has highest second law efficiency followed by multi vapor compression then multi-effect distillation then HDH system, so further research development will be needed for HDT to increase its efficiency.

Nematollahi et al. [68] performed an energy and exergy analysis of humidification-dehumidification solar desalination system. A mathematical model of HD system was presented in order to determine exergy or energy efficiency and calculating exergy destruction characteristics of equipment. HDT solar desalination system is mainly composed of solar collector that made of galvanized iron with 2 m^2 area where the air is heated, humidifier, and dehumidifier column which are existed in a compact tower. This tower is made of the cylindrical galvanized iron tube with 2 m height and 20 cm diameter. A packed column humidifier with using pall Rings was used to enhance mass and heat transfer between air and water. Air condenser (dehumidifier) was shell and tube heat exchanger with 20 cm diameter and 1 m length. Mathematical models for solar collector and humidification column separately were presented. In addition, exergy analysis model was performed. In this model, kinetic and potential exergies were neglected and only physical exergy was considered. Exergetic efficiency of HDT system which measures its performance was calculated. The major part which was responsible for exergy destruction was the packed bed humidifier. Effect of tower height was discussed and it was found that by increasing the height of the column, outlet air temperature is decreased but, outlet air humidity is increased and overall exergy destruction is increased. Exergy of inlet air is increased by increasing inlet air temperature but, exergy destruction is increased. By increasing tower diameter and other factors were kept constant, outlet temperature of air, outlet temperature of water, outlet air humidity, and exergy destruction were decreased. It was observed that using a large column diameter with low length that increases the overall exergetic efficiency of HDH system.

Srithar et al. [69] introduced the performance of enhanced air heater which is used in HDT desalination system by performing exergy efficiency evaluation of air heater with adding some inserts for improving heat transfer rate through the heater. Half perforated circular inserts were added in air heater in order to increase heat transfer coefficient and improve HDT performance. System performance evaluation using exergy analysis was presented. Effect of various parameters was studied such as air flow rate (14–21 kg/h), circular baffles pitch ratio (1.5, 3), and orientation angles (45°, 90°, 180°). HDT system consists of enhanced air heater, humidifier, dehumidifier, and water heater. Air heater is made of galvanized iron pipe (33 mm diameter–500 mm length) and insulted by asbestos rope to prevent heat dissipation of heat to the environment. Packed bed humidifier (152 mm diameter–800 mm height) with oriented gunny bags packing materials for enhancing contact surface area and increasing contact time between air and water was used. Water heater with 13 mm diameter and 500 mm length was used for water heating. Double pipe condenser was used as a dehumidifier (32 mm diameter, 500 mm length) for humid air cooling and producing of freshwater. Results showed that heat transfer rate is enhanced by increasing Reynolds number, increasing the angle of orientation and decreasing of pitch ratio with using circular inserts. Heat transfer rate in air heater is enhanced by increasing orientation angle as turbulences are increased. It was found that exergy efficiency of enhanced air heater is increased by increasing orientation angle between plates and decreasing of pitch ratio between baffles and inlet air mass flow rate. Maximum exergetic efficiency was found to be 96% when orientation angle was 180°, 1.5 pitch ratio, and 0.04 kg/s air flow rate.

5. Conclusions

Water desalination by humidification-dehumidification technology has been discussed in details. HDH system is one of the most suitable methods for small-scale freshwater production. Different types of humidifier and dehumidifier have been mentioned for studying the effect of operating conditions varying on HDT efficiency such as saline water inlet temperature, inlet and outlet air temperature, saline water-air mass flow rate ratio, and feed salinity. Thermodynamic analysis of HDT especially exergy analysis which is a measure of maximum utilization of energy in the system has been introduced. From the literature, it is found that HDT exergetic efficiency is low so, a further research development of HDT is required to enhance system performance

Symbols

h, H — Specific enthalpy (kj/kg)
h_{fg} — Specific enthalpy of vaporization of water (kj/kg)
$L_{w.vap}$ — Latent heat of vaporization of water (j/kg)
m, M — Streams mass flow rate (kg/s)
Q — Heat transfer rate (kj/s)
W_c — Power of air compressor (kj/s)

Greek

Ω — Air humidity (kg_{da}/kg_{wv})
$\omega_{sat.air}$ — Saturation humidity of outlet air (kg_{da}/kg_{wv})
Η — Efficiency
ε — Effectiveness

Subscripts

A — Air
D — Desalination
H — Humidification
W — Water

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